ARRA

Basic Asphalt Recycling Manual

U.S. Department of Transportation

Federal Highway Administration

ASPHALT RECYCLING AND RECLAIMING ASSOCIATION

Basic Asphalt Recycling Manual

Cover Photo: Downtown Houston, Texas

U.S. Department
of Transportation

**Federal Highway
Administration**

ASPHALT RECYCLING AND RECLAIMING ASSOCIATION

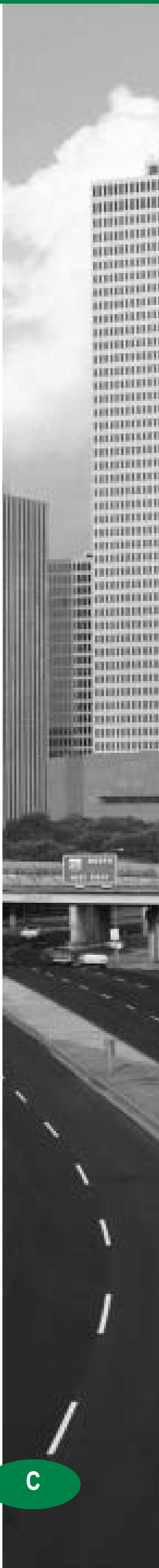
DISCLAIMER

The Asphalt Recycling and Reclaiming Association (ARRA) have taken every care and precaution during the preparation of this manual, recognizing that the “State-of-the-Art” of in-place asphalt recycling is continually evolving. Mature engineering judgement and skill must be used to properly apply the information, guidelines, and principles contained within this manual, taking into account existing conditions, locally available materials, equipment, and expertise. ARRA can accept no responsibility for any defects or failures in the performance of any recycled materials, pavement structures, analysis or designs resulting from an inappropriate application or use of information contained within this manual.

The photographs, drawings, and/or processes used in this manual are for illustration purposes only. They do not imply preferential endorsement of any particular make, model, or process by ARRA.

PRINTED IN THE USA

Forward



ARRA has published this first edition of the Basic Asphalt Recycling Manual (BARM). The BARM was prepared by Mr. Leonard Dunn, P.Eng. under contract with ARRA. Dr. Stephen Cross, P.E. (University of Kansas) was subsequently retained to assist in the preparation of Chapters 15 to 17, on Cold Recycling.

A steering committee consisting of Mr. Brian Hansen (Dustrol, Inc.), Mr. Stephen Damp (Miller Paving Limited), and Mr. Todd Casey (Base Construction Co., Ltd.) directed and oversaw the preparation of the BARM.

Mr. Fred Miller of the ARRA office undertook the initial editing of the BARM.

Mr. John Huffman, P.E. (Brown & Brown, Inc.) was an invaluable resource during the initial preparation and acted as the final editor of the BARM.

Valuable input and advice were received from the general ARRA membership. In particular, the assistance of the following ARRA members is greatly appreciated.

- Mr. Angelo Benedetti (Angelo Benedetti, Inc.)
- Mr. Todd Casey (Base Construction Co., Ltd.)
- Mr. Kenneth Damgaard (Arizona Department of Transportation)
- Mr. Stephen Damp (Miller Paving Limited)
- Mr. Charles Dane (Slurry Pavers, Inc.)
- Mr. Barry Dunn (Viking Construction Inc.)
- Mr. John Emery, P.Eng. (John Emery Geotechnical Engineering Ltd.)
- Mr. Ken Fyvie (Terra Engineering Ltd.)
- Mr. Jim Halverson (J.A. James Construction Company)
- Mr. Brian Hansen (Dustrol, Inc.)
- Mr. Terry Hauer (Caterpillar Paving Products, Inc.)
- Mr. John Huffman, P.E. (Brown & Brown)
- Mr. Ed Kearney, P.E. (Gorman Bros., Inc.)
- Mr. Brian Mountjoy, P.Eng. (Hard Rock Paving Company Limited)
- Mr. Stuart Murray (Wirtgen America, Inc.)
- Mr. Bill Petersmeyer (ARC Asphalt Recycling Corporation)
- Mr. Michael Polak (E. J. Breneman, Inc.)
- Mr. John Rathbun (Cutler Repaving, Inc.)
- Mr. Dennis Ryan (Copperstate Emulsions)
- Dr. Tom Siddon, P.Eng. (Martec Recycling Corporation)
- Mr. Bryan Vuillaume (Pallette Stone Corporation)
- Mr. Phillip Wise (Hamm Compactors Inc.)

BASIC ASPHALT RECYCLING MANUAL

TABLE OF CONTENTS

PART 1: INTRODUCTION, RECYCLING OVERVIEW, AND PROJECT EVALUATION

PART 2: HOT IN-PLACE RECYCLING (HIR)

PART 3: COLD PLANING (CP)

CHAPTER 9: COLD PLANING SPECIFICATIONS AND INSPECTION 127

PART 4: FULL DEPTH RECLAMATION (FDR)

CHAPTER 10: FULL DEPTH RECLAMATION - DETAILED PROJECT ANALYSIS 133

CHAPTER 11: FULL DEPTH RECLAMATION - MIX DESIGN 143

CHAPTER 12: FULL DEPTH RECLAMATION - CONSTRUCTION 157

CHAPTER 13: FULL DEPTH RECLAMATION - SPECIFICATIONS AND INSPECTION 179

PART 5: COLD RECYCLING (CR)

CHAPTER 16: COLD RECYCLING - CONSTRUCTION 215

CHAPTER 17: COLD RECYCLING - SPECIFICATIONS AND INSPECTION 229

Chapter 1

INTRODUCTION

The growing demand on our nation’s roadways over that past couple of decades, decreasing budgetary funds, and the need to provide a safe, efficient, and cost effective roadway system has led to a dramatic increase in the need to rehabilitate our existing pavements. The last 25 years has also seen a dramatic growth in asphalt recycling and reclaiming as a technically and environmentally preferred way of rehabilitating the existing pavements. Asphalt recycling and reclaiming meets all of our societal goals of providing safe, efficient roadways, while at the same time drastically reducing both the environmental impact and energy (oil) consumption compared to conventional pavement reconstruction.

The Board of Directors of the Asphalt Recycling and Reclaiming Association (ARRA), in their ongoing commitment of enhancing and expanding the use of asphalt recycling and reclaiming, recognized a need for a “Basic Asphalt Recycling Manual”. The manual was needed in order to expose more owners, specifying agencies, consultants, and civil engineering students to the value and current methods of asphalt recycling. To fill that need, this manual was produced to serve as a handy one-stop reference to those starting out in one of the various forms of asphalt recycling. In addition, it is hoped that this manual will provide additional useful information to those already involved in asphalt recycling.

This manual is not written in such detail so that one could use it to completely evaluate, design, specify, and/or construct an asphalt recycling project. It does however, provide information on:

- various asphalt recycling methods
- benefits and performance of asphalt recycling
- procedures for evaluation potential projects
- current mix design philosophies
- construction equipment requirements and methods
- Quality Control/Quality Assurance, inspection and acceptance techniques
- specification requirements
- definitions and terminology

Sufficient information is provided so that a rational decision can be made with respect to the feasibility and/or cost benefits of asphalt recycling. From that point, detailed design issues will need to be addressed by those experienced in asphalt recycling techniques prior to the final project design, advertising, tendering or letting and construction.

Asphalt recycling provides an additional rehabilitation method for maintaining existing roadways. The benefits of asphalt recycling include:

- reuse and conservation of non-renewable natural resources
- preservation of the environment and reduction in land filling
- energy conservation
- reduction in user delays during construction

- shorter construction periods
- increased level of traffic safety within construction work zone
- preservation of existing roadway geometry and clearances
- corrections to pavement profile and cross-slope
- no disturbance of the subgrade soils unless specifically planned such as for Full Depth Reclamation (FDR)
- improved pavement smoothness
- improved pavement physical properties by modification of existing aggregate gradation, and asphalt binder properties
- mitigation or elimination of reflective cracking with some methods
- improved roadway performance
- cost savings over traditional rehabilitation methods

It is important to recognize that asphalt recycling is a powerful method to rehabilitate pavements. When properly applied, it has long term economic benefits—allowing owner agencies to stretch their available funds while providing the traveling public with a safe and reliable driving surface.

It is also important to recognize that, although asphalt recycling technology and methods has advanced, not all roadways are appropriate candidates for asphalt recycling. With the almost endless supply of roadways needing rehabilitation, it would be a disservice to the public and the industry to use poor judgement in attempting an inappropriate recycling project. Hopefully, with this manual and the advice of those experienced in asphalt recycling, only projects that are suitable candidates will be undertaken.

The primary focus of the manual is on the in-place and cold recycling of asphalt pavements. Hot recycling of asphalt pavements through various types of asphalt plants is a well established recycling method. There is a wide variety of information on the subject available from well established sources and therefore has not been covered in any detail in this manual.

1.1 BACKGROUND

Population growth and economic development have resulted in an extensive network of asphalt paved roadways in the last 50 to 70 years. Many thousand of miles (kilometers) were constructed to meet the demands of increased traffic and the majority of these roads are near/at/or past the end of their original design life.

When the roadway network was rapidly expanding, the initial construction cost was the most important issue, with little or no attention being paid to the ongoing maintenance costs. However, as the roadway network has matured, as the traffic volume and gross vehicle weights have increased, and as funds have become more tightly budgeted, increased emphasis has been placed on preventive maintenance and preservation of the existing roadways. In many jurisdictions, the funds available have not been able to keep pace with the increased preventive maintenance and preservation costs as the roadway network aged. This has resulted in a significant reduction in the condition and the level of service provided by the roadways within the network. This has in turn resulted in increased overall preventive maintenance and more expensive rehabilitation/reconstruction costs.

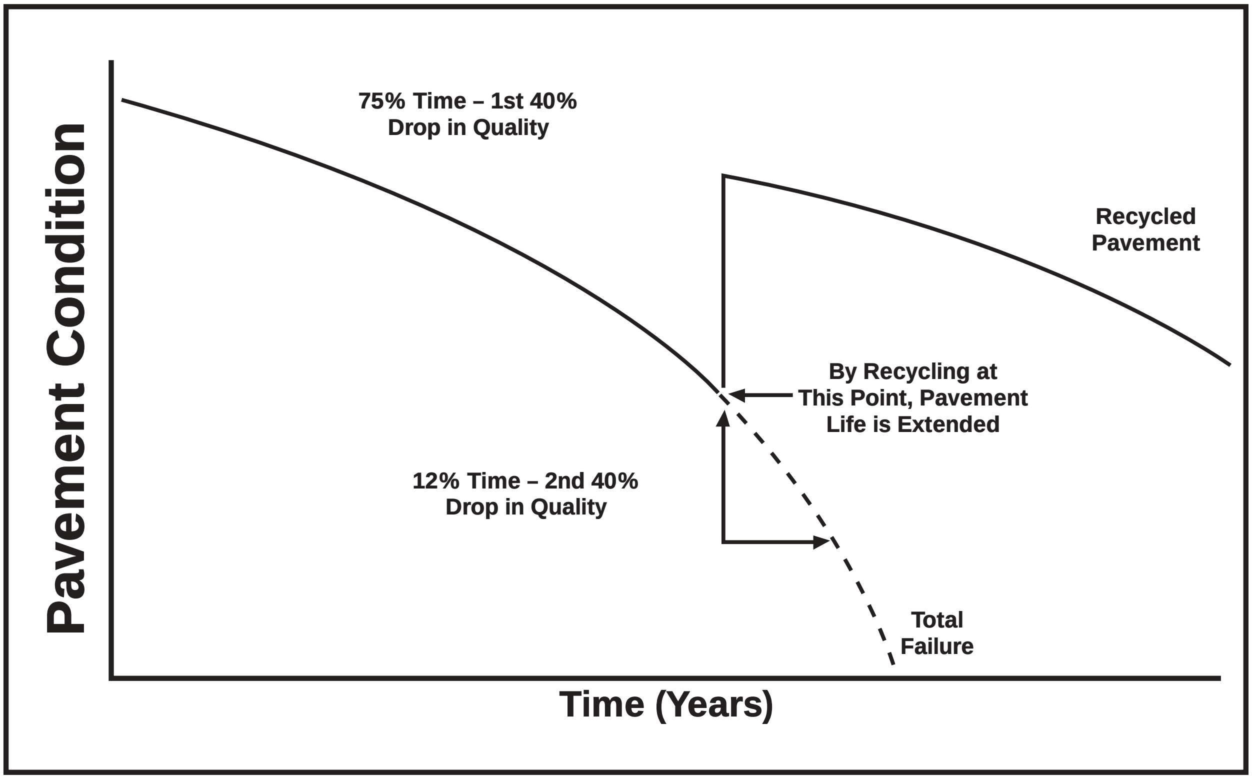


Figure 1-1: Pavement deterioration and recycling rehabilitation vs. time

It is well recognized that a sound infrastructure, including roadways, is required for a good economy with an adequate level of growth. Studies have indicated that if a roadway is maintained, at an acceptable level of service, it will ultimately cost the owner less. A World Bank study indicates that each $1.00 expended at the first 40 percent drop in roadway quality will result in a savings of $3.00 to $4.00 compared to the expenditure which would be required at the 80 percent drop in quality, as indicated in Figure 1-1.

Since funding for preventive maintenance, preservation, rehabilitation, and reconstruction of roadways will have to compete with other demands on the public purse, innovation is required in order to do more with less. Asphalt recycling is one way of increasing the effectiveness of existing budgets in order to maintain, preserve, rehabilitate and reconstruct more miles (kilometers) of roadway for each dollar spent.

Asphalt recycling is not a new concept. Cold recycling/rehabilitation of roadways with asphalt binders dates to the early 1900's. The first documented case of asphalt recycling, in the form of Hot In-Place Recycling (HIR), was reported in the literature of the 1930's. However, only moderate advancements in asphalt recycling technology and equipment occurred until the mid 1970's

Two events of the 1970's rekindled the interest in asphalt recycling which has resulted in its worldwide use today. The petroleum crisis of the early 1970's and the development and introduction in 1975 of large scale cold planing equipment, complete with easily replaceable tungsten carbide milling tools, were the catalyst for renewed interest in asphalt recycling. Since that time, the equipment manufacturing and construction industries have been proactive in the development of asphalt recycling methods and technologies which have advanced exponentially in the last 25 years.

Society has become increasingly aware of the effects of all types of development on the environment. Many countries have already enacted legislation which requires that certain percentages of materials, particularly the ones used in roadway construction and rehabilitation, must be recycled or include recycled materials. By demonstrating the technical viability, the savings in energy and non-renewable natural resource (crude oil and granular materials) and the cost savings associated with asphalt recycling, progress towards one of society's goals of environmentally responsible construction processes will be achieved. It is noted, that asphalt pavements are presently the most commonly recycled material in North America.

1.2 ASPHALT RECYCLING METHODS

Five broad categories have been defined by ARRA to describe the various asphalt recycling methods. These categories are:

- Cold Planing (CP)
- Hot Recycling
- Hot In-Place Recycling (HIR)
- Cold Recycling (CR)
- Full Depth Reclamation (FDR)

Within these five broad categories of asphalt recycling, there are a number of sub-categories which further define asphalt recycling. These include:

- HIR
    - Surface Recycling (Resurfacing)
    - Remixing
    - Repaving
- CR
    - Cold In-Place Recycling (CIR)
    - Cold Central Plant Recycling (CCPR)
- FDR
    - Pulverization
    - Mechanical stabilization
    - Bituminous stabilization
    - Chemical stabilization

In addition, asphalt recycling methods can be used in conjunction with one another on some roadway rehabilitation projects. For instance, an existing roadway could have an upper portion removed via CP and the resultant Reclaimed Asphalt Pavement (RAP) could be stockpiled at the asphalt plant. The cold planed surface, once prepared, could be overlaid with hot mix asphalt (HMA) containing the RAP from the milled off layer. Alternatively, prior to the placement of the recycled mix, the exposed CP surface could have been HIR, CIR or FDR in order to mitigate or eliminate the effects of reflective cracking.

Figure 1-2: Typical front loading milling machine

The abbreviations or acronyms noted on the previous page, are the ones ARRA and the Federal Highway Administration (FHWA) have been using and promoting to ensure that everyone is speaking the same language with respect to the various asphalt recycling categories.

1.3 COLD PLANING (CP)

CP is the controlled removal of an existing pavement to a desired depth, longitudinal profile, and cross-slope, using specially designed equipment, as indicated in Figure 1-2.

The resulting textured surface can be immediately used as a driving surface, can be further treated with one of the other asphalt recycling methods, or once cleaned and tack coated, overlaid with HMA or recycled mix. In addition, CP can be used to roughen or texture pavements to restore low friction numbers and eliminate slipperiness, as indicated in Figure 1-3.

The modern cold planer or milling machine has a large diameter rotary cutting drum or “cutter/rotor/mandrel” housed in a “cutting chamber.” The cutter is equipped with specially designed replaceable tungsten carbide cutting “teeth” or “tools” that remove or “mill” the existing pavement. A small amount of water is used during the milling operation to control the amount of dust generated and to extend the life of the tools. The water is sprayed unto the tools by a number of nozzles in the cutting chamber. Milling machines are self-power/self-propelled and of sufficient size to provide the traction and stability needed to remove the pavement surface to the specified profile and cross-slope. Most are equipped with automatic grade control systems to mill to the specified elevations and grades.

Figure 1-3: Milled pavement surface texture improve friction numbers

Figure 1-4: Half-lane cold planing machine

The RAP generated during the CP operation is loaded onto haul trucks by the milling machine and removed from the site. The RAP is then further recycled using the CCPR or hot recycling process. The RAP could also be reused as base aggregate for roadway construction and widening, ditch linings, pavement repairs or a dust free surfacing on gravel roads. The reuse of the RAP, as a base aggregate or similar material, is a form of the three "R's" of recycling (reduce, recycle, and reuse) but the higher "value added" application would be in CCPR or recycled mix.

CP advantages include:

- removal of wheel ruts, washboarding, deteriorated pavement surfaces, and/or oxidized asphalt
- correction of longitudinal profile and cross-slope
- restore drainage
- removal of the total asphalt structure for further recycling on roadway reconstruction or shoulder widening projects
- removal of crack sealant or seal coats prior to HMA overlays
- improvement of friction numbers
- removal of built up pavement at curbs to restore reveal height
- surface preparation prior to an additional form of asphalt recycling
- energy conservation compared to other reconstruction methods
- increased project efficiency and reuse of existing materials
- higher productivity with less disruption to the public

1.4 HOT RECYCLING

Hot recycling is the process of combining RAP with new or "virgin" aggregates, new asphalt binder, and/or recycling agents (as required) in a central plant to produce a recycled mix. Hot recycling utilizes the heat-transfer method to soften the RAP to permit mixing with the virgin aggregates and asphalt binder and/or recycling agent. Specially designed or modified batch or drum mix plants, as indicated in Figures 1-5 and 1-6, are used for hot recycling.

Hot recycling of RAP currently is the most widely used asphalt recycling method in the world. Over 50 million tons (45 million tonnes) of RAP are generated annually by State Highway Agencies. Of this, approximately 33 percent is being used in hot recycling, 47 percent is being used in other asphalt recycling or reuse applications and less than 20 percent is being discarded.

Agencies have different approaches to the amount of RAP which is permitted in recycled mix, and where in the pavement structure recycled mix can be used. The most progressive of agencies have successfully used recycled mix in all the pavement layers, including surface courses, provided proper evaluation of the RAP, mix design, Quality Control/Quality Assurance, and construction has been undertaken.

The results of the Strategic Highway Research Program (SHRP) and the Superpave system for the design of HMA mixes are now being implemented in hot recycling, although additional research and evaluations are ongoing.

Generation of the RAP for hot recycling is either by CP or by ripping, removing, and crushing of the existing pavement, although CP is preferred.

Figure 1-5: Asphalt batch plant with RAP infeed for hot recycling

Figure 1-6: Drum mix plant with RAP infeed for hot recycling

As the heat-transfer method is used to soften the RAP for mixing during hot recycling, it is essential that moisture in the RAP be kept to a practical minimum. Excess moisture in the RAP, which tends to retain moisture longer than virgin aggregates, decreases plant production rates as heat is used to turn the moisture to steam instead of heating and softening the RAP.

The amount of RAP used in hot recycling has some practical limitations which are related to plant technology, gradation of the aggregates within the RAP, physical properties of the asphalt binder in the RAP, and gaseous emission regulations. The ratio of RAP to virgin aggregates used in hot recycling, has been as high as 85 to 90 percent. However, it is more typically around 15 to 25 percent for batch plants and 30 to 50 percent for drum mix plants.

Once the recycled mix has been produced, it is transported, placed, and compacted with conventional HMA equipment. No special techniques are required for laydown and compaction, but recycled mix is frequently placed at slightly lower temperatures than new HMA. The lower temperature is a result of efforts to reduce the effects of extremely high temperatures at the asphalt plant. Since the mix temperature is somewhat lower, the recycled mix is “stiffer” which slightly reduces the amount of time available for compaction.

Hot recycling advantages include:

- conservation of non-renewable resources
- energy conservation compared to other reconstruction methods
- disposal problems inherent in conventional methods are eliminated
- problems with existing aggregate gradation and/or asphalt binder can be corrected with proper selection of virgin aggregates, asphalt binders and/or recycling agents
- curb reveal height and overhead clearance can be maintained
- provides the same, if not better, performance as pavements constructed with 100 percent new materials
- economic savings are realized

Due to the fact that hot recycling is such a common recycling method with extensive information available, it will not be covered further within this manual.

1.5 HOT IN-PLACE RECYCLING (HIR)

With HIR, 100 percent recycling of the existing asphalt pavement is completed on site. Typical treatment depths range from 3/4 to 2 inches (20 to 50 mm) although some equipment can treat up to 3 inches (75 mm). The process consists of heating and softening the existing asphalt pavement, permitting it to be scarified or hot rotary milled to the specified depth. The scarified or loosened asphalt pavement is then thoroughly mixed and subsequently placed and compacted with conventional HMA paving equipment. Virgin aggregates, new asphalt binder, recycling agents and/or new HMA can be added on an as-required basis. Generally, virgin aggregates or HMA addition rates are limited by equipment constraints to less than 30 percent, by mass of HIR mix. The addition rates of the various additives are determined from an analysis of the existing asphalt pavement properties and subsequent laboratory mix designs, to confirm compliance with the required mix specifications.

There are three sub-categories within HIR which are used to further define asphalt recycling, based on the process used. These processes include Surface Recycling, Remixing, and Repaving. The HIR process uses a number of pieces of equipment, including pre-heaters, heaters, heater/scarifiers, mixers, pavers, and rollers. Consequently, the combined equipment spreads out over a considerable distance and is often referred to as a "train."

Surface Recycling is the HIR process in which softening of the asphalt pavement surface is achieved with heat from a series of pre-heating and heating units. The heated and softened surface layer is then scarified with either a series of spring activated teeth or "tines," or a small diameter rotary milling head to the desired treatment depth. Once the surface has been scarified, the addition of a recycling agent (if required) takes place, the loose recycled mix is thoroughly mixed and then placed with a standard paver screed.

Specified treatment depths generally range from 3/4 to 1 1/2 inches (20 to 40 mm). No new HMA or virgin aggregates are added during the Surface Recycling process so the overall pavement thickness remains essentially the same. Surface Recycling is often used in preparation for a subsequent HMA overlay.

Surface Recycling is the oldest HIR process and is indicated in Figures 1-7 to 1-9.

Compaction of the recycled mix is with conventional rubber-tired, static steel, and/or vibrating steel drum rollers.

A chip seal or HMA overlay is generally placed in a subsequent operation, although the recycled mix has been left as the surface course on some low volume roads.

Figure 1-7: Surface Recycling heating units

Figure 1-8: Surface Recycling scarification teeth

Figure 1-9: Recycled mix placement

Figure 1-10: HIR Remixing train

Remixing is the HIR process in which the existing asphalt pavement is heated, softened, and scarified—and virgin aggregate, new asphalt binder, recycling agent, and/or new HMA is added (as required) and the resultant, thoroughly mixed. Homogeneous recycled mix is placed in one layer, as indicated in Figure 1-10.

Remixing is generally used when the properties of the existing pavement require significant modification through the addition of any or all of the following: virgin aggregates, new asphalt binder, recycling agent, and/or new HMA. The recycled mix is usually left as the wearing surface but it could be chip sealed or overlaid with new HMA, as a separate operation.

Remixing is also further classified into single and multiple stage methods. In the single stage method, the existing asphalt pavement is sequentially heated and softened, and the full depth of the pavement to be treated is scarified at one time, as indicated in Figure 1-11. Treatment depths for single stage Remixing are generally between 1 to 2 inches (25 and 50 mm).

In the multiple stage Remixing method, the existing asphalt pavement is heated, softened, and scarified in a number of thin layers until the full treatment depth is reached. Usually between two and four layers are heated and scarified, with the scarified material being placed in a windrow to permit heating and scarification of the underlying layer, as indicated in Figure 1-12. The specified treatment depth for multiple stage Remixing is generally between 1 1/2 to 3 inches (40 to 75 mm).

Both the single and multiple stage Remixing method can add virgin aggregate or new HMA to improve the characteristics of the existing pavement materials or to increase the overall pavement thickness. The multiple stage method will permit slightly more new materials to be added than the single stage method but both are restricted to about 30 percent new materials. Hence, the Remixing process will only marginally increase the overall pavement thickness unless a subsequent HMA overlay is placed.

Figure 1-11: Single stage Remixing train

Figure 1-12: Multiple stage Remixing with windrow of scarified material

Figure 1-13: Multiple pass repaving

Repaving combines the Surface Recycling or Remix process with the placement of a simultaneous or "integral" overlay of new HMA. The Surface Recycled or Remixed layer and the HMA overlay are compacted together. The thickness of the HMA overlay can be less than a conventional thin lift overlay since there is a thermal bond between the two layers and they are compacted simultaneously.

In the Repaving process, the surface recycled mix functions as a leveling course while the new HMA acts as the surface or wearing course. The thickness of the new HMA wearing course is a function of the maximum aggregate size of the mix, but can be as thin as 3/4 inch (20 mm) or as thick as 3 inches (75 mm). Hence, the overall pavement thickness can be increased a significant amount in the Repaving process.

Repaving can also be further classified into multiple and single-pass methods. In the multiple pass method, the surface recycled mix is placed to the proper longitudinal profile and cross-slope by its own placing and screeding unit. The new HMA overlay material is then immediately placed on the hot, uncompacted recycled mix with a conventional asphalt paver, as indicated in Figure 1-13.

The two layers are then compacted simultaneously with a series of rubber-tired and double steel drum vibratory rollers.

With single pass Repaving, one unit equipped with two screeds is used. This unit also scarifies the heated, softened pavement, adds the required amount of recycling agent, mixes the recycled mix prior to the first screed, receives the new HMA, and transports it over the recycled mix. The first screed places the recycled mix while the second screed places the new HMA overlay on top of the recycled mix, as indicated in Figure 1-14. The two layers are then compacted with a series of rubber-tired and vibrating steel drum rollers.

Figure 1-14: Single pass repaving

HIR advantages include:

- conservation of non-renewable resources
- energy conservation compared to other reconstruction methods
- reduced truck hauling compared with other rehabilitation methods
- eliminates the disposal problems inherent in conventional methods
- treatment of complete roadway width or only the driving lanes
- surface irregularities and cracks are interrupted and filled
- improves ride quality
- rutting, potholes, and raveling are eliminated
- curb reveal height and overhead clearance can be maintained
- oxidized asphalt binder can be rejuvenated with the use of recycling agents to restore pavement flexibility
- problems with existing aggregate gradation and/or asphalt binder can be corrected with proper selection of virgin aggregates, new asphalt binders and/or recycling agents
- aggregates stripped of asphalt binder can be remixed and recoated
- friction numbers can be restored
- hot or thermal bond between longitudinal joints
- in-place construction reduces traffic disruptions and user inconvenience
- roadway opened to traffic at end of day with little or no edge drop off
- economic savings are realized

1.6 FULL DEPTH RECLAMATION (FDR)

FDR is the rehabilitation technique in which the full thickness of the asphalt pavement and a predetermined portion of the underlying materials (base, subbase and/or subgrade) is uniformly pulverized and blended to provide an upgraded, homogenous base material. FDR is performed on the roadway without the addition of heat, similar to CIR. Treatment depths vary depending on the thickness of the existing pavement structure, but generally range between 4 to 12 inches (100 and 300 mm).

FDR consists of pulverization/reclamation of the existing materials, adding more materials (when necessary), mixing, initial shaping of the resultant mix, compaction, final shaping or "tight blading," and application of a bituminous surface or wearing course.

Reclamation of the existing asphalt bound layers with the underlying materials produces a "granular" pavement layer which can be used as is, can have additional granular materials placed over it, or can be enhanced with the addition of an additive or "stabilizing additive." The addition of a stabilizing additive is usually required if the reclaimed material does not, by itself, have the necessary mechanical properties and/or structural strength to support the anticipated loads.

A broad range of stabilizing additives, in either a dry or liquid form, can be used including calcium chloride, magnesium chloride, lime (hydrated or quicklime), fly ash (type C or F), cement kiln dust (CKD) or lime kiln dust (LKD) Portland cement (dry or slurry), asphalt emulsion (normal, high-float, polymer), foamed/expanded asphalt or combinations of two or more of these additives. If the existing materials will not provide the desired gradation, material properties or depth required, additional granular or other materials can be added to the roadway prior to or during the FDR process.

Over the years, a number of reclamation methods have been tried, including the use of rippers, scarifiers, pulvi-mixers, milling machines, and stabilizing additives to reclaim the existing surface and underlying materials. However, the development of large, high horse-powered, self-propelled reclaiming machines, as indicated in Figure 1-15, has increased the use of FDR due to the increased treatment depths, higher productivity, and more sophisticated metering systems for the controlled addition of the stabilizing additives.

These reclaimers have a specially designed pulverizing/mixing drum equipped with special replaceable tungsten carbide tipped cutting tools. The drum normally rotates in an "up cut" or opposite direction to the forward movement of the reclaimer during the initial pulverization pass. The size of the reclaimed material is controlled by the forward speed of the reclaimer, the rotation speed of the pulverization/mixing drum, the position of breaker bar and/or mixing chamber, and the exit door opening on the mixing chamber. In some processes, the stabilizing additive is added by the reclaimer during the pulverization pass. This technique has the advantage of eliminating the mixing pass by the reclaimer, and works well for the thinner treatment depths. Addition of the stabilizing additive after the pavement has been pulverized, has the advantage of increased and more consistent working speed, and results in a more consistent, uniform application of the stabilizing additive.

FDR equipment consists of a reclaimer unit, stabilizing additive unit or units, motor grader, and rollers. Although not as long as either a HIR or a CIR operation, it is still commonly referred to as a "train."

FDR recycling trains are configured differently, depending on the recycling application and the type of stabilizing additive or agents being used. In all cases, the reclaimer either pushes or pulls the stabilizing additive equipment coupled to it, as indicated in Figure 1-16.

Figure 1-15: FDR reclaimer

Figure 1-16: FDR reclaimer and stabilizing additive tanker

Figure 1-17: Initial shaping with motor grader and compaction

The initial shaping of the roadway after the stabilizing additive (if used) has been added and mixed by the reclaimer, is performed with a motor grader. This is followed with initial compaction by large sized pneumatic-tired or vibrating steel drum rollers, as indicated in Figure 1-17.

Final compaction and shaping to the required longitudinal profile and cross-slope is followed by a curing period, if a stabilizing additive has been used. The curing period is dependent on the type or combination of stabilizing additives used and the ambient conditions and can range from 1 to 14 days. It is preferable that heavy truck traffic be kept off the stabilized material during the curing period. The application of a surface treatment or HMA overlay is undertaken as a separate operation at the end of the curing period.

FDR advantages include:

- conservation of non-renewable resources
- energy conservation compared to other reconstruction methods
- few pieces of equipment are required
- elimination of bumps and dips, rutting, potholes, patches, and cracks
- subgrade deficiencies can be corrected by stabilization
- problems with existing aggregate gradation can be corrected with proper selection of new granular materials
- deteriorated base can be reshaped to restore surface profile and drainage
- significant structural improvement with the addition of stabilizing additive(s)
- produces thick, bound layers that are homogeneous

- permits more flexibility in the choice(s) of wearing surface type and thickness
- in-place construction and high production rates improve safety by reducing traffic disruptions and user inconvenience
- economic savings are realized

1.7 COLD RECYCLING (CR)

CR consists of recycling asphalt pavement without the application of heat during the recycling process to produce a rehabilitated pavement. Two sub-categories within CR are used to further define CR based on the process used. These processes are Cold In-place Recycling (CIR) and Cold Central Plant Recycling (CCPR). The CIR process uses a number of pieces of equipment including tanker trucks, milling machines, crushing and screening units, mixers, pavers, and rollers. Like HIR, the combined equipment spreads out over a considerable distance and therefore, is commonly referred to as a “train.”

CIR is undertaken on site and generally uses 100 percent of the RAP generated during the process. The CIR treatment depth is typically within the 2 to 4 inches (50 to 100 mm) range when the recycling agent is only an asphalt emulsion or an emulsified recycling agent. Treatment depths of 5 to 6 inches (125 to 150 mm) are possible when chemical additives, such as Portland cement, lime, kiln dust or fly ash are used to improve the early strength gain and resistance to moisture damage. If lime or Portland cement is added to the recycled mix, they can be added in dry form or as slurry. The slurry method eliminates potential dust problems and permits greater control of the amount of recycling modifier being added.

There are different types of CIR trains with different equipment configurations. The trains differ from one another in how the RAP is removed and sized, how the recycling additives and modifiers are added, how they are mixed and controlled, and how the resultant mix is placed.

In a single unit CIR train, removal of the RAP is usually performed by a milling machine using a down cutting rotor. The maximum size of the RAP can be kept less than 2 inches (50 mm) by controlling the forward speed. Addition and mixing of the recycling additive is performed in the milling machine’s cutting chamber. The placement of the recycled mix is performed with a screed attached to the back of the unit, as indicated in Figure 1-18.

In a single unit train, a predetermined amount of recycling additive is added based on the treatment volume which is determined by the treatment width, depth, and the anticipated forward speed of the unit. This approach provides the lowest degree of process control, since the treatment volume and the recycling additive application rate are not directly linked.

Two-unit CIR trains usually consist of a large full lane milling machine, and a mix paver. The milling machine removes and sizes the RAP and deposits it into the mix paver. The mix paver has an infeed belt with belt scale and a processing computer to accurately control the amount of recycling additive and modifier being added. Some mix pavers are equipped with scalping screens to remove oversized material. The mix paver contains a pugmill that mixes the materials and has an automatically controlled screed for mix placement and initial compaction, as indicated in Figure 1-19.

Figure 1-18: Single unit CIR train

Figure 1-19: Two-unit CIR train

Figure 1-20: Multi-unit CIR train

In a two-unit train, the liquid recycling additives are added based on the weight of RAP being processed, independent of the treatment width, depth, and forward speed of the train. The two-unit train provides an intermediate to high degree of process control since the treatment volume and the recycling additive application rates are directly linked.

The multi-unit CIR trains typically consist of a very large, full lane milling machine, a trailer mounted screening and crushing unit, and a trailer mounted pugmill mixer. The milling machine removes the RAP, and final sizing of the RAP is performed in a separate mobile screening/crushing unit. Liquid recycling additives are added and the components mixed in a separate pugmill unit. The resultant mix is deposited in a windrow and placed with conventional HMA pavers equipped with a windrow pickup machine. In some CIR trains, the screening/crushing unit and the additive/pugmill units are combined into one larger unit. Another variant is to have the additives and mixing performed in a mix paver, as indicated in Figure 1-20.

The maximum size of the RAP is controlled by the screen sizes used in the screening/crushing unit. Any oversize RAP is sent to the crusher and returned for re-screening. The amount of liquid recycling additive is controlled with the use of a belt scale and a processing computer on the pugmill unit. The liquid recycling additives are added based on the weight of RAP being processed, independent of the treatment width, depth and forward speed of the train, and therefore, provides the highest degree of process control.

Densification of CR mixes requires more compactive energy than conventional HMA. This is due to the high internal friction developed between the mix particles, the higher viscosity of the binder

Figure 1-21: CIR compaction

due to aging, and colder compaction temperatures. Compaction is usually achieved with a large sized pneumatic-tired roller and vibrating steel drum rollers, as indicated in Figure 1-21.

CIR mixes are compacted as the mixture begins to "break," turning from brown to black. When asphalt emulsions or emulsified recycling additives are used, this could take from 30 minutes to 2 hours, depending on the characteristics of the asphalt emulsion, thickness of the CR mix, and environmental conditions. The compacted CIR mixture must be adequately cured before a wearing surface is placed. The rate of curing is quite variable and depends on several factors, including environmental conditions and drainage, and moisture characteristics of the mix. Typical curing periods are several days to 2 weeks, depending on the above mentioned factors, and the recycling additive and any modifiers used.

CCPR is the process in which the asphalt recycling takes place in a central location using a stationary cold mix plant. The stationary plant could be a specifically designed plant or a CIR train, minus the milling machine, set up in a stationary configuration. The CCPR mix can be used immediately or it can be stockpiled for later use in such applications as maintenance blade patching or pothole repair.

The RAP used in the CCPR is obtained by CP or by ripping, removing, and crushing operations, and is stockpiled at the plant location. Asphalt emulsions or emulsified recycling agents are typically used as the recycling additive. The asphalt emulsion or emulsified recycling agent type, grade, and addition rate are determined through evaluation of the RAP and the mix design process. New aggregates, if required, are also stockpiled at the plant site. The CCPR plant usually consists of a number of cold feed bins for the RAP and new aggregate, a belt scale, a computer controlled liquid recycling additive system, a pugmill, a hopper for temporary storage and

Figure 1-22: CCPR plant

Figure 1-23: CIR train set up as a stationary plant

Figure 1-24: CCPR mix placement

loading of haul trucks or a conveyor/belt stacker, if the CCPR mix is being stockpiled. Figures 1-22 and 1-23 on previous page indicate central plant set-ups.

The CCPR mix is hauled to the job site with conventional haul/dump trucks or belly dump trucks if a windrow pickup machine is being used. Placement of the CCPR mix is with conventional HMA pavers, as indicated in Figure 1-24, but a motor grader could also be used. Compaction is with conventional large sized rubber-tired and vibrating steel drum rollers. The compacted CCPR mix is generally overlain with a layer of HMA, although for some very low traffic roadways a single or double seal coat is sometimes used.

CR advantages include:

- conservation of non-renewable resources
- energy conservation compared to other reconstruction methods
- eliminates the disposal problems inherent in conventional methods
- surface irregularities and cracks are interrupted and filled
- rutting, potholes, and raveling are eliminated
- base and subgrade materials are not disturbed
- pavement cross-slope and profile can be improved

- problems with existing aggregate gradation and/or asphalt binder can be corrected with proper selection of new granular materials and stabilizing additives
- significant structural treatment and improved ride quality
- in-place construction and high production rates improve safety by reducing traffic disruptions and user inconvenience
- economic savings are realized

CHAPTER 2: REHABILITATION STRATEGIES

The period of rapid expansion of roadway networks through new construction has peaked, the existing roadway infrastructure has aged, and a significant number of roadways are nearing the end of their useful service life. Limited funding and demands on existing resources have shifted the emphasis from new construction to preservation and/or extending the service life of the existing roadways. The implementation of more timely or proactive preventative maintenance and rehabilitation treatments is being used as a means of preserving the existing roadway infrastructure.

Pavement Management Systems (PMS) have been designed and implemented in order to assist an agency in its planning, programming, construction, preventative maintenance, and rehabilitation functions. PMS are also used to evaluate and quantify the condition of a roadway, as a function of age and/or traffic.

The deterioration of a pavement results from a number of different causes and can occur at different rates. Data indicates that the deterioration of a roadway pavement will follow a fairly predictable pattern, for given traffic and environmental conditions.

The serviceability of a pavement is usually related to the pavement's ability to accommodate the roadway user at a reasonable level of comfort—which is directly related to the roughness of the pavement surface. The serviceability of the pavement changes with time and is related to the:

- original construction quality
- type and thickness of individual layers
- stiffness of the various layers
- subgrade soil type and moisture content
- environmental factors
- types and effectiveness of maintenance activities
- traffic composition and loading

The change in serviceability with time is called "Pavement Performance or Pavement Serviceability" and is usually expressed as a function of pavement age or cumulative traffic loading. The quantification of pavement serviceability is usually expressed in terms of a subjective, user-related value such as the Riding Comfort Index (RCI), Present Serviceability Index (PSI) or some similar value.

Soon after initial construction, roadways begin to deteriorate, as indicated by a reduction in RCI or PSI values, due to traffic and environmental factors. The shape of the pavement deterioration curve is dependent on a number of factors, including:

- pavement type
- pavement thickness
- initial construction quality
- pavement material properties
- traffic levels
- environmental conditions
- level of maintenance activities, etc.

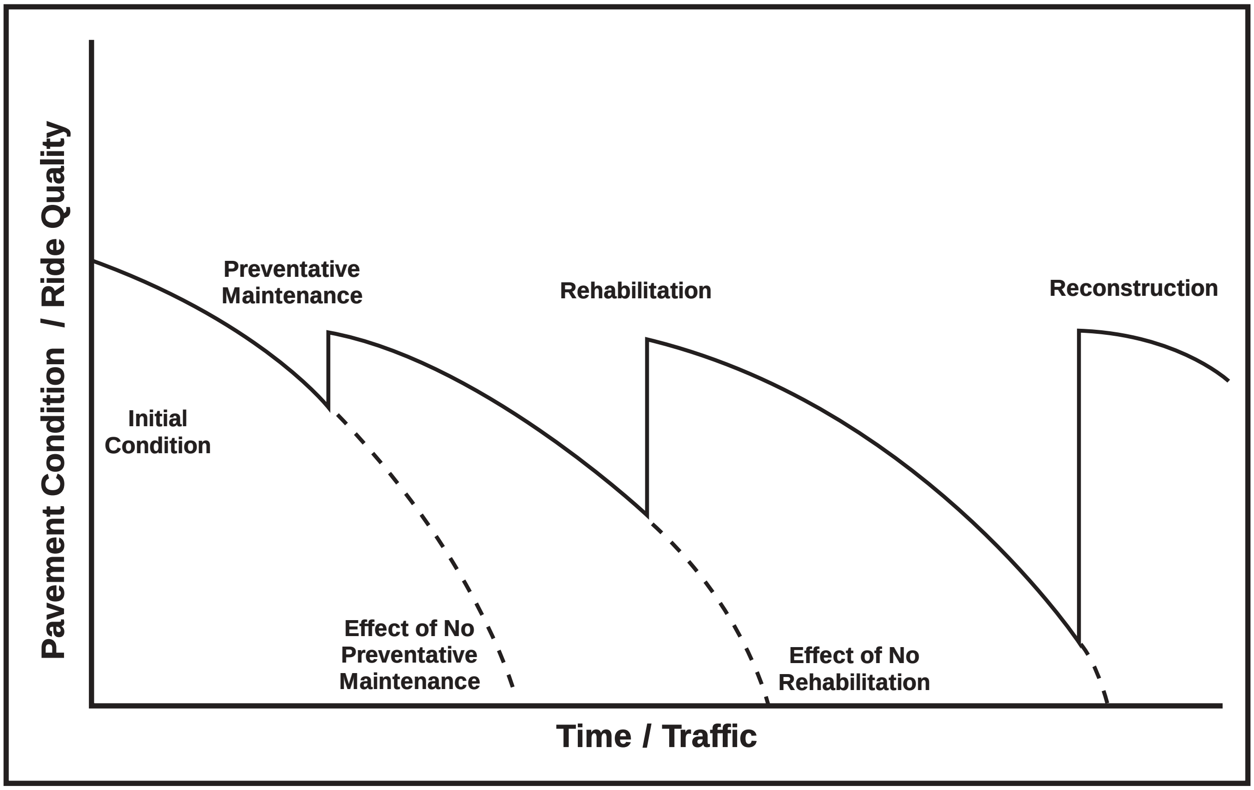


Figure 2-1: Pavement Deterioration vs. Time

The rate of pavement deterioration accelerates with increasing age and traffic. As the deterioration continues, the cost of the rehabilitation increases dramatically, as was indicated in Chapter 1. If no preventative maintenance or rehabilitation is undertaken at the appropriate times, the roadway will quickly deteriorate to the point where expensive reconstruction will be the only option. Fortunately, with the timely application of preventive maintenance and rehabilitation activities significant extensions to the roadway's service life can be achieved, as indicated in Figure 2-1.

A wide variety of preventive maintenance and rehabilitation procedures exist which can be used individually or in combination to form a strategy to extend the service life of the pavement, in the most cost effective manner.

2.1 PAVEMENT MAINTENANCE

Pavement maintenance can be categorized as "corrective" or "preventive," depending on the intended purpose. In general, maintenance activities are intended to:

- prevent moisture from infiltrating the pavement structure
- correct or prevent deterioration due to environmental effects

Preventive maintenance consists of any activity that is intended to preserve or extend the service life of a pavement until a major rehabilitation or complete reconstruction is required. In order to maximize the cost-effectiveness of preventive maintenance, the procedures need to be applied prior to the pavement showing significant signs of distress or deterioration. Preventive maintenance is intended to maintain the durability and flexibility of the pavement. It does not increase the

Figure 2-2: Candidate Road for Preventive Maintenance Recycling

structural strength/capacity, so is generally limited to pavements in good structural condition.

Preventive maintenance includes such activities as:

- Hot In-Place Recycling (HIR)
- HIR with a subsequent surface treatment or thin Hot Mix Asphalt (HMA) overlay
- Cold In-Place Recycling (CIR) with a surface treatment or thin HMA overlay
- fog sealing or coating
- slurry sealing
- micro-surfacing
- chip sealing
- cape sealing
- ultra-thin HMA overlays such as Open Graded Friction Course (OGFC) or Stone Matrix Asphalt (SMA)

The effectiveness of these preventive maintenance techniques varies from agency to agency, and is dependent on the type of technique and materials used, and the quality of the workmanship. The service lives can vary from 1 to 2 years for fog seals to 10 years or more for HMA overlays.

Corrective maintenance addresses existing pavement problems, and includes such routine activities as:

- crack sealing
- pothole repairs
- spray patching

- shallow patching to repair locally distressed areas or to rectify surface irregularities such as bumps and dips
- rut filling
- drainage improvements including cleaning culverts and drains, cleaning and/or re-grading existing ditches, etc.

The effectiveness of these corrective maintenance techniques varies from agency to agency, and is dependent on the type of technique and materials used, and the quality of workmanship. Corrective maintenance techniques have expected service lives of about 1 to 5 years.

2.2 PAVEMENT REHABILITATION

As the pavement condition deteriorates, there comes a point when maintenance activities are no longer cost-effective and rehabilitation is required. Rehabilitation techniques are more expensive than maintenance activities, but the rehabilitated pavement condition will generally be equivalent to what was achieved during the initial construction. Pavement rehabilitation can address:

- poor ride quality or roughness
- pavement deformation, cracking, and rutting
- low friction numbers/safety issues
- surface deterioration and defects
- structural deficiencies
- high user costs
- excessive maintenance patching and costs

There are a considerable number of techniques that can be used either individually or in combination to rehabilitate a pavement. Rehabilitation techniques include:

- HIR
- HIR with a subsequent surface treatment or HMA overlay
- CIR with a surface treatment or HMA overlay
- Full Depth Reclamation (FDR) with a surface treatment or HMA overlay
- Thin HMA overlays
- Thick HMA overlays
- Cold Planing (CP) and HMA overlay
- CP followed by either HIR, CIR, FDR or Cold Central Plant Recycling (CCPR), and then a HMA overlay

The most important part of the rehabilitation process is the proper selection of the rehabilitation technique or techniques to be used. It is often difficult to determine which is the “best” or “right” one to use. In choosing the right rehabilitation technique one must:

- assess the type, amount, and depth of distress the pavement has undergone
- collect and review existing historical information on original construction and subsequent maintenance activities

- evaluate the thickness and structural strength of the existing pavement
- determine the physical properties of the existing pavement materials
- determine the cause or causes of the distress
- assess geometric requirements
- select a number of potential rehabilitation techniques based on the previously collected information
- undertake an economic analysis including first cost and life-cycle costs of the potential rehabilitation techniques
- select the most cost-effective rehabilitation technique

Rehabilitation techniques that incorporate asphalt recycling have a number of unique advantages over the traditional HMA overlay rehabilitation methods. These include:

- reuse and conservation of non-renewable natural resources.
- preservation of the environment and reduction in land filling.
- energy conservation
- shorter construction periods
- reduction in user delays during construction
- increased level of traffic safety within the construction work zone
- preservation of existing roadway geometry and clearances
- corrections to pavement profile and cross-slope
- no disturbance of subgrade soils unless specifically planned, such as for FDR
- improved pavement smoothness
- improved pavement physical properties by modification of existing aggregate gradation, and/or asphalt binder properties
- mitigation or elimination of reflective cracking with some methods
- improved roadway performance
- cost savings

Each of the asphalt recycling rehabilitation techniques offer specific advantages over conventional methods. The selection of a particular rehabilitation method must be made based on a detailed project assessment, as indicated in Figure 2-2, since not all asphalt recycling methods are equally suited to treat the various pavement distresses.

In addition, when selecting the rehabilitation technique, the process of "Staged Rehabilitation" should be considered. Staged rehabilitation is similar to staged construction, in which not all of the required rehabilitation is initially undertaken. Staged rehabilitation is the process whereby the roadway is partially rehabilitated, usually with some form of asphalt recycling technique, and then monitored for performance and/or structural capacity. The completion of the staged rehabilitation is undertaken in the future with a HMA overlay, once the overlay thickness reaches a practical or economic thickness. Roadways which have a rough ride or poor surface condition, but require no or minimal strengthening, are good candidates for staged rehabilitation.

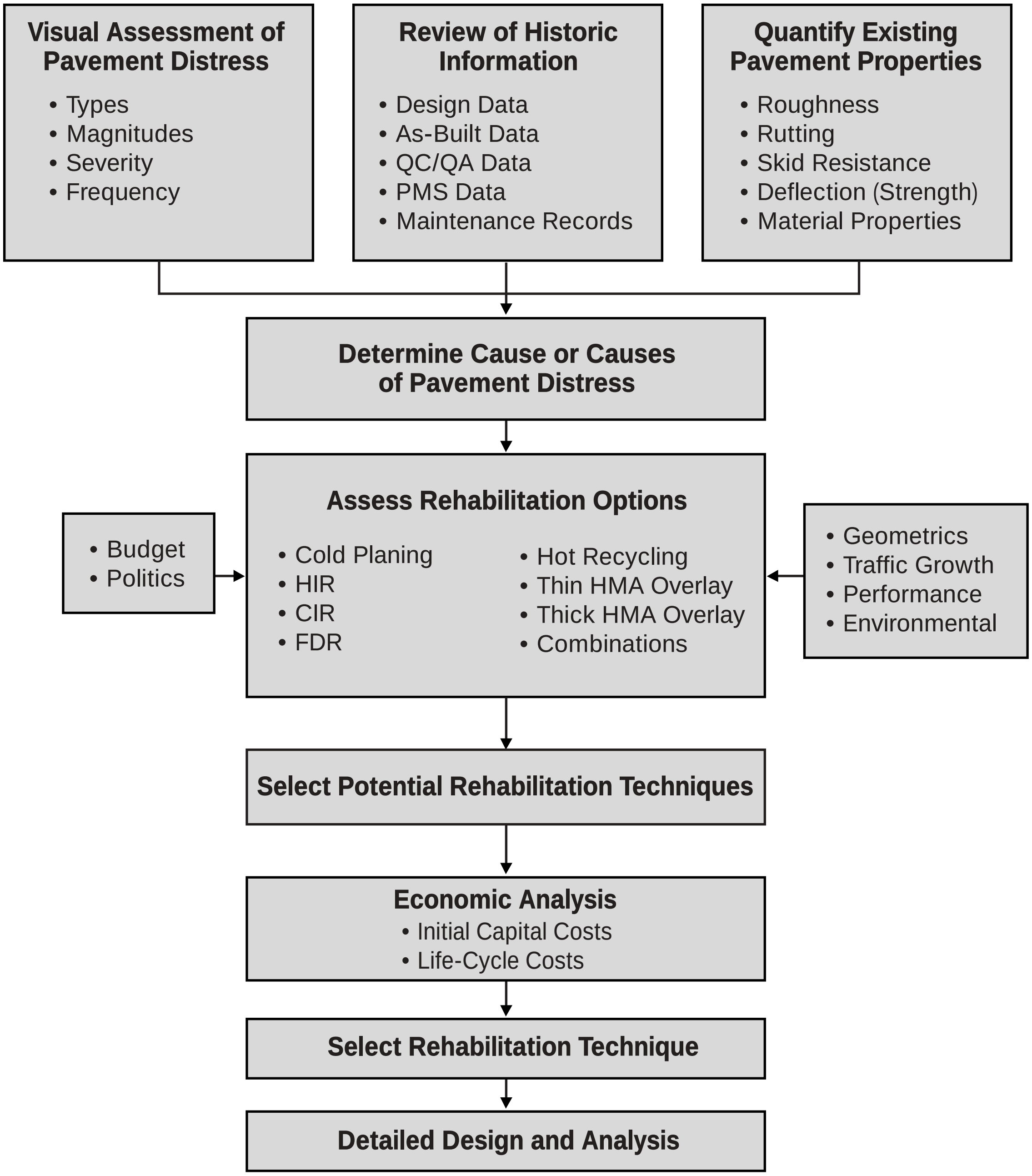


Figure 2-3: Rehabilitation technique selection process

Staged rehabilitation alternatives for roadways meeting the preceding requirements include:

- CP with or without a surface treatment
- HIR
- CIR with a surface treatment
- FDR with a surface treatment

A HMA overlay would be placed when conditions warrant. Staged rehabilitation has the added benefit of spreading major capital expenditures out over longer periods.

Figure 2-4: Candidate Road for Rehabilitation Treatment

Similarly, staged rehabilitation could also be considered for roadways which need immediate attention, but where funds are not available or the roadway will need geometric improvements/grade widening in the near future. Staged rehabilitation could be considered as a "stop-gap" measure in order to delay the expenditure of major capital amounts until the full rehabilitation can be undertaken.

As with all rehabilitation methods, project selection for staged rehabilitation is critical to the successful application of the technique.

The effectiveness and performance of the various rehabilitation techniques varies from agency to agency and is dependent on:

- local conditions
- climate
- traffic
- type of technique and quality of materials used
- quality of the workmanship

2.3 PAVEMENT RECONSTRUCTION

Reconstruction can be considered the most extreme type of rehabilitation technique. It is often the preferred method when roadway widening or extensive re-alignment, due to geometric considerations, is required. Reconstruction is also required when roadway maintenance or rehabilitation has not been undertaken or has not been effective, and the existing pavement has deteriorated to the point where trying to use the existing structure would not be cost-effective.

Reconstruction consists of the total removal of the existing pavement structure, reworking or improving the subgrade soil, re-compacting the subgrade soil, and placement of a pavement structure with new and/or recycled materials. Due to the extensive construction requirements, associated traffic control, and user inconvenience, it is the most expensive rehabilitation method.

The asphalt pavement and granular base materials can be recycled, reclaimed or reused during the reconstruction process. The use of CP, CCPR, Hot Recycling, and/or FDR techniques can help to significantly reduce the overall roadway reconstruction costs.

The effectiveness of the reconstruction varies from agency to agency, and is dependent on the type of structure constructed, climate, traffic, the type and quality of materials used, and the quality of the workmanship. Reconstructed roadways have expected service lives consistent with similarly designed and constructed new roadways of up to 20 years.

CHAPTER 3: PROJECT EVALUATION

In order to ensure a successful project, project evaluation is by far the most important aspect of asphalt recycling or reclamation. Although asphalt recycling and reclamation are powerful rehabilitation methods, not all pavements are appropriate candidates. In addition, not all asphalt recycling and reclamation methods are equally suited to treat the various types of pavement distresses. If poor judgement is used during the project evaluation process and an inappropriate rehabilitation method is selected, sub-standard roadway performance is sure to follow.

The steps in the rehabilitation selection process were broadly outlined in the discussion of rehabilitation strategies and indicated in Figure 2-2. The project evaluation process, although generally similar for all asphalt recycling and reclamation methods, does have some specific steps which are unique to each particular method. In general, the rehabilitation selection process includes:

- visual assessment of the pavement surface
- historical information review
- pavement properties assessment
- distress evaluation
- preliminary rehabilitation selection
- economic analysis
- detailed project design

3.1 PAVEMENT ASSESSMENT

An essential part of the project evaluation process is the determination of the condition of the existing pavement, by conducting a pavement condition or pavement assessment survey. A poor or inadequate pavement assessment could result in the selection of an inappropriate recycling or reclamation method—which might result in less than expected performance.

Surface distress of asphalt pavements is caused by one or more of the following factors:

- environmental or climatic effects
- traffic effects
- construction deficiencies
- material deficiencies

It is often difficult to allocate surface distress to one single factor since they are usually interrelated. For instance, a pavement would not rut without heavy traffic loading, but it also would not rut if the pavement temperature didn’t get too hot, if the correct aggregate gradation and asphalt binder type were used or if it had been adequately compacted at the time of construction. Therefore, rutting distress could be related to traffic, climate, material deficiencies, construction deficiencies, or a combination of all four.

The pavement assessment must consist of a detailed visual inspection which rates all of the surface irregularities, flaws, and imperfections found in a given area. The visual inspection should assess:

- all distress types encountered
- severity of distress types
- frequency of distress types

Various procedures for conducting pavement assessments have been developed by many different agencies. These include the US Army Corps of Engineers, the American Public Works Association, Strategic Highway Research Project – Long Term Pavement Performance (SHRP-LTPP FR-90-001), etc. The various systems generally use a manual that provides detailed descriptions of each type of pavement distress, how the distress is to be measured, along with guidelines for the classification of the severity and frequency of the distresses. The manuals usually include photographs that illustrate the various distress types, along with severity levels, to assist the surveyor in doing a proper and consistent classification.

It is extremely important that whatever procedure is adopted, it be constantly applied throughout an agency, since the various procedures could produce significantly different results. Consistency of the visual condition survey data is achieved through providing the survey team proper training, establishing control sections, and the use of blind comparisons among surveyors.

Collection of the pavement surface condition by automated or semi-automated inspection equipment is increasing—due to improvements in the assessment technology, increased concern for surveyor safety, rising costs of manual inspections, and the cost and inconvenience to motorists.

Although the various pavement assessment methods vary from one another, the general principles remain the same, i.e., visually assess, record, assign severity rating, and determine frequency of each distress type. The pavement assessment is generally summarized or quantified into a numerical value such as a Pavement Condition Index (PCI), Surface Distress Index (SDI) or similar value.

Surface distress of an asphalt pavement can be grouped into six major categories which include:

- surface defects
- deformations
- cracking
- maintenance activities
- base/subgrade problems
- ride quality
- safety

3.1.1 SURFACE DEFECTS

Surface defects are generally related to material and construction deficiencies, with secondary contributions by traffic, and climatic conditions. Surface defects include:

- **Raveling** or weathering which is the deterioration of the pavement surface due to the loss of aggregate particles and asphalt binder. The distress is progressive in nature. The fine aggregate particles are lost first, followed by coarser aggregate particles as the condition increases in severity. Raveling may also be an early indicator that the aggregates are water sensitive and may be susceptible to stripping.

Figure 3-1: Pothole Pavement

Raveling can also be associated with poor quality Hot Mix Asphalt (HMA) (low asphalt binder contents, soft aggregates, etc.), construction deficiencies (low compaction, mix segregation, etc.), age-hardening of the asphalt binder (overheating of the HMA mix during production), certain types of traffic conditions (studded tires, tracked vehicles, etc.), and environmental conditions (freeze-thaw, wet-dry, abrasion effects of winter sanding operations).

In isolated instances, raveling can be caused by the effects of oil or fuel spills which soften the surface of the pavement, permitting the aggregate particles and asphalt binder to be removed.

- **Potholes** are bowl-shaped depressions in the pavement surface in which a significant thickness of the pavement surface has been dislodged. They are generally less than 30 inches (750 mm) in diameter, greater than 3/8 inches (10 mm) in depth, have sharp edges, and vertical sides near the top.

Potholes can be associated with poor quality HMA (low asphalt binder contents, soft aggregates, etc.), construction deficiencies (low compaction, mix segregation, etc.), structural problems (insufficient pavement thickness, reduced base support, etc.), and environmental conditions (freeze-thaw cycles, etc.).

- **Bleeding** or flushing are areas of the pavement surface that have a shiny, glass-like reflecting appearance that usually becomes quite sticky in warmer weather due to a film of excessive asphalt binder. Bleeding areas become very slippery, particularly in wet weather conditions.

Bleeding can be associated with poor quality HMA (excessive asphalt binder contents, too soft of an asphalt binder, low air voids, etc.), construction deficiencies (excessive tack or prime coat application, etc.), environmental conditions (excessively hot weather, etc.), and traffic effects (high traffic volumes, etc.). Bleeding occurs when excess asphalt binder fills the voids in the mix and then moves upward to the pavement surface in a non-reversible, cumulative process.

Bleeding may also develop with chip seals where the asphalt binder application rate was too high, the aggregate application rate too low or excessive aggregate loss has occurred.

- **Friction Number** is the amount of friction between the pavement surface and vehicle tires. The friction number is reduced when the surface of the pavements are wet/icy; when the portion of the coarse aggregate particles extending above the asphalt binder is very small; when there are no angular particles to provide a rough surface texture; and/or under traffic the coarse aggregates becomes polished. Pavements which have low numbers usually have a very smooth surface texture. Loss of friction number is detected by testing and is usually progressive, particularly if the coarse aggregate is susceptible to polishing due to traffic.
- **Lane/Shoulder Drop-off** is a difference in elevation between the pavement edge and the roadway shoulder. This distress can be a result of shoulder erosion, shoulder settlement, or by the build up of the roadway through HMA overlays without adjustment of the shoulder level. It presents a safety concern which should be addressed during the project evaluation and rehabilitation selection process.

3.1.2 DEFORMATIONS

Asphalt pavements may exhibit permanent deformation or distortion which are generally related to traffic loading and material deficiencies, with secondary contributions due to construction deficiencies and climatic conditions. Deformations in one form or another are usually caused by a combination of traffic effects or HMA which lacks internal stability due to high asphalt binder contents, has too soft of an asphalt binder, has high fine aggregate contents, contains too much round natural sand, has excessive smooth or round coarse aggregates, and/or were inadequately compacted. Deformations include:

- **Rutting** which are longitudinal depressions or channels within the wheelpaths of roadways. Three basic types of rutting can occur in an asphalt pavement consisting of wear rutting, structural rutting, and instability rutting. Rutting is generally more noticeable after rainfalls, when the rut fills with water. As the rut depth increases, the amount of water trapped in the rut increases, reducing the friction number and increasing the risk of hydroplaning.

Wear rutting is caused by the progressive loss of material from the roadway surface. It is usually due to poor quality HMA, inadequate compaction of the HMA at the time of construction, and/or by the use of studded tires. Wear rutting is not accompanied by an upward movement of the pavement surface adjacent to the rut. The surface texture within the rut has a slight raveled appearance, and the rut widths are fairly narrow or confined.

Structural rutting is the cumulative, permanent vertical deformation of the various pavement layers as the result of repeated heavy traffic loads. Most structural rutting occurs within the underlying subgrade, particularly when the thickness of the pavement is insufficient to adequately distribute the imposed traffic loads. In structural rutting the width of the ruts are usually fairly wide in cross-section, the rut is bowl shaped with the greatest deformation occurring at or near the middle of the rut, and no noticeable upward deformation of the pavement adjacent to the rut can be observed.

Instability rutting is the result of shear displacement of one or more of the HMA layers from beneath the wheelpath areas. The HMA is displaced downward, laterally, and then upward to form ridges on either side of the wheelpath. Instability rutting has become more prevalent due to higher tire pressures, increased wheel loadings, and higher traffic volumes. Instability rutting is usually accompanied by an upward movement of the pavement surface adjacent to the rut, a rut within a rut or “W” shape, and a narrow to medium rut width.

- **Corrugations** or washboarding are a series of closely spaced ridges and valleys or “ripples” of the pavement surface primarily in wheelpath areas. The corrugations are at a regular and closely spaced interval, usually less than 10 feet (3 meters) and ripples are perpendicular to the direction of traffic. Corrugations can occur where traffic starts/stops or on steep hills where vehicles brake sharply going downhill.

  Corrugations are permanent deformations that are progressive in nature, starting from small indentations or “dimples” and progressively becoming larger under the influence of traffic.

  “Mini-corrugations” of a new HMA can sometimes be observed outside of the wheelpath areas. These mini-corrugations are very closely spaced; usually less than 4 inches (100 mm) apart and the ripples are very shallow. This type of corrugation is caused by improper operation of steel drum vibratory rollers during the HMA compaction operation. The mini-corrugations can occur when the steel drum vibratory rollers are being operated at a forward speed greater than what is required for the proper number of vibratory impacts per foot (meter).
- **Shoving** is also a form of permanent deformation caused by plastic movement of the HMA in a longitudinal direction. Shoving appears as a localized bulging of the pavement surface and is usually associated with some form of discontinuity within the pavement structure, such as where the pavement abuts a Portland Cement Concrete (PCC) structure.

3.1.3 CRACKING

There are three primary types of asphalt pavement cracking: load associated; non-load associated; and combination. Load associated cracking is due to the repeated application of heavy wheel loads. Non-load associated cracking is due to environmental factors, and combination cracking is due to a combination of both load and non-load effects.

Load associated cracking includes:

- **Fatigue** or “alligator” cracking is a series of interconnected cracks caused by a fatigue failure of the pavement structure due to repeated heavy traffic loading. The fatigue cracks usually begin at the bottom of the asphalt layer, where the tensile stresses are the highest under wheel loading. The cracks propagate to the pavement surface initially as a series of parallel, longitudinal cracks or wheelpath cracks. Under continued traffic loading, the cracks connect, forming many-sided, sharp-angled pieces that develop a pattern which resembles the skin of an alligator or the shape of chicken wire. The broken pieces of pavement are generally less than 20 inches (500 mm) on the longest side.

  In most cases, the fatigue cracking is caused by excessive deflection of the pavement surface over an unstable base or subgrade.
- **Edge** cracks are parallel to and usually within 12 to 24 inches (300 to 600 mm) of the outer edge of the asphalt pavement. Edge cracking is accelerated by traffic loading, particularly for

Figure 3-2: Cracking Distress

pavements with no or only partially paved shoulders. Edge cracking is initially caused by lack of lateral support from the pavement shoulder or base weakening as a result of ingress of moisture, poor drainage, and/or frost action.

- **Slippage** cracks are typically crescent or half-moon shaped and are transverse to the direction of traffic. They usually occur when vehicles brake or turn causing the pavement to slide or deform. Slippage cracks usually occur with HMA overlays when there is a lack of tack coat or poor bond between the underlying pavement and the new overlay.

  Slippage cracks can also be caused by excessive deflection of the underlying pavement structure under the HMA compaction equipment or haul trucks. The weight of the rollers or haul trucks cause the pavement structure to deflect or bend and then rebound as the roller or truck passes, causing the surface of the pavement to go into tension, forming the slippage crack.

Non-load associated cracking includes:

- **Block** cracks that are interconnected and divide the pavement into large, approximately rectangular pieces, with sharp corners or angles. The blocks may range in size from 12 inches by 12 inches (300 mm by 300 mm) to 10 feet by 10 feet (3 meters by 3 meters). Block cracking normally occurs over large portions of the asphalt pavement area, but will occasionally occur in non-traffic areas only.

  It is sometimes difficult to determine whether block cracking is caused by volume changes in the asphalt pavement or in the base/subgrade materials. It is most often associated with shrinkage of the asphalt pavement and daily temperature cycling which results in daily stress/strain cycling. Block cracking can also indicate that the asphalt binder has hardened significantly.

- **Longitudinal** cracks are parallel to the centerline of the roadway or HMA laydown direction. They can develop along the construction joint between adjacent passes of the paver or at a location which corresponds to the center of the paver. Poorly constructed paving joints or worn out paver kicker screws/paddles accelerate the development of longitudinal cracking.
- **Transverse** or thermal cracks extend across the asphalt pavement approximately at right angles to the pavement centerline or direction of HMA laydown. Transverse cracks start at the pavement surface and propagate downward through the asphalt layers. They initially occur as a single crack but can develop into multiple or “braided” cracks under the influence of traffic.

  Transverse cracks are due to the shrinkage of the asphalt pavement due to low temperatures, hardening of the asphalt binder, and/or large daily temperature cycling. They usually start one or two seasons after construction (particularly, low temperature transverse cracks) at a wide spacing, in the order of 300 to 1000 feet (100 to 300 meters) apart. The crack frequency increases or the crack spacing decreases progressively over time. For a given environment, the occurrence of transverse cracks is directly related to the temperature susceptibility of the asphalt binder used in the original HMA.
- **Reflection** cracks are cracks in HMA overlays which reflect the crack pattern that existed in the underlying pavement prior to placement of the overlay. Reflection cracks can be longitudinal, transverse or random depending on the configuration of the underlying cracks. They are due to stress created by the horizontal and vertical movement of the underlying pavement structure.

Combined load and non-load associated cracking includes:

- **Joint Reflection** cracking that occurs in asphalt pavement placed on PCC slabs and are due to the thermal or moisture induced movement of the PCC. The initial crack reflection is non-load associated, but traffic loading usually causes a further breakdown of the asphalt pavement surface adjacent to the crack. These cracks progress from a single crack, to a braided crack, to a “spalled” crack in which pieces of asphalt pavement are dislodged.
- **Discontinuity** cracks occur when there is a significant difference in total pavement structure or age of the pavement structures. They typically are associated with roadways which have been widened. Discontinuity cracks are a result of the differential movement between the existing and widening pavement structures. They tend to be more severe if the discontinuity happens to be in or near a wheelpath.

3.1.4 MAINTENANCE ACTIVITIES

Maintenance activities include skin patching, failure repairs, pothole filling, utility cut repair/restoration, crack sealing, spray patching, etc. These types of surfacing activities are usually undertaken to correct a pavement deficiency and are considered a defect no matter how well it is performing. A patched area or the pavement adjacent to a maintenance activity usually does not perform as well as the intact pavement. There is generally some increased roughness associated with the maintenance activity, no matter how well it was placed.

The presence of surface treatments such as fog seals, chip seals, micro-surfacing, etc. should also be noted and their condition recorded.

Figure 3-3: Base and Sub-Base Deficiences

3.1.5 PROBLEM BASE/SUBGRADES

Severe cracking, pavement failures, settlements, depressions, and structural rutting of asphalt pavements are often the result of a poor base or subgrade, particularly with thinner pavement structures. A wet, soft base or subgrade creates problems due to its lower strength and load-carrying capabilities. Problem bases and subgrades are susceptible to pumping and displacement of material through the cracks in the pavement structure. Base and subgrade problems can also manifest themselves as swells, bumps, sags or depressions which can initiate surface cracking.

- **Swells** are characterized by upward displacement of the pavement surface in a long, gradual wave which is more than 10 feet (3 meters) in length. Swells are usually the result of frost heaving or swelling soils.
- **Bumps** are characterized by small, localized upward displacement of the pavement surface. They can be caused by localized frost heaving and swelling soils, infiltration and build up of non-compressible materials in the crack which can lead to “tenting,” and/or buckling or bulging of underlying PCC slabs.
- **Sags** are small, abrupt downward displacement of the pavement surface, usually initiated with loss or settlement of the underlying base or subgrade. When sags occur in association with cracking, they are sometimes referred to as “dipping” or “cupping.”
- **Depressions** are localized areas which have a slightly lower elevation than the surround pavement surface. They are not normally noticeable except after rainfall when they pond water creating “birdbaths.” Depressions are usually created by consolidation or settlement of the

subgrade or underlying soils. They also can be created as a result of improper construction. Depressions increase the roadway roughness and if deep enough can create safety hazards when filling with water, causing hydroplaning.

Problem base and subgrades can be affected by the drainage condition adjacent to the roadways. Ditch grades, culvert condition, groundwater/springs, etc. must also be assessed to determine whether they are having an impact on the performance of the pavement.

The size, location, and frequency of base and subgrade problems give a good indication of the overall structural integrity of the existing pavement structure.

3.1.6 RIDE QUALITY

Ride quality must be evaluated in order to establish a severity level for roughness, with the following factors being included:

- bumps and sags
- corrugations, shoving and rutting
- swells and depressions
- cracking (tenting and dipping)
- bridges and railway crossings
- maintenance activities
- cross-slope and general unevenness

To determine the effect of theses factors on ride quality, the roadway should be driven at the posted speed limit in a vehicle that is representative of those typically using the roadway. Pavement sections near intersections and stop signs should be evaluated at an appropriate deceleration speed.

3.1.7 SAFETY EVALUATION

When a pavement is evaluated in terms of safety, several components are assessed, including:

- friction number
- overall condition of the pavement surface
- light reflectivity
- side slopes and adjacent structures
- lane markings
- roadside hazards

Friction number, rutting, and overall pavement surface condition are the most common indicators of a potential safety problem.

3.2 HISTORIC INFORMATION REVIEW

Historic or existing information should also be reviewed as part of the rehabilitation selection process. Information which should be gathered and assessed includes:

- original design information

- as-built/constructed data
- Quality Control/Quality Assurance construction data
- Pavement Management System (PMS) data
- maintenance activity records

The amount of historic information will vary from project to project and from agency to agency. Obviously, the greater the amount of historic information and the more detailed or project specific it is, the easier it will be to determine the cause or causes of the pavement distresses observed in the pavement assessment. If the cause or causes of the pavement distresses can be determined to a higher degree of certainty or confidence, then evaluation and selection of an appropriate rehabilitation technique will be easier.

3.3 PAVEMENT PROPERTIES ASSESSMENT

During the pavement assessment phase the condition of the roadway surface was subjectively rated based on its visual appearance. In order to provide additional data, to assist in the determination of the cause or causes of the pavement distress, quantification of the existing pavement properties will need to be undertaken. This will include determination of the physical properties of the pavement both in the field and in the laboratory by means of testing. Physical properties of the pavement which should be measured include:

- roughness
- rutting
- friction number
- strength
- material properties

3.3.1 ROUGHNESS

Roughness is distortion of the pavement surface which contributes to an uncomfortable or undesirable ride quality. The degree to which a rough roadway affects the operation of vehicles using it depends on a number of factors, including the amplitude and frequency of the pavement distortions, suspension characteristics of the vehicles, and vehicle speed.

The devices and methods used to quantify pavement roughness can be divided into three basic categories:

- subjective ratings
- profile measuring devices to obtain pavement profile data
- response measuring devices which measure the reaction of a vehicle as it moves over the pavement

The devices and methods for collecting roughness data range from the traditional rod and level surveys, to high speed, non-contact methods. The device or method selected depends on the required speed of data collection, required accuracy of the data, and size of the sample.

The subjective rating methods are the least accurate but relatively fast. The profile measuring devices are the most accurate, but relatively slow, and the response measuring devices fall in between. Each method produces it own unique way of expressing roughness such as Riding Comfort Index (RCI), Riding Comfort Rating (RCR), or something similar.

The International Roughness Index (IRI) is becoming the standard for pavement roughness measurement and analysis, since it is valid for any road surface type, and it covers all levels of roughness. Roughness measurements and ratings from the difference measurement devices and methods have sometimes been correlated with each other and to the IRI, for comparison purposes, although the correlations are not universally applicable.

Pavement roughness can be used to monitor pavement serviceability, and is directly related to vehicle operating costs. The initial or as-built smoothness of a pavement directly affects its service life, as smooth pavements will generally last longer and require less maintenance than rough pavements.

Roughness is most frequently the triggering factor which identifies a roadway as a candidate for rehabilitation or reconstruction.

3.3.2 RUTTING

As the severity of pavement rutting increases, there is a corresponding decrease in roadway safety, since severe ruts adversely affect the handling characteristics of vehicles using the roadway. The roadway safety is impacted by:

- rut shape and depth
- type of vehicle and vehicle speed
- types of tires and tire wear
- porosity of the pavement surface, cross-slope and longitudinal profile
- surface conditions (wet or dry)
- rainfall intensity and duration, etc.

Pavement ruts can be assessed from simple visual estimates—to automated techniques which use ultrasonic or lasers to measure the transverse profile of a roadway from a vehicle moving at highway speeds. However, most often the depth of the rutting is measured by placing a reference straightedge, usually 4 to 10 feet (1.2 to 3.0 meters) in length, across the rut, and measuring the distance from the bottom of the straightedge to the deepest part of the rut. This indicates the maximum rut depth relative to the length of the straightedge. It is noted that other ways of reporting rut depth exist, such as average rut depth (the maximum rut depth divided by rut width), hence, any comparison of rut depth needs to be accompanied by a description of how the rut depth was measured.

Rutting is the second most frequent trigger factor identifying roadways as candidates for rehabilitation or reconstruction.

3.3.3 FRICTION NUMBER

Friction number is a very complex phenomenon which depends on the interrelationships between pavement, vehicle, environmental, and driving factors. It is largely dependent on the “micro-texture” of the coarse aggregates at the pavement surface. Micro-texture is a function of aggregate mineralogy and its interaction with traffic and climatic effects. Friction number can change rapidly in the short term, usually related to surface conditions such as rainfall. Over the longer term, with the application of traffic, most pavements show a progressive decrease in friction number. Changes in the pavement surface which are possible contributors to reduction in friction number over time and traffic are:

- surface wear
- rutting
- bleeding or flushing of asphalt binder
- contamination
- porosity of the surface
- polishing of surface aggregates

Many different methods and devices are currently used to collect friction number data in a variety of modes. Standards have been established, such as American Society for Testing and Materials (ASTM) E274 "Test Method for Skid Resistance of Paved Surfaces Using a Full Scale Tire," since ascribing a friction number value to a pavement without specifying tire, speed, temperature, water film thickness, etc., is not technically correct. Friction number as measured by ASTM E274 is termed "Skid Number."

3.3.4 STRENGTH

The evaluation of pavement strength, structural adequacy, structural strength, load-carrying capacity or structural capacity can be estimated by an evaluation of the pavement materials, subgrade, and thicknesses, or by direct field measurements. The ability of an existing pavement to carry the anticipated future traffic at a reasonable level of service is directly related to its structural capacity.

Evaluation of the structural capacity of an existing pavement can be determined by either destructive or non-destructive methods.

Destructive or intrusive methods include probe holes, test pits or coring too:

- determine the existing pavement layer thicknesses
- assess the existing strength by means of Dynamic Cone Penetrometer (DCP) tests, Field Vane tests, field California Bearing Ratio (CBR) tests, etc.
- sample the existing pavement materials for subsequent material characterization in the laboratory

Knowing the thickness of the various pavement layers and the results of the laboratory testing, the existing roadway structure can be mathematically converted, by means of material equivalencies, into a single value such as the Granular Base Equivalency (GBE), Structural Number (SN) or something similar. This computed value can then be compared to the minimum acceptable value required to accommodate the anticipated future traffic.

The material equivalency values range widely from material to material and are area/region or agency specific. Use of material equivalencies from different regions or agencies must be verified for their applicability on a project specific basis. Due to the somewhat subjective method in determining the material equivalencies, the evaluation of the roadway's existing structural capacity, by this method, is also somewhat subjective.

Non-destructive methods evaluate the existing structural capacity, usually by determining the pavement response or deflection to an imposed load. Non-destructive deflection testing devices can be divided into three broad categories which include:

- static deflection or slow-moving devices
- vibratory devices
- dynamic impact devices

Static or slow-moving devices include the Benkelman beam, plate load tests, curvature meters, etc. These devices are simple to use and inexpensive to purchase, but they take longer to obtain data, present a safety concern for operators during data collection, and are labor intensive. In addition, the tests do not accurately simulate the effects of moving wheel loads and their repeatability is low.

Vibratory devices include Dynaflect, Road Rater, WES heavy vibrator, etc. These devices have the ability to measure the deflection basin, as opposed to a single point, are generally easy to operate, acquire data quickly, and have good repeatability, but they are expensive. In addition, the test loads applied to the pavement are generally much lower than actual wheel loads, therefore extrapolation of the data is necessary.

Dynamic impact devices include Falling Weight Deflectometers (FWD), etc. They tend to simulate moving wheel loads with a higher degree of accuracy, repeatability is very good, data acquisition is quick and automated, but they are very expensive. In addition, deflection basin/bowl information can be used in more advanced mechanistic-empirical design methods by back-calculation of the subgrade resilient modulus and the effective pavement modulus. Deflection bowl measurements can also be used to calculate various pavement parameters that can be compared to performance criteria, including:

- surface curvature index
- base damage index
- base curvature index

The surface curvature index indicates the relative stiffness of the upper portions of the pavement which are usually asphalt bound layers. The base damage index and base curvature index indicate the relative stiffness of the materials lower in the pavement section. High values for the surface curvature index would indicate a weakness of the upper pavement layers, while high values for the base damage index and base curvature index would indicate weakness in the lower pavement structures.

3.3.5 MATERIAL PROPERTIES

Utilizing the information gathered during the visual assessment of the pavement surface, the review of historic documents, and the pavement property assessment, the project is divided into sections which have the same performance characteristics or which are homogeneous/uniform. For each section of the project, two different means of choosing sample locations could be used. The first is a fixed interval sampling plan and the second is a random sampling plan. Whichever sampling method is used, it should be unbiased and avoid sampling the worst areas exclusively, since this will result in a misleading view of the project. In addition, sample locations should vary across the roadway width so as not to be in a constant position such as the outer wheelpath. Obviously, the location of the samples needs to be recorded and assessed during the evaluation stage, since different results are expected for samples obtained in wheelpath areas, as opposed to nonwheelpath areas. If additional sampling is undertaken to assess specific areas, distresses or failures, these should be kept separated from the overall project assessment samples and evaluation.

Field samples are then obtained to determine the:

- in-situ asphalt pavement density, asphalt binder content, extracted aggregate gradation, aggregate angularity, flat and elongated particles, and perhaps petrographic analysis
- in-situ asphalt pavement air voids (Va), voids in mineral aggregates (VMA), voids filled with asphalt (VFA), and perhaps resilient modulus
- penetration, absolute and/or kinematic viscosity of the recovered asphalt binder, and perhaps it's temperature susceptibility or Superpave PG characterization
- gradation, moisture content, angularity, Plasticity Index, and perhaps resilient modulus of the base and sub-base aggregates
- subgrade soil type, Plasticity Index, moisture content, and strength
- groundwater conditions

Samples should be of sufficient size so that they will provide a reasonable representation of the material. All samples should be visually inspected as part of the assessment process to see whether they match what was indicated in the historical records. This is particularly important for the asphalt pavement layers, since interlayers such as seal coats/chip seals, rubber modifiers, delaminations, paving fabrics/geotextiles, etc. can have a significant impact on the choice of rehabilitation techniques. The pavement samples should be evaluated for evidence of stripping of the asphalt binder, such as bare or uncoated aggregate, friable or disintegrating mix, and excessive moisture retention. Water retention in older pavements can affect the rehabilitation alternative and is often overlooked, since core samples are usually obtained with water as the cooling fluid.

3.4 DISTRESS EVALUATION

The results of the visual assessment, historical information review, and pavement property assessment are used to evaluate and determine the cause or causes of the pavement distress. If a definite cause for the pavement distress cannot be found, additional investigative work may be required in order to fully understand the behavior of the pavement.

One method that can be used to help determine where the weakness in a pavement structure is located is to correlate the surface deflection with rut depth. If there is a positive correlation between deflection and rut depth, i.e., an increase in rut depth with an increase in deflection, a weak subgrade/base structure is indicated. If there is no correlation between rut depth and deflection, weakness in the upper pavement layers is most likely indicated.

Width of the surface rutting is also a useful indicator of where the pavement weakness may be found. Wide ruts can indicate deeper seated weaknesses, while relatively narrow ruts can indicate upper layer weakness.

The various pavement distresses and potential contributing factors to the pavement distresses are as follows:

Pavement Distress Mode	Potential Contributing Factors to Pavement Distress					
	Base/ Subgrade	HMA Properties	Traffic	Environment	Construction	Pavement Structure
Raveling	□	■	▒	▒	■	□
Potholes	▒	■	▒	▒	■	▒
Bleeding	□	■	▒	▒	■	□
Skid Resistance	□	■	▒	□	□	□
Shoulder Drop Off	▒	□	□	▒	▒	▒
Rutting	▒	■	▒	▒	■	▒
Corrugations	□	■	▒	▒	■	□
Shoving	□	▒	▒	□	□	■
Fatigue Cracking	■	▒	▒	□	□	■
Edge Cracking	■	□	▒	■	□	■
Slippage Cracking	▒	□	▒	□	■	▒
Block Cracking	■	■	□	■	□	□
Longitudinal Cracking	□	□	□	□	■	□
Transverse Cracking	□	■	□	■	□	□
Reflection Cracking	■	□	▒	▒	□	▒
Discontinuity Cracking	■	□	▒	□	□	■
Swells	■	□	□	▒	□	□
Bumps	■	□	□	▒	□	□
Sags	■	□	□	▒	□	□
Depressions	■	□	□	▒	□	□
Ride Quality	▒	▒	▒	▒	▒	▒
Strength	■	▒	□	▒	□	■

■ ▒ □

More Likely → **Less Likely**

Comparison of the results of the investigations and the original design assumptions or methods can also be useful in determining the cause or causes of pavement distress.

3.5 PRELIMINARY REHABILITATION SELECTION

Once the cause or causes of the pavement distress have been determined, assessment and selection of candidate or preliminary rehabilitation techniques/methods to address the pavement distress can begin. It has been assumed that the pavement surface condition has deteriorated to the point where preventive and corrective maintenance techniques are no longer viable alternatives and that some form of rehabilitation is required.

The first step in the assessment of preliminary rehabilitation techniques is to determine:

- What and how severe are the distresses which require the pavement to be rehabilitated?
- Are the existing materials of sufficient quality to be recycled? If not can they be improved during the rehabilitation process?
- What design life is expected of the rehabilitated pavement?
- What is the anticipated traffic growth and Equivalent Single Axle Loads (ESAL's) for the expected design life?
- What is the structural capacity of the existing pavement?
- Does the existing pavement have sufficient structural capacity to handle the expected design life and/or traffic without strengthening?

- Is the existing structure strong enough to support the rehabilitation equipment?
- If strengthening is required what thickness of HMA overlay is needed?
- Is the surface and sub-surface drainage adequate?
- What performance standard, such as riding quality, etc., is required of the rehabilitated pavement?
- What level of maintenance is envisioned during the expected design life of the rehabilitated pavement?
- Are any geometric corrections, such as alignment, width, etc., required during the design period?
- Are there any safety issues which need to be addressed during the rehabilitation?
- What are the types and location of surface and underground services/utilities which will be affected by the rehabilitation?
- Are there any environmental issues, such as temperature, rainfall, etc. which need to be addressed?
- What are the construction limitations, such as traffic accommodation, hours of work, long grades, roadway widths, shaded areas, overhead clearances, drainage structures, curb and gutter, guardrails, etc. which will have an impact on the rehabilitation technique?
- What will be the impact on adjacent businesses/public?
- What size is the rehabilitation project?
- What is the availability of experienced contractors and equipment?
- What is the available budget?

The answers to these questions will significantly influence the type of rehabilitation or reconstruction technique that should be considered.

There are a considerable number of rehabilitation techniques which can be used either individually or in combination to rehabilitate a pavement. Rehabilitation techniques include:

- Hot In-Place Recycling (HIR) - Surface Recycling
- HIR Surface Recycling with a subsequent surface treatment or a HMA overlay
- HIR Remixing
- HIR Remixing with a subsequent HMA overlay
- HIR Repaving
- Cold In-Place Recycling (CIR) with a surface treatment or HMA overlay
- Cold Planing (CP) with or without a HMA overlay
- Thin HMA overlay
- Thick HMA overlay
- CP followed by either HIR, CIR, FDR or Cold Central Plant Recycling (CCPR), and then a HMA overlay
- Full Depth Reclamation (FDR) with a surface treatment or HMA overlay
- Reconstruction with CP, FDR and/or CCPR, and then HMA

The selection of candidate or feasible rehabilitation techniques can be made based on:

- judgement and experience
- a decision tree or logic diagram which models local practice
- an artificial intelligence approach such as expert systems

The following table provides a general guideline for the preliminary selection of candidate recycling or reclamation methods for the rehabilitation of asphalt pavements.

Pavement Distress Mode	Candidate Rehabilitation Techniques							
	CP	HIR	CIR	Thin HMA	Thick HMA	FDR	Combination Treatments	Reconstruction
Raveling	░	▓	▒	▓	░	□	▓	□
Potholes	□	▒	▓	░	▒	░	▓	□
Bleeding	▒	▒	▒	□	░	▒	▓	□
Skid Resistance	▒	▒	▒	▓	░	░	▓	□
Shoulder Drop Off	▒	□	□	□	□	□	□	▓
Rutting	▒	▒	▓	□	░	░	▓	░
Corrugations	▒	▒	▓	□	░	░	▓	░
Shoving	▒	▒	▓	□	░	░	▓	░
Fatigue Cracking	□	□	▓	□	▓	▓	▓	▓
Edge Cracking	□	□	░	□	░	▓	▓	▓
Slippage Cracking	□	▒	▓	□	░	▒	▓	▒
Block Cracking	□	□	▓	□	░	▓	▓	▒
Longitudinal Cracking	□	▒	▓	□	░	▒	▓	▒
Transverse Cracking	□	▒	▓	□	░	▓	▓	▒
Reflection Cracking	□	▒	▓	□	░	▓	▓	▒
Discontinuity Cracking	□	□	▓	□	░	▓	▓	▒
Swells	░	▒	▒	░	▓	▒	▓	░
Bumps	░	▒	▒	░	▓	▒	▓	░
Sags	░	▒	▒	░	▓	▒	▓	░
Depressions	░	▒	▒	░	▓	▒	▓	░
Ride Quality	░	▓	▓	░	▓	□	▓	□
Strength	□	░	▒	□	▓	▓	▓	▓

▓ ▒ ░ □

Most Appropriate → Least Appropriate

All of the candidate rehabilitation techniques have advantages and disadvantages relative to one another, since not all rehabilitation techniques are equally suited to treat the various pavement distresses. The ability of a rehabilitation technique to correct a pavement distress is dependent on the type of pavement distress, as well as the extent of the distress and its severity. In addition, local aggregate quality, amount/type of traffic, and climatic conditions are also important factors which need to be considered.

The choice of preliminary rehabilitation techniques should be made based on engineering considerations and the subsequent economic analysis.

3.6 ECONOMIC ANALYSIS

An economic analysis is undertaken to compare the different rehabilitation techniques, in order to determine the one which will maximize the monetary effectiveness. This is usually done by comparing the life-cycle costs of the various rehabilitation alternatives being considered.

A life-cycle cost refers to all costs/expenses and benefits related to the roadway which occur over a fixed analysis period. Some of the cost components to be accounted for in the analysis period include:

- initial rehabilitation costs

- future rehabilitation costs
- maintenance costs
- residual or salvage value
- engineering and administrative costs
- user costs (travel time, vehicle operation, accidents, discomfort, delay costs and extra operating costs) during rehabilitation and maintenance activities

Other costs might include aesthetics, pollution, noise, etc., but these are difficult to quantify and are usually dealt with in a subjective manner.

Several different economic models can be used, including:

- present worth
- equivalent uniform annual cost
- rate-of-return
- benefit-cost ratio
- cost-effectiveness

The Present Worth Method is the most widely used in the transportation field. It consists of combining all costs and benefits, in terms of discounted dollars which occur at different times over the analysis period, and translates them into a single amount at a particular point in time, usually the present.

The Equivalent Uniform Annual Cost Method combines all initial capital costs and all recurring future expenses into equal annual payments over the analysis period.

The Rate-of-Return Method considers both the costs and benefits. It involves a determination of the rate at which costs/benefits for a project are equal. It can also be in terms of the rate at which the equivalent uniform annual cost is exactly equal to the equivalent uniform annual benefit.

The Benefit-Cost Ratio Method involves expressing the ratio of the present worth of benefits of any alternative to the present worth of costs or the ratio of the equivalent uniform annual benefits to the equivalent uniform annual costs. The benefits are established by a comparison of alternatives.

The Cost-effective Method can be used to compare alternatives which have significant, non-monetary benefits. It involves a determination of the benefits to be gained, in subjective terms, from additional expenditures which require the establishment of subjective measures of effectiveness or benefit.

The first factor which needs to be considered, whichever economic model is used, is the identification of the service life of the rehabilitation alternatives being considered. The service life is the period of time the rehabilitation method will be effective before additional rehabilitation or reconstruction will be required. The service life of rehabilitation techniques vary from region to region, and agency-to-agency, and typical values are given in the subsequent Chapters on Detailed Project Assessment for HIR, FDR and CR.

The next factor which will need to be determined is the analysis period or life-cycle period. In general, the analysis period should not extend beyond the period of reliable forecasts. The length of the analysis period is a policy decision which is dependent upon the agency and circumstances. Life-cycle periods for new construction alternatives usually extend out to twice the initial service life of the longest performing pavement. Hence, the life-cycle period for assessment of the various rehabilitation alternatives should be twice the initial service life of the longest performing technique. Another approach is to extend the life-cycle period to the point where the discounted costs or benefits become very small or below a preset minimum level. The life-cycle period can change depending on the discount rate used and the preset minimum level selected.

Selection of a discount rate is needed to reduce future expected expenditures/benefits to present day terms or time base. Discount rates must not be confused with interest rates which are associated with borrowing money. The discount rate chosen for the economic analysis is also a policy decision of the agency but it most often is the effective rate or the difference between the expected interest rate and expected inflation.

Residual or salvage value is usually included in the economic analysis, and it is usually based on the anticipated remaining life of the last rehabilitation technique at the end of the analysis period.

Although the economic analysis will provide a basis for selection of the rehabilitation technique, several other factors need to be considered in order to make a rational decision. These factors include, but are not limited to:

- the type and severity of the existing distresses
- age/condition of the existing pavement materials and their potential for recycling
- expected design life and performance requirements of the rehabilitation
- traffic growth
- structural capacity of existing roadway
- environmental conditions
- acceptable future maintenance activities
- geometric, drainage, underground and surface utilities
- traffic accommodation and safety
- construction limitations
- project location and size
- contractor availability and experience
- impacts on adjacent businesses and public
- available budget
- good engineering judgement

CHAPTER 4: HOT IN-PLACE RECYCLING – DETAILED PROJECT ANALYSIS

Through the project evaluation, economic analysis, and preliminary selection process outlined in Chapter 3, the potential rehabilitation alternatives were narrowed down to one specific technique. The next step in the rehabilitation design is the detailed project analysis—which will lead directly into the final project design, advertising, tendering or letting, and construction.

The Hot Mix Asphalt (HMA) overlay, hot recycling, and reconstruction rehabilitation methods will not be addressed since they are routinely used by all agencies. The rehabilitation techniques of Cold Planing (CP), Cold Recycling (CR), and Full Depth Reclamation (FDR), are covered in depth in other chapters. It is recognized that many of the steps in the detailed project analysis are common to all the rehabilitation methods but are addressed in each process, for continuity.

4.0 HOT IN-PLACE RECYCLING REHABILITATION

Hot In-Place Recycling (HIR) is an on-site, in-place rehabilitation method which consists of heating, softening, scarifying, mixing, placing, and compacting the existing pavement. Virgin aggregates, asphalt binder, recycling agents, and/or new HMA can be added, on an as required basis, to improve the characteristics of the existing pavement. Virgin aggregates or new HMA which is incorporated into the HIR process, is commonly referred to as “admix”. Pavement distresses which can be treated by HIR include:

- raveling
- potholes
- bleeding
- friction number
- rutting
- corrugations
- shoving
- slippage, longitudinal, transverse, and reflection cracking
- poor ride quality caused by swells, bumps, sags, and depressions

There are three sub-categories of HIR, defined by the construction process used, consisting of Surface Recycling, Remixing, and Repaving. Not all of the HIR processes treat all of the above noted pavement distresses equally. In addition, unless the cause or causes of the pavement distress are addressed during the rehabilitation process, the distresses will be mitigated but they will not be eliminated.

The expected design life, performance requirements during the design life, and acceptable future maintenance requirements are also different for the three HIR processes. Hence, the detailed project analysis will further refine which of the three HIR processes is most appropriate.

4.1 HISTORIC INFORMATION ASSESSMENT

In the detailed review of historic or existing information, the data which needs to be assessed includes:

- Age of roadway and surface layer including any surface treatments. Surface treatments tend to be high in asphalt binder and therefore must be accounted for in the mix design process. In addition, multiple surface treatments tend to reduce HIR productivity, due to slower heating of the underlying pavement, and increase the risk of fugitive emissions in the form of blue smoke.
- Past condition surveys, in order to assess the rate of pavement deterioration.
- Thickness of the existing pavement structure and asphalt pavement layers. A minimum of 3 inches (75 mm) of asphalt pavement is generally required for HIR.

  If the HIR treatment depth is 2 inches (50 mm) and the asphalt pavement layer is less than 3 inches (75 mm), pieces of the underlying asphalt pavement may break loose during the HIR process and create mixing and laydown problems. In addition, sufficient pavement structure is needed to support the HIR equipment during construction.
- Thickness of the top lift/surface lift of asphalt pavement. If the surface lift and HIR treatment depth are similar, moisture trapped at interface between the surface lift and underlying layer, delamination of the surface lift and underlying layer, and/or stripped aggregates could be encountered. HIR will remix and recoat the stripped aggregate but unless the mix is modified to address the stripping problem, it will eventually reoccur.
- Type of asphalt binder used in surface lift since it will affect the type and amount of recycling agent that may be required. It may also have an effect on the type/grade of asphalt binder used in any admix which may be needed.
- Top size of aggregates used in surface lift. Depending on the top size of the aggregate, large stone mixes may not be able to be effectively recycled using all HIR processes.
- Presence of any paving fabrics or interlayers in the anticipated treatment depth plus 25 percent. Paving fabrics cannot be recycled with HIR, and the presence of an interlayer needs to be assessed further depending on its characteristic and location.
- Presence of exotic or specialty mixes such as Open Graded Drainage Layers, Open Graded Friction Courses, Stone Matrix Asphalt, etc., will have an effect on HIR process selection and production rates.
- Presence of rubber in the surface lift or rubberized seal coats will require special attention in the mix design process. It will also cause some difficulties during construction, since it has such a high affinity for the rubber in the tires of the HIR and compaction equipment.

The detailed review of existing information, contained in a maintenance database which needs to be assessed includes:

- patching locations and ages
- patching material including HMA, cold mix asphalt, injection spray patching, etc.
- crack sealing activities, product types and ages

The detailed review of the existing Quality Control/Quality Assurance (QC/QA) information, from construction of all pavement layers within the anticipated HIR treatment depth includes:

- asphalt binder content

- aggregate gradation, angularity, flat/elongated particles, and/or petrographic analysis
- mix void properties, air voids (Va), Voids in Mineral Aggregates (VMA), voids filled with asphalt (VFA)
- field compaction
- recovered asphalt binder properties

In order to delineate or isolate areas of substantial difference and/or uniformity within the project limits, a comparison of the QC/QA test results should be undertaken. Two times the standard deviation of the QC/QA test results, compared to the construction production tolerances will give a quick indication of whether or not the mix variability is high or low. High mix variability is less desirable since 100 percent of existing material will be recycled in HIR process. The construction specifications may have to be modified to account for projects with high mix variability, if other factors indicate that HIR is a viable option.

Special attention must be paid to the presence of surface treatments, such as chip seals, slurry seals or micro-surfacing, crack sealant, and thermoplastic lines, since their presence have an impact on environmental and economic considerations. Surface treatments, crack sealant and/or thermoplastic lines can be incorporated into the HIR mix but they will have to be accounted for in the mix design process. These materials also have an effect on the selection of type of recycling agent, admix (gradation, grade, amount and asphalt binder content), and admix addition rate.

4.2 PAVEMENT ASSESSMENT

In the detailed pavement assessment, the type, severity, and frequency of the pavement distress needed to be corrected is determined. Not all of the three HIR processes can correct the same pavement distresses and the condition of the surface and upper layer of pavement has significant impact on the HIR process selected.

An unusual surface texture may indicate the presence of a specialty HMA mix in the upper layer of the pavement which will need to be assessed further during the material properties assessment.

If surface treatments, seal coats, crack sealant, thermoplastic lines, and specialty mixes present too great a problem, they could be removed by CP prior to HIR.

The presence of large or frequent surface patches increases the variability or decreases the homogeneity of the existing materials—which has an effect on the consistency of the HIR mix. Large patches may require their own specific mix design, since they are usually newer and of different materials than the original pavement.

In the Surface Recycling process, if the existing pavement is susceptible to polishing, the HIR pavement will also be susceptible to polishing, unless it is subsequently overlain with a non-polishing HMA. With the Remixing process, the susceptibility of the pavement to polishing can be reduced if appropriate steps are taken during the selection of the admix aggregate type and determination of admix added rate. As admix addition rates are typically in the order of 30 percent maximum, admix aggregate selection will be critical. In the Repave process, polishing aggregates are covered with a new HMA integral overlay—which should be specifically selected so that it has the required resistance to polishing.

Deep ruts, when typically greater than about 1/2 of the anticipated HIR treatment depth, will impose limitations on the type of HIR process which should be used. All three HIR processes can be used if the rutting is wear rutting. For instability, rutting the Remix process can be used provided the mix instability can be corrected with the selection of an appropriated admix and recycling agent. The Repave process can be used for instability rutted pavements, if the Remix process, with an appropriate admix and recycling agent, is used prior to placement of the integral overlay. When a minor amount structural rutting is present, the Repave process can be used if the integral overlay thickness is sufficient to address the structural deficiency.

The types of pavement distress which can be addressed with the various HIR processes are indicated in the following table.

Pavement Distress Mode	Candidate HIR Process		
	Surface Recycling	Remix	Repave
Raveling	■	■	■
Potholes	▒	■	■
Bleeding	▒	■	▒
Skid Resistance	□	▒	■
Shoulder Drop Off	□	□	□
Rutting	▒	■	▒
Corrugations	▒	■	▒
Shoving	▒	■	▒
Fatigue Cracking	□	▒	■
Edge Cracking	□	▒	■
Slippage Cracking	▒	▒	■
Block Cracking	▒	▒	■
Longitudinal Cracking	▒	▒	■
Transverse Cracking	▒	▒	■
Reflection Cracking	▒	▒	■
Discontinuity Cracking	□	□	▒
Swells	▒	▒	▒
Bumps	▒	▒	▒
Sags	▒	▒	▒
Depressions	▒	▒	▒
Ride Quality	■	■	■
Strength	□	□	▒

■ ▒ □

More Appropriate → Less Appropriate

4.3 STRUCTURAL CAPACITY ASSESSMENT

The first step is to assess the structural capacity of the existing pavement and the anticipated traffic during design life of the rehabilitation. Typically, the HIR process requires a minimum of 3 inches (75 mm) or more of existing asphalt pavement to ensure that the process will be successful. If the existing structural capacity needs strengthening, a determination of the required strengthening thickness must be undertaken using conventional pavement design methods.

Pavements with major or extensive structural failures will not be good candidates for HIR and other rehabilitation methods should be assessed.

Pavements with existing structural capacity sufficient to handle the anticipated design traffic can be treated with any one of the three HIR processes.

Required strengthening thickness less than about 3/4 inch (20 mm) of HMA can be treated with the Remixing and Repaving processes or with Surface Recycling and a subsequent thin HMA overlay. Current Remixing equipment can accommodate up to 30 percent admix which for a 2 inch (50 mm), treatment depth is a 5/8 inch (15 mm) increase in thickness. The newer HIR Remixing equipment is reported to be able to add in the order of 50 percent admix or increase the pavement thickness by 1 inch (25 mm). The Repaving process can place an integral HMA overlay as thin as 1/2 inch (12.5 mm), providing the appropriate HMA is used.

If the strengthening thickness required is greater than 3/4 inch (20 mm) but less than about 2 inches (50 mm) the Repaving process can be assessed further. Surface Recycling or Remixing could also be used with a subsequent thin HMA overlay.

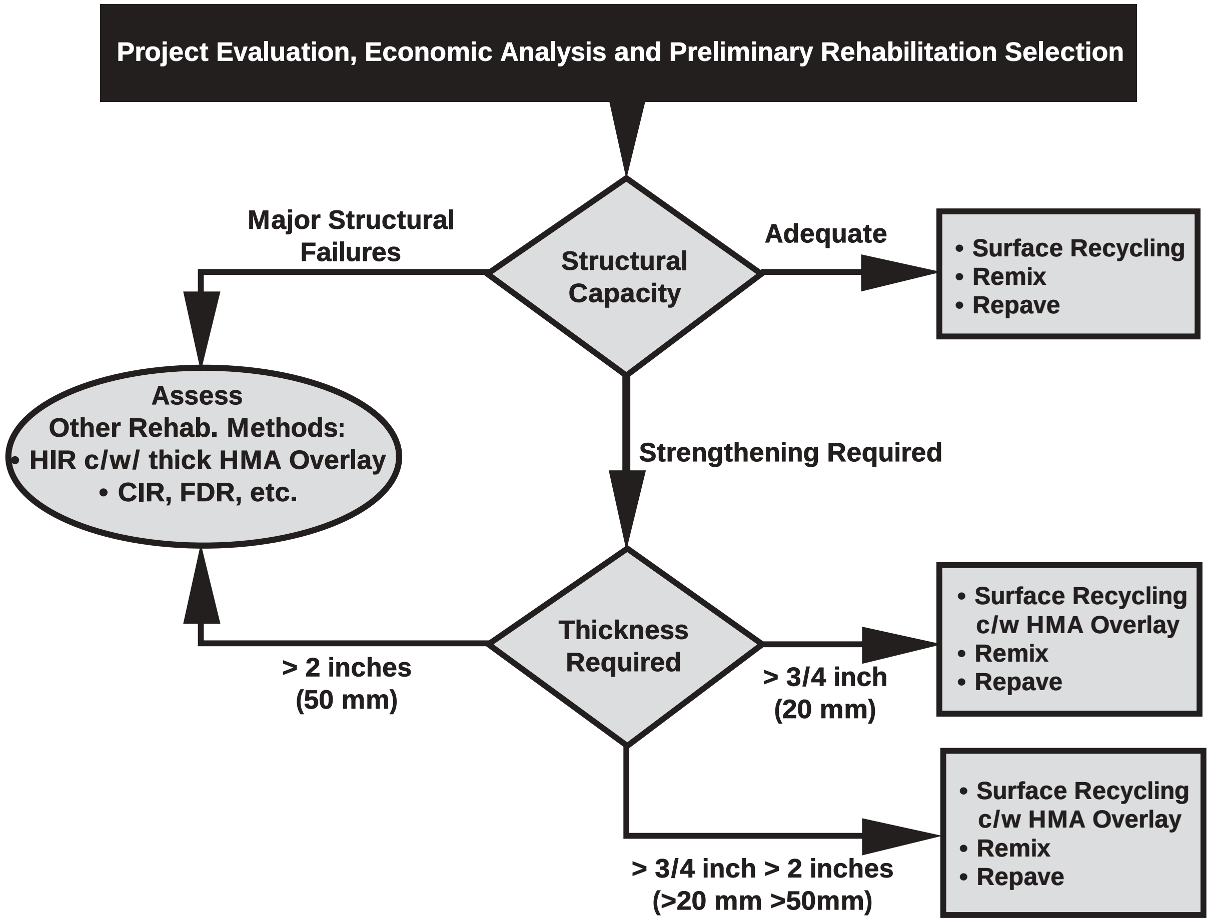
Typically, the Repaving process can include an integral HMA overlay of around 2 inches (50 mm) in thickness. The maximum thickness of the integral HMA overlay is related to the treatment depth of the Surface Recycling or Remixing process—which precedes the placement of the integral HMA overlay. When the combined thickness of the integral HMA overlay and the underlying HIR treatment depth is in excess of about 3 to 4 inches (75 to 100 mm), increased difficulties with placement, compaction and achieving the desired smoothness can be encountered.

Roadways with existing structural capacity requiring more than 2 inches (50 mm) of strengthening should be treated with other rehabilitation methods such as combined rehabilitation methods, staged rehabilitation, or HMA overlays. Stage rehabilitation is the process where the pavement is partially rehabilitated now and monitored for structural capacity, then overlaid once the HMA overlay depth becomes a practical/economic thickness.

If the existing roadway needs to be strengthened after the HIR process, it can be strengthened with an appropriate HMA overlay.

Whichever rehabilitation technique is chosen, the source/cause of any isolated structural problems in the pavement must be identified and corrected or they will likely reappear.

A flow chart depicting the HIR rehabilitation selection process follows:



4.4 MATERIAL PROPERTIES ASSESSMENT

Utilizing the results of the existing information review and the pavement assessment, the project is divided into areas/segments of similar materials or performance. A field sampling plan is then established, using either fixed interval or random sampling methods, to determine the location of the field samples. Field sampling is usually by means of coring. Block sampling, by means of sawing, can also be used but it is usually more expensive and disruptive than coring.

Some of the field samples should be obtained with compressed air as opposed to water during the coring/sawing process, to accurately determine the moisture content of the asphalt pavement. Moisture content significantly influences the production rates of the various HIR processes. It is noted that the moisture content of an asphalt pavement can change in response to seasonal climatic variations. As the moisture content of the pavement increases, there is a corresponding increase in the heat energy required to remove the moisture and then heat the asphalt pavement to the desired temperature. HIR equipment is usually designed with a fixed amount of available heat energy, and the more energy that is used to remove moisture, the less there is available to heat and soften the pavement. Consequently, in order to achieve the desired mix temperature, the HIR train must move slower—which reduces productivity.

In the HIR processes, the asphalt pavement is soft and pliable due to its "thermoplastic" nature, prior to the scarification or rotary milling process, so no appreciable degradation of the mineral aggregates occurs. Therefore, it is critical that field samples not be obtained by cold planing, with a small milling machine, since this method will result in more degradation of the mineral aggregates than will occur in the HIR process. Rather, cores should be used, since they will provide more representative samples. The larger the diameter of the core, the smaller the ratio of cut surface to volume which corresponds to less degradation in aggregate gradation. Core samples in the order of 6 to 8 inches (150 to 200 mm) in diameter are preferred. However, 4 inch (100 mm) diameter cores could be used for some of the laboratory testing such as field density, Marshall Stability, etc. It is important that the full depth of the asphalt bound layers be cored in order to assess their condition.

The frequency of field sampling varies with the size of the project, size of the areas of similar materials or performance, and the variability of the existing materials, as determined from the review of existing QC/QA data. Generally, the number of sample locations ranges from 3 to 5 for smaller, consistent areas, to 20or more for larger, less consistent areas. Samples are obtained at a frequency of approximately one location per 5/8 mile (kilometer) per lane direction. The number of cores obtained at each field sampling location will depend on the number of field sample locations, the amount of laboratory testing to be performed, and whether or not samples will be needed for subsequent HIR mix designs. If a 5 point Marshall mix design is to be undertaken, a total of 18 to 20 cores, 2 inches (50 mm) thick, and 6 inches (150 mm) in diameter or approximately 90 pounds (40 kilograms) of material, is usually required.

The core samples should be carefully examined in order to detect the different pavement layers, previous surface treatments, interlayers, geotextile paving fabrics, specialty mixes, evidence of stripping, friable or disintegrating mix, retention of excessive moisture, and any tendency to delaminate. Once the cores have been inspected, the observations recorded, and selected cores photographed, the cores are trimmed to the depth of the anticipated HIR treatment. Representative cores are then tested to determine:

- bulk specific gravity/density
- field moisture content
- asphalt binder content
- aggregate properties including gradation, angularity, etc.
- recovered asphalt binder properties including penetration, absolute and/or kinematic viscosity, and perhaps temperature susceptibility or Superpave PG grading
- Maximum Theoretical Density of the existing mix
- in-situ void properties of the existing mix including Va, VMA, and VFA

4.5 GEOMETRIC ASSESSMENT

In the detailed geometric assessment, determine whether the project:

- requires major realignment, widening or drainage corrections
- contains underground utilities/drainage structures
- requires upgrading of any underground utilities
- contains bridges/overpasses
- needs longitudinal/grade corrections
- requires cross-slope/fall corrections.

Major realignments, widening or drainage corrections may eliminate HIR, depending on the extent of the reconstruction, but HIR could still be included as a stage in the overall rehabilitation process.

The presence, frequency, and elevation of utility covers (manholes and valves) need to be assessed, particularly in the urban setting. Manholes and valves can be raised or lowered depending on existing elevations, but their presence tends to reduce productivity. Obviously, if any upgrading of the existing underground utilities is required, it should be undertaken prior to rehabilitating the roadway surface.

Bridges/overpasses need to be assessed to determine:

- whether an asphalt pavement is present and whether it is to be rehabilitated with the remainder of the project
- depth of existing asphalt pavement
- presence of waterproofing membranes, their depth, and sensitivity to heat
- presence of any specialty waterproofing mixes (latex, polymers, etc.)
- structural capacity to accommodate weight of the HIR equipment
- allowable weight and effect of compaction equipment, particularly vibratory steel drum rollers

HIR equipment generally has fixed treatment widths, although there are some newer models which will allow some variable treatment widths. The HIR treatment width is usually one lane or 12 feet (3.7 meters), since typically only the driving lanes are treated. However, full width treatment of the pavement can be undertaken, particularly for wider roadways. Pavements which are not exactly a whole multiple of the treatment width of the HIR equipment will require some overlap to ensure full HIR coverage. Ideally, an overlap between adjacent HIR passes of 2 to 6 inches (50 to 150 mm) is desired. If the overlaps become significantly larger, there are potentially both economic and performance implications, particularly if significant amount of admix or recycling agent is being used in the process.

The HIR process being used also affects the amount of longitudinal and transverse profile corrections which can be practically undertaken. The amount of longitudinal and transverse correction which can be performed with:

- Surface Recycling is minor since little or no admix is added during the process
- Remixing is average but is related to the amount of admix being added, with more correction being possible with higher admix addition rates
- Repaving is above average but is related to the thickness of the integral HMA overlay being placed. The thicker the integral overlay, the greater the correction

In some instances, it may be more practical/economic to place a thin HMA preliminary leveling course, or reprofile the roadway with a milling machine prior to HIR. If Cold Planing (CP) or a preliminary leveling course is to be used, it must be accounted for in the HIR mix design process.

The HIR equipment is very long, due to the number of pieces in the train. Therefore, roadway geometry, particularly in an urban setting, will influence the types of areas which can be treated. The HIR equipment can handle moderate radius turns such as acceleration/deceleration lanes, turning bays, etc., provided there is sufficient room for the equipment to exit the area. Roadways containing “T” intersections cannot be treated all the way to the top of the “T.”

4.6 TRAFFIC ASSESSMENT

Traditionally, HIR has been utilized on low to medium traffic volume roadways. There is no practical reason why it cannot be used on high traffic volume roadways, particularly for the Remix and Repave processes.

The HIR process minimizes traffic disruptions and user inconvenience due to the short construction time, compared to conventional pavement rehabilitation methods. HIR can also be undertaken at night or in off peak hours to further reduce traffic disruptions.

Depending on the width of the existing roadway, the HIR operation will occupy 1 1/4 to 1 1/2 lanes within the HIR construction zone. For narrow roadways, accommodation of large/wide truck or oversized loads will need to be addressed.

On two lane roadways, one-way traffic through the construction zone will need to be maintained with appropriate traffic control such as flag people, lane demarcation devices, and/or pilot vehicles. Very narrow two lane roadways increase the traffic accommodation difficulties, particularly if there is little or no paved shoulder.

Traffic control at intersections and business approaches also needs to be addressed in an urban environment. Due to the speed of the HIR processes, the intersections and approaches are not out of service for very long and traffic is usually controlled with flag people and lane demarcation devices.

4.7 CONSTRUCTABILITY ASSESSMENT

As the HIR equipment is relatively wide and long, overnight parking/storage of the equipment is a concern. A level and wide overnight parking area is required, or the equipment must be allowed to be parked on the side of the roadway overnight—with the use temporary traffic delineation devices, warning lights and/or temporary signals to direct traffic. The width of the roadway being treated will determine whether overnight parking on the roadway shoulder is a viable alternative.

The location/spacing of these parking areas are critical, since a HIR train can treat between 1 1/4 to 2 1/2 lane miles (2 and 4 lane kilometers) per day. Typically, parking areas should be on the order of 2 miles (3 kilometers) apart to reduce the amount of equipment travel during daily mobilization and demobilization. Although the individual pieces of HIR train are very mobile due to their length, the access to and the parking area have to be relatively level since most HIR equipment can easily become high centered.

Clear heights for bridges and underpasses must be checked not only for the HIR equipment but the admix haul trucks, as well.

Generally, HIR equipment can process to the edge of a curb and gutter section. For straight-faced concrete sections (with no gutter), a portion of roadway will not be able to be treated. Depending on the HIR equipment set-up, an area of approximately 8 to 12 inches (200 to 300 mm) in width cannot be processed. If needed, these areas could be CP prior to HIR, and the area paved by extending the paver screed during the HIR laydown process.

If admix or HMA is required to be added in the HIR process, then the availability of aggregates and access to an asphalt plant must also be assessed.

4.8 ENVIRONMENTAL IMPLICATIONS

HIR has the potential to create fugitive emissions in the form of blue or white smoke depending on:

- the type, efficiency, and design of the HIR equipment
- the presence of surface treatments, seal coats, crack sealant, and/or thermoplastic lines
- the ambient conditions including temperature, wind velocity, and direction

New HIR equipment; adequately maintained and operated; prior removal of surface treatments; warm ambient temperatures; and little wind will significantly reduce the risk and/or amount of potential fugitive emissions. Fugitive emissions are of increased concern in an urban environment.

As with all rehabilitation construction projects, there will be a certain amount of noise associated with the process. Typically, due to the speed of the HIR operation and the transient nature of the process, the noise effects will be short term. This issue will have increased concerns in an urban setting.

The possibility of flammable substances near the work site needs to be assessed. In general, this is not a problem, but overhanging trees and vegetation can be scorched during the HIR operation. The scorching wilts the leaves, causing them to turn brown, but the trees usually remain unharmed as the leaves return the following spring. Deflectors on the exhaust stacks of both the emission controls and the equipment power plants have been used to reduce the amount of scorching to overhanging vegetation. In critical circumstances, the overhanging vegetation can be trimmed back or covered with protective material to prevent scorching.

Immediately prior to the HIR equipment passing over or near any manholes, catch basins, vaults, etc., they must be checked for the presence of any flammable vapors/gases, and should be cleared by the Fire Authority having jurisdiction within the project area.

4.9 ECONOMIC ASSESSMENT

The expected service lives of the various HIR rehabilitation techniques, when undertaking a life-cycle economic analysis, generally fall within the following ranges:

• HIR Surface Recycling with no subsequent surface treatment	2 - 4 years
• HIR Surface Recycling with surface treatment	6 - 10 years
• HIR Remixing	7 - 14 years
• HIR Remixing with subsequent HMA overlay	7 - 15 * years
• HIR Repaving	6 - 15 * years

Note: * Equivalent to agency's thick lift HMA service life.

The effectiveness and performance of the various HIR rehabilitation techniques varies from agency to agency and is dependent on:

- local conditions
- climate
- traffic
- type of technique and quality of materials used
- quality of the workmanship

CHAPTER 5: HOT IN-PLACE RECYCLING – MIX DESIGN

Like Cold Recycling (CR) and Full Depth Reclamation (FDR), there is no nationally accepted method for undertaking a Hot In-Place Recycling (HIR) mix design. A number of different HIR mix design methods have been used by the various agencies which include HIR in their pavement rehabilitation strategies. Several of these mix design methods have been reported in the literature. In general, the philosophy for the HIR mix designs has been to restore the properties of the existing aged asphalt pavement to those of (or close to what would be expected of) virgin Hot Mix Asphalt (HMA). This approach attempts to account for the changes which have occurred in the existing HMA due to time, traffic, and the HIR process itself. For example, the asphalt binder may have age-hardened (oxidized) since the HMA was originally placed; the HMA may have undergone densification/reduced field air voids due to traffic; or the HIR process may age-harden the asphalt binder prior to the addition of a recycling agent. This approach has been successful on many projects, but opportunities for additional mix improvements may have been possible.

For example, an asphalt pavement that is 10 years old may be distressed and in need of rehabilitation due to environmental and traffic effects. If the amount of pavement distress is excessive for its age, as part of determining whether HIR is a viable rehabilitation alternative, it should be determined whether the distress is due to:

- increased traffic loading above what was originally anticipated
- inferior quality materials being used
- failure to follow the job mix formula
- mix properties outside the acceptable tolerance limits
- reduced lift thickness and substandard field compaction
- failure of the mix to perform as indicated by the original mix design

Using the results of the historical information and material properties assessment, as discussed in Chapters 3 and 4, the mix design engineer should determine whether the original HMA mix design was adequate, and whether restoration of the existing HMA pavement is achievable. If not, the mix design engineer should consider upgrading and improving the mix properties during the HIR mix design process, to account for the shortcomings of the original mix.

An example of upgrading the existing mix would be to modify the gradation of the existing HMA with the addition of virgin aggregate during the HIR process. This could have the effect of improving stiffness to better resist rutting or reducing the total asphalt binder content if it were determined that the original mix was over-asphalted and contributed to excessive rutting.

The asphalt binder plays a pivotal role in the performance of the asphalt pavement. Recycling agents or very soft asphalt binders can be used to upgrade the overall quality of the asphalt binder in the recycled mix. The HIR mix design is the place to recognize the opportunity, through careful evaluation and materials selection, to improve the recycled mix properties and extend the performance of the pavement beyond that originally expected.

HIR mix designs are more complex than standard virgin HMA mixes. A mix design for a HIR Remix project will have nine variables compared to five for a HMA mix design. The variables in the mix design for the HIR Remix project will include:

- recycling agent type
- recycling agent source
- recycling agent amount
- virgin aggregate gradation
- virgin aggregate amount
- virgin aggregate source
- new asphalt binder type
- new asphalt binder source
- new asphalt binder amount

The conventional HMA mix design variables include:

- virgin aggregate gradation
- virgin aggregate source
- new asphalt binder type
- new asphalt binder source
- new asphalt binder amount

Consequently, the mix designs take more time and have increased costs. The increased costs involved create two questions. How much mix design work can be afforded? What are the consequences of not performing a mix design? The owner agency will have to weigh the benefits and risks associated with conducting no, partial or complete HIR mix designs. When the owner agency is assessing the risks associated with not performing a HIR mix design, consideration could be given to having different requirements for low traffic volume roadways compared to high traffic volume roadways. It is noted that very few owner agencies would consider purchasing/using HMA, without some assurance that a mix design had been undertaken and that the HMA meets the requirements of their specifications, regardless of the roadway classification it would be used on.

5.1 ASPHALT BINDER REJUVENATION

Within the framework of the HIR mix design, consideration of what mechanisms are affecting the performance of the original mix, and efforts to correct these deficiencies, in recycled mix, should be undertaken. The rejuvenation of the existing asphalt binder is one key mechanism and there are several viewpoints on how it should be accomplished. These are summarized as follows:

- Use only a recycling agent to restore/rejuvenate the existing asphalt binder properties. This assumes that the recycling agent is effective in combining with the aged asphalt binder during the HIR process.
- Use a soft, new asphalt binder rather than a recycling agent. This assumes that a recycling agent may not completely combine with the aged asphalt binder and the soft, new asphalt binder, combined with the original binder, will result in an “average” binder that is adequate.

- Use both a recycling agent and a soft, new asphalt binder in conjunction with a virgin aggregate, to rejuvenate the aged asphalt binder,
- Use recycled mix properties such as resilient modulus, stability, etc., rather than asphalt binder properties, to determine the final mix selection. This recognizes the uncertainties of adjusting asphalt binder properties in the laboratory and that the overall recycled mix behavior reflects the net effect of asphalt binder rejuvenation.

An understanding of the nature of the rejuvenation action on the existing asphalt binder is needed in order to understand how to approach the HIR mix design. If one were to carefully examine a highly enlarged portion of an existing HMA, the cross-section would indicate aggregate particles surrounded or coated with an aged asphalt binder, and interspersed with air voids. In the HIR process, the mix is heated, softened, and loosened so that a recycling agent and/or an admix can be added. Immediately following its addition and through the mixing process, the recycling agent coats the surface of the existing aged asphalt binder. The recycling agent penetrates the aged asphalt binder at a rate that is dependent on the properties of the aged asphalt binder and on the properties or reactivity of the recycling agent.

If the recycling agent does not readily penetrate and combine with the aged asphalt binder, it will form a lubricated interface, which can cause instability in the recycled mixture. When this happens during HIR construction, it gives the recycled mix the appearance of being over-asphalted or having too much recycling agent. This is a result of assuming the recycling agent and aged asphalt binder are compatible, and can be completely blended during the time available in the HIR process.

If the conditions are optimum and the recycling agent is compatible with the aged asphalt binder, the recycling agent diffuses into the aged asphalt binder producing a co-mingled material which acts as a single, softer material. The resultant recycled mix looks like virgin HMA and behaves as designed.

During the 1970’s, when mix design methods were being developed for conventional hot recycling, there were concerns that the relatively small amounts of recycling agent being added was not well dispersed in the recycled HMA. The Federal Highway Administration (FHWA) sponsored a project on the degree of mixing/dispersion of recycling agent in recycled mixes, using a unique two-part dye system. The study indicated that the recycling agent was very well dispersed throughout the final mixture and that effectiveness of the recycling agent was dependent on the temperature of the materials and the time available for dispersion/diffusion. The amount of diffusion of the recycling agent in the aged asphalt binder dramatically slowed when the recycled mix temperature dropped/cooled or as the time at the elevated temperature was reduced.

The overall effect of adding a recycling agent can be determined by testing the physical properties of both the recovered asphalt binder and/or the recycled mixture. When using the asphalt binder approach, the aged asphalt binder is recovered from the existing asphalt pavement and its physical properties such as penetration, viscosity, Superpave PG grading etc., are determined. The recovered, aged asphalt binder is blended with various percentages of recycling agent, and then tested to determine the change in physical properties which has occurred at the various recycling agent addition rates. The change in asphalt binder physical properties is an indication of the amount of rejuvenation which has occurred in the aged asphalt binder.

Alternatively, samples of the existing asphalt pavement can be heated until it has softened sufficiently to become pliable or workable. Various amounts of recycling agent are then added, along with any admix, consisting of a virgin aggregate mixed/lightly coated with a new asphalt binder, and the combined materials are then thoroughly mixed into one homogeneous mass. Samples of the asphalt binder in the resultant recycled mix are then recovered and tested to determine its physical properties. The physical properties of the combined asphalt binder are then compared to the original aged asphalt binder in order to determine the amount of rejuvenation which has taken place.

The second approach is to determine the amount of rejuvenation which has occurred in the aged binder, by comparing the physical properties of the mix before and after the addition of the recycling agent, and/or admix. The Hveem stability, and to a lesser extent the Marshall stability, has been shown to be sensitive to the addition of various amounts of recycling agent. The physical effects of the softening/rejuvenation of the aged asphalt binder by recycling agent can also be determined by resilient modulus testing. If the resilient modulus is determined by a diametral indirect tension test, most of the loading stresses are predominately in tension. This significantly reduces the aggregate effects, compared to the Hveem and Marshall stability tests. Therefore, the stresses are focused on the asphalt binder and any change in asphalt binder property, i.e., amount of rejuvenation, can be more readily determined.

5.2 MIX DESIGN PROCESS

The HIR mix design process has remained the same for most agencies for a long time. More recently, through the Strategic Highway Research Program (SHRP) program and the development of the Superpave system, an alternate approach may possibly be applied to HIR mix designs. The overall HIR mix design process, whether traditional or Superpave, involves some or all of the following steps:

- evaluation of the existing HMA including asphalt binder, aggregates, and mix properties
- determining whether the existing asphalt binder needs rejuvenation
- selecting the type and amount of recycling agent
- determining the need for and amount of admix including aggregate gradation, type, and amount of soft, new asphalt binder
- preparing and testing both asphalt binder and mix specimens in the laboratory
- evaluating test results and determining the optimum combination of admix and recycling agent.

No matter which HIR mix design method is used, standard sampling and testing methods such as the American Association of State Highway and Transportation Officials (AASHTO), American Society for Testing and Materials (ASTM) or the owner agencies' adaptation of these standards should be followed, whenever possible.

5.2.1 BLENDING CHARTS

Originally, HIR mix designs considered primarily the viscosity of the aged asphalt binder and the amount of rejuvenation required. The flow chart presented in Figure 5-1, indicates the original or blending chart HIR mix design process.

The asphalt binder content and physical properties of the recovered aged asphalt binder, from the intended depth of recycling, establish the uniformity of the pavement to be recycled and are used to estimate the type and quantity of the recycling agent needed. There are three basic purposes for using a recycling agent, including:

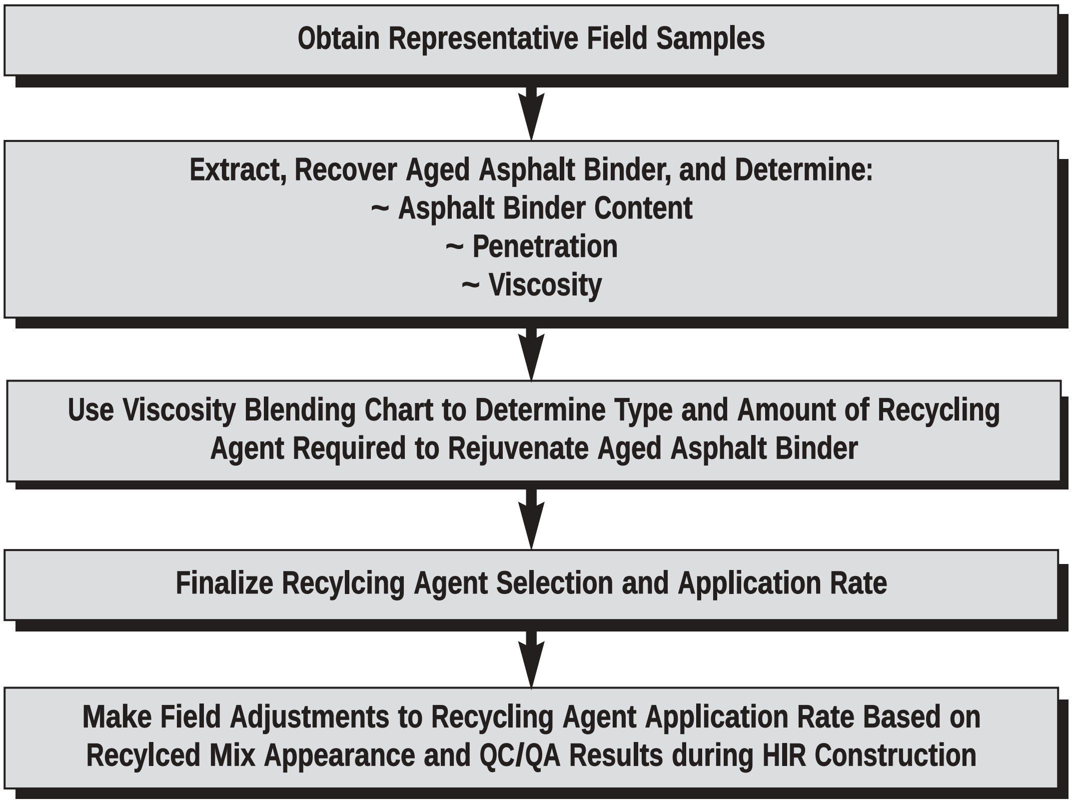


Figure 5-1: Blending chart design flow chart

- restore the aged asphalt binder properties to a consistency level appropriate for construction purposes and end use of the recycled mix
- provide sufficient additional binder to coat the existing mix and any virgin aggregate added
- provide sufficient asphalt binder to satisfy the mix design requirements

HIR recycling agents are generally hydrocarbon materials with chemical and physical properties which restore aged asphalt binders to the desired specifications. Soft asphalt binders, specialty/proprietary products or even some types of asphalt emulsions can act as recycling agent. Soft asphalt binders are usually less expensive than specialty products but they are not as efficient at rejuvenation. They also need to be added to a carrier such as the virgin aggregates, as opposed to being directly applied to the recycled mix. In order to achieve their intended purpose recycling agents must be:

- easy to disperse in the recycled mix
- compatible with the aged asphalt binder to ensure that syneresis or exudation of the paraffins from the existing asphalt binder does not occur
- able to re-disperse the asphaltenes in the aged asphalt binder
- capable of altering the properties of the aged asphalt binder to the desired level
- resistant to excessive hardening during hot mixing to ensure long-term durability
- uniform/consistent from batch to batch
- low in volatile organic compounds or contaminants to minimize smoking and volatile loss during construction

The quantity of recycling agent required is determined using a blending chart/viscosity nomograph and procedures such as those contained in American Society for Testing and Materials (ASTM) D 4887 "Preparation of Viscosity Blends for Hot Recycled Bituminous Materials." Similar types of blending charts are also available from the various recycling agent suppliers which are specific to their individual products.

The percentage of recycling agent required to meet the target viscosity is initially determined on a weight basis. The target viscosity for the rejuvenated asphalt binder is selected by the owner agency and is dependent on the project environment, anticipated traffic, past performance of the existing pavement, etc. Usually, the target viscosity is selected to be close to the asphalt binder properties that were observed when the roadway was originally constructed unless the original asphalt binder properties were the source of the poor pavement performance.

Some owner agencies prefer to use the penetration value to determine whether the existing asphalt binder needs to be rejuvenated during the HIR process. The appropriate penetration values are used in place of the viscosity values in the specifications and during the selection of the recycling agent.

For some owner agencies or for very low traffic volume roadways, the determination of recycling agent type and amount by means of the blend chart would mark the end of the HIR mix design process.

It is noted that not all recycling agent and aged asphalt binders are compatible. Some owner agencies may want to prepare and test laboratory samples of the recovered aged asphalt binder and recycling agent in order to confirm that the target viscosity has been achieved. If the target viscosity has not been met then other trial blends are prepared using different proportions of the same recycling agent or with a different recycling agent, until the target viscosity has been achieved. The asphalt binder content and the relative density of the pavement to be recycled, together with the recycling agent application percentage, is used to determine the field recycling agent application rate in gallons per square yard (litres per square meter). The mix design would then be completed and construction would proceed.

Use of the viscosity blending chart mix design method usually provides a reasonable but slightly high estimate of the amount of recycling agent needed. Hence, field adjustment in the amount of recycling agent being added is usually required. Field adjustments would be made based on the visual appearance of the recycled mix and/or on the results of QC/QA testing of the recovered asphalt binder.

Use of blending charts does not assess the effect that adding the recycling agent has on the recycled mix, including void properties, stability, resilient modulus, water sensitivity, workability, etc.. For local or lower traffic volume roadways, changes in these properties may not have an effect on field performance, but as the roadway classification or as traffic volumes increase, these items should be addressed.

5.2.2 TRADITIONAL / COMPREHENSIVE

The more comprehensive HIR mix designs consider not only the rheological properties of the asphalt binder but also the recycled mix properties. The following flow chart, presented in Figure 5-2, indicates the more comprehensive HIR mix design process.

This HIR mix design flow chart may appear to be exceedingly complex but it actually is a logical, easy to use approach. As a starting point, the steps outlined in the flow chart, should be followed in order to address the significant factors that impact on the recycled mix performance.

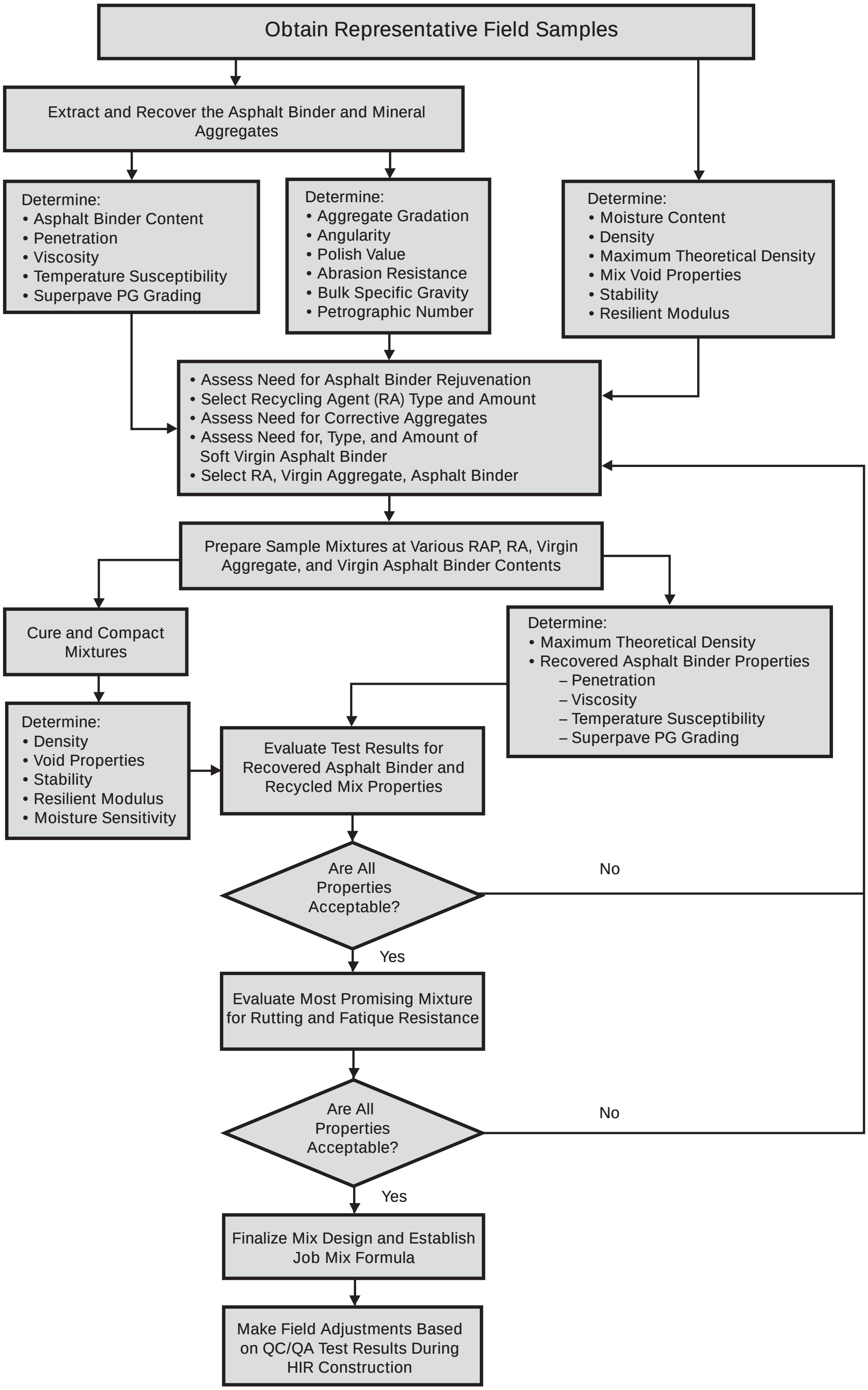


Figure 5-2: Comprehensive mix design flow chart

Some of the data may already be available through the detailed project analysis outlined in Chapter 4. It is recognized that there are several approaches that can be used to arrive at an appropriate HIR mix design, and with experience, some of the steps could be eliminated.

Extracting and recovering the aged asphalt binder and mineral aggregates is a convenient way to analyze the components of the existing HMA. The Abson method of asphalt binder recovery is usually preferred since it has the least effect on the properties of the asphalt binder but other recognized methods can also be used. Variations or special considerations may need to be used, particularly if the existing pavement contains polymers, rubber, etc. As a minimum the penetration and viscosity of the recovered asphalt binder should be determined. Additional properties of the recovered binder such as temperature susceptibility and/or Superpave PG grading could be undertaken, depending on owner agency preference and project specific requirements.

The gradation of the mineral aggregate is required in order to determine whether the existing HMA meets the owner agency gradation specifications for recycled mixes. A number of owner agencies have increased or modified gradation requirements for recycled mixes, compared to virgin HMA. The modified gradation specification limits reflect the inherent variability which occurs with existing pavement and that in the HIR process 100 percent of the existing material will be recycled.

A small amount of aggregate degradation can be expected during the HIR process. The amount of degradation that occurs is dependent on the type of HIR process being used, on the type of HIR equipment being used, and on the workmanship of the contractor. Generally, the amount of aggregate degradation is small and is comparable to what occurs during the coring process. The amount of aggregate degradation can be exacerbated if rotary milling being used in the HIR process and the treatment depth exceeds the depth of heat penetration needed to adequately soften the existing pavement.

In addition to gradation, the angularity of the existing aggregate should be determined using the owner agency's existing procedures. It is now widely accepted that aggregate angularity plays a significant role in determining whether a mix will be susceptible to rutting. The overall angularity of the existing aggregates may need to be improved in order to account for the effects of increased wheel loading. Other aggregate properties should also be determined, particularly if the existing pavement distress is related specifically to the aggregate, i.e., friction number. If the bulk specific gravity of the aggregates is not known from the historical data, it should be determined in order to be able to calculate the recycled mix void properties.

The moisture content, relative density, and Maximum Theoretical Density of the existing HMA, needs to be determined in order to calculate the void properties of the existing pavement. The existing void properties will influence the type and amount of recycling agent and admix which may be required. Additional mix properties such as Hveem or Marshall stability and/or resilient modulus can be subsequently used to assess the effectiveness of the recycling agent.

If the existing asphalt binder has aged excessively, rejuvenation will be required. The amount of rejuvenation will depend on the amount of aging which has occurred and on the owner agency's requirements for new asphalt binder or recycled mixes. Traditionally, viscosity or penetration has been used as the target property for assessment of rejuvenation. The target property is usually selected to be the midpoint in the grade of asphalt binder—which would normally be used for the project's climatic conditions, traffic conditions, and construction method, i.e., will the recycled mix be overlaid?

Some agencies have recognized that the properties of the asphalt binder in a recycled mix can be harder or stiffer than conventional virgin mixes, without compromising performance or inducing additional distress. Hence, the degree of rejuvenation of the aged asphalt binder needs to be assessed on a project-by-project basis and should be consistent with the owner agency's experience on other recycling projects. It is also noted that the same target properties for recycled and conventional mixes may not result in the same field performance.

If the existing aggregate gradation needs to be modified to meet the current aggregate specifications, then blending with a virgin aggregate will be required. For virgin aggregates which have not been used previously, their physical properties such as petrographic number, abrasion resistance, polish value and stripping resistance must be considered. This also applies to the existing pavement aggregates, if the pavement distress is aggregate related.

The amount of virgin aggregate that can be added is limited by the capacity of the existing HIR equipment and is usually less than 30 percent. Coarse, highly angular aggregates are usually added to improve stability, rutting resistance, and friction number. Clean, fine aggregates are usually added to improve mix void properties such as Va, VMA, and VFA. In order to reduce costs, the virgin aggregates selected for use should be readily available. Heating of the virgin aggregates is recommended since it improves productivity. Pre-coating of the virgin aggregates with an asphalt binder helps to reduce dust, assists in coating of the coarse aggregates and can help in rejuvenation of the aged asphalt binder.

Preliminary selection of the recycling agent is based on previous experience, to ensure compatibility, and on blending charts to determine an approximate quantity. The addition rate will need to be adjusted, particularly if a soft asphalt binder is used with the virgin aggregates, so that the combined asphalt binder has the desired physical properties.

Preparation of samples at various contents of recycling agent, virgin aggregate, new asphalt binder, and existing pavement or RAP can be undertaken. No universally accepted testing protocol for the preparation of the samples is available. However, owner agency procedures for conventional HMA and hot recycling mix designs, such as the Marshall or Hveem methods, could be adapted with some slight modifications. The laboratory conditions should model HIR field conditions as closely as possible.

The representative sample of the existing pavement, consisting of 6 or 8 inch (150 or 200 mm) diameter cores, trimmed to the intended depth of recycling, should be very carefully dried and heated in order that additional hardening of the aged asphalt binder does not occur. This is usually achieved by heating the cores in lightly closed containers in a non-forced air oven and by minimizing the time the RAP is at elevated temperatures. Past experience with numerous HIR projects around North America, has indicated that the HIR process, without the addition of any admix or recycling agent, results in a:

- decrease in penetration of approximately 20 to 25 percent
- increase in kinematic viscosity of approximately 150 to 200 percent

Hence, the hardening of the aged binder that occurs in the mix design process should approximate the hardening which happens during construction. Usually, the hardening which occurs in the laboratory is in excess of that which occurs in the field. Hence, a fixed amount of recycling agent is required to overcome a hardening which is generally not needed during construction.

The virgin aggregate and new asphalt binder are prepared in the same manner as for a virgin HMA mix design and is usually called "admix." The mixing temperature for the admix should be determined based on the viscosity of the new asphalt binder and is typically 170 +/- 20 mm2/s (approximately 0.17 +/- 0.02 Pa•s for an asphalt binder density of 1.00 g/cm3). The use of this mixing viscosity results in excessively high temperatures for the RAP due to the high viscosity of the aged asphalt binder. Consequently, a mixing temperature of 10°F (5°C) above an arbitrary selected recycled mix compaction temperature, usually 250 to 265°F (120 to 130°C), is commonly used.

Once both the RAP and admix have stabilized at the mixing temperature they are combined and preliminarily mixed. The recycling agent, if used, is then added and the mixing continues until a homogenous recycled mix is achieved. Mixing time should be as short as possible but sufficiently long so as to model the mixing time which occurs in the field and to provide a uniform mix. Ideally, five different combinations of RAP, admix, and recycling agent should be assessed. The different combinations should be sufficiently different from one another to provide a measurable difference in physical properties but not so different as to make comparisons difficult. The visual appearance of the recycled mix, at the completion of the mixing time, is assessed and recorded.

The recycled mix should then be cured in a lightly closed container in a non-forced air oven, set at the compaction temperature. There is no standardized curing time but it is usually between 30 minutes to one hour after the recycled mix has reheated to the compaction temperature. The curing period should be long enough to permit the recycling agent to diffuse through the aged asphalt binder but not overly long as to overestimate what happens in the field. Care must also be taken with the laboratory recycled mix to ensure that excessive hardening of the rejuvenated asphalt binder does not occur. Some owner agencies may choose to cure the recycled mix after it has been compacted.

Aliquot samples of the cured recycled mix are tested for Maximum Theoretical Density, the asphalt binder is recovered and tested to determine the degree of rejuvenation which has taken place.

The compaction of the recycled mix could be by any method the owner agency chooses but it is usually by either the standard Marshall or Hveem method. The compaction level is adjusted to correspond to the anticipated project traffic. The compacted recycled mix is cooled and tested like conventional virgin HMA samples to determine the relative density, stability, flow, resilient modulus, moisture sensitivity, Va, VMA and VFA. The amount of testing performed will depend on the capabilities of the owner agency, the size, and location of the project.

The test results at the various recycling agent, admix, and RAP contents are assessed for conformance with the specifications. As noted previously, the amount of rejuvenation of the aged asphalt binder should be assessed on a project-by-project basis and be consistent with the owner agency's experience on other recycling projects. Recycled mix properties such as Va, VMA, VFA, etc., have traditionally been compared to those required of virgin HMA.

It is known that central plant hot recycled mixes have higher relative densities and lower air voids than equivalent virgin mix, even though the RAP contents are usually less than 50 percent. These central plant hot recycled mixes have been shown to have the same if not superior performance to conventional virgin HMA. HIR mixes use significantly higher ratios of RAP, so the effects of increased relative density and lower air voids are even more pronounced. The original pavement was usually constructed at or near the optimum asphalt content for the aggregate gradation, and the addition of recycling agent to rejuvenate the aged asphalt binder can lead to even more air void reduction. The traditional HIR mix design approach was to add a virgin aggregate to dry the recycled mix out and/or open up the voids in order to achieve conventional HMA air void contents. The net effect is an overall reduction in asphalt content and reduced asphalt film thickness, both of which have the effect of reducing long-term durability of the recycled mix.

Recognizing this, several owner agencies are using a different set of criteria or mix properties to design and accept HIR recycled mix. They have recognized that equivalent performance to virgin HMA can be achieved with HIR mixes even though they have different physical properties. In most cases, a significant reduction in recycled mix air voids can be accepted without affecting performance. Each owner agency is encouraged to evaluate the recycled mix properties which can be accepted while still maintaining performance. Development of these unique recycled mix properties will, in most cases, permit additional asphalt binder rejuvenation (although care must be taken to ensure that the rejuvenated binder is not too “soft”) or lower threshold acceptance limits on the recovered asphalt binder, a reduction in the amount of admix required, and a reduction in overall HIR costs.

Some owner agencies may want to conduct some additional testing to assess the rutting and fatigue resistance of the most promising or economic mix. This would normally be reserved for recycled mixes which would be intended as a surface mix, such as in the Remix process or for projects with very high design traffic. Conventional HMA rutting and fatigue resistance test methods could be used but it is noted that experience is limited in translating the test results into acceptable HIR recycled mix performance.

Once the analysis has been completed, the HIR mix design can be finalized and the job mix formula established. The recycled mix with the optimum physical properties and acceptable economics should be selected. The submitted HIR mix design should include the following information:

- asphalt binder content of the existing pavement for the intended recycling depth
- rheological properties of the asphalt binder in the existing pavement treatment depth
- gradation and aggregate properties of the portion of the existing pavement to be recycled
- gradation and aggregate properties of any virgin aggregate that is required
- type and amount of new asphalt binder required to be added to any virgin aggregate
- type and amount of recycling agent
- rheological properties of the asphalt binder in combined recycled mix
- gradation and aggregate properties of the combined recycled mix
- recycled mix void properties and physical properties

As with all mix designs, the job mix formula establishes the most promising or likely combination of materials based on laboratory conditions. Once construction begins, the actual recycled mix should be sampled and tested. Based on the results of the field testing, adjustment or fine tuning of the job mix formula should be undertaken.

Existing pavements with excessive age-hardening of the asphalt binder or having sever stripping may present an insurmountable challenge for the HIR mix designer. If this occurs, either an alternate rehabilitation method should be used, or the mix can be accepted at reduced properties—knowing that a corresponding reduction in performance or service life will occur.

5.2.3 SUPERPAVE

The Superpave technology/system is a product of SHRP that was conducted between 1988 and 1993. Superpave is an acronym that stands for SUperior PERforming PAVEments. Additional research/implementation work is continuing with the Superpave system. The principle outcome of SHRP was the performance-based or performance-graded (PG) specifications for asphalt binder, and the Superpave volumetric mix design process using the Superpave Gyratory Compactor (SGC).

As of this writing, no documentation or confirmation exists that indicates that the Superpave technology is completely applicable to HIR mixes. Research has been conducted on RAP contents of up to 40 percent, so it is unknown whether the same assumptions and trends will hold for RAP contents of 70 to 100 percent found in HIR mixes.

In the SHRP Superpave PG system of classifying asphalt binder, the Dynamic Shear Rheometer (DSR) is used to characterize the viscous and elastic components of the behavior of asphalt binders at high and intermediate temperatures. At normal pavement service temperatures, most asphalt binders behave like viscoelastic materials, i.e., they simultaneously act like an elastic solid and a viscous fluid.

The DSR measures the complex shear modulus G* (G star) and phase angle s (delta) of the asphalt binder at given temperatures and frequencies of loading. The complex modulus can be considered to be the total resistance of the asphalt binder to deformation when repeatedly sheared and consists of two components G’ (G prime) and G” (G double prime) which are related to each other by the phase angle s. G’ is the storage modulus or the elastic (recoverable) behavior of the asphalt binder while G” is the loss modulus or the viscous (non-recoverable) part of the asphalt binder’s behavior.

Originally, SHRP used only new asphalt binders and HMA mixes. More recently, additional research work on modified asphalt binders and recycled asphalts/mixes with up to 40 percent RAP has been conducted. The following is a summary of the current Superpave design approach for conventional hot recycled mixes.

The Superpave specifications were designed to improve the performance of HMA pavements by selecting asphalt binders which do not contribute to:

- tenderness during laydown by requiring the G*/sin s of the unconditioned asphalt binder to be less than 1.0 kPa
- permanent deformation by requiring the G*/sin s of the rolling thin film oven test (RTFOT) residue be greater than 2.2 kPa
- fatigue cracking by requiring the G* sin s of the RTFOT and pressure aging vessel (PAV) residue to be less than 5 MPa
- low temperature cracking by requiring the creep stiffness value (S) and slope value (m) of the RTFOT + PAV residue to be less than 300 MPa and greater than 0.30, respectively. Alternatively, if the creep stiffness value is between 300 and 600 MPa the result of the Direct Tension Test (DTT) can be used, in lieu of the creep stiffness, but the direct tension test must have a minimum of 1.0 percent strain at failure. The creep stiffness and slope values are determined by the Bending Beam Rheometer (BBR).

Since the above noted physical properties are dependent on temperature, any asphalt binder can meet the requirements given the appropriate test temperature. Therefore, the Superpave PG system is based on specified test temperatures, with the required physical property remaining constant for all PG grades. The Superpave asphalt binders are graded according to a high service temperature, a low service temperature, and an intermediate temperature of 25°C. For example, a PG58-34 (PG 58 minus 34) asphalt binder is expected to meet the tenderness and permanent deformation requirements up to a high temperature of 58°C, and the low temperature cracking requirement down to a temperature of –34°C. The PG58-34 asphalt binder is also expected to have adequate intermediate performance between the high and low temperatures by meeting the fatigue cracking requirement at a temperature of 25°C. Therefore, two tests are required to determine the high temperature value, one test is needed to determine the intermediate value, and three tests are needed to determine the low temperature value of an asphalt binder.

This means that as many as six Superpave blending charts are needed in order to determine the six test parameters needed for Superpave PG grading of any recycled mix asphalt binder. Research, to date, has been confined to the high and intermediate temperature values with no published data for the low temperature parameters. This reduces the number of required blending charts to three. The two for the high temperature are called “high temperature sweep blending chart – 1.0 kPa” and “high temperature sweep chart – 2.2 kPa” and one for the intermediate temperature parameters, called “intermediate temperature sweep blending chart – 5 MPa.” However, the issue of low temperature performance has not been addressed.

Blending charts need to be developed for blending aged asphalt binder, and new asphalt binder/recycling agent in the same way as was outlined in Section 5.2.1. The asphalt grade is based on the Superpave PG grading, rather than viscosity, used previously. The asphalt binder test parameters obtained from the DSR are used in place of the viscosity or penetration blending charts. The temperatures at which the various Superpave parameters are achieved, i.e., G*/sin s = 1.0 kPa, are determined by performing a temperature sweep (testing at different temperatures) at different percentages of aged and new asphalt binder. These temperature results are plotted and an “iso-stiffness curve” is produced. Any point on the iso-stiffness curve represents a possible combination of aged and new asphalt binder which meets the particular Superpave parameter.

Blending charts determine the temperature value required for the aged and new asphalt binder to have a specific stiffness, as opposed to conventional viscosity blending charts which determine the viscosity (stiffness) of the aged and new asphalt binder at specific temperatures. Therefore, temperature value is plotted on the Y-axis of the temperature sweep blending charts, as opposed to viscosity value on the viscosity blending charts, the percentage of new asphalt binder is plotted on the X-axis.

Data indicate that when the high temperature blending charts are plotted on a linear X-Y graph, the iso-stiffness curve approaches a straight line. Therefore, the high temperature sweep blending chart – 1.0 kPa can be constructed by plotting the two temperatures at with the aged asphalt binder and the virgin binder/recycling agent is 1 kPa, and drawing a straight line through the two points. The same holds true for the high temperature sweep blending chart – 2.2 kPa. However, the iso-stiffness curve for the intermediate temperature sweep blending chart is not a straight line but curves downward. Intermediate temperature sweep blending charts constructed assuming that the iso-stiffness line is straight will slightly under-predict the amount of new asphalt binder/recycling agent required.

According to the Superpave system, both high temperature sweep blending charts should be used. However, data indicates that the amount of new asphalt binder/recycling agent predicted by using only one high temperature sweep blending chart does not change significantly from those predicted by using both high temperature sweep blending charts. Therefore, only one blending chart need be used to determine the amount of new asphalt binder/recycling agent or conversely the amount of aged asphalt binder that can be used in a recycled mix. The high temperature sweep blending chart – 1.0 kPa is normally used since it avoids running the time-consuming RTFOT test.

Construction of high temperature sweep blending charts involves conducting temperature sweep tests on both the aged and new asphalt binders in order to determine the temperature at which G*/sin s = 1.0 kPa. The inconvenience of running temperature sweep tests can be eliminated by constructing a "Specific Grade Blending Chart". The Y-axis of a specific grade blending chart is in log-log, similar to viscosity/penetration blending charts. By plotting G*/sin s, on a log-log scale on Y-axis versus percent new asphalt binder on the X-scale which is linear, a near linear relationship or straight line is obtained. Therefore, the information needed to construct a specific grade blending chart are the G*/sin s of the unconditioned new asphalt binder and the aged asphalt binder at only the specific test temperature.

Use of the intermediate temperature sweep blending chart predicted unusually high percentages of aged asphalt binder which is inconsistent with the field experience with recycled HMA. Hence, the intermediate temperature sweep blending chart is currently not used to determine the maximum amount of aged asphalt binder which can be used in a recycled mix.

In its place, a three tiered system of selecting the PG grade of the new asphalt binder is being used for hot recycled mixes. The tiers are as follows:

- **Tier 1:** If the amount of RAP is equal or less than 15 percent, the selected PG grade of the new asphalt binder should be the same as the Superpave required PG grade.
- **Tier 2:** If the amount of RAP is more than 15 percent but equal to or less the 25 percent, the selected PG grade of the new asphalt binder should be one grade below, i.e., softer, in both the high and low temperature grade which would be required by the Superpave system.
- **Tier 3:** If the amount of RAP in more than 25 percent, use the specific grade blending chart to select the high temperature grade of new asphalt binder. The low temperature grade should be at least one grade lower than the binder grade specified by the Superpave system.

Research conducted as part of NCHRP 9-12 indicates that the high stiffness RAP (PG88-4 after recovery) used in the study had a greater effect on the low temperature properties of the blended asphalt binder than the medium and low stiffness RAP. This data suggests that limiting RAP values noted above could possible be modified depending on the low temperature stiffness of the recovered RAP asphalt binder.

A recycled asphalt binder would always meet the G*/sin s = 1.0 kPa minimum, for unconditioned asphalt binders and the G*/sin s = 2.2 kPa minimum, for RTFOT residue, at any RAP content provided the appropriate high temperature grade of new asphalt binder is used. This happens since the addition of RAP increases the G*/sin s values of the unconditioned and RTFOT residue. If the new asphalt binder is one or two grades below the specified Superpave PG requirement, a procedure is needed to determine the maximum amount of new asphalt binder, to increase the high temperature stiffness of the recycled asphalt binder, above the minimum values specified by Superpave. The recommended blending chart, to determine the maximum amount of new asphalt binder, is the "specific grade blending chart," for the Superpave required PG grade and a 1.0 kPa stiffness line.

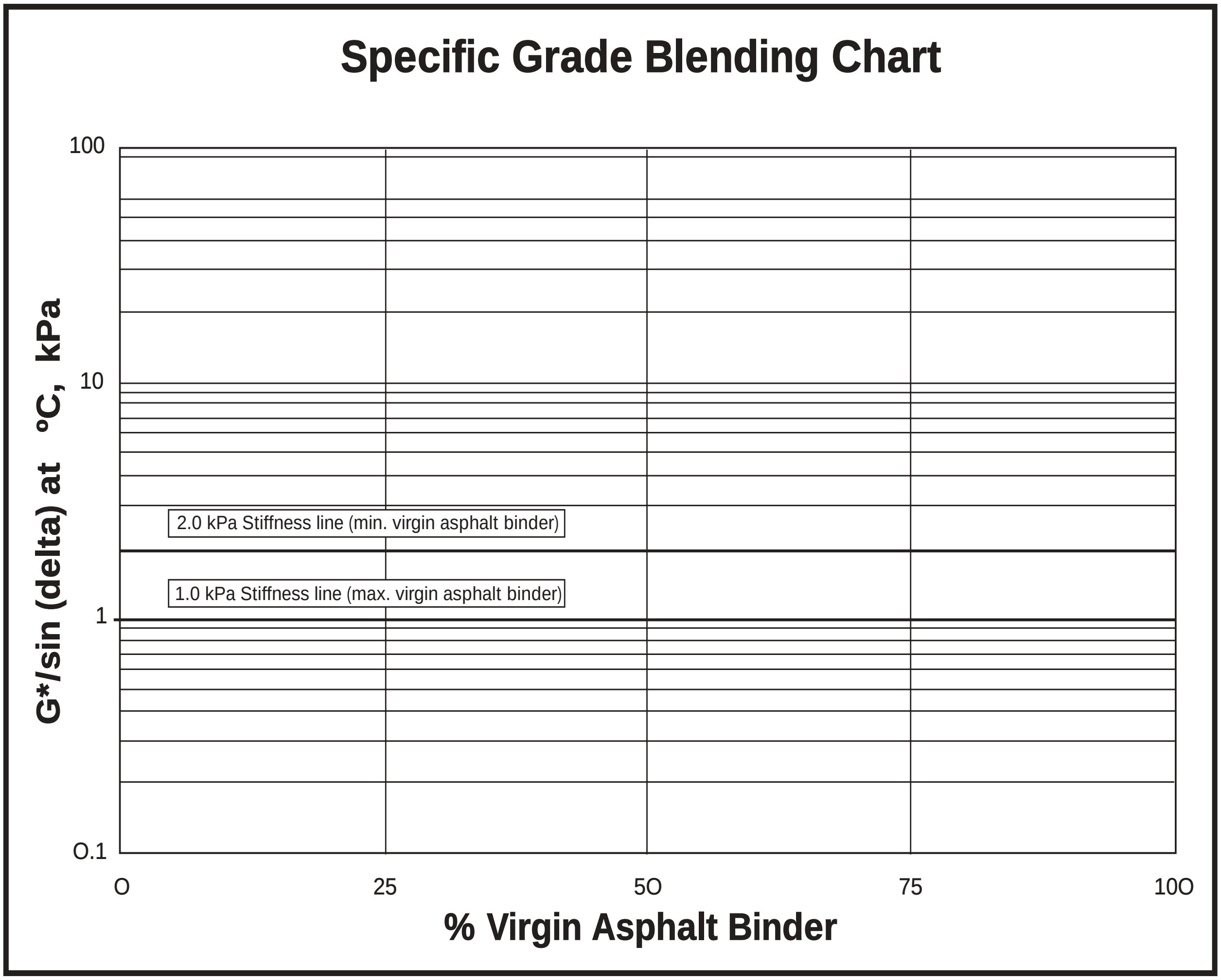


Figure 5-3: Specific grade blending chart

A procedure is needed to determine the minimum amount of new asphalt binder that is required. Data has indicated that use of a 2.0 kPa maximum stiffness value for the G*/sin s, at high temperature, to determine the minimum amount of unmodified new asphalt binder which should be used. An example of a specific grade blending chart is as indicated in Figure 5-3.

The Superpave system uses a gyratory compactor to densify the HMA samples and produce a volumetric mix design base for the anticipate traffic. Trial mixes of the HIR recycled asphalt using the SGC following the Superpave mix design procedures with various recycling agent and admix addition rates.

Various agencies have initiated programs to assess the Superpave volumetric mix design in lieu of the Marshall or Hveem methods. To date, no documentation or confirmation data exists to indicate whether the Superpave volumetric mix design method is suitable for designing HIR mixes. Owner agencies will have to establish their own evaluation criteria based on a combination of laboratory and field trials.

CHAPTER 6: HOT IN-PLACE RECYCLING - CONSTRUCTION

The equipment used in Hot In-Place Recycling (HIR) has many different configurations depending on the HIR process, i.e., Surface Recycling, Remixing or Repaving, where and who manufactured the equipment, and the particular contractor undertaking the project. Surface Recycling was the first HIR process to be developed and it has its origins in the 1930's, when the first rudimentary machines were introduced. In the late 1970's and early 1980's, the HIR equipment had a significant transformation, resulting in the Repave and Remix HIR processes being developed. HIR equipment and technology are continually evolving and being upgraded, with the use of hot air/low infrared heating and a mixing drum, in lieu of a pugmill, being two of the more recent innovations.

Equipment trains used in each of the HIR processes have some similarities and some significant differences. The key is to focus not so much on the configuration of a particular piece of equipment as to understand the function or functions performed by the individual pieces of equipment.

Some common preparatory measures should be undertaken prior to HIR, regardless of the HIR process being used. These include:

- detailed safety or hazard assessment
- development of a detailed traffic control plan
- repair of any areas with drainage problems
- repair of any isolated base failure areas
- leveling of excessive deformations, either by cold planing or by preliminary leveling, to provide a satisfactory working platform
- ensuring the pavement surface is clean and free of deleterious materials such as dirt, etc.
- detailed project analysis, as outlined in Chapter 4, and preparation of a mix design and job mix formula, as outlined in Chapter 5

Each HIR construction process will be discussed in more detail in the subsequent sections.

6.1 SURFACE RECYCLING

Surface Recycling has been known by a number of different names over the years including heater-scarification, heater-planing, reforming, resurfacing, etc., and has been in fairly common use since the mid-1960's. Compared to the other HIR processes Surface Recycling is the most fundamental/least technologically complex process. It primarily consists of:

- drying and heating the upper layers of the existing pavement
- scarifying the heated/softened asphalt pavement
- adding a recycling agent, if required by the mix design and job mix formula
- mixing the loose recycled mix
- spreading and placing the recycled mix with a free floating screed
- compacting the recycled mix using conventional HMA rollers and procedures

No virgin aggregate or HMA is added during the Surface Recycling process, so modification of the existing asphalt pavement is restricted to the rejuvenation of the aged asphalt binder. Production rates for Surface Recycling vary widely depending on:

- ambient temperatures and wind conditions
- characteristics of the asphalt pavement being treated
- moisture content of the existing pavement
- the number and heat output of the equipment

Production rates from as low as 5 to as high as 50 feet per minute (1.5 to 15 meters per minute) can be experienced.

Drying and heating/softening of the existing asphalt pavement is performed with one or more preheating units. Early preheating units used open or direct flame to dry and heat the asphalt pavement, but this method has now been replaced with indirect radiant and/or infrared heating. The move to indirect radiant and infrared heaters was made to reduce undesirable fugitive emissions and damage to the asphalt binder. Most heaters are now fueled by propane or a similar compressed gas, although the new hot air/low infrared heating units use diesel fuel.

The preheaters operate in close proximity to one another to maximize the heat penetration. Three variables affect the transfer of heat to the asphalt pavement consisting of:

- maximum temperature of the heat source
- pavement surface temperature/ambient conditions
- length of time pavement surface is exposed to the heat source

In order to heat the asphalt pavement without significant damage to the existing asphalt binder, either lower heat sources or longer heating times are required. Therefore, to heat the pavement surface in a more controlled manner, the length of time the reduced heat source is exposed to the pavement needs to be increased. This can be accomplished by slowing the rate at which the heat source moves over the pavement or increasing the number of heat sources. Slowing the heat source increases costs by reducing production rates. Consequently, contractors optimize production by using additional preheaters, as indicated in Figure 6-1.

The number of preheating units is not as important as the length of the heating areas/hoods on each preheater, assuming the same heat output per unit of length. For example, two preheaters with 26 foot (8.0 meter) heating hoods will have a longer total heat exposure time than three preheaters with 16 feet (5.0 meter) heating hoods.

The preheating units should increase the temperature uniformly across the treatment area or “mat” without any hot spots or scorching of the existing pavement. The temperature of the scarified material, after mixing, should be an average of at least 230°F (110°C) and no more than 300°F (150°C).

Following immediately behind the preheaters is a heating/scarification unit, as indicated in Figure 6-2.

Figure 6-1: Surface Recycling preheaters

Figure 6-2: Heating and scarifying unit

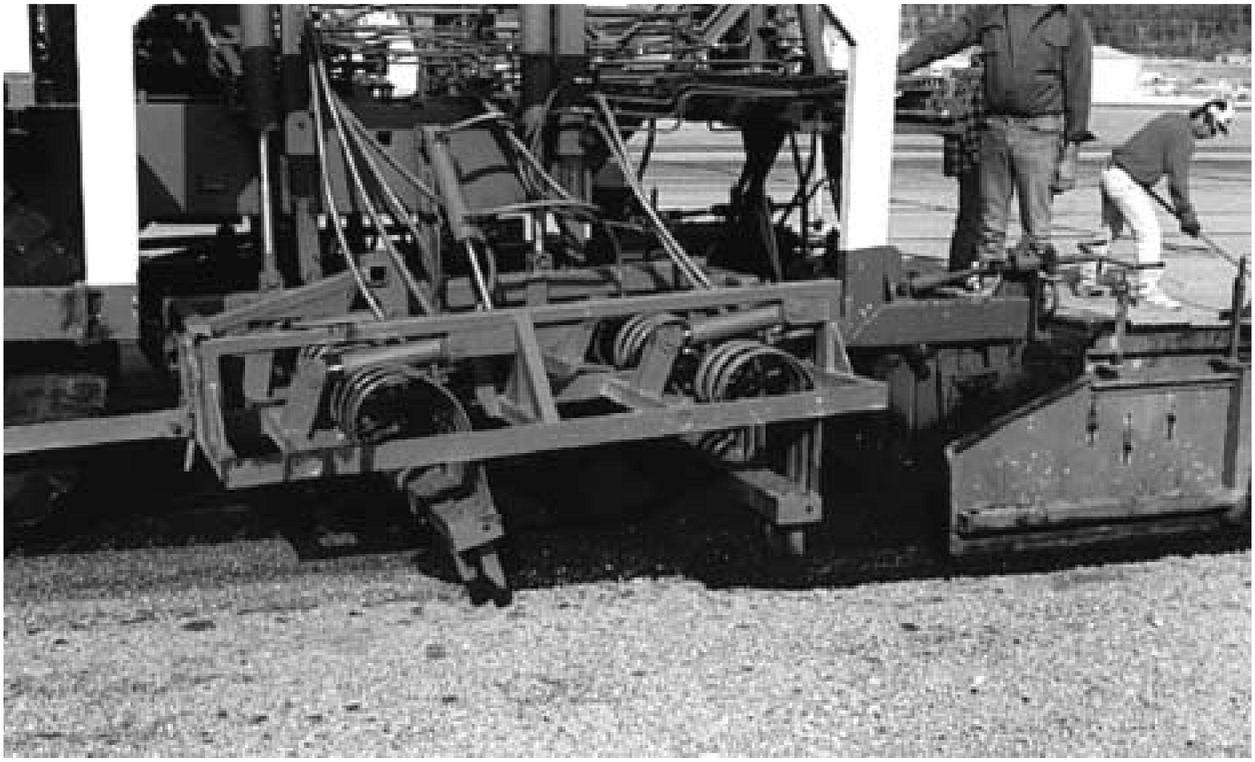


Figure 6-3: Spring loaded scarifying tines

This unit adds the final heating and then scarifies the softened asphalt pavement. Traditionally, the softened asphalt pavement is scarified or loosened by one or more rows of spring loaded leveling rakes/scarifying teeth/tines, as indicated in Figure 6-3.

The scarifying tines on some units may be pneumatically or hydraulically activated in order to minimize fracturing of the coarse aggregate in the underlying cooler pavement. They are also capable of overriding or being lifted over obstacles such as manhole covers, concrete structures, etc.

The depth of scarification usually specified for the surfacing recycling process is between 3/4 and 1 1/2 inches (20 and 40 mm) with 1 inch (25 mm) being most common. The scarification tines are normally in alignment with the finished pavement surface to ensure a uniform depth of scarification. Obviously, due to different hardness and depth of heat penetration of different portions of the pavement, particularly with rutted or distorted pavements, some variation in scarification depth may occur.

Scarification depth can be controlled somewhat by changing the spring tension, adjusting the pneumatic/hydraulic pressure on the tines or varying the forward speed of the equipment. With proper operation of the preheaters and heater/scarification unit, variations in scarification depth will be kept to a minimum, typically on the order of 3/16 inch (5 mm).

In addition to the scarifying tines, some scarifying units are being equipped with small diameter hot milling drums. Such drums are equipped with replaceable tungsten carbide tipped milling tools to uniformly loosen the heated/softened asphalt pavement to a level plane. There may be more than one hot milling drum to cover the treatment width, each being operated independently of the other. In this way, they can be lifted over obstacles such as manhole or utility covers.

Figure 6-4: Recycling agent addition

Experience indicates that oxidation/hardening of the asphalt binder occurs at a faster rate in the upper levels of a pavement, compared to lower levels. Surface Recycling permits the introduction of a recycling agent in the portion of the pavement that it can do the most good, as indicated in Figure 6-4.

The recycling agent, if required, is usually added to the loosened asphalt pavement by a computer-controlled system which is linked to the forward operating speed of the equipment. Valves provide positive control of the recycling agent as the equipment starts and stops. The recycling agent application rates vary, depending on the condition of the aged asphalt binder, the type of recycling agent being used, and the requirements of the mix design. Recycling agent application rates of from 0 to 0.5 gallons per square yard (0 to 2 litres per square meter) can be easily added.

In some operations, the recycling agent is added by the heater/scarifier unit, while in others it is added by a separate piece of equipment, as indicated in Figure 6-5.

The recycling agent is contained in an onboard storage tank, and is usually heated so that it can be applied close to the highest temperature recommended by the recycling agent supplier. This enhances the dispersion of the recycling agent through the loosened/scarified material. If the recycling agent is an asphalt emulsion, it will absorb some of the heat energy of the scarified material in order to heat and evaporate the emulsion water. Hence, the temperature of the scarified material may need to be increased a few degrees to account for the heat loss during the emulsion moisture evaporation.

Once the recycling agent has been added to the scarified material, they are then mixed into a homogeneous recycled mixture. Mixing is usually performed with a set of standard augers, as

Figure 6-5: Recycling agent addition, mixing, and paving unit

Figure 6-6: Auger mixing

Figure 6-7: Free floating screed on scarification unit

indicated in Figure 6-6. The recycling agent is sometimes added prior to the asphalt pavement being scarified, in which case the scarifying tines not only loosen the asphalt pavement but mix it, as well. In some rare applications, the recycling agent is added in a fog coat type application, after the asphalt pavement has been scarified, placed, and compacted.

Surface Recycling is normally used to eliminate surface irregularities, cracks, and to restore the pavement surface to a uniform grade line and cross-section. Hence, leveling and spreading of the recycled mix is undertaken with a free floating screeding unit. Material is moved into any low areas by an auger in front of the screed prior to the screeding unit leveling and imparting the initial compaction to the recycled mix. Some contractors use a modified HMA paver to place the recycled mix, as was indicated in Figure 6-5, while other use a free floating screed attached to the heater/scarification unit, as indicated in Figure 6-7.

The screeds are generally manually controlled in order to ensure adequate material is always available in front of the screed. The screeds are usually heated and vibrate to initially compact the recycled mix. Once the recycled mix has been screeded into place, it is compacted with conventional HMA rollers.

Traditionally, a rubber-tired pneumatic roller is used to perform the breakdown rolling while a double steel drum vibratory roller is used for finishing rolling, as indicated in Figure 6-8. Some contractors use static steel rollers for compaction. Since the existing asphalt pavement below the recycled mix is warm, a thermal bond is provided with the recycled mix and there is more than sufficient time for the rollers to achieve the required degree of compaction.

Once the compaction has been completed and the pavement cools, the HIR process is completed and roadway can be then be opened to traffic.

Figure 6-8: Compaction equipment

Figure 6-9: Surface Recycling before and after

Figure 6-10: Surface Recycling before and after

On some low traffic volume roadways, the recycled mix can be left as the wearing course. However, more commonly it subsequently has a surface treatment applied or a thin lift HMA overlay is placed. Placement of a thin lift HMA overlay is possible since the recycled roadway is level, rejuvenated, and crack free, as indicated in Figures 6-9 and 6-10.

When the wearing course is subsequently placed on the recycled mix surface the process is commonly called "multiple pass" Surface Recycling.

The HMA overlay can also be of a significant thickness if strengthening of the roadway structure is required. Usually there is a delay between completion of the Surface Recycling and the application of the HMA overlay, in the multiple pass Surface Recycling process, permitting the HMA overlay contractor to proceed at higher production rates, resulting in decreased costs. If the specifications require that the HMA overlay be placed immediately on the recycled mix, the paving contractor must proceed at the same rate as the HIR contractor. This usually increases the overall costs.

6.2 REMIXING

Remixing is used when:

- Significant modification of the physical properties of the existing asphalt pavement must be undertaken to correct specific pavement distresses. Changes to aggregate gradation, aggregate abrasion/friction number, asphalt binder content, asphalt binder rheology, mix stability, and mix void properties can be made with the appropriate selection of admix and recycling agent.

- The recycled mix is to function as the wearing course for higher traffic volume applications,
- A modest amount, i.e., less than 3/4 inch (20 mm), of pavement strengthening is required.

Remixing is classified into either single or multiple stage methods. In the single stage method, the existing asphalt pavement is sequentially heated/softened and then the full treatment depth is scarified at one time. Additional heating of the scarified material, could be undertaken in some equipment setups, but no more scarification of the existing pavement takes place, as indicated in Figure 6-11.

Treatment depths for the single stage method are generally between 1 and 2 inches (25 and 50 mm) with 1 1/2 inches (40 mm) being most common.

In the multi stage method the existing asphalt pavement is sequentially heated/softened and scarified in a number of layers usually between two and four. The scarified material from the first layer is placed in a windrow to permit heating/softening of the underlying layer, as indicated in Figure 6-12. In some equipment setups, the scarified material is picked up and carried over the subsequent heating units.

Treatment depths for the multiple stage method are between 1 1/2 and 3 inches (40 and 75 mm) with 2 inches (50 mm) usually being most common.

The single stage Remixing method was developed in the late 1970’s and early 1980’s in Europe and Japan, while the multi-stage Remixing method was developed in North America in the late 1980’s and early 1990’s. Steady improvements to the Remixing equipment, since their initial development, have been made in the areas of:

- increased mix temperatures
- deeper treatment depths
- adjustable treatment widths
- improved productivity
- quieter operation
- improved air quality
- increased capabilities to add recycling agent and admix
- better control of recycling agent and admix addition

HIR Remix trains are currently being used on projects around the world and, whether single or multiple stage, primarily consists of:

- drying and heating the upper layer of the existing pavement
- scarifying the heated/softened asphalt pavement
- adding a recycling agent and admix or HMA, as required by the mix design and job mix formula
- thoroughly blending/mixing into a homogenous recycled mix
- spreading and placing the recycled mix with a free floating screed
- compacting the recycled mix using conventional HMA rollers and procedures

Production rates for Remixing vary widely, depending on the same variables listed for Surface Recycling plus the amount of admix being added and the Remix treatment depth. Production rates from as low as 5 to as high as 35 feet per minute (1.5 to 10.7 meters per minute) can be experienced.

Figure 6-11: Single stage Remixing train

Figure 6-12: Multiple stage Remixing train

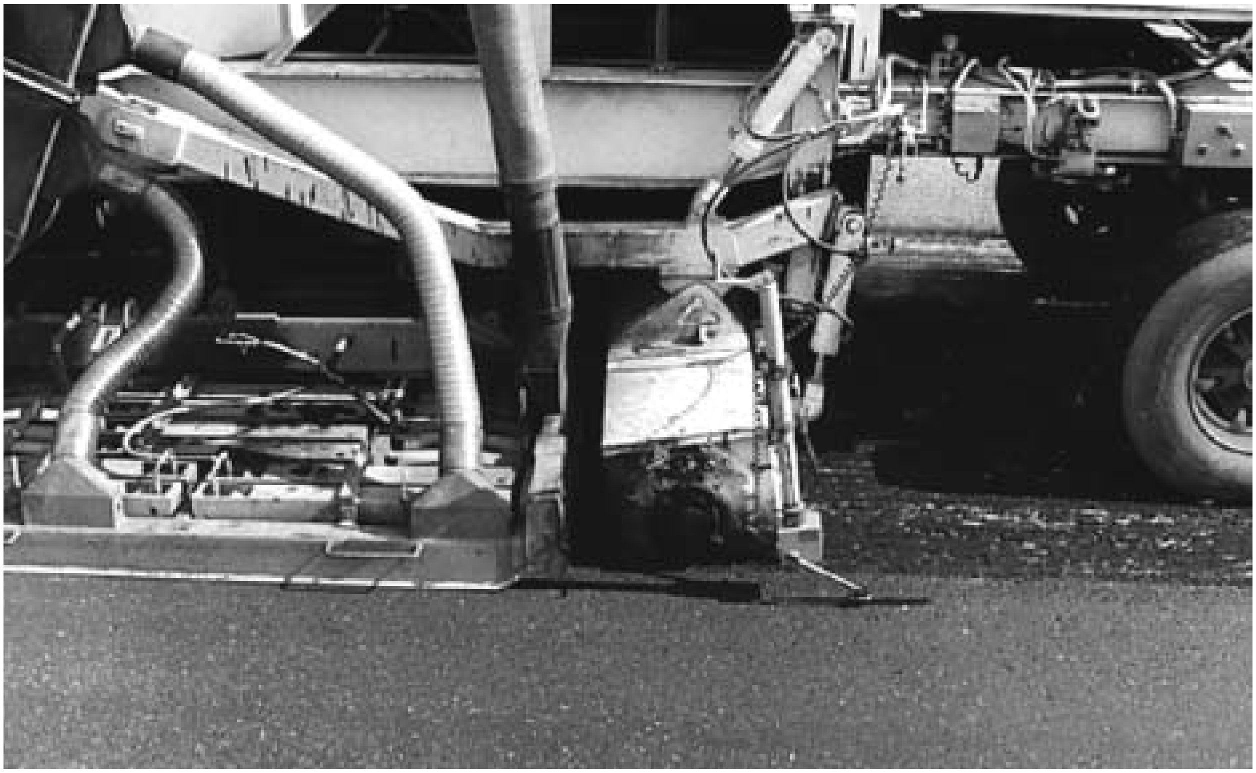


Figure 6-13: Hot milling drum and matching shoe

Drying and heating/softening of the existing asphalt pavement is performed with one or more preheating units in the same fashion as for Surface Recycling.

Scarifiers and/or hot milling drums loosen the softened material which is then augured towards the center of the unit. The scarifying/hot milling units usually have “moldboards” to help collect the reclaimed material and are depth and slope controlled by automatic sensors operating off a short reference ski or matching shoe, as indicated in Figure 6-13. Some equipment setups will permit variable heating and scarification widths of between 11 to 14.5 feet (3.5 to 4.5 meters).

In the single stage method, the loose material is directed into a mixing chamber consisting of pugmill or in some equipment setups a mixing drum. A variation to this process are setups where further heating and drying, in a heater stirrer unit, is performed prior to the loose material entering the mixing chamber.

In the multiple stage method, the loose windrowed material passes below the next heating unit or it is picked up and carried over the heating bed of the next unit by a slat conveyor. The slat conveyor has a variable speed control in order to match the forward speed of the HIR train. The sequence is continued until the required Remix treatment depth is achieved and all the loose material enters the mixing chamber. The average temperature of the loosened mix, as it enters the mixing chamber, should be between 250 to 300°F (120 and 150°C).

In all equipment setups, the measured amount of recycling agent, admix or virgin HMA is added prior to the mixing phase. The exact location in which the various materials are added may vary, but it is always at or prior to the mixing chamber. Addition of the recycling agent is most often applied as early as possible in the process in order to maximize the dispersion time with the aged asphalt binder.

Figure 6-14: High fluids content in first layer of a multi stage project

If the roadway being treated with the Remix process has a surface chip seal and/or a significant amount of recycling agent is being added, particularly for the multiple stage method, the fluid content of the first layer of loosened material can become very high and the material may tend to “slump” or act as a slurry in the windrow, as indicated in Figure 6-14. The slumped material is then re-windrowed, combined with the subsequently heated/scarified layers, admix, and then thoroughly mixed prior to placement. The recycled mix, in Figure 6-14, was placed in 1995 and has had excellent performance since then.

The admix or virgin HMA is supplied to the HIR train via standard tandem axle haul trucks to a hopper in front of one of the units prior to the mixing chamber, as indicated in Figure 6-15.

The admix and recycling agent are added to the loosened material by a computer controlled system which is linked to the forward operating speed of the HIR train, in order to provide reliable and precise control. Valves and relays provide positive shut off of the recycling agent and admix as the equipment starts and stops. The admix and recycling agent application rates vary, depending on the condition of the aged asphalt, the type of recycling agent being used, and the requirements of the mix design. Recycling agent application rates of from 0 to 0.5 gallons per square yard (0 to 2 litres per square meter) can be easily added. The admix application rate is limited to a maximum amount of about 30 percent by weight of recycled mix or 110 pounds per square yard (55 kilograms per square meter).

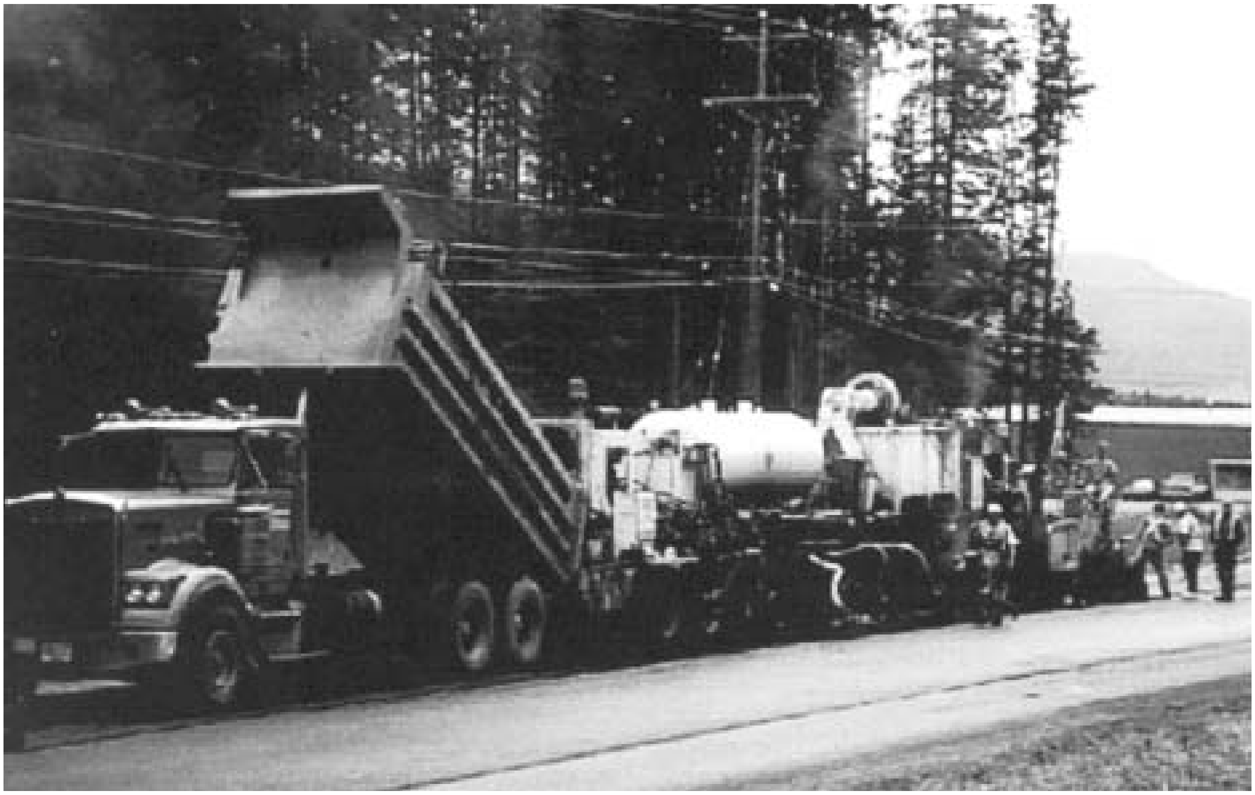


Figure 6-15: Haul truck supplying admix to HIR train

Figure 6-16: Remixing unit and integrated screed

Figure 6-17: Conventional HMA paver placing recycled mix

Mixing with augers and/or hot milling drums has been used, but the most successful Remix processes use a twin shaft pugmill or rotary drum mixer to uniformly and completely mix the recycled material. As with Surface Recycling, the recycled mix is placed with a free floating screed attached to the mixing unit or with a separate HMA paver, as indicated in Figures 6-16 and 6-17.

The screeds are usually of the heated, vibratory or tamping bar type and are equipped with automatic slope and grade controls similar to those found on modern HMA pavers, as indicated in Figure 6-17. The warmed underlying pavement is usually between 120 and 180°F (50 and 80°C) and the recycled mix is usually between 230 and 265°F (110 and 130°C) after being placed, resulting in a thermal bond between the two layers. In addition, the heating beds normally extend beyond the scarification width by 4 to 6 inches (100 to 150 mm) which heats and softens the adjacent material. This provides a thermally integrated bond between the existing asphalt pavement and the recycled mix resulting in a seamless longitudinal joint which is more resistant to environmental and traffic effects.

If the project contains any utility covers or infrastructure they are paved over and then raised to grade, as indicated in Figure 6-18.

Compaction is achieved with conventional HMA rollers usually consisting of a rubber-tired pneumatic roller for breakdown and a double drum steel vibrating roller for finishing, as indicated in Figure 6-19, although some contractors use static steel rollers.

Rubberized chips seals and asphalt pavements containing crumb rubber and polymer modified asphalt binders have all been remixed without significant difficulties. Increased heating requirements,

Figure 6-18: Raising water valve after remixing

Figure 6-19: Compaction of recycled mix

the affinity of the rubber/polymer for the rubber tires of the HIR and compaction equipment, and the possibility of increased fugitive emissions are difficulties which can be overcome.

Emission control systems have been developed to control the gaseous hydrocarbons generated in the HIR process. These systems include some method of collecting the fumes generated during the heating process and incinerating them at very high temperatures in a combustion chamber or after burner. The after burner reduces the hydrocarbons/combustible materials to primarily carbon dioxide and water vapor. The emission systems are designed to reduce or eliminate the opacity, irritants, and particulates to levels which comply with the air pollution standards. HIR trains equipped with emission control systems have met the very strict emission regulations of Washington and California, including the Los Angles area.

6.3 REPAVING

Repaving is used when:

- Surface Recycling and/or Remixing alone cannot restore the pavement profile or surface requirements, such as friction number
- When a conventional HMA overlay operation is not practical
- A very thin HMA or specialty mix which is to act as the wearing course is required, and/or
- A significant amount, i.e., 2 inches (50 mm) or less, of pavement strengthening is required

The application of very thin HMA overlays, on the order of 1/2 inch (12.5 mm), is possible in the Repave process provided the appropriate mix is used. This is significantly thinner than the 1 to 1 1/2 inches (25 to 40 mm) minimum overlay thickness which can be placed with conventional HMA equipment. In addition, since the overlay can be a very thin layer of specialized mix or a HMA they can be placed more economically. Specialty mixes such as Open Graded Friction Courses, polymer modified mixes, etc., can be used.

Repaving is classified into either single or multiple pass methods. In the single pass method the existing asphalt pavement is recycled and the last unit in the HIR train also places an integral overlay of new HMA/specialty mix on the screeded but uncompacted recycled mix, so that both layers are compacted at one time, as indicated in Figure 6-20.

In the multiple pass method, the last unit in HIR train screeds and places the recycled mix. A separate paver then follows immediately behind and places the conventional HMA/specialty mix on the uncompacted recycled mix. Both the recycled mix and the new overlay material are then compacted as one thick lift, as indicated in Figure 6-21.

Treatment depths of the existing asphalt pavement vary, depending on which method is being used. Treatment depths therefore vary between 1 and 2 inches (25 and 50 mm). The depth of treatment of the existing asphalt pavement is also related to the thickness of the integral HMA overlay or specialty mix which needs to be placed. A combined thickness of integral overlay and underlying recycled mix greater than 3 to 4 inches (75 to 100 mm) can result in increased placement, compaction, and smoothness difficulties. Typically, a 1 to 2 inch (25 to 50 mm) recycled depth and a 1 to 2 inch (25 to 50 mm) integral overlay thickness is used.

The single pass Repaving method was developed in the late 1950’s and early 1960’s in North America. Steady improvements to the repaving equipment have been made since then.

Figure 6-20: Repaving c/w haul truck for integral overlay

Figure 6-21: Recycled mix and integral overlay ready for compaction

Repaving trains are also currently being used on projects around the world, and whether single or multiple pass, primarily consist of:

- HIR of the existing pavement
- simultaneously or sequentially placing the new HMA/specialty mix
- compacting the recycled mix and new material together using conventional HMA rollers and procedures

Production rates for Repaving are the same as what was previously indicated for the Surface Recycling and Remixing processes.

Equipment, procedures, and issues for the recycling of the existing asphalt pavement have been identified in the Surface Recycling and Remixing sections and are applicable to the Repaving process. The new HMA/specialty mix is supplied to the last unit in the HIR train or to the conventional paver by standard tandem axle haul trucks. If the HIR train is to place the integral overlay in the single step method, the new material is conveyed from a hopper through the equipment and is distributed on top of the already screeded recycled mix, in front of the second or finishing screed, as indicated in Figure 6-22.

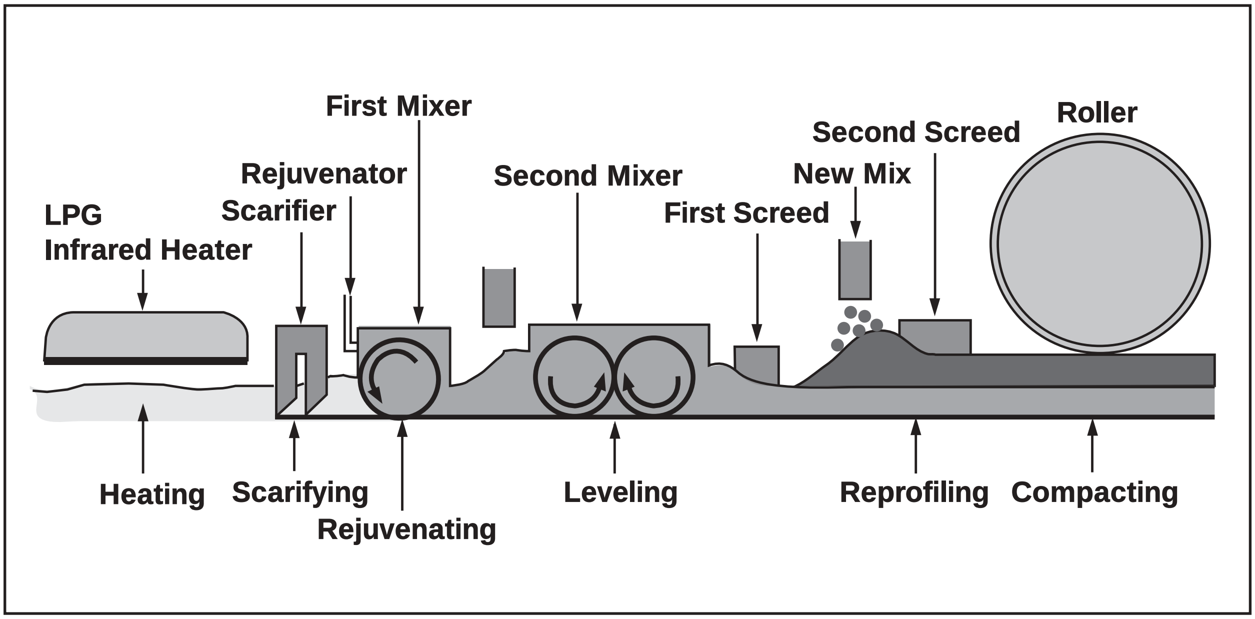


Figure 6-22: Admix movement through Repave equipment

In the multiple pass method, the new HMA is supplied directly into the hopper of the conventional HMA paver and is placed using standard HMA construction procedures.

The screeding units are usually of the heated, vibratory or tamping bar type, and are equipped with automatic slope and grade controls similar to those found on modern HMA pavers. The warm, underlying, untreated asphalt pavement, the hot recycled mix and the hot new materials are all thermally bonded to one another during the compaction process. Once again, compaction is achieved with conventional HMA rollers, usually consisting of a rubber-tired pneumatic roller for breakdown and a double drum steel vibrating roller for finishing, as was indicated previously in Figure 6-19.

Figure 6-23: HIR Repave before and after

Figure 6-23 indicates the before and after condition of a roadway which had been treated with the HIR Repave process, consisting of 1 1/2 inches (40 mm) of Remix and 1 1/2 inches (40 mm) of an integral HMA overlay.

CHAPTER 7: HOT IN-PLACE RECYCLING – SPECIFICATIONS AND INSPECTION

As with all roadway construction processes, two key steps are required to ensure the satisfactory construction and performance of a Hot In-Place Recycling (HIR) project. First is the development of an adequate and equitable set of specifications, and second is the inspection of the HIR project during construction to ensure that the intent of the specifications has been achieved.

In the Hot Mix Asphalt (HMA) industry, two common types of specifications are currently being used. These consist of the traditional, recipe or method specifications and end product or end result specifications.

Method specifications generally describe, in varying amounts of detail, the materials, equipment, and procedures to be used by the contractor in order to obtain the desired quality or performance of the recycled mix/project. A key component of the method specification is the need to include detailed descriptions of all variables or contingencies which may affect the quality or performance of the recycled mix.

End Result specifications set limits on a number of physical properties of the finished product, while most of the material selection, equipment used, and construction methods are left to the contractor. A key component of the end result specifications is the need to know what physical properties and the limits for these physical properties that are critical to the long-term performance of the recycled mix.

There are advantages and disadvantages with each type of specification.

The advantages of method specifications include:

- owner agency has a great deal of control over the equipment, construction methods, and materials used on the project
- for a knowledgeable owner agency, with extensive experience with the various HIR processes, writing the specifications will be lengthy but straightforward
- material assessment, selection of the materials to be used, and the mix design are undertaken by the owner agency.
- full time inspection of the construction process and Quality Control/Quality Assurance (QC/QA) testing are undertaken by the owner agency
- owner agency makes the major decisions with respect to project management
- the majority of the risk is borne by the owner agency which generally reduces the overall HIR costs

The disadvantages of method specifications include:

- contractor has little input into construction equipment, methods or quality
- there is little or no incentive to provide higher than the required quality or to advance innovative alternatives

- specifications for existing equipment and materials do not readily accept new or different equipment and materials
- some end result or acceptance requirements are usually included such as aggregate gradation limits, construction tolerances, percent compaction, smoothness, etc.
- confrontations arise when not all aspects of the specifications or acceptance requirements are achieved
- when acceptance requirements are not achieved, the owner agency can reject and not pay for deficient material, even if it has some value or, as is usually the case, accept and pay full price for substandard material

The advantages of end result specifications include:

- contractors are given responsibility for the construction process and control over those items which they are in a better position to control, i.e., quality
- materials selection and mix designs are undertaken by the contractor
- QC is the responsibility of the contractor and QA is the responsibility of the owner agency
- end result expectations are clearly outlined, along with how these expectations will be measured in an objective and unbiased manner
- new/more advanced equipment and materials are more readily accepted and encouraged
- the physical properties of the finished product are defined along with payment factors that are linked to the quality, including incentives for increased quality
- acceptance is based on the well-established principles of Statistical Quality Assurance (SQA), including an appeal mechanism
- confrontations are eliminated since the course of action is defined when superior or substandard quality is achieved

The disadvantages of end result specifications include:

- difficulties in determining which physical properties are required to ensure quality/long-term performance of the finished product
- difficulties in determining what limits should be used on the required physical properties of the finished product. This is more problematic when the variability of the existing pavement materials is high, as 100 percent of the existing material is recycled in the HIR process, and the contractor has no control over its consistency
- not all end result requirements can be practically defined or specified, necessitating the inclusion of good construction/paving practice requirements which tend to be more method oriented, such as lift thickness, mix compaction temperatures, raking of joints, etc.
- some transition difficulties can be expected when moving from method specifications, where the owner agency provides all the technical expertise, to end result specification, where the contractor is expected to have considerable technical expertise
- confrontations can arise when QC and QA test results are not in agreement
- increased budget uncertainty, since it is more difficult to predict final construction costs as the amount of additional payments for increased quality is unknown
- significant change in approach for owner agencies, from having direct control in the construction process to ensuring quality is being achieved through an observational/acceptance role

The trend in the HMA industry is towards greater reliance on end result specifications, with some owner agencies introducing performance warranties in conjunction with end result specifications. Implementation of end result specifications in the HMA industry is a slow process, has had some difficulties, and not all jurisdictions have or are adopting end result specifications.

Many projects that have been appropriate candidates for HIR have been completed with method specifications, and these projects are performing well. Although not as many HIR projects have been completed with end result specifications, most have been very successful and are performing well. The type of specification used for any given HIR project ultimately rests with the owner agency. The decision will be heavily influenced by the owner agency's approach to HMA specifications and their experience with the HIR process.

7.1 METHOD SPECIFICATIONS

When it has been decided that a method specification will be used for HIR projects, a number of items are usually included within the specifications. These include:

- general description
- definitions and terminology
- HIR method to be used
- material requirements
- equipment requirements
- construction methods
- inspection and QC/QA
- acceptance requirements
- measurement and payment

The general description, usually one or two short paragraphs long, introduces the project, the HIR process, and construction methodology in broad terms. It may or may not identify other sections of the owner agency's existing specifications that are related to the HIR specifications and the various documents which need to be submitted by the contractor.

Some method specifications include a section outlining the terminology and definitions used within the specifications. The terminology and definition section is more often included when HIR is being used for the first time and not everyone is familiar or comfortable with the terms used.

A more detailed section indicating which HIR method is to be used, either Surface Recycling, Remixing or Repaving (with Surface Recycling or Remixing) is included within the specifications. In addition, the requirement for single or multiple pass Surface Recycling or Repaving and single stage or multiple stage Remixing is also indicated within this section.

The section on materials includes requirements for the recycling agent, virgin aggregate, new asphalt binder, and HMA. The recycling agent required is usually indicated by a specific product, an equivalent product, existing owner agency recycling agent specifications or other published recycling agent specifications such as those contained in the American Society for Testing and Materials (ASTM). The virgin aggregates, if added in the Remix process, are usually required to meet the owner agency's existing aggregate specifications. The new asphalt binder is also usually required to meet the existing requirements of the owner agency. Any HMA used in the multiple pass Surface Recycling, the Remix or Repave process is usually specified as one of HMA mix types which would normally be used by the owner agency.

In a method specification, as part of the mix design process, the owner agency selects the:

- recycling agent type and source
- recycling agent application rate
- aggregate source and gradation
- asphalt cement source and grade
- admix (the combination of virgin aggregates and new asphalt binder) addition rate

Therefore, the materials section is primarily to indicate to the contractor the types of materials that will be used on the project, as opposed to requiring the contractor to select the particular materials to be used.

The section on equipment requirements contains a fair amount of detail and can be rather lengthy. It includes details for all equipment from the HIR preheater units through to the placement and compaction equipment. The specifications can include requirements for:

- age or operating condition of the equipment
- types of heating units and heating fuel
- minimum heater output, number of heating units or minimum equipment processing capabilities
- emission controls
- type of scarification/rotary milling
- method, control, and accuracy of recycling agent addition
- method, control, and accuracy of admix addition
- blending and uniformity of the recycled mix
- type of spreading and leveling equipment
- number and type of compaction equipment

In addition, requirements for pre-approval or acceptance of the equipment, prior to use, by the owner agency is usually included. In some instances, the specifications include the requirement for the proposed HIR equipment to undertake a “test strip” in order for the owner agency to evaluate and approve the equipment, contractor and/or workmanship.

Construction methods included in the specifications are usually the existing owner agency specifications or industry publications for good paving practices. There will be some additional requirements which address such issues as:

- pavement surface preparation prior to HIR
- pre-heating width
- minimum and maximum pavement surface temperature prior to scarification/rotary milling
- HIR processing width and depth
- minimum and maximum mix temperature at laydown

- minimum mix temperature during compaction
- number and type of rollers required for compaction
- weather conditions at the time of HIR construction
- transition requirements at the start and end of HIR sections
- longitudinal and transverse joint requirements
- checking of underground utilities for flammable vapors
- adjustment of manholes, catchbasins, valves and other roadway castings
- local, county, regional, state and federal regulatory requirements
- site cleanup

With method specifications, the owner agency is in control of the construction process and therefore needs to have full time inspection and testing. The owner agency personnel on the project must have the experience to evaluate the test results and authority to make field adjustments to the HIR process.

The specifications usually outline the frequency of sampling and the testing methods that will be used. Wherever possible, these should be published industry standards, such as the American Association of State Highway and Transportation Officials (AASHTO) or ASTM methods or the owner agency's own adaptation of these procedures. Since the owner agency is essentially in control of the construction process, the QC and QA testing are usually one and the same, and increased inspection is used to control the HIR process.

A section of the specifications, outlining the acceptance requirements for the HIR work, is also included. The acceptance requirements include such things as:

- treatment depth
- recycled mix temperature
- recycled mix void properties
- percent compaction
- smoothness
- workmanship
- obvious defects

Some of these are obviously end result requirements but they have traditionally been included in method specifications.

The final section deals with measurement and payment issues for the HIR project. The specifications usually outline how items will be measured such as HIR by the square yard (square meter), recycling agent by the gallon (litre), and admix by the ton (tonne). In addition, the specifications indicate what is to be included in each of the payment items.

HIR payment typically includes full compensation for all labor, equipment, tools and incidentals necessary for the completion of the HIR in accordance with the specifications, including surface preparation (sweeping roadway only), heating, scarification/rotary milling, addition of recycling agent and admix, mixing, placement, compaction of the recycled mix, and site clean up. The owner agency usually has specific compensation items for mobilization/demobilization and for traffic accommodation, but these are sometimes included within the HIR payment item.

Recycling agent and admix payment is for the amount incorporated into the HIR mix and includes compensation for supply, delivery, storage, handling, and addition of the recycling agent and admix.

Compensation for other items such as localized asphalt pavement repairs prior to HIR, repairing or raising roadway castings, supply and placement of HMA leveling prior to HIR, cold planing to correct roadway irregularities prior to HIR, HMA used as the wearing course, etc., are made as individual payment items.

Special Provisions, appended to the HIR specifications, are used to indicate specific project requirements such as:

- limits of work
- construction schedule, staging or limitation on hours of work
- trucking requirements
- traffic accommodation requirements
- interaction and cooperation with other contractors
- parking and storage of equipment
- existing roadway material properties
- mix design information
- any other site-specific requirements

The degree to which these various issues are addressed within the specification and the special provisions will depend on the owner agency's experience with HIR and the type of HIR process to be used.

7.2 END RESULT SPECIFICATIONS

When it has been decided that an end result specification will be used for HIR projects, a number of issues will need to be addressed within the specifications. In order to develop an end result specification there must be a clear understanding of the end product properties required and how these properties can be quantified or measured. On the other hand, the end result specifications should be kept as simple and straight forward as possible.

As with conventional HMA, there are a number of end product properties which could be specified for HIR mixes. These include:

- aggregate characteristics
- aggregate gradation
- asphalt binder content
- recovered asphalt binder rheological properties
- recycled mix void properties
- recycled mix stability and flow properties
- recycled mix friction number and rutting properties
- field compaction
- smoothness
- workmanship, etc.

Like conventional HMA, the HIR mix needs to be stiff, durable, uniform, and smooth in order to have acceptable long-term performance. To be stiff, the recycled mix has to be adequately compacted. To be durable, it must have adequate void and asphalt binder rheological properties. To be uniform, it must be free of segregation and surface defects. To be smooth, it must have an acceptable California Profilograph Index (PrI), International Roughness Index (IRI) or similar measurement. When the HIR pavement has met these six end product properties, it will have an acceptable service life.

End result specifications need to incorporate SQA testing procedures into the specifications. SQA is an unbiased method used to make decisions related to areas of specification development, construction, and inspection. It gives the person in charge a definite degree of confidence in the decision to accept a given product. SQA has three principle components:

- random sampling
- process control
- acceptance procedures

Statistical concepts for QA in construction are based on the laws of probability and the premise that all parts of the whole have an equal chance of being chosen as the sample to be tested.

The sampling locations must be selected by random or stratified random sampling techniques, with some practical limitations, to ensure that the sample location is indicative of the material being evaluated. An example of a practical limitation would be a minimum distance from the start or stop of a day’s production.

Process control or QC is the sole responsibility of the producer/contractor. Quality is controlled, within the required specification limits, so that all of the material produced will be accepted at full contract price.

Acceptance procedures are based on lot-by-lot testing, for the purpose of assessing the quality of the materials or workmanship. A lot is a uniquely defined, homogeneous portion of material or work about which a decision has to be made. A lot is normally divided into a minimum number of sub-lots and one sample, chosen/located at random, is obtained and tested from each sub-lot. Typically, a lot is one day’s production and there are usually five sub-lots per lot.

All test results should be reviewed for anomalies which may have occurred due to faulty testing equipment, improper sampling, improper testing procedures and/or calculations. If an anomaly is found, the sub-lot should be retested. The results from each sub-lot are then averaged to determine the results for the lot.

The key to end result specifications is the inclusion of payment adjustment factors, which link the payment to the quality of the final product. Payment adjustment factors ideally reflect the increased or decreased performance of the as-constructed asphalt pavement related to the increased or decreased quality provided. The establishment of the link between quality and pavement performance is difficult to quantify, even for conventional HMA. However, the relationship between physical properties of the asphalt pavement and pavement performance are generally well established and intuitively obvious, for conventional HMA. They may not be as intuitively obvious for HIR pavements.

Good engineering judgement should be used to establish the initial end result specifications and payment adjustment factors, based on previous experience, achievable results, and geographic considerations. In the HIR process, it must be recognized that the contractor has absolutely no control over 70 to 100 percent of the material being used, i.e., the existing asphalt pavement.

Payment adjustment factors should include an equivalent incentive/bonus to provide superior quality as the penalties imposed for substandard quality. The bonus will be factored back into the contract prices, by quality orientated contractors, with the net effect of reduced overall project costs and increased long-term performance.

Payment adjustment factors need to be linear or curvilinear, as opposed to stepped, so that small changes in test results do not result in large changes in the payment adjustment factor. This also reflects the performance of asphalt pavements which are linear or curvilinear in nature.

End result specifications and payment adjustment factors need to be reviewed on a yearly basis in order to take advantage of new information and performance of HIR roadways constructed under the end result specifications.

Finally, the end result specifications should contain an appeal mechanism to reduce the risk of having an acceptable product penalized or rejected in cases where the lot test results do not truly reflect the actual value of the lot, due to random chance in the sampling process. In general, the QA test results are correct but they may not be fully representative of the material/workmanship in the lot. The appeal mechanism should take this into account.

7.3 SPECIFICATION LIMITS

Applying or adapting HMA job mix tolerances for HIR mix properties such as asphalt content, gradation, voids, etc., will not be reasonable, practical or cost-effective for most HIR projects. The job mix tolerances and QA plan have to be developed on a project specific basis.

As was indicated in Chapter 5, it is recognized that conventional hot plant recycled HMA tends to have higher densities and lower mix void properties when RAP contents of less than 50 percent are used. These effects are even more pronounced with HIR mixes which contain 70 to 100 percent RAP. It is also widely accepted that HMA mixes containing RAP have the same, if not better, performance than conventional HMA.

The existing asphalt pavement was originally constructed at or near the optimum asphalt binder content in order to met the conventional HMA void and stability requirements. Over time the asphalt binder may have aged or oxidized somewhat and there may have been some aggregate degradation, but in general the original optimum asphalt binder content should still be applicable. If a recycling agent is used to rejuvenate the aged asphalt binder, it has the effect of increasing the binder content which in turn results in a reduction of mix air voids. If conventional HMA void requirements are applied to the HIR mix, it would be considered to be too low in void properties and corrective action would be needed. The corrective action has historically been to reduce the binder content of the mix with the addition of virgin aggregates. The virgin aggregates dry out the mix and the mix void properties are raised into the range acceptable for HMA. Although the HIR mix void properties are within the acceptable HMA range, the net effect is to reduce the effective asphalt binder content of the mix with a corresponding reduction in asphalt binder film thickness. Therefore, the existing asphalt pavement which had an appropriate film thickness for long-term durability, has had the film thickness reduced by trying to make the HIR mix have the same void properties as a conventional HMA. The ultimate effect of the reduced film thickness will be reduced durability and a reduced service life.

Consequently, when setting the specification limits for the recycled mix, it is important to recognize that equivalent physical properties between a conventional HMA and a HIR mix do not necessarily mean equivalent field performance. More often, it means reduced field performance for the HIR mix. The goal of the specifications should be to obtain equivalent field performance between the conventional HMA and the HIR mix. In order to achieve equivalent performance it is anticipated that in most jurisdictions, there will be differences in the physical properties of the conventional HMA and HIR mix.

In the HIR process 100 percent of the existing asphalt pavement is used and it makes up 70 to 100 percent of the recycled mix. Therefore, the variation or consistency of the existing asphalt pavement will have the greatest influence on the variation or consistency of the recycled mix. The HIR contractor has no control over the variation of the existing asphalt pavement, and the specifications should reflect this reality.

The evaluation of the existing asphalt pavement, as indicated in Chapter 4 on Detailed Project Analysis, will give an indication of the variability of the existing materials. This variability should then be used to set the tolerance limits for the HIR mix properties being measured. A rule of thumb approach to setting the HIR tolerance limits would be to assess the variability of the existing asphalt pavement with the owner agency’s HMA production tolerances. If the standard deviation of the existing pavement test results is less than one half the corresponding HMA production limits, then the HMA limits could be used. If the variability of the existing asphalt pavement is greater than one half the standard deviation of the HMA production limits, then the HIR production tolerance limits will have to be increased to reflect this variability.

Like conventional HMA, the HIR mix needs to be stiff, durable, uniform, and smooth in order to have acceptable long-term performance. To be stiff, the recycled mix has to be adequately compacted. To be durable, it must have adequate void and asphalt binder rheological properties. To be uniform, it must be free of segregation and surface defects, and to be smooth, it must have an acceptable ride. If a HIR pavement has met these four conditions, then it will have an acceptable service life.

To be stiff, the recycled mix has to be adequately compacted. To determine whether the recycled mix has been adequately compacted, the field density is compared to the corresponding density of the same mix compacted in the laboratory. It is critical that the field density be compared to the laboratory density of the same mix, due to the inherent variability of the existing asphalt pavement. This inherent variability affects the density of the laboratory and field samples, and consequently affects the calculated degree of compaction. The specified degree of compaction is typically the same as for the conventional HMA, and ranges between 95 and 98 percent of the laboratory density or 92 to 95 percent of the corresponding Maximum Theoretical Density (MTD).

To be durable, the recycled mix has to have adequate mix void properties and asphalt binder properties. As discussed previously, the mix void properties of the recycled mix should be selected to ensure that it has field performance equivalent to a conventional HMA. In general, it is anticipated that this will result in somewhat lower air voids (Va) and Voids in Mineral Aggregates (VMA) contents, somewhat higher stability and flow properties, and similar film thickness requirements as a conventional HMA.

The asphalt binder properties selected for equivalent performance to conventional HMA, are typically somewhat harder or more viscous than for new asphalt binders. In the selection of the asphalt binder properties, it is important to recognize that some additional hardening will occur in the HIR process and that sufficient rejuvenation is required to ensure the recycled mix is not excessively stiff or has adequate fatigue resistance. In addition, for colder climates the asphalt binder properties should be selected so that no additional low temperature transverse cracking occurs with the recycled mix.

To be uniform, the recycled mix must be free of segregation and surface defects. The conventional HMA specifications for segregation and surface defects can be used for HIR mixes.

To be smooth, the recycled mix must have an acceptable ride as determined by a maximum California Profilograph Index (PrI), International Roughness Index (IRI) or similar measurement. It must also be free of bumps and dips. The conventional HMA specifications for smoothness and bumps/dips can be used for HIR mixes.

7.4 INSPECTION, QUALITY CONTROL AND QUALITY ASSURANCE

Due to the wide variation in HIR equipment types and processes, generic inspection, QC or QA plans cannot be given in this manual. The inspection and QC/QA plans need to be developed, based on the HIR process specified and then amended for the specific type of HIR equipment being used on the project. The inspection and QC/QA plan for a HIR Surface Recycling project will have only one component while a HIR Remix or a Repave project QC/QA plan will have two components: one for the HIR portion of the work and one for the admix or HMA used in the integral overlay portion of the work.

QC includes those activities undertaken by the contractor to monitor production and placement of the recycled mix and are intended to eliminate sub-standard materials or poor workmanship to ensure compliance with the specifications. Compliance with the specifications, in turn, ensures the long-term performance of the finished product. QA includes those activities performed by the purchaser/owner or their agent, to ensure that the contractor has met the requirements of the specifications and that the risk of acceptance of the final product which contains sub-standard materials or poor workmanship, will be within acceptable limits.

A recent trend has been towards using QC test results in place of some or all of the QA tests. The rational for this is to reduce duplication of efforts and costs. However, care must be taken since the QC plan’s objective is to control the quality of the product being produced, at specific control points, on an ongoing basis. QC may use modified or surrogate test methods in order to reduce the testing turn around time, so that adjustments to the production process (if required) can be made on a more timely basis. Hence, the QC samples are not usually statistically chosen on a random basis, and therefore may not be indicative of the production as a whole and should not be used in a SQA plan.

If the specifications indicate:

- the test samples are to be randomly selected
- the frequency of sampling
- how the samples are to be tested

then the test results are truly QA tests, and can be used in the SQA process to accept the product or work. In reality, the purchaser/owner has handed over or contracted out the QA function to the contractor. However, reliance on these QA test results by the contractor to control the construction process will be reactive and not proactive. The contractor will be running the risk that large quantities of materials or workmanship will be produced, outside of the required specification tolerance limits and that it will be rejected or have significant payment adjustments applied to it. The prudent contractor will still conduct QC tests to reduce the risk of producing non-compliant materials or poor workmanship.

There are a number of areas of concern which the QC plan needs to address. These areas are the same for the contractor during HIR production or the owner agency using a method specification and include:

- heating of the existing asphalt pavement
- treatment depth
- addition of recycling agent
- addition of admix
- placement of recycled mix
- compaction of recycled mix

Heating of the existing asphalt pavement needs to be undertaken in such a manner as to minimize the oxidation or hardening of the asphalt binder while at the same time ensuring:

- that excess moisture has been removed
- the asphalt pavement is sufficiently softened so that it can be scarified/rotary milled without undue aggregate degradation
- the recycling agent and admix can be thoroughly mixed in
- an adequate temperature for compaction has been achieved

There are no definitive QC tests which will determine when the heating process has excessively hardened the asphalt binder so that the project specifications will not be achieved. However, there are a number of visual or “tell tale signs” that indicate when corrective action may be required in the heating process. These include:

- blue or black smoke emissions from the heating units
- differences in surface appearance across the width of the mat
- scorched or charred pavement surface
- excessive temperature variations across the width of the mat

Emissions from the heating units which are white and dissipate quickly indicate removal of moisture from the pavement in the form of water vapor. Blue or black smoke generally indicates some combustion and removal of hydrocarbons from the asphalt binder. If this occurs, immediate corrective action such as reducing the intensity of the heating units, raising the heating units from the pavement surface or increasing the forward speed of the heating units is immediately required.

The heating of the pavement surface should be as uniform as possible both transversely and longitudinally. This will help to ensure a uniform treatment depth and degree of compaction. The pavement temperatures have historically been determined with thermometers, thermistors or thermocouples. Although still useful, these are being replaced by the convenience and speed of hand held infrared temperature measuring devices, usually called “heat guns.” These heat guns must be used with caution since they determine surface temperature which is affected by both the heating process and environmental conditions. To determine the temperature with a heat gun, other than at the surface, the material has to be manually exposed.

Temperatures should be checked continually at a number of different locations in the HIR process. The locations vary depending on the configuration of the HIR equipment but should include:

- after each pre-heating unit
- prior to final heating
- prior to final mixing
- immediately behind the screed

The addition of the recycling agent and admix needs to be linked to the forward operating speed of the recycling unit. The application rates are usually adjusted, to account for variations in operating speed, by a microprocessor linked to the forward speed of the recycling unit. The microprocessor has to be calibrated to the required HIR treatment depth in order to accurately control the amount of recycling agent and admix being added. The microprocessor has no means of determining whether the required HIR treatment depth is being achieved. This must be done manually and on a continuous basis. If the actual treatment HIR depth varies from the required treatment depth, there will be a corresponding change in the application rate of the recycling agent and admix. This in turn will have an effect on the:

- gradation of the recycled mix
- asphalt binder content of the recycled mix
- rheology of the recovered asphalt binder
- recycled mix void properties
- recycled mix strength properties
- uniformity of compaction of the recycled mix

Therefore, uniformity of treatment depth is critical to the consistency of the HIR process. A number of methods for determining HIR treatment depth have been used, with varying degrees of success. These include:

- precession level surveys before and after scarification
- measurements at the outside edges after scarification
- removal and weighing of all the scarified material in a known area and converting the weight to a treatment depth using a conversion factor
- dipstick or probing of the uncompacted mix behind the paver screed
- measurements from recovered cores

No matter which method is used, a number of individual measurements must be taken and then averaged in order to obtain a representative HIR treatment depth.

The addition of the recycling agent has to be linked to the forward operating speed of the recycling unit, with a typical tolerance of +/- 5 percent of the specified application rate. The recycling agent needs to be uniformly applied or blended into the recycled mix in order to ensure consistency. The application rate is checked by determining the amount of recycling agent used over a given distance. The amount of recycling agent used is usually recorded by the microprocessor or by some form of quantity totalizer such as a mass flow meter or similar device. The application rate should be checked hourly throughout the day and also for the overall daily application rate.

The addition of admix or HMA used in the integral overlay of a HIR Repave project, is also linked to the forward operating speed of the recycling unit, through a microprocessor and a calibrated feed belt. A typical tolerance of +/- 5 percent of the required application rate is also used. The application rate is checked by noting the amount of admix/HMA being supplied in the haul truck and measuring the distance the recycling unit traveled to empty the truck. The application rates should be checked hourly throughout the day and also for overall daily application rate.

The QC plan for the admix and/or the HMA used in the Repave process should follow standard HMA QC methods.

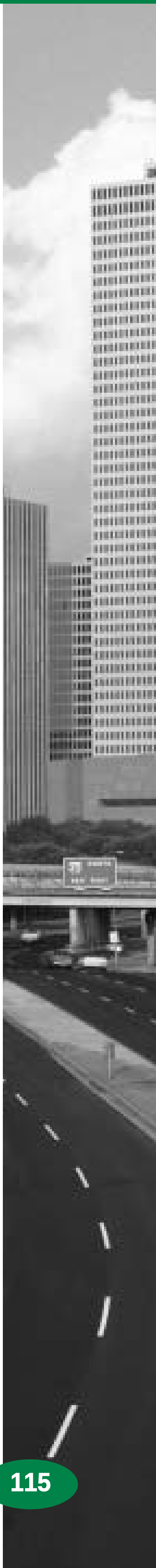
Placement of the recycled mix is normally performed by a screeding unit attached either to the recycling unit or on a separate paver. Standard HMA paving practices should be used during the placement of the recycled mix.

Compaction of the recycled mix is usually done with a combination of pneumatic and steel rollers operating immediately behind the screeding unit. A test strip could be used to determine the type, number of rollers, roller passes, and roller coverage required to achieve the specified degree of compaction. Periodic checks with nuclear density gauges should be undertaken throughout the day. The nuclear density gauges should be calibrated to field core samples.

When the HIR project is being undertaken using end result specifications, the contractor's QC plan will include all of the items identified previously plus any other items which may be unique to the end result specifications. These could include such things as aggregate properties, gradation, recovered asphalt binder properties, recycled mix void properties, etc..

The owner agency's QA plan or requirements, particularly for end result specifications, need to be outlined in some detail within the specifications. The specifications should identify how the:

- end product properties will be measured
- sample locations will be selected
- samples will be tested
- anomalous test results will be treated
- appeal mechanism will work



CHAPTER 8: COLD PLANING - CONSTRUCTION

8.0 COLD PLANING REHABILITATION

Cold Planing (CP) is the controlled removal of the surface of the existing pavement to the desired depth, with specially designed milling equipment to restore the pavement surface to the specified grade and cross-slope. CP can be used to remove part or all of the existing pavement layers. The amount of material removed can also be varied in order to meet project specific requirements. The resulting textured pavement can be used immediately as a driving surface. CP is more commonly used as a surface preparation for one of the other rehabilitation techniques such as Hot In-Place Recycling (HIR), Cold In-Place Recycling (CIR), Full Depth Reclamation (FDR) or Hot Mix Asphalt (HMA) overlays.

The product of a CP operation is a crushed, somewhat “gap-graded” reclaimed asphalt pavement (RAP) which acts like an asphalt coated granular material. The RAP can be used for hot recycling, Cold Central Plant Recycling (CCPR) or as a granular aggregate.

Pavement distress which can be treated by CP includes:

- raveling
- bleeding
- shoulder drop off
- rutting
- corrugations
- shoving
- removal of deteriorated, stripped or aged asphalt
- poor ride quality caused by swells, bumps, sags, and depressions
- potential bonding problems between existing pavement and new HMA overlay
- diminished curb reveal heights

8.1 CP DETAILED PROJECT ANALYSIS

Through the project evaluation, economic analysis and preliminary selection process outlined in Chapter 3, the potential rehabilitation alternatives were narrowed down to one specific technique. The next step in the rehabilitation design is the detailed project analysis which will lead directly into the final project design, advertising, tendering or letting, and construction.

The HMA overlay, hot recycling, and reconstruction rehabilitation methods will not be addressed since they are routinely used by all agencies. The rehabilitation techniques of HIR, CIR, and FDR are addressed in detail in other chapters.

As CP is primarily used in conjunction with another rehabilitation technique, the detailed project analysis tends to be governed by the subsequent rehabilitation method. The CP detailed project analysis is limited to an assessment of geometric and constructability issues.

Pavements of most widths, shapes, and profiles can be routinely handled due to the wide range in equipment sizes and capabilities. The ability of the cold planer to overlap a previously milled area without adversely affecting the finished product makes most geometric shapes candidates for CP.

Constructability issues primarily concern traffic accommodation and overhead clearance requirements. Traffic interruptions can be kept to a minimum since CP production is relatively high and the roadway can be used by traffic as soon as it has been swept clean of any loose millings. Typically, overhead clearance height, even for the larger milling machines is not a problem, but the project area should be checked for any low overhead obstructions.

When the specifications indicate that significant depths of the existing asphalt pavement are to be removed by CP, the area to be treated should be checked for buried utilities, abandoned rail or streetcar lines, manholes, values, and other castings. These fixtures are usually indicated on existing plans but a field magnetic/metal detector survey should be undertaken.

Some common preparatory measures should be undertaken prior to CP. These include:

- detailed safety or hazard assessment
- development of a detailed traffic control plan

These have become increasingly important as more and more CP is being undertaken at night to reduce the impact on the travelling public.

The equipment used to undertake CP will vary from contractor to contractor but no matter what the CP equipment looks like, it is required to perform the same general steps, including:

- reclaiming and sizing of the existing pavement
- removal of the reclaimed pavement from the roadway
- cleaning of the milled surface
- application of traffic control markings or wearing course

8.2 CP EQUIPMENT

The minimum equipment requirements for CP are:

- modern, self-propelled cold planer
- haul trucks
- water truck
- sweeper or power broom

Development of the cold planer or milling machine began in the late 1970's when a grade trimmer was upgraded to mill asphalt pavement. Since that time significant advancements in size, horsepower, milling width, milling depth, production, and cost-efficiency have been made. CP has become commonplace in construction and is now the preferred method of removing and/or reclaiming pavement materials.

CP equipment is available in a variety of sizes from mini-milling machines, for localized milling around manholes and valves, etc., as indicated in Figure 8-1, to high capacity machines capable of milling up to 16 feet (4.9 meters) wide and over 12 inches (300 mm) in one pass, as indicated in Figure 8-2.

Figure 8-1: Mini cold planer working around a manhole

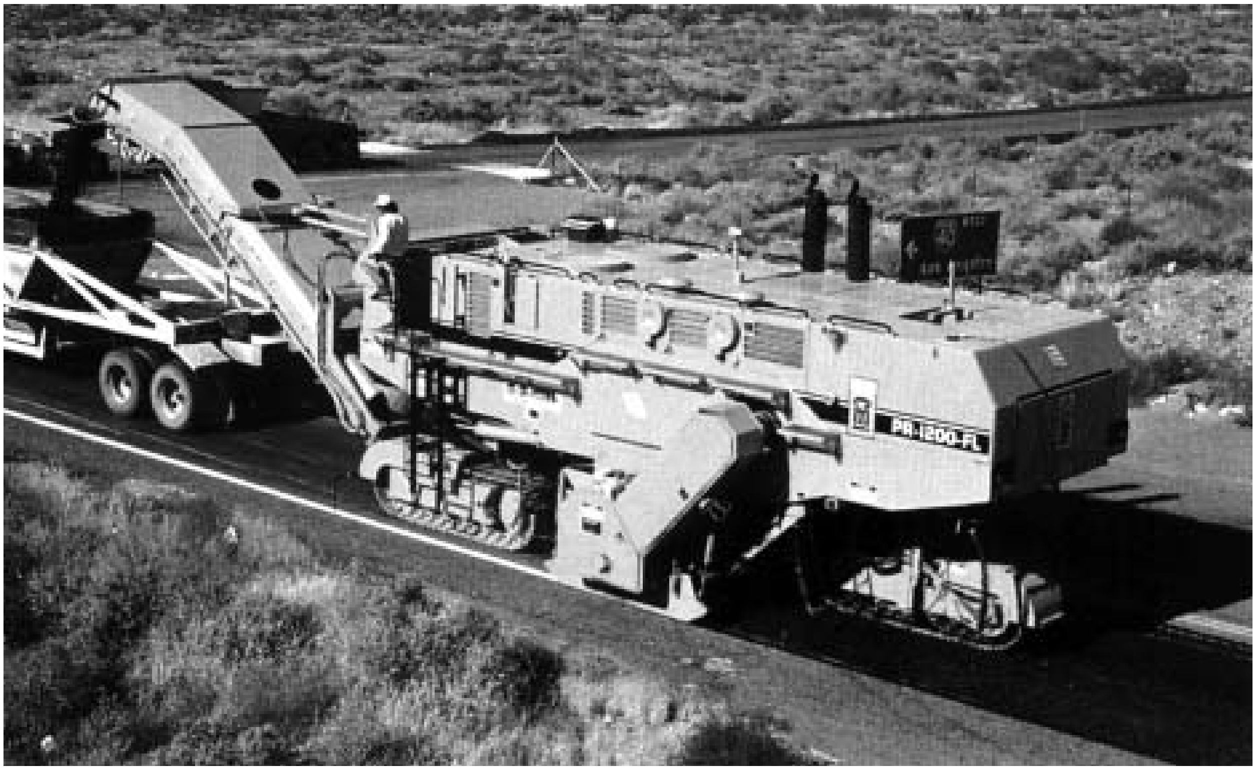


Figure 8-2: High capacity full lane cold planer

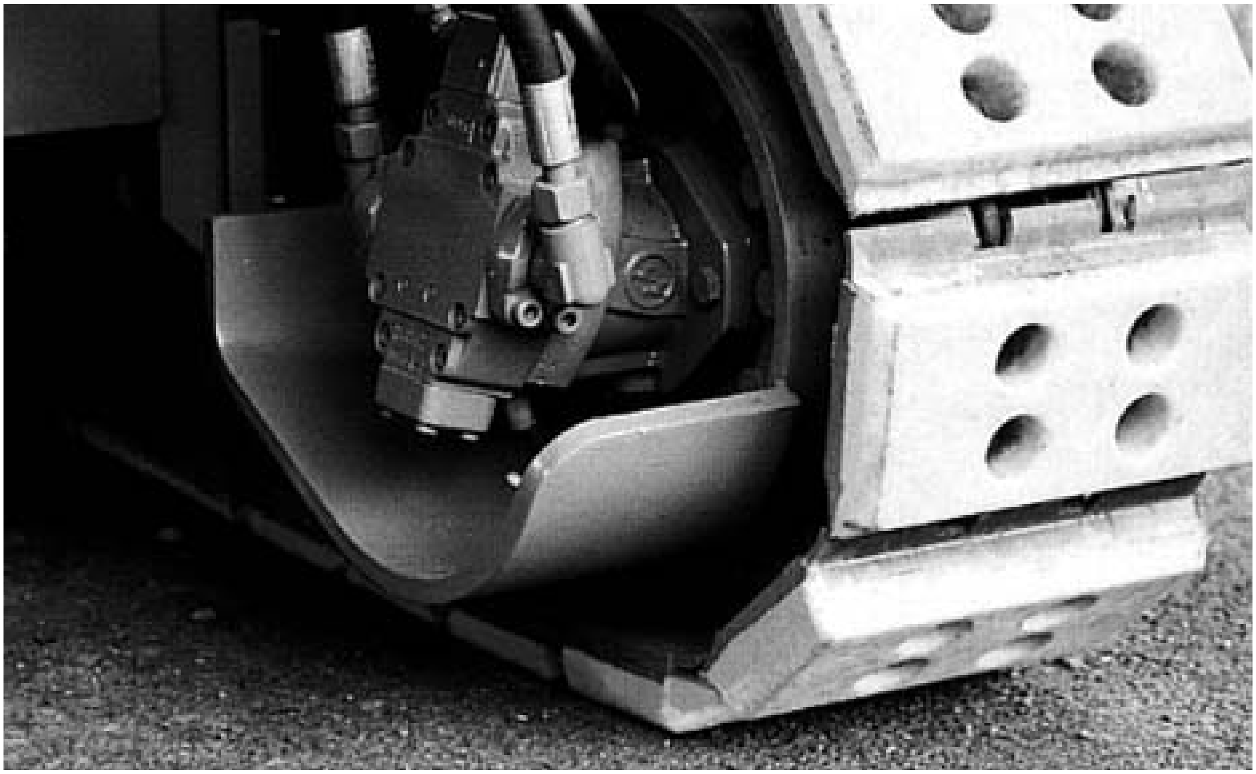


Figure 8-3: Individual track hydraulic drive motor and track pad

The modern cold planer is sized so that the overall weight and available horsepower are related to the milling width and depth in order that traction is always maintained. Cold planers are equipped with either three or four tracks for load distribution, mobility, and traction. Some cold planers are equipped with hard rubber tires for increased maneuverability.

Typically, each track/wheel is driven by a separate hydraulic motor, as indicated in Figure 8-3, which are powered by a common hydraulic pump. Uniform traction is increased on slippery surfaces by various traction locking devices which divert power away from the track that is slipping to the ones that have traction.

The use of rubber/polyurethane track pads, as indicated in Figure 8-3, increases traction and minimizes damage to the roadway surface.

To increase maneuverability, the cold planer can be operated with front steering, rear steering, and/or all track steering. This permits easy maneuvering of the cold planer which allows it to mill around the tight radius turns found on some roadway intersections, as indicated in Figure 8-4. This maneuverability ensures access to most areas, increases production, and reduces costs.

Cutting drums are available in a variety of widths which can be increased with bolt on extensions. The cutting drums can usually be changed relatively quickly depending on the treatment width and surface texture required. Cutting drums generally operate in an "up-cut" direction, i.e., the rotation of the cutting drum is opposite to the direction of the cold planer. Most cold planers have a variable sized shoe which exerts down pressure on the pavement in front of the milling drum. The shoe is used to hold broken pieces of pavement in place so that large pieces or slabs are not

Figure 8-4: Cold planer milling urban intersection

broken loose by the up cutting action of the cutting drum. The shape of the shoe and amount of down pressure used will depend on the condition of the pavement being milled and the size requirements for the RAP being produced. Increasing the cutting drum rotation speed and reducing the forward speed of the cold planer will also help in sizing the RAP.

The cutter drum is equipped with easily replaceable tungsten carbide cutting tools. The development of more robust cutting tools has contributed to the development of larger cold planers. The orientation of the cutting tools is in a helical or spiral pattern that is intended to move the reclaimed material to the center of the cutting drum, as indicated in Figure 8-5. The service life of the cutting tools varies, depending on the material being milled and the depth of milling. Cutting tools may need to be changed from once per hour to once per shift.

The cutting drum drive system is powered by a diesel engine, clutch, power transmission belt/pull, and gearing inside the cutting drum. Automatic power control devices sense the varying load on the cutting drum, due to changes in material condition/hardness and adjusts the forward speed of the cold planer to ensure maximum performance without overloading the drive system.

A heavy-duty scraper blade or “moldboard” is used behind the cutting drum to help collect the reclaimed material and to shave off any high points in the milled surface. The scraper blade usually contains a tungsten carbide wearing surface to enhance durability.

Side plates are used to contain the material within the cutting drum chamber. The side plates can move up and down to accommodate milling adjacent to a concrete curb or area that has been previously milled.

Figure 8-5: Helical pattern of tungsten carbide tools on cutting drum

When milling pavements for utility trench cuts, it is advisable to leave some of the RAP in the trench until the trench is subsequently excavated. The scraper blade at the rear of the cutting drum chamber is raised so that only a portion of the RAP is loaded into the haul trucks with the remainder staying in the trench. In some milling machines, the RAP can be windrowed by leaving an opening in the scraper blade and not using the loading conveyor.

A small amount of water is used during the milling operation, to control the amount of dust generated and to extend the service life of the cutting tools. The water is supplied from the cold planer's onboard storage tank which is refilled by a water truck.

Modern milling machines are of sufficient size to provide the traction and stability needed to remove the pavement surface to the specified profile and cross-slope. Most are equipped with automatic grade controls systems to control the milling process. Typically, one or more automatic leveling systems, operating independently, and a number of different sensors can be used to control the milling machine. Cable sensors can be used for mechanical scanning of the side plates attached to the cutting drum. Non-contact ultrasonic sensors can be used to scan the height of the side plate and also the reference surface beside, in front or behind the cutting drum.

Transducing sensors are used to scan a moving reference line such as a ski or a fixed reference line such as a stringline for grade control, as indicated in Figure 8-7. A slope sensor attached to the milling machine can be used in conjunction with the depth sensor for both grade and cross-slope control. Laser sensors are also being used with a laser transmitter for very tight grade control, usually in specific locations.

Figure 8-6: Front loading milling machine

The RAP generated during the CP operation is usually loaded onto haul trucks by the milling machine and removed from the site. Self-loading milling machines are available in all sizes from the large full lane cold planer, as indicated previously in Figure 8-2, to the smaller partial lane width milling machines, as indicated in Figure 8-8.

Front loading milling machines are now the standard in the industry as they save time and money, since the only lane which needs to be closed to traffic is the lane that is being milled. Front loading also provides a safer work site as all equipment and haul trucks are operating in the same direction as traffic, eliminating the difficult task of backing up the haul trucks. The loading conveyor on the milling machine can be raised or lowered, and in conjunction with an adjustable belt speed, even the longest of haul trucks can be loaded over their full length. The loading conveyors usually can be angled to either side so that the haul truck could be loaded by traveling along side the milling machine. Alternatively, the RAP could be deposited directly onto the adjacent shoulder as a windrow, if desired.

Rear loading of RAP is now typically only used in the smaller class of milling machines particularly for the 3 foot (1 meter) and less utility trench applications in which smaller haul trucks are used, as indicated in Figure 8-8.

The scraper blade and loading conveyor remove most of the RAP, although some smaller particles remain on the milled surface due to its rough grid patterned texture. These fine, loose pieces of RAP are removed from the roadway surface by means of power brooms, vacuum sweepers, and/or power sweepers. The use of power brooms in urban, residential or other sensitive areas may not be allowed due to the potential for dust generation during the cleaning operation.

Figure 8-7: Transducing sensor and stringline for control of the cutting drum

Figure 8-8: Small self loading, partial lane width milling machine

The cleaning/sweeping of the milled surface needs to be completed prior to the roadway being opened to traffic. If not, the fine, loose pieces of RAP will be compacted into the milled surface by the vehicle tires. They will then become extremely difficult to remove.

At the completion of the cleaning operation, the milled roadway can be opened to traffic. Some owners place restrictions on the length of time (days to months) milled roadway surfaces can be left open to traffic prior to placement of a HMA overlay. Many owners specify that all milled surfaces requiring a HMA overlay must be paved prior to any winter shutdown. For some projects, particularly those with high traffic or safety issues, the milled area is paved the same day.

If the underlying pavement structure is adequate, the milled surface can be left indefinitely and needs only traffic control lines to accommodate traffic.

8.3 PREPARATION AND PLANNING

Some preliminary preparation and planning activities are required prior to the start of the CP process. These activities are intended to improve the uniformity of the milled surface. The preliminary activities are also intended to result in better equipment utilization and increased productivity.

The detailed project analysis will have identified many of the preliminary activities. However, field verification immediately prior to construction provides an independent check which reduces the risk that something unexpected will occur.

Identification of buried utilities, abandoned rail or streetcar lines, manholes, valves, and other castings needs to be undertaken prior to the start of CP. If solid, buried obstructions are encountered during the milling operation, damage to the cutting tools, cutting tool holders, cutting drum, and under particularly adverse conditions even to the drive mechanism, can result. The associated down time, inconvenience to the public, and repair costs can be extensive.

In the case of manholes, valves and other roadway castings, these are treated with a mini cold planer as was indicated previously in Figure 8-1. The mini cold planer mills to the required depth in advance of the larger machine so that there is a smooth transition between the two areas, as indicated in Figure 8-9.

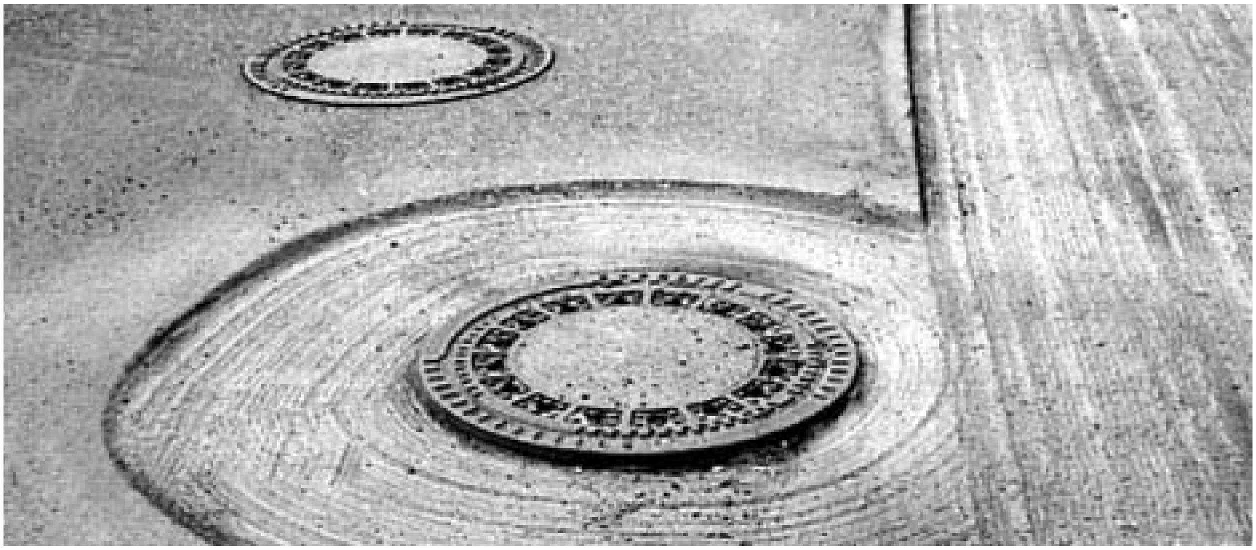


Figure 8-9: Milling around street castings

8.4 CP MICRO MILLING

CP micro milling or “carbide grinding” is a CP process that uses a cutting drum equipped with significantly more cutting teeth in order to produce a much finer textured surface. Micro milling’s primary application is for a milled surface that is to be used as the final riding surface without a HMA overlay. Micro milling can also being used to correct some minor pavement distresses by removing a very thin layer of existing pavement. A surface treatment such as micro-surfacing, chip seal, cape seal, etc., is then placed as the wearing surface at a significantly reduced cost.

Micro milling is also used to remove pavement markings which need to moved due to changing traffic flows or reconstruction activities.

Conventional milling machines are used for micro milling, so only the cutting drum needs to be changed. The conventional drum on a cold planer has cutting tools spaced approximately 5/8 to 3/4 inch (15 to 20 mm) apart. This cutting tool spacing produces a grid patterned textured surface with discontinuous longitudinal striations approximately the same distance apart as the cutting tools, as indicated in Figure 8-10. The micro milling drum has cutting teeth spaced approximately 3/16 inch (5 mm) apart so the grid patterned textured surface with discontinuous longitudinal striations are much close together, as indicated in Figure No. 8-11. Other cutting teeth spacing can existing in the range of 1/4 to 1/2 inch (6 to 12 mm) apart and is commonly referred to as “fine milling.”

The surface texture, regardless of the type of cutting drum being used, is affected by the condition of the cutting tools, rotational speed of the cutting drum, and the forward speed of the cold planer. The milled surface has a finer texture when the cutting tools are new, the milling drum rotates faster or the forward speed of the cold planer is reduced.

The same grade and slope controls that are on the cold planer for conventional CP are also used during the micro milling process to ensure that the roadway is reprofiled according to the plans and specifications.

A vacuum sweeper usually follows the cold planer equipped with a micro milling drum, to clean the finely milled surface so that the roadway can be opened to traffic.

8.5 CP SAFETY WARNINGS

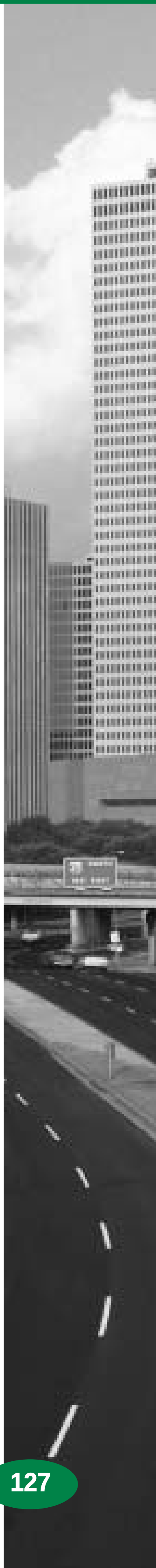
CP can be used to install safety warnings such as longitudinal “rumble strips”, as indicated in Figure 8-12. Transverse grooves can also be milled into the pavement surface prior to intersections or stop lines, in place of speed bumps.

The rumble strips or transverse grooves are noticeable both physically and audibly to alert the driver to a potential roadway hazard.

Figure 8-10: CP surface texture produced with a conventional milling drum

Figure 8-11: CP surface texture produced with a micro milling drum

Figure 8-12: Installation of longitudinal rumble strips



CHAPTER 9: COLD PLANING – SPECIFICATIONS AND INSPECTION

Although other areas of roadway construction are moving towards end result specifications, this has not yet happened to Cold Planing (CP). Specifications for CP are still in method specification format, for the most part. Some owner agencies are beginning to introduce more end result requirements into the CP specifications, particularly smoothness, when the milled area is to used as the driving surface.

9.1 STANDARD SPECIFICATIONS

Standard specifications for CP projects need to address a number of items, including:

- general description
- material requirements
- equipment requirements
- construction methods
- inspection and Quality Control/Quality Assurance (QC/QA)
- acceptance requirements
- measurement and payment

The general description, usually only one paragraph long, introduces the project, the CP process, and construction methodology in broad terms.

A terms and definition section is not normally included within the CP specifications since it is such a universally used and accepted process. ARRA has defined five classes of CP as follows:

- **Class I: Fix Existing Conditions**

  CP the existing pavement surface, as necessary, to remove surface irregularities. It may include milling for Hot Mix Asphalt (HMA) to fixed elevations. Automatic grade and cross-slope controls are not required.

- **Class II: Grade Control**

  CP the existing pavement surface to a uniform depth, requiring automatic grade but not cross-slope control.

- **Class III: Grade and Slope Control**

  CP the existing pavement surface to a uniform depth and cross-slope, requiring the use of automatic grade and cross-slope controls.

- **Class IV: Full Depth**

  CP the existing pavement structure full depth from the roadway surface to the underlying granular base or subgrade.

- **Class V: Variable Depth**

  CP the existing pavement surface to a variable depth as shown on plans and/or specifications. Automatic grade and cross-slope controls may be required.

The CP specifications may refer to the various ARRA classes of milling which may be required on the project.

The section on materials is included to indicate who will own the reclaimed asphalt pavement (RAP) after it has been milled from the roadway. Ownership of the RAP will be either the contractor or the owner agency. When an owner agency retains ownership of the RAP they usually have subsequent specifications which indicate where the RAP is to be transported, how it is to be stockpiled, and what the maximum size of the largest RAP particle is permitted to be.

The section on equipment requirements contains a fair amount of detail and can be rather lengthy. It can include details for all equipment from the cold planer through to the cleaning/sweeping equipment. The specifications can include requirements for:

- age or operating condition of all equipment
- cold planer size/production capability
- removal of RAP from roadway surface/integral loading system of cold planer
- method for controlling dust generation
- automatic grade and slope controls on the cold planer
- sweeping or roadway cleaning equipment

In addition, requirements for pre-approval or acceptance of the equipment, particularly the cold planer, prior to use are sometimes included. The specifications may include the requirement for the proposed CP equipment to undertake a test or demonstration section in order for the owner agency to evaluate and approve the equipment, construction methodology, contractor, and/or workmanship. This is usually reserved for those projects in which the milled surface will be left as the driving surface.

Construction methods included in the specifications address such issues as:

- production plan indicating number and type of cold planers to be used, width and location of each milling pass, and the number and type of sweepers to be used
- type and location of traffic warning signs
- accommodation of traffic through the work zone
- weather limitations prior to and during CP
- lighting requirements for night work
- preliminary surface preparations
- protection of adjacent infrastructure and/or property from damage
- prevention of RAP from entering underground utilities
- direction of milling
- amount of water used during milling
- gradation requirements of the RAP
- striation pattern and/or surface texture

- changing of cutting tools
- loading of haul trucks and consequences of overloading
- grade and cross-slope requirements including use of independent, moving or fixed reference lines
- ramping requirements for longitudinal edge drop-offs
- ramping requirements for transverse and localized edges, i.e., valves, manholes, etc.
- cleaning of the milled surface
- opening area to traffic

With method specifications, the owner agency is in control of the construction process and therefore needs to have sufficient inspection during the CP operations. The owner agency personnel on the project have to have the experience to evaluate the milled surface and authority to make field adjustments to the CP process.

The specifications sometimes outline the frequency of sampling and the testing methods that will be used, particularly if the owner agency is to use the RAP. Wherever possible, these should be published industry standards, such as American Association of State Highway and Transportation Officials (AASHTO) or American Society for Testing and Materials (ASTM) methods or the owner agency's own adaptation of these procedures. With method specifications, the QC and QA testing are usually one and the same and increased inspection is used to control the CP process.

A section of the specifications outlining the acceptance requirements for the CP work is also included. The acceptance requirements include such things as:

- milling depth and width
- gradation of the RAP
- surface texture
- grade and slope requirements
- surface smoothness

Some of these are obviously end result requirements but are included in the method specifications for CP.

The final section deals with measurement and payment issues. The specifications usually outline how items will be measured such as:

- mobilization/demobilization
- surface preparation prior to CP
- CP of existing pavement
- removal and/or hauling of the RAP
- cleaning of the milled surface
- traffic control

In addition, the specifications indicate what is to be included in each of the payment items.

Mobilization/demobilization is more commonly being included as a specific payment item. Some specifications fix the amount/lump sum or limit it to a percentage of the total contract price.

Other specifications require that mobilization/demobilization be included as part of the other payment items.

Surface preparation, usually by sweeping, prior to the start of the CP process is normally included in the CP compensation. It could be paid for by the square yard (square meter) of surface area on specific projects.

Compensation for CP can be by the cubic yard (cubic meter) or ton (tonne) of RAP milled from the roadway or more commonly by the square yard (square meter) for a specified treatment depth. In all cases, the payment is for the final treatment volume, weight or surface area independent of the number of passes needed to mill a given area, and regardless of the hardness/condition of material being milled.

Removal and/or hauling the RAP is usually included within the compensation for CP. However, when the owner agency retains ownership of the RAP and requires that it be hauled a significant distance to a stockpile site, a hauling/trucking payment item may be used.

Traffic accommodation is also generally included in the CP compensation but can be a separate payment item particularly for higher traffic roadways with specific requirements.

Special Provisions, appended to the CP specifications, are used to indicate specific project requirements such as:

- limits of work
- construction schedule, staging or limitation on hours of work
- trucking requirements
- particular traffic accommodation requirements
- interaction and cooperation with other contractors
- parking and storage of equipment
- any other site-specific requirements

9.2 SPECIFICATION LIMITS

Specifications typically include limits and/or tolerances on a number of physical properties related to CP a pavement surface and could include some or all of the following:

- milling depth
- gradation of the RAP
- surface texture
- grade and cross-slope
- smoothness

Milling depth(s) are typically indicated on the plans or in the specifications. Some variation in milling depth is to be expected, particularly when improvements to grade, cross-slope and smoothness are to be made with CP. Usually the specifications indicate milling is to depths indicated by the owner agency. For specific application such as milling and inlay paving, a tolerance of plus or minus a given amount from the design thickness is allowed. A value such as +/- 3/16 inch (5 mm) could be specified or milling depth tolerance can also be specified as a percentage of the design milling depth such as +/- 10 percent.

Regardless of the method of indicating the tolerance, specifications usually indicate that the milling depth should not be uniformly high or uniformly low.

The gradation or sizing of the RAP can be somewhat controlled by adjusting how the cold planer is being operated. There are physical and economic limits on how fine the existing pavement can be milled with a cold planer.

The surface texture of the milled surface is usually specified in terms of visual appearance. Some agencies are assessing the use of different types of test methods, such as a sand patch test, infrared imagery, or road profiler methods as a way of quantifying the surface texture of the milled surface.

Typically, the milled surface texture is to be a grid-patterned surface with uniform discontinuous longitudinal striations or other similar pattern which has not been torn, gouged or otherwise injured during the milling operation. It is possible to “out run” the cutting drum if the forward speed of the cold planer is to fast compared to the rotational speed of the cutting drum. To maintain an acceptable standard of quality, the ratio of forward speed to cutting drum rotational speed could be specified.

Other specifications attempt to quantify the surface texture by indicating the number of striations produced for each cutting tool for a given longitudinal length, the number of striations in the transverse direction, the maximum dimension between the adjacent striations and/or the maximum depth of the striations. When the dimensions of the striations are used in the specifications, the maximum distance between adjacent striations is usually specified to be a maximum of 3/4 inch (20 mm) and the maximum depth as 3/16 inch (5 mm). The dimensions of the striations may decrease somewhat if micro milling is being specified.

The grade and cross-slope are specified by the owner agency and are checked using precision survey, stringline, and/or straightedge level. Usually the tolerance from grade and cross-slope is around +/- 3/16 inch (5 mm) or if specified as a percentage +/- 10 percent.

Smoothness of the milled surface has traditionally been specified by a straightedge requirement. Typically, this has been +/- 3/16 inch (5 mm) for a 10 foot (3 meter) straightedge. Alternatively, some specifications indicate that a longer stringline be used with maximum variations not exceeding +/- 5/16 inch (8 mm) for a 25 foot (7.5 meter) stringline. If bumps or dips are noted these are usually required to be corrected, so they meet the specified tolerance.

There is a trend towards specifying smoothness in terms of overall ride quality for projects in which CP is being used to prepare the roadway for a thin lift of HMA, a chip seal or similar surface treatment or that will be left as the driving surface. Two approaches are beginning to be used by owner agencies to specify the smoothness of the milled surface. One approach is to determine the roadway smoothness prior to milling, using a conventional measuring device such as a California Profilograph, Mays Ride meter or similar device. After the roadway has been milled, the smoothness is again checked with the same device. The specifications indicate the required percentage improvement in ride quality from before milling to after milling. The other method is to measure the smoothness of the roadway after it has been milled and to specify that it must achieve a maximum value or index for ride quality. A higher percent increase in smoothness or a lower maximum smoothness index is used for interstate roadways and/or for projects in which the milled surface will be left as the driving surface. Incentive payments are usually included for milled surfaces that are smoother than the limits specified.

When choosing the appropriate limits for overall smoothness for both of the approaches noted above, the required texture of the milled surface must be taken into consideration.

9.3 INSPECTION, QUALITY CONTROL AND QUALITY ASSURANCE

The inspection and QC/QA plan used for CP need to be developed based on the CP application and then amended for the specific type of equipment being used on the particular project.

During the CP process the areas of concern that the owner agency/contractor QC/QA plan may need to address include:

- milling depth
- RAP moisture content
- surface texture
- grade and cross-slope
- smoothness

To ensure that the automatic grade controls are working correctly on the cold planer, the milling depth needs to be physically measured. Depth measurements should be performed on a regular basis by measurements at the outside of the cut.

When required the maximum particle size and moisture content of the RAP should be checked periodically. Samples of the RAP are obtained from the discharge conveyor belt and tested. Care must be taken to ensure that representative samples of the RAP are obtained and tested.

Surface texture is assessed both visually and by taking a number of measurements of the striations and then averaging them to determine whether the specifications are being achieved.

Grade, cross-slope, and smoothness are checked based on what is required in the specifications. A number of locations should be checked and then averaged in order to arrive at a representative result.

CHAPTER 10: FULL DEPTH RECLAMATION – DETAILED PROJECT ANALYSIS

Through the project evaluation, economic analysis and preliminary selection process, outlined in Chapter 3, the potential rehabilitation alternatives were narrowed down to one specific technique. The next step in the rehabilitation design is the detailed project analysis which will lead directly into the final project design, advertising, tendering or letting, and construction.

The Hot Mix Asphalt (HMA) overlay, hot recycling, and reconstruction rehabilitation methods will not be addressed since they are routinely used by all agencies. The rehabilitation techniques of Cold Planing (CP), Hot In-Place Recycling (HIR), and Cold Recycling (CR), are covered in depth in other chapters. It is recognized that many of the steps in the detailed project analysis are common to all the rehabilitation methods but are addressed in each process, for continuity.

10.0 FULL DEPTH RECLAMATION REHABILITATION

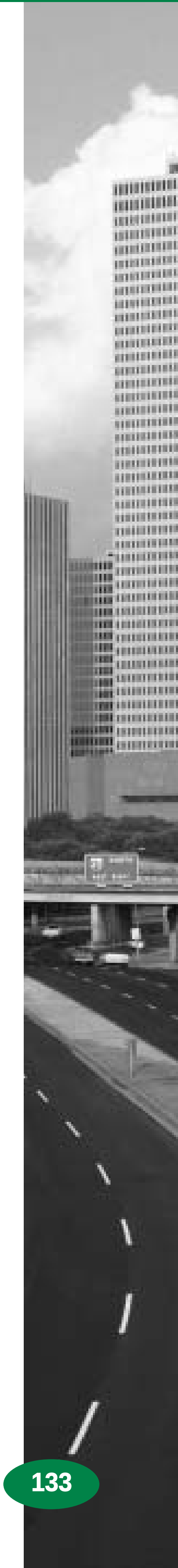
FDR is the rehabilitation technique in which the full thickness of the asphalt pavement and a predetermined portion of the underlying materials (base, subbase, and/or subgrade) is uniformly pulverized and blended to provide an upgraded, homogeneous material. Often this blend of material alone, without any additional stabilizing additives, is sufficient to act as the base for a new surface course. However, if after proper project evaluation it is determined that the reclaimed materials need improvement or modification, there are three different types of stabilization that can be used:

- mechanical
- chemical
- bituminous

Mechanical stabilization is achieved with the addition of granular materials such as virgin aggregate or recycled materials such as reclaimed asphalt pavement (RAP) or crushed Portland cement concrete. Chemical stabilization is achieved with the addition of lime, Portland cement, fly ash, lime or cement kiln dust, calcium/magnesium chloride or various proprietary chemical products. Bituminous stabilization is accomplished with the use of liquid asphalt, asphalt emulsion, and/or foamed (expanded) asphalt. For increased stabilization requirements, combinations of all three can also be used.

Pavement distresses which can be treated by FDR include:

- cracking in the form of age, fatigue, edge, slippage, block, longitudinal, reflection, and discontinuity
- reduced ride quality due to swells, bumps, sags, and depressions
- permanent deformations in the form of rutting, corrugations, and shoving
- loss of bonding between pavement layers and stripping
- loss of surface integrity due to raveling, potholes, and bleeding
- excessive shoulder drop off
- inadequate structural capacity



Pavements that have extensive distortion or deterioration due to subgrade or drainage problems are candidates for FDR only when additional work is undertaken to correct the subgrade and drainage deficiencies. To correct subgrade problems the reclaimed material typically is moved to one side, the subgrade is reworked or stabilized with an additive and then the reclaimed material is placed back on the prepared subgrade.

The expected design life, performance requirements during the design life, and acceptable future maintenance requirements are related to the treatment depth of the FDR, the types and amount of stabilizing agents used, and on the type and depth of the subsequent wearing course.

10.1 HISTORIC INFORMATION ASSESSMENT

In the detailed review of historic or existing information the data contained in the Pavement Management Systems (PMS) which needs to be assessed includes:

- age of the roadway including any surface treatments
- past condition surveys in order to assess the rate of pavement deterioration
- type of asphalt binder used in the asphalt pavement layers
- thickness of the existing asphalt pavement and underlying granular materials
- top size of aggregates used in the asphalt pavement layers and underlying granular materials
- presence of any paving fabrics or interlayers within the asphalt pavement. Some paving fabrics are very difficult to recycle with FDR and the presence of an interlayer may need to be assessed further, depending on its characteristic and location
- presence of exotic or specialty mixes, such as Open Graded Drainage Layers, Open Graded Friction Courses, Stone Matrix Asphalt, etc. which may have an effect on the selection of granular materials and on the type and amount of stabilizing agent(s) used

The detailed review of existing information contained in a maintenance database which needs to be assessed includes:

- patching locations and ages
- patching material including HMA, cold mix asphalt, injection spray patching, etc.
- crack sealing activities, product types and ages

The detailed review of the existing Quality Control/Quality Assurance (QC/QA) information, from construction of all asphalt pavement layers, includes:

- asphalt binder content
- aggregate gradation, angularity, flat/elongated particles, and/or petrographic analysis
- field compaction

In addition, existing QC/QA information, from construction of all granular base and sub-base layers, should be reviewed, including:

- aggregate gradation, angularity, flat/elongated particles, and/or petrographic analysis
- field compaction

Figure 10-1: Candidate for FDR Treatment

10.2 PAVEMENT ASSESSMENT

In the detailed pavement assessment, the type, severity, and frequency of the pavement distress which needs to be corrected is determined. The FDR process destroys the existing asphalt pavement cracks and deterioration since the entire asphalt bound layer is pulverized to produce an improved, homogeneous granular material on which a new pavement structure can be placed.

The presence of large or frequent surface patches increases the variability of the existing materials which will have an effect on the consistency of the reclaimed material. Large/deep patches may require their own specific mix design since they are usually newer and of different materials than the original pavement. Patching may also indicate locations of thinner pavement structures, higher groundwater conditions or poor subgrades which may need to be corrected as part of the roadway rehabilitation.

Rutting in the form of wear rutting is easily treated with FDR but it can usually be treated more economically with one of the other recycling methods.

Instability rutting can also be corrected with FDR if the appropriate stabilizing agent(s) and/or granular material are selected and designed into the process. Structural rutting, provided it is not originating in a very weak/wet subgrade, can be addressed with FDR and then selecting the appropriate thickness of HMA as the wearing course. If structural rutting is a result of a very weak or wet subgrade, the pavement structure can be pulverized and moved to one side, the deficient subgrade can then be stabilized or removed and replaced, the pulverized material can be moved back, and the FDR process completed.

10.3 STRUCTURAL CAPACITY ASSESSMENT

Two aspects of the structural capacity assessment need to be addressed. The first aspect is to determine what structural capacity is required for the anticipated traffic during the design life of the rehabilitation using conventional pavement design methods. If a mechanistic-empirical pavement design method is used to determine the required overall pavement structure, the structural layer coefficient of a FDR mix typically ranges from 0.15 to 0.40 with an average value of about 0.20. The range in structural layer coefficient value is related to the amount and types of stabilizing agents used. Each agency will have to determine an appropriate structural layer coefficient typical of the FDR mixes used in their jurisdiction.

Reclaimed mixes which have had lime, Portland cement or Class C fly ash added, in addition to a bituminous stabilizing agent typically have significantly higher initial strength values and slightly higher long-term strengths, compared to reclaimed mixes stabilized with bituminous materials only. These mixes also tend to be stiffer and consequently are less flexible than reclaimed mixes modified with a bituminous stabilizing agent only.

FDR mixes modified with a combination of a bituminous stabilizing agent and either lime, Portland cement or Type C fly ash are significantly more resistant to moisture damage initially, than mixes stabilized with only bitumen. However, mixes with only a bitumen stabilizing agent achieve very similar long-term moisture damage resistance results.

The second aspect is the ability of the underlying subgrade to provide sufficient support so that adequate compaction of the reclaimed mix can take place. The FDR equipment is considerably lighter and smaller than CIR equipment, and generally uses high floatation tires, so that equipment break-through is not usually an issue. However, if the underlying subgrade does not provide enough support, excessive deflection will occur and adequate compaction cannot take place. Weak, wet or deflecting subgrades will require improvement or stabilization in order to ensure that adequate compaction of the reclaimed mix is achieved, otherwise a significant drop in strength and performance will be noted.

The two most useful methods of assessing the load-carrying capacity of the existing subgrade are Dynamic Cone Penetrometer (DCP) and Falling Weight Deflectometer (FWD) testing. With the DCP, the underlying materials can be assessed by coring/drilling through the asphalt pavement layers to expose the granular base/sub-base and subgrade materials. Obviously, if water has been used in the coring operation, the resultant moisture may effect the DCP values of the upper portion of the underlying materials. Assessment of the load-carrying capacity is usually conducted at the same locations that samples of the asphalt pavement, for material property assessment, are obtained. However, for weak and/or thin pavement structures, additional DCP testing should be conducted to more fully assess the load-carrying capacity and/or isolate weak areas. This is critical since the consequence of lower compaction is usually a significant reduction in the performance of the FDR material.

DCP results will change throughout the year in response to changes in base and subgrade moisture conditions. The DCP results should ideally be obtained when the moisture conditions in subgrade will be similar to those at the time of FDR construction. If this is not possible, then an adjustment of the DCP evaluation criteria, to account for the differences in moisture contents from the time of testing to time of construction, will need to be made. Each agency will need to establish its own DCP blow count profile vs. feasibility of FDR construction evaluation criteria, since it will be sensitive to material types, soil and groundwater conditions.

The FWD can also be used to assess the load-carrying capacity of the existing subgrade by back-calculating the subgrade resilient modulus. Other parameters such as the base damage index and/or base curvature index can be determined from the deflection bowl measurements produced by the FWD. As with the DCP testing, each agency will have to establish its own evaluation criteria based on their local conditions.

10.4 MATERIAL PROPERTIES ASSESSMENT

Utilizing the results of the existing information review and the pavement assessment, the project is divided into areas/segments of similar materials or performance. A field sampling plan is then established utilizing either fixed interval or random sampling methods to determine the location of the field samples. Samples should be obtained at a frequency of approximately one location per 800 to 1600 feet (250 to 500 meters) or more often, if changing conditions warrant.

Field samples can be obtained by means of either wet or dry coring, usually 6 inches (150 mm) in diameter, and then crushing the cores in the laboratory. Field coring and laboratory crushing of the recovered asphalt pavement produces sample gradations that more closely resemble what is achieved in the field during the FDR process. Block sampling of the asphalt pavement materials by means of sawing and then excavating a test pit to expose, sample and test the underlying materials can also be used, but it is usually more expensive than coring, takes longer and has a significant impact on traffic. Test pits have the benefit that larger, more representative samples, particularly of the granular base materials, can be obtained.

The frequency of field sampling varies with the size of the project, size of the areas of similar materials or performance, and the variability of the existing materials, as determined from the review of existing QC/QA data. Generally, the number of sample locations ranges from 1 to 3 for smaller, consistent areas, to 20 or more for larger, less consistent areas. The number of cores obtained at each field sampling location will depend on the number of field sample locations, the amount of laboratory testing to be performed, whether or not samples will be needed for subsequent FDR mix designs, and what type of mix design method will be used. If a modified Proctor/Marshall mix design method is used the total number of cores will depend on the anticipated FDR treatment depth and core diameter. Typically, approximately 110 pounds (50 kilograms) of the asphalt pavement and underlying granular base material is required for each mix design. If the effects of additional stabilizing agents are to be assessed, then more material will be required.

The core samples should be carefully examined, throughout their full depth, in order to detect the different pavement layers, previous surface treatments, interlayers, geotextile paving fabrics, specialty mixes, evidence of stripping, friable or disintegrating mix, retention of excessive moisture, and any tendency to delaminate. Once the cores have been inspected, the observations recorded, and selected cores photographed, the cores are crushed. Representative samples are then tested to determine:

- moisture content (if dry coring has been used)
- gradation of the crushed RAP
- asphalt binder content, if an asphalt emulsion is to be used as a stabilizing agent

- aggregate properties including gradation, angularity, etc.
- recovered asphalt binder properties including penetration, absolute and/or kinematic viscosity if an asphalt emulsion is to be used as a stabilizing agent

In addition, the granular base or subgrade material will need to be sampled in the field for the depth that will be included in the FDR process. Representative samples are then tested to determine:

- moisture content (if dry coring has been used)
- gradation and angularity
- Plasticity Index
- sand equivalent value

The combined gradation of the RAP and granular base is calculated using the relative proportions of each that will be used in the FDR process.

The above information will assist in the estimation of the type and amount of stabilizing agent(s) to be used, and in determining whether a granular material is needed to improve the RAP characteristics.

10.5 GEOMETRIC ASSESSMENT

In the detailed geometric assessment determine whether the project:

- requires major realignment, widening or drainage corrections
- contains underground utilities/drainage structures
- requires upgrading of any underground utilities
- needs longitudinal/grade corrections
- requires cross-slope/fall corrections.

Major realignment, widening or drainage corrections are easily accommodated in the FDR process since the existing asphalt pavement is totally pulverized and blended with all or part of the underlying granular material. FDR facilitates the reuse of the existing pavement materials within the construction site, with or without the addition of stabilization/modification agent(s).

FDR has been successfully used on projects where existing granular shoulder has been paved in the rehabilitation process. In order to be successful, the existing shoulder area has to: have sufficient granular material; have good subgrade conditions; the appropriate stabilizing agent(s) selected; and have a HMA wearing course of sufficient thickness.

The presence, frequency, and elevation of utility covers (manholes and valves) need to be assessed, particularly in the urban setting. Manholes and valves should be lowered at least 4 inches (100 mm) below the FDR treatment depth and their locations accurately recorded. Manholes should be covered with a sufficiently thick steel plate and the excavation backfilled with RAP or granular base. Treatment of the roadway should take place in an uninterrupted manner so that the FDR depth and material consistency can be maintained. After placement of the subsequent wearing course, the manholes and valves are located, neatly excavated, and raised to the appropriate level of the wearing course to provide a smooth profile. Obviously, if any upgrading of the existing underground utilities is required, it should be undertaken prior to rehabilitating the roadway surface.

The width of the roadway to be treated is of primary importance since it will dictate the number of pulverization passes or “cuts” which will have to be made by the reclaimer in order to cover the full width. Reclaimers are of fixed width, typically between 6 to 12 feet (1.8 to 3.7 meters) wide which can result in different amounts of overlap between cuts, depending on required treatment width. Overlaps between adjacent passes are usually about 4 inches (100 mm). The location of the existing roadway crown will influence the number of passes since crowned roadways should be treated in half-widths, to ensure a uniform treatment depth across the crown. The location of the longitudinal overlays should avoid the outer wheelpath area, if possible. Tapers for turning bays, acceleration and deceleration lanes are usually treated first. Care should be taken to ensure that double application of any stabilizing agent being used does not occur in the overlap areas.

The FDR equipment is very mobile and maneuverable so roadway geometry, even in an urban setting, has little influence upon the types of areas which can be treated. Roadways containing “T” intersections can be treated all the way to the top of the “T.” Paved driveways and other entrances, mailbox pullouts, and other short and narrow areas in the roadway can normally be treated, as well.

The FDR process can correct most longitudinal and transverse profile deficiencies prior to placement of the wearing course. However, if the existing pavement profile is severely defective, one of the following corrective operations may be required to ensure uniform treatment depths:

- If the existing asphalt pavement is of sufficient thickness, cold plane the roadway to correct the profile deficiencies prior to FDR or remove excess material after the pulverizing pass.
- Add either virgin aggregate or RAP from an external source prior to the FDR process, particularly for thinner pavement structures,
- Correct as much of the profile deficiencies as possible with the FDR process and then correct the remaining profile deficiencies with additional wearing course material.

10.6 TRAFFIC ASSESSMENT

Originally, FDR was used on low to medium traffic volume roadways because there was no effective way to pulverize the thicker pavements usually found in high-volume roadways. However, with the newer/larger equipment available, FDR is now being used on higher traffic volume roadways, as well. There is no upper limit to roadway traffic volumes provided a pavement structural design is undertaken as part of the rehabilitation process, to ensure that the effects of future traffic is accounted for.

The FDR process minimizes traffic disruptions and user inconvenience due to the short construction time—compared to conventional pavement reconstruction methods and the ability to keep one-half of the roadway open during construction. If possible, it is advantageous to completely detour traffic to other roadways since this will permit the full width of the road to be treated at one time. FDR can be undertaken in off peak hours to further reduce the traffic disruptions but this results in reduced daily productivity and increased costs.

Depending on the width of the existing roadway the FDR operation will usually occupy one-half the width of the roadway at a time. For narrow roadways, accommodation of large/wide truck or oversized loads will need to be addressed.

On two lane roadways, one-way traffic through the construction zone will need to be maintained with appropriate traffic control such as flag people, lane demarcation devices and/or pilot vehicles. Very narrow two lane roadways increase the difficulties for traffic accommodation, particularly if there is little or no paved shoulder.

Traffic control at intersections and at business approaches also needs to be addressed in an urban environment. Due to the speed of the FDR processes the intersections and approaches are not out of service for very long and traffic is usually controlled with flag people and lane demarcation devices.

10.7 CONSTRUCTABILITY ASSESSMENT

As the FDR equipment is relatively light and highly maneuverable, overnight parking or storage of the equipment is usually not a concern. Typically, 4,750 to 9,500 square yards (4,000 to 8,000 square meters) can be completed in a day.

Clear span heights for bridges and underpasses must be checked for not only the FDR equipment but for any haul trucks, as well.

Generally, FDR equipment can process to the edge of a curb and gutter section. For straight-faced concrete sections (with no gutter), a portion of roadway will have to be removed with smaller equipment in order that the area can be fully treated.

The underlying granular materials must be free of oversized rocks and boulders so that damage to the reclaimer does not occur. The maximum aggregate size of the underlying granular materials will need to be less than the maximum particle size permitted in the reclaimed mix.

If granular material is required in the FDR process, then the availability of aggregates of suitable gradation and quality must also be assessed.

10.8 ENVIRONMENTAL IMPLICATIONS

Areas that are extensively shaded receive little or no direct sunlight to assist in the breaking and initial curing of bituminous stabilizing agents, and therefore, take longer to cure and compact. Similar curing conditions/problems can occur if the work is being undertaken in cold, damp conditions typical of early spring, late fall, or winter weather, where there are pavement areas with poor drainage or higher than average moisture content. In these types of conditions, the use of an additional stabilizing agent such as lime, Portland cement or Type C fly ash usually reduces the curing period, and accelerates the strength gain sufficiently to permit the areas to be opened to light traffic within a couple of hours.

FDR should not be undertaken if it is raining or if rain is imminent, since rain dilute the bituminous stabilizing agent and reduce the effectiveness of dry stabilizing agents spread on the surface—resulting in reduced reclaimed mix strength. Similarly, work is usually not undertaken in excessively foggy or humid conditions that can result in longer curing times for the bituminous stabilizing agent.

As with all rehabilitation construction projects, there will be a certain amount of noise associated with the process. Typically, due to the speed of the HIR operation and the transient nature of the process, the noise effects will be short term. This issue will have increased concerns in an urban setting.

10.9 ECONOMIC ASSESSMENT

The expected service lives of the various FDR rehabilitation techniques, when undertaking a life-cycle economic analysis, generally fall within the following ranges:

- FDR with surface treatment . . . . .7 - 10 years
- FDR with HMA overlay . . . . .up to 20* years

Note: * Equivalent to agency's new construction service life.

The effectiveness and performance of the various FDR rehabilitation techniques varies from agency to agency and is dependent on:

- local conditions
- climate
- traffic
- type of technique and quality of materials used
- quality of the workmanship

CHAPTER 11: FULL DEPTH RECLAMATION – MIX DESIGN

Like Hot In-Place Recycling (HIR) and Cold Recycling (CR), there is no nationally accepted method for undertaking a Full Depth Reclamation (FDR) mix design. A number of different FDR mix design methods have been used by various agencies but not many of these mix design methods have been reported in the literature.

When FDR is used as part of the rehabilitation strategy, it is intended to eliminate the existing pavement distresses, to reuse the existing materials, and to create a stronger, higher load-carrying base for the roadway. To increase the reclaimed materials load-carrying capability, stabilizing agent(s) are often added to improve its:

- strength
- durability
- moisture susceptibility

Stabilizing agent(s) can be:

- **mechanical** in the form of particle interlock with the addition of granular materials such as virgin aggregates, Reclaimed Asphalt Pavement (RAP), and/or crushed/reclaimed Portland cement concrete
- **chemical** in the form of calcium chloride, magnesium chloride, lime (hydrated or quicklime), fly ash (type C or F), kiln dust (cement/CKD or lime/LKD), Portland cement (dry or slurry) or other chemical products
- **bituminous** in the form of an asphalt emulsion, emulsified recycling agent or as a foamed/expanded asphalt
- **combination** of two or more of the above

Regardless of the type or number of stabilizing agents used, a laboratory mix design needs to be undertaken in order to optimize the quantity of stabilizing agent and the physical properties of the reclaimed mix. It must also be recognized that the mix design process cannot definitively model what will happen in the field at the time of construction. Therefore, the mix design represents the best possible starting point but field adjustments must be expected. Field adjustments are made based on Quality Control/Quality Assurance (QC/QA) test results and on the workability of the reclaimed mix.

Using the results of the Detailed Project Analysis, as discussed in Chapter 10, the design engineer will determine what type of stabilization mechanism, agent or combination of stabilizing mechanisms and agents, should be assessed.

The results of the historical, structural capacity, and material property assessments will indicate whether pulverization of the existing pavement structure will be adequate. In some cases, additional mechanical stabilization, in the form of additional granular materials, may be required. The amount and gradation of the granular materials will depend on the existing roadway conditions and properties of the reclaimed material. The reclaimed material and any granular materials which have been added will act like an unbound granular base in the rehabilitated pavement structure.

If pulverization or mechanical stabilization alone or if the addition of granular materials cannot be used because of economics or is restricted due to roadway geometry and additional strengthening is required, then chemical or bituminous stabilization may have to be used. There are no hard and fast rules with respect to the selection of a stabilizing mechanism or modification agent(s) but the choice of which stabilizing mechanism and modification agent(s) to use is a function of the:

- thickness of the existing pavement structure
- reclaimed material properties
- amount of strengthening/modification required
- availability of stabilizing agent(s)
- previous experience of the owner agency and local contractors
- economics

A wide range of bituminous and chemical stabilizing agents are currently available and are used to improve the physical properties and/or water resistance of the reclaimed materials. For specific reclaimed materials, some stabilizing agents are more effective and economic than others are but for other reclaimed materials, different stabilizing agents may be more effective and economic. Each type of stabilizing agent has its place in the FDR process or for specific rehabilitation strategies.

The most common chemical stabilization method is with the use of cementitious stabilizing agents including Portland cement, lime, type C fly ash, and/or blends of these materials. The primary function of these stabilizing agents is to increase strength of the reclaimed material by cementing the particles together. In addition, the lime component of Portland cement, fly ash, and calcium oxide (CaO) reacts with the clay particles in the reclaimed materials, reducing its plasticity. Typically, Portland cement is limited to reclaimed materials in which the Plasticity Index is less than 10. If the Plasticity Index of the reclaimed material is in excess of 10, then lime is more often used.

The amount of strength gain is primarily related to the amount of cementitious stabilizing agent added to the reclaimed material. It is noted that more is not necessarily better, since reclaimed materials treated with a cementitious stabilizing agent tend to become a more rigid or brittle material. Increasing the amount of cementitious stabilizing agent increases the rigidity of the reclaimed mix with an associated reduction in fatigue properties and an increase in the amount/severity of the associated shrinkage cracking. The amount of shrinkage cracking associated with cementitious materials can be mitigated by:

- keeping the application content as low as possible, but consistent with the mix design
- compacting the reclaimed mix below the Optimum Moisture Content (OMC) or 75 percent saturation
- reducing or controlling the rate of drying of the reclaimed mix

Therefore, it is important that the physical properties or performance requirements of the chemically stabilized reclaimed mix be linked to the overall pavement design.

The use of bituminous stabilizing agents in the form of asphalt emulsion or foamed (expanded) asphalt has increased due to recent technological advances. Reclaimed materials stabilized with bitumen produces a flexible material with better fatigue properties, compared to those treated with cementitious stabilizing agents. Bituminous stabilized mixes have no shrinkage cracking and can be opened to traffic sooner than cementitious treated mixes. FDR with a bituminous stabilizing agent, creates a bituminous stabilized material not HMA, so it has a higher void content of between 10 and 20 percent. The bituminous stabilized material tends to act partly as a granular material with inter-particle friction and partly as a visco-elastic material capable of handling repeated tensile stresses.

Some bituminous stabilizing agents can be used with marginal reclaimed materials but the stabilized mixes are sometimes susceptible to moisture effects. Moisture sensitivity can be addressed with the addition of small amounts of cementitious materials usually Portland cement, lime or Type C fly ash in combination with the bituminous stabilizing agent. Typically, the addition of 1 to 3 percent by weight of reclaimed material, can significantly increase in retained strength or moisture resistance without adversely affecting the fatigue properties of the reclaimed mix. The addition of small amounts of cementitious materials also acts as a catalyst to increase the strength gain of the stabilized reclaimed mix. This can provide an additional enhancement during construction since the roadway can be opened to traffic sooner. Hence, it is becoming common practice to use Portland cement or lime in conjunction with bituminous stabilizing agents, particularly if the reclaimed materials are of marginal quality.

Asphalt emulsions were developed in order to overcome the difficulties of mixing hot asphalt binders with cold, damp materials. An asphalt emulsion consists of an asphalt binder, water, and emulsifying agent(s). On occasion, the asphalt emulsion may contain other additives such as stabilizing agents, coating improvers, anti-stripping agents, break control agents or polymers. Since asphalt binder and water do not readily mix, the object is to make a dispersion of asphalt binder in water that is stable enough for pumping, prolonged storage, and mixing. The asphalt emulsion should “break” or the asphalt binder should separate from the water within an acceptable period after contact with the recycled materials. Upon curing, the remaining or residual asphalt retains all of the adhesion, durability, and water resistance of the asphalt binder from which the asphalt emulsion was originally produced.

The primary reason for using an asphalt emulsion as a stabilizing agent is to make it possible to mix the asphalt bitumen with the cold, moist, reclaimed material. Mixing of the reclaimed materials with the asphalt emulsion is the first step, since the ultimate goal is to have a bitumen-bounded reclaimed mix. For this to occur, the asphalt binder must break out of suspension in order to act as the stabilizer or “glue” which holds the reclaimed materials together. The chemistry of both the asphalt emulsion and the reclaimed materials has a major influence on the stability and “breaking-time” of the asphalt emulsion. Therefore, it is important to confirm the compatibility of the asphalt emulsion with the reclaimed materials during the mix design.

Foamed asphalt can also be used as the bituminous stabilizing agent but with a more defined type of reclaimed material. For foamed asphalt to be successful, the reclaimed materials need to fall within more controlled gradation and Plasticity Index limits, and may require the addition of fines.

Foaming occurs when a small amount of cold water is introduced into a very hot asphalt binder. The water causes the asphalt binder to expand very rapidly into millions of bubbles resulting in a “froth” or foam. The foamed asphalt is well suited for mixing with cold, moist materials. In the foamed state, the asphalt binder’s viscosity is greatly reduced and its surface area is greatly increased, enabling it to be readily dispersed throughout the reclaimed materials.

The potential for using foamed asphalt as a bituminous stabilizing agent was first realized by Professor Ladis Csanyi at the Engineering Experimental Station of Iowa State University in 1956/57, using a steam injection process to make the foam. The technology was subsequently refined and patented by the Mobil Oil Company, which developed the first expansion chamber—where atomized water was mixed with the hot asphalt binder to produce the foam. Since the expiration of the original patent in the early 1990's, additional technological development and a significant increase in use of the foamed asphalt process has occurred worldwide.

Unlike HMA, reclaimed materials stabilized with foamed asphalt are not black in color. This is because the coarser aggregate particles are not coated and are usually free of bitumen. When foamed asphalt comes into contact with the reclaimed materials, the bitumen bubbles burst into millions of tiny "globules" that seek out and adhere to the fine particles, specifically the minus No. 200 (0.075 millimeter) fraction. This preferential attraction to the fine particles creates a bitumen bound filler that acts as a mortar binding the coarse particles together. This results in only a slight darkening of the reclaimed mix.

The main advantages of using foamed asphalt as the bituminous stabilizing agent are:

- reclaimed materials treated with foamed asphalt can be worked in a wider range of weather conditions
- reclaimed materials treated with foamed asphalt remain workable for a sufficient period of time to facilitate placement and compaction
- the road can be opened to traffic immediately after compaction to expedite construction

Similar to stabilization with asphalt emulsion, Portland cement or lime is can be added in small amounts with the foamed asphalt to accelerate the initial strength gain and improve the reclaimed mix's resistance to moisture effects.

When using an asphalt emulsion or a foamed asphalt it is also important to confirm the compatibility of the water used in the process.

11.1 MECHANICAL STABILIZATION MIX DESIGN

When pulverization, mixing, and densification of the reclaimed materials does not produce the required degree of structural support, improvements can be made with the addition of granular materials such as virgin aggregates, reclaimed granular materials or RAP. The amount of granular material that can be added will depend on the:

- gradation and physical properties of the reclaimed materials
- existing roadway geometry
- achievable mixing and compaction depths
- economics

If the reclaimed material is too coarse and clean for adequate compaction, then the granular material will have to be a sandier/finer material in order to produce a more uniformly graded material. Conversely, if the reclaimed material is too fine or has a high Plasticity Index, then a clean, granular material will be required.

Figure 11-1: Mechanical stabilization with RAP as additive

The existing roadway geometry, such as curb reveal heights, clear spans beneath overhead structures, width, and side slopes may limit the amount of granular material that can be added. The granular material will increase the thickness of the reclaimed materials and so must be accounted for in the overall design.

Modern reclaimers used in the FDR process can pulverize and mix existing pavement structures to significantly greater depths than can be readily densified in one lift with current compaction equipment. When the addition of the granular materials results in a layer thickness greater than can be densified in one lift, a portion of the reclaimed material will have to be moved to one side prior to the start of compaction. This impacts the overall costs and affects the economics of the project.

Once the amount and gradation of the granular material (if any) has been determined the mix design can proceed. The mix design consists of determining the appropriate moisture content to maximize the strength properties of the reclaimed mix through adequate densification and particle interlock. To determine the appropriate or OMC and corresponding Maximum Dry Density (MDD), common moisture-density test methods, such as the Standard or Modified Proctor or similar test methods are used.

If required, further strength testing on the reclaimed mix, compacted at the OMC, can be conducted. Strength testing methods include the California Bearing Ratio (CBR), Resilient Modulus or similar tests. The results of the strength testing are used to confirm the minimum strength properties of the reclaimed mix or used by the design engineer to determine the overall pavement structure required.

Figure 11-2: Chemical stabilization on rural roadway

11.2 CHEMICAL STABILIZATION MIX DESIGN

The same mix design process is used, regardless of the chemical stabilizing agent being considered, and generally consists of:

- determining the suitability of the reclaimed material
- establishing the proportions of reclaimed material, stabilizing agent, and water
- confirmation of the mechanical properties of the stabilized mix

In the first part of the mix design, the suitability of the reclaimed material for use as a chemically stabilized base course is assessed in a manner similar to what was required for mechanical stabilization, listed previously. The physical properties of the reclaimed material, primarily the gradation and Plasticity Index, are used to assess the need for granular material and to select a potential chemical stabilizing agent.

The second part of the mix design is the establishment of the proportions of reclaimed material, chemical stabilizing agent, and moisture content, by means of trial mixes. The initial trial mix proportions are established through trial and error or through experience. Typically, multiple chemical stabilizing agent application rates are assessed during the mix design. Experience with various chemical stabilization agents will help narrow the range of application rates required in the mix design. If a number of application rates are evaluated, the individual application rates are usually varied from each other by at least 1 percent.

For the given chemical stabilizing agent application rate, the OMC and MDD are established by common moisture-density test methods, such as the Standard or Modified Proctor or similar test.

In establishing the OMC and MDD, the mix design should attempt to model what happens in the field. During the mix design, the reclaimed material is brought to a moisture content similar to what will be encountered in the field. The chemical stabilizing agent is then added and preliminarily mixed into the reclaimed material. Additional moisture is added to give a range in total moisture contents and the combination is then thoroughly mixed. Typically, the moisture contents are varied by approximately 1 to 2 percent from each other. When the chemical stabilizing agent is a fluid or if it is being added in the form of a slurry, the moisture content of the chemical stabilizing agent/slurry must be accounted for in the mix design process. If not, the resultant reclaimed mix will be too wet to adequately compact.

Prior to compacting the samples, a laboratory curing period of between 2 to 4 hours is commonly used. This simulates the time during which the last of the field mixing and the initial grading of the reclaimed mix takes place in the field. During the curing period, the laboratory mixed samples are covered to prevent loss of moisture and are periodically mixed with a trowel or spatula.

At the end of the laboratory curing period, the samples are compacted following the moisture-density test method being used. An aliquot sample is used to determine the moisture content of the reclaimed mix at the time of compaction. Utilizing the compacted sample's wet weight, the moisture content, and the volume of the compaction mold, the dry density of the reclaimed mix can be determined. The data is then plotted on normal graph paper and the OMC and MDD are determined using conventional criteria.

The third and final part of the mix design process is to evaluate the strength and durability properties of the reclaimed mix. With chemically stabilized mixes this is usually done by determining the R-Value or unconfined compressive strength, although other strength tests, such as the Indirect Tensile Strength test could be used. To evaluate the strength properties of the reclaimed mix a number of specimens are prepared and compacted at the OMC and then cured under controlled conditions. Typically, the strength specimens are cured for 7 days at a relative humidity of 95 to 100 percent, at a temperature of between 72 to 77°F (22 to 25°C), although other curing times and temperatures can be used.

After compaction the strength specimens are carefully removed from the molds, placed on carrier plates, and then cured for the required time. The moisture content and dry density of the strength samples are usually determined to confirm the results of the moisture content-density test. With some chemical stabilizing agents and reclaimed materials, it may be necessary to leave the strength specimens in the molds for 24 hours in order to develop sufficient strength before removing them from the molds. Spilt molds may facilitate the removal of the specimens.

At the end of the required curing period, the samples are tested for their strength using the selected testing procedures. Typically, three strength specimens are tested at each chemical stabilizing agent application rate and the results averaged.

To determine the required chemical stabilizing agent application rate, the average strength results are plotted on normal graph paper versus application rate. The application rate that produces a strength in excess of the required minimum is selected. In selecting the required application rate of the chemical stabilizing agent, the data is reviewed and any obvious outliers are eliminated or retested.

After selection of the chemical stabilizing agent application rate, some owner agencies may require that the durability and moisture sensitivity of the stabilized reclaimed mix be verified. Established procedures for wet-dry, freeze-thaw or other similar tests are used to evaluate the durability and moisture sensitive of the stabilized reclaimed mix.

11.3 BITUMINOUS STABILIZATION MIX DESIGN

The bituminous stabilization mix design process varies somewhat depending on whether an asphalt emulsion or a foamed asphalt is used as the stabilizing agent. Regardless of which bituminous stabilizing agent is used, the mix design follows the same general outline consisting of:

- determining the suitability of the reclaimed material
- establishing the OMC and Optimum Fluid Content (OFC)
- determining the optimum bitumen content
- confirmation of the mechanical properties of the stabilized mix

For both asphalt emulsion and foamed asphalt, the first part of the mix design determines the suitability of the reclaimed material for use as a bituminous stabilized base course. A procedure similar to what was required for mechanical and/or chemical stabilization listed previously is used. The physical properties of the reclaimed material, primarily the gradation and Plasticity Index, are used to assess the need for granular material and to select a potential bituminous stabilizing agent.

The gradation requirements are more restrictive if foamed asphalt is to be used as the stabilizing agent. Reclaimed materials deficient in fines will not mix well with foamed asphalt. When reclaimed materials have insufficient fines, the foamed asphalt does not disperse properly and tends to form “stringers” or bitumen rich agglomerations of fines. These stringers will vary in size according to the fines deficiency, with a large deficiency of fines resulting in many large stringers. These stringers will tend to act as a lubricant and result in a reduction in strength and stability of the reclaimed mix. The reclaimed material should have between 5 and 15 percent passing the No. 200 (0.075 mm) sieve.

Sieve analysis results may indicate that a reclaimed material may have the appropriate amount of fines, but if the fines have a high Plasticity Index, they will act in a cohesive manner. The field performance of these high plasticity reclaimed materials has generally been poor. The cohesive nature of the fines causes them to bind together, thereby preventing the foamed asphalt from adequately coating and subsequently stabilizing the mix.

When it has been determined that an asphalt emulsion will be used as the bituminous stabilizing agent, the second part of the mix design is to establish the OFC. To do this, the sample of reclaimed material is oven dried to a constant mass and then cooled to room temperature. The OFC of the reclaimed material is determined using common moisture-density testing procedure such as the Standard of Modified Proctor or similar method. The fluid used in the moisture-density test is a combination of 50 percent asphalt emulsion and 50 percent water or a combination which will provide for the minimum amount of water needed for good asphalt emulsion coating. Typically, the fluid content is varied by 1 to 2 percent over a fairly wide range. The dry density of the reclaimed mix is determined for each fluid content, and the results are plotted on normal graph paper. The data should be reviewed for anomalies and any outliers disregarded or retested. The fluid content at which the dry density of the reclaimed mix is a maximum is defined as the OFC.

As noted previously, not all asphalt emulsions and reclaimed materials are compatible. As part of the asphalt emulsion mix design process, the compatibility of the asphalt emulsion and the reclaimed material must be verified. Compatibility is verified by mixing the proposed asphalt emulsion with the reclaimed material and assessing the degree of coating that is achieved. If a high percentage of the reclaimed material cannot be coated, in spite of adjustments in moisture and asphalt emulsion contents and intensive mixing, then an incompatibility exists and a different

Figure 11-3: Asphalt emulsion stabilization in urban setting

asphalt emulsion should be used. If adequate coating or cohesion is achieved in the mixing test, the compatibility of the reclaimed material and asphalt emulsion is further assessed by an adhesion test. In the adhesion test, a sample of the reclaimed mix is cured in a forced air oven. The oven cured mix is then placed in boiling, distilled water for a short period of time. After boiling, the mix is placed on a white absorbent paper and visually assessed for the amount of retained asphalt coating. If the degree of retained asphalt coating is not acceptable, a different asphalt emulsion needs to be used.

It is critical that the sample of asphalt emulsion used in the compatibility and adhesion tests be identical to the one that will be used in the field. Different emulsion suppliers commonly use different emulsifying agents and additives for the same grade of asphalt emulsion which may have an effect on compatibility.

The third step in the asphalt emulsion mix design is determining the optimum bitumen content. The optimum bitumen content is determined by adding a range of asphalt emulsion and water to oven dried samples of reclaimed material so that the previously determined OFC is maintained constant. The various combinations of asphalt emulsion and water are added to the reclaimed material and mixed thoroughly at room temperature. The Marshall, Hveem or other methods modified for cold mixes are used to form and compact the stabilized mix. The dry density of the compacted reclaimed mix is determined for each asphalt emulsion content tested. After compaction, the specimens are allowed to cure in the mold for 24 hours at room temperature. After 24 hours the samples are extruded from the molds and placed on a smooth, flat tray and cured for an additional 72 hours in a forced draft oven at 100°F (40°C), although other curing temperatures and times could also be used.

Figure 11-4: Foamed asphalt operation

When it has been determined that foamed asphalt will be used as the bituminous stabilizing agent, the second part of the mix design is to determine the foaming characteristics of the asphalt binder and to establish the OMC. The objective is to optimize the foaming properties of the asphalt binder by maximizing the expansion ratio and the half-life of the foamed asphalt by determining the percentage of water needed for a given asphalt binder temperature.

Foamed asphalt is characterized in terms of expansion ratio and half-life. The expansion ratio is defined as the ratio between the maximum volume achieved in the foamed state and the volume of the asphalt binder once the foam has completely subsided. The half-life is the time taken, in seconds, for the foamed asphalt to settle to half of the maximum volume attained. The foaming characteristics of a given asphalt binder are influenced by a number of variables, the most important of which are the:

- Temperature of the asphalt binder. The higher the asphalt binder temperature, the higher the foaming characteristics. Typically, the asphalt binder has to be hotter than 320°F (160°C).
- Amount of water added to the hot asphalt binder. Generally, the expansion ratio increases with increasing amounts of water but there is a corresponding decrease in the half-life. The amount of water added is generally 2 percent +/- 1 percent by weight of asphalt binder.
- Pressure under which the hot asphalt binder is injected into the expansion chamber. Low pressure, below 45 pounds per square inch (3 bars), decreases both the expansion and half-life.
- Proportion of asphaltenes in the asphalt binder. Generally, the greater the amount of asphaltenes, the poorer the foam,
- Presence of anti-foaming agents, such as silicone compounds, in the asphalt binder.

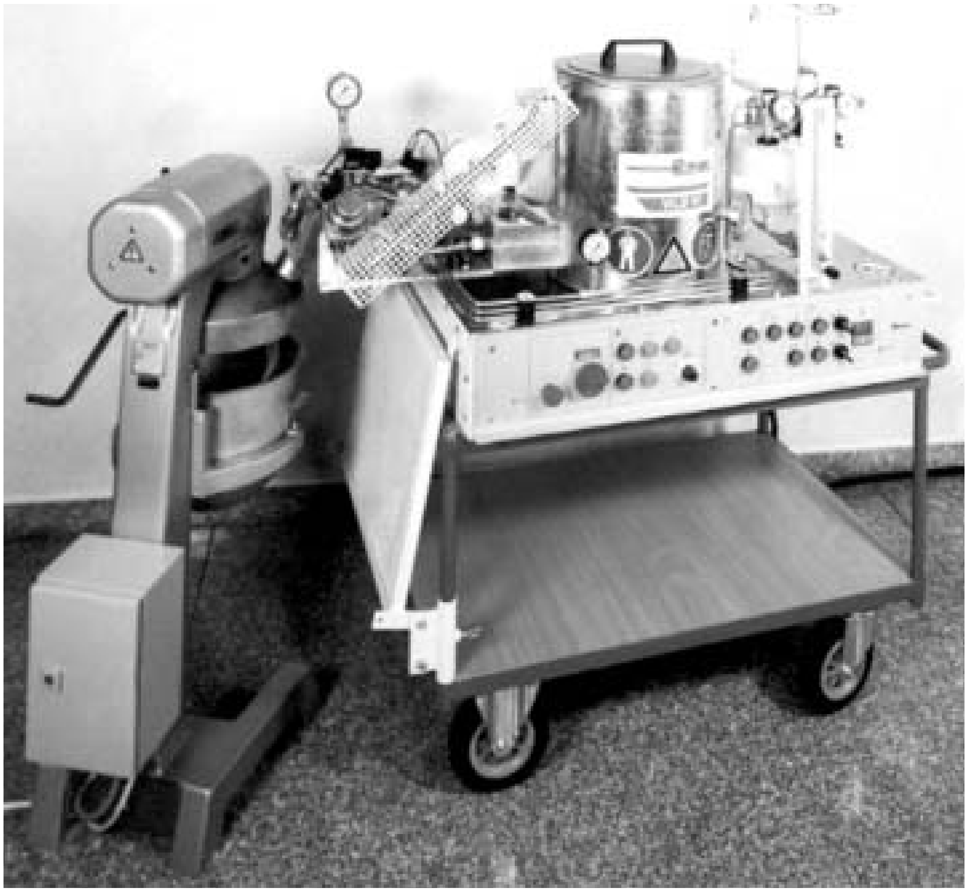


Figure 11-5: Laboratory Asphalt Foaming Plant

The ideal foamed asphalt is one which optimizes both the expansion and the half-life. In general, the better the foaming characteristics of the asphalt binder, the better will be the quality of the resulting mix. There are no absolute limits governing the foaming characteristics since large expansion ratios are obtained at the expense of the half-life and vice versa. Generally, a mix produced with a very high expansion or a very long half-life is of poorer quality than when both the expansion and half-life values are optimized. It is usually difficult to achieve an acceptable mix when the foaming characteristics are extremely poor, i.e., expansion less than 5 and half-life less than 5 seconds. An alternative source of asphalt binder or a foaming agent may be required if the foaming characteristics are not in excess of these minimums.

Softer asphalt binders generally have better foaming characteristics but the selection of asphalt binder grade is primarily related to the in-service temperatures of the bituminous stabilized mix. Harder asphalt binders, with penetrations less than 100, are generally used in hot climates. Use of softer asphalt binders should be verified by conducting comparative strength test on the stabilized mix.

To optimize the foaming characteristics, the expansion and half-life are determined for at least three asphalt binder temperatures and a range of water contents from 1 to 5 percent by weight of asphalt binder. This requires the use of a small laboratory plant as indicated in Figure 11-5, such as the Wirtgen WLB-10 or similar, to produce the foamed asphalt. It is critical that this equipment closely simulates the foamed asphalt used during construction. The results of expansion ratio and the half-life versus the water content for the three asphalt binder temperatures tested are plotted on normal graph paper. From this plot, the combination of asphalt binder temperature and water content which maximizes the expansion ratio at the longest possible half-life time, is selected for use.

The OMC for the reclaimed material is established, as indicated previously, with water as the compaction fluid.

The third step in the foamed asphalt mix design, is determining the optimum bitumen content. Samples of the reclaimed material are oven dried and cooled to room temperature and then re-wetted to 90 percent of the previously determined OMC. A range of foamed asphalt is then added to the reclaimed material and mixed thoroughly at room temperature. The Marshall, Hveem or other methods modified for cold mixes are subsequently used to form and compact the stabilized mixes. The dry density of the compacted mix is determined for each foamed asphalt content tested. After compaction, the specimens are allowed to cure in the mold for 24 hours at room temperature. The samples are then extruded from the molds and placed on a smooth, flat tray and cured for an additional 72 hours in a forced draft oven at 100°F (40°C), although other curing temperatures and times could also be used.

The fourth and final part of both the asphalt emulsion and foamed asphalt mix design process is to evaluate the strength and moisture sensitivity properties of the stabilized mix. With bituminous stabilized materials, this is usually done by determining the Marshall Stability, Hveem Stability or Indirect Tensile Strength, although other strength tests could be used. The samples, previously prepared and cured, are tested at 77°F (25°C). To assess the moisture sensitivity of the bituminous stabilized mix, companion samples to those tested in the dry state are soaked in water prior to testing. The traditional method is to soak the samples in 77°F (25°C) water for 24 hours prior to testing although vacuum saturation for shorter soaking times can also be used. At the completion of the water-soaking period, the specimens are surface dried and tested for strength using the same procedure as for the dry samples. A comparison of the strength after water soaking to the dry strength is made which determines the moisture sensitivity of the bituminous stabilized reclaimed mix.

The test results are plotted on normal graph paper with the test result on the ordinate axis and the bitumen content on the abscissa. The bitumen content at which the soaked strength is a maximum is defined as the Design Bitumen Content (DBC) provided the minimum moisture sensitivity value is exceeded. Where required, additional tests such as the resilient modulus, dynamic creep, etc., are performed on the cured stabilized reclaimed mix, at the DBC. The results of these tests can be used in empirical-mechanistic design methods to determine the required bituminous stabilized base thickness and overall pavement structure.

11.4 COMBINED STABILIZATION MIX DESIGN

Combined stabilization mix designs will usually consist of a combination of the chemical and bituminous mix design methods. Mechanical stabilization is incorporated into both the chemical and bituminous mix design methods when the decision whether or not to use a granular material is made. The most common combined stabilization method is to use a cementitious stabilizing agent such as lime or Portland cement with a bituminous stabilizing agent. As indicated previously, the cementitious stabilizing agent, when added in small quantities, accelerates the strength gain and enhances the moisture resistance of the bituminous stabilized mix.

Figure 11-6: Bituminous stabilization operation with cement slurry (combination stabilization)

The same mix design process is used, regardless of the cementitious stabilizing agent being considered, and generally consists of:

- determining the suitability of the reclaimed material
- selecting the percentage of cementitious stabilizing agent to be added
- determining the OMC and/or OFC
- establishing the optimum bitumen content
- confirmation of the mechanical properties of the stabilized reclaimed mix

In the first part of the combined stabilization mix design, the suitability of the reclaimed material follows the procedures outlined previously in the bituminous stabilization mix design method.

If an asphalt emulsion is to be used as the bituminous stabilizing agent the cementitious stabilizing agent is added and mixed into the reclaimed material immediately prior to the introduction of the blend of asphalt emulsion and water. The method for determining the OFC and the optimum bitumen content, as given previously, are then followed.

If a foamed asphalt is to be used, then the cementitious stabilizing agent is added to the reclaimed material during the determination of the OMC. The cementitious stabilizing agent is also added and mixed into the moist reclaimed material immediately prior to the introduction of the foamed asphalt in the determination of the optimum bitumen content procedures given previously.

The combined stabilized mix must also be checked for stiffness or fatigue properties since the addition of the cementitious stabilizing agent increases the rigidity of the reclaimed mix.

The cementitious stabilizing agent content should be high enough to improve the durability/moisture sensitivity of the reclaimed mix, but not so high as to cause the reclaimed mix to lose the visco-elastic properties of a bituminous stabilized mix. The Marshall flow or other similar property is used to assess the cementitious stabilizing agent content. There is a minimum amount of cementitious stabilizing agent that can be practically added in the field. This minimum amount varies depending on whether it is being added as a dry powder or as a slurry. The addition of the cementitious stabilizing agent increases the cost of the FDR, so there is an economic benefit to using only the minimum necessary.

CHAPTER 12: FULL DEPTH RECLAMATION – CONSTRUCTION

Reclamation of paved roadways has historically been undertaken by scarifying the existing asphalt bound layers with rippers attached to motor graders or crawler tractors. The ripping process produced large blocks of asphalt pavement which were subsequently reduced to smaller, more manageable sizes by travelling hammer mills, grid rollers or similar equipment.

The development of rotary mixers in the 1950's enhanced sizing of the previously ripped asphalt pavement and increased productivity. The mixing equipment increased steadily in size over the years, but generally, the asphalt pavement had to be ripped since the rotary mixers could not effectively or efficiently pulverize an un-ripped pavement.

The development and widespread use of cold planing machines and the ease in which they removed and sized asphalt pavements, led to the production of large, self-propelled, high horse-powered reclaimers, as indicated in Figure 12-1.

These reclaimers were equipped with specialty designed cutting drums equipped with replaceable tungsten carbide tipped cutting tools which allowed the reclaimers to pulverize and mix the asphalt pavement without it first being ripped into large chunks. This development significantly increased production and facilitated sizing and mixing of the existing asphalt pavement and resulted in FDR, as it is known today.

Figure 12-1: Modern FDR reclaimer

In FDR, all of the asphalt bound layers are pulverized and mixed with some or all of the underlying granular base, subbase or subgrade materials. The decision on how much of the underlying granular base to mix with the pulverized asphalt layers depends on the:

- thickness of the asphalt layers relative to the granular base, subbase or subgrade thickness
- gradation/physical properties of the pulverized asphalt layers
- gradation/physical properties of the granular material
- type and condition of the underlying subgrade soils
- whether or not a stabilizing agent(s) will be used
- desired end result of the FDR process

In any event, some portion of the underlying material must be incorporated during the pulverization of the asphalt layers. This is to prevent:

- excessive wear of the cutting tools
- significant reduction in productivity
- corresponding increase in costs

During pulverization, the cutting drum rotates in an "up-cut" or opposite to the forward direction of travel of the reclaimer, as indicated in Figure 12-2. The up-cut rotation is required so that the cutting tools are cooled as they move through the underlying, moist materials, to enhance pulverization, and to assist in sizing of the reclaimed materials. Incorporating a minimum of 1 inch (25 mm) of underlying granular material is a good rule of thumb. When there is unsuitable material directly below the asphalt layer, the specifications may require that the pulverization depth be kept even with the bottom of the asphalt layer. If the asphalt layer is not penetrated by the cutting drum, the drum is prone to bouncing. This results in a variable depth of pulverization, decreased productivity, increased cutting tool wear, and increased reclaimer maintenance.

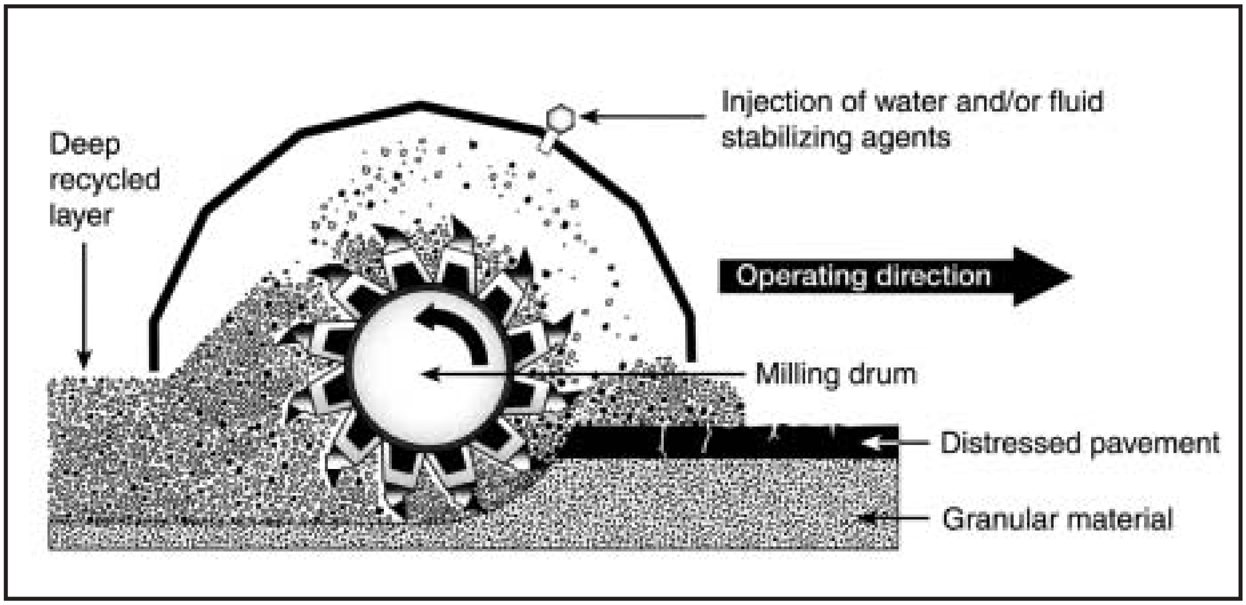


Figure 12-2: Cutting drum operating in up-cutting direction

Some common preparatory measures should be undertaken prior to FDR. These include:

- detailed safety or hazard assessment
- development of a detailed traffic control plan
- repair of any areas with drainage problems
- repair of any subgrade failure area unless chemical stabilization has been specified
- detailed project analysis, as outlined in Chapter 12
- preparation of a mix design, as outlined in Chapter 13

The equipment used to undertake FDR will vary from contractor to contractor but no matter what the FDR train looks like, it is required to perform the same general steps, including:

- pulverization and sizing of the existing asphalt bound layers
- incorporation and mixing of the underlying granular base, subbase or subgrade soil
- application of mechanical, chemical, bituminous or combination stabilizing agent(s), if required
- mixing of the reclaimed materials and stabilizing agent(s)
- initial or breakdown compaction
- rough grading or initial shaping
- intermediate compaction
- intermediate shaping
- final compaction
- final trimming or “tight blading”
- removal of all loose material
- curing
- application of seal or wearing course

12.1 FDR EQUIPMENT

The FDR process does not require a large amount of equipment, most of which is normally used in roadway construction. The minimum equipment required in the FDR process is a:

- modern, self-propelled reclaimer
- motor grader
- one or more compactors

For more complex FDR projects including the application of stabilizing agent(s), the additional construction equipment could include some or all of the following:

- end or bottom dump haul trucks
- windrow sizer or calibrated aggregate spreader
- water truck complete with spray bar
- calibrated bulk spreader for dry stabilizing agents
- mixer and tankers for slurry application of stabilizing agents

Figure 12-3: Reclaiming Operation

- asphalt emulsion tanker(s) and distributor truck
- computerized liquid or foamed asphalt additive system on the reclaimer
- front end loader

A variety of different reclaimers are available to pulverize and mix the reclaimed materials and it is the essential piece of equipment in the FDR process. Most reclaimers have an 8 foot (2.4 meter) wide cutting drum, while extensions can be added to some models of reclaimers to increase the cutting drum width to 12 feet (3.7 meters). The reclaimer should have the capability to pulverize and mix a minimum of 12 inches (300 mm) of asphalt pavement and underlying materials. The cutter drum should be equipped with replaceable tungsten carbide tipped cutting tools and have both manual and automatic depth control capabilities. The cutting drum should be capable of being rotated at a number of different speeds for pulverizing and mixing a variety of material thicknesses and types. The orientation of the cutting tools is typically in a chevron pattern which promotes mixing as opposed to a helical pattern found on cold planing machines which is intended to move the material to the center of the cutting drum. The chevron pattern of the cutting tools minimizes lateral movement of the reclaimed material, leaving it ready to be struck off by the bottom edge of the rear door on the mixing chamber. The propulsion system should have a load sensing mechanism to automatically control the forward speed of the reclaimer.

Some reclaimers have four-wheel drive and/or four-wheel steering to improve traction and maneuverability. Others have the ability to operate in both directions. This feature means that the cutter drum can be operated in the up-cut direction for pulverization and in both the up-cut and

Figure 12-4: Dry stabilizing agent being spread prior to FDR

the opposite down-cut direction for subsequent mixing. In reality, the cutter drum always rotates in the same direction, it is the reclaimer which operates in a reverse direction.

Haul trucks will be required to provide any granular material required to:

- increase the thickness of the layer to be processed
- modify the gradation of the reclaimed material
- provide additional mechanical stabilization

Some means of accurately controlling the addition rate of the granular material is required. Haul trucks may also be required to move any excess reclaimed mix after the final tight blading and compaction has been completed.

Typically, the reclaimed material is not at the optimum moisture content (OMC) for compaction. Either aeration will be required to dry the reclaimed material or, more often, moisture will have to be added. A water truck can act as a supply truck to the reclaimer's onboard liquid additive system or it can be equipped with a spray bar to add moisture directly to the reclaimed material. Additional moisture can be added during pulverization by the reclaimer or after pulverization in order to better assess the amount which needs to be added. The water truck should be equipped with a pump/metering system and a spray bar with nozzles if it is to be used to add moisture directly to the reclaimed material. A water distributor truck may also be required to periodically add a fine spray of moisture for curing, particularly if cementitious stabilizing agent(s) are used.

Figure 12-5: Motor grader blading FDR mix

When the stabilizing agent is added in dry powder form, a calibrated bulk spreader will be needed, as indicated in Figure 12-4. Dry stabilizing agents can be added prior to pulverization of the asphalt layers or they can be added after pulverization and prior to the mixing pass of the reclaimer. Dry stabilizing agents are more susceptible to environmental effects such as wind and rain showers. Care must be taken in order not to create an excessive dust cloud during placement and mixing of dry stabilizing agents.

When the stabilizing agent is a liquid or is being added as a slurry, supply tankers will be required. A “nurse” truck or means of connecting the tanker to the reclaimer is required if the liquid is being added by the reclaimer, as was indicated previously in Figure 1-16. If stabilizing agents in liquid or slurry form are to be added by the reclaimer, it needs to have a computerized onboard liquid addition system. The on-board additive system should be equipped with a meter capable of recording the rate of flow and total amount of each liquid being added to the reclaimed material. It should also have a positive interlock system linked to the forward speed of the reclaimer so that the amount of liquid stabilizing agent being added will change according to the operational speed of the reclaimer.

When foamed asphalt is being used as the stabilizing agent, the reclaimer will need to be equipped with a computerized on-board foam generating system. It must also have a heated asphalt binder surge tank, a storage tank for the water used in the foaming process, and some means of producing and injecting the foamed asphalt into the reclaimed material. The computerized system should be able to adjust the amount of foamed asphalt being added relative to the forward speed of the reclaimer and to the volume of reclaimed material being processed.

A motor grader is used to spread and shape the reclaimed mix after the reclaimer has completed all the mixing passes, as indicated in Figure 12-5.

Figure 12-6: Compaction of FDR mix

If the reclaimed material is above the OMC, the motor grader will be used to help aerate the material. When the depth of reclaimed mix is too thick to be adequately compacted, the motor grader will move a portion of the reclaimed mix to one side to permit compaction of the lower lifts.

The number and type of compactors used on a FDR project will depend on:

- specified degree of compaction required
- material properties of the reclaimed mix
- thickness of the reclaimed mix
- support characteristics of the underlying subgrade
- type of wearing surface to be used
- productivity required

Vibratory padfoot, vibratory smooth drum, pneumatic, and static steel rollers can be used for compaction, as indicated in Figure 12-6.

Due to the thickness and material properties of the reclaimed mix, the rollers used are typically large and heavy. Large pneumatic, vibratory smooth drum or padfoot rollers may be used for initial compaction. Intermediate compaction is typically undertaken with a pneumatic roller, while finishing rolling is performed with a vibrating smooth drum or static steel roller.

The large pneumatic roller can also be used to proof roll the reclaimed area to identify weak areas in the subgrade which need replacement.

A skid steer or small rubber tire loader is used to remove any excess material after tight blading. Excess material can be used to fill in low areas in the roadway ahead of the reclaimer.

12.2 PREPARATION AND PLANNING

Some preliminary preparation and planning activities are required prior to the start of the FDR process. These activities are intended to improve the uniformity of the reclaimed mix since stopping the FDR train results in discontinuities in the finished product. Discontinuities in the reclaimed mix, similar to discontinuities in other construction operations like Hot Mix Asphalt (HMA) paving can create areas of potential weakness and should be avoided whenever possible. The preliminary activities are also intended to result in better equipment utilization and increased productivity.

The Detailed Project Analysis, as indicated in Chapter 10, will have identified many of the preliminary activities. However, field verification immediately prior to construction provides an independent check which reduces the risk that something unexpected will occur.

Identification of buried utilities, abandoned rail or streetcar lines, manholes, valves and other castings should be undertaken prior to the start of FDR. These fixtures are usually identified from existing plans but a field magnetic/metal detector or Ground Penetrating Radar (GPR) survey should be undertaken. If solid, buried obstructions are encountered during the pulverization or mixing passes of the reclaimer, damage to the cutting tools, cutting tool holders, cutting drum, and under particularly adverse conditions even to the drive mechanism, can result. The associated down time, inconvenience to the public, and repair costs can be extensive. In addition, shallow buried utilities have a habit of moving from where they are located on the plans. A serious safety hazard can be created if the buried utility is not correctly located, including depth, particularly if the buried utility happens to be a high-pressure gas line or something similar.

In the case of manholes, valves and other roadway castings, these are lowered to at least 4 inches (100 mm) below the anticipated FDR treatment depth a day or more in advance. They are reinstated to the proper grade after completion of the FDR process, prior to or after the wearing surface has been placed. Other buried items are removed, relocated or buried below the FDR treatment depth, depending on the specifics of the project.

When the FDR process is undertaken in an urban setting it is sometimes necessary to cold plane some of the existing asphalt material prior to pulverizing the roadway. Cold planing is usually undertaken in order to maintain existing roadway surface elevations, thereby eliminating the costs associated with adjusting concrete curbs, drainage, and other facilities. The existing roadway has to be checked, particularly at the curb lines, to ensure that the upper portion of asphalt pavement can be removed without compromising the overall strength of the pavement structure. It is also wise to check the condition of the underlying granular base materials in the areas to be cold planed, to ensure they are of sufficient thickness, as well. Obviously, if an area is cold planed the reduction in asphalt bound material will have to be accounted for in the mix design process, particularly if a stabilizing agent is being used.

Roadways that are very distorted or out of shape, both longitudinally and transversely, should be corrected (if possible) prior to the start of the FDR process. This is to ensure that the thickness of the reclaimed mix is consistent both laterally and longitudinally after tight blading has been performed by the motor grader. Shape corrections include adjustments to cross-slope, superelevation, elimination of localized bumps and dips, and gradeline adjustments for heaves or settlements. Pre-shaping is intended to establish the final surface shape of the roadway, thereby ensuring the geometric integrity of the reclaimed area.

Prior to the start of the FDR process, it is important to develop a plan that encompasses the various steps, operations, and issues which need to be undertaken or addressed. The plan should consider the:

- specification requirements
- roadway geometrics
- traffic accommodation during construction
- condition/properties of existing materials
- behavior of reclaimed mix
- restrictions on opening roadway to traffic
- production rates

A review of the project specifications needs to be undertaken in order to determine:

- treatment depth, widths, and project limits
- type and amount, if any, of granular material and/or stabilizing agent(s) to be added
- degree of compaction
- disposal of surplus materials
- curing requirements
- surface texture, smoothness, and tolerances

Roadway geometrics, particularly width, will influence the number of passes of the reclaimer required to treat the full width of the road. In addition, the existing surface shape, i.e., crowned or cross-slope, will influence the positioning of the longitudinal joints between adjacent passes. The longitudinal joint, for roadways with a pronounced crown, is at or slightly offset from the crown. If the crown of the existing roadway has flattened, the need to have adjacent passes near the crown is reduced. Tapered sections for acceleration/deceleration lanes, turning bays or passing lanes must also be considered when setting out the location of the various passes. Typically, these areas are processed first, and double processing in the transition areas is inevitable. Care must be taken to ensure that any stabilizing agent(s) are added only once and, usually, when the main area is being processed.

Existing traffic, in terms of total volume and amount of heavy vehicles and how it will be handled during construction, will also influence the way work is laid out. Limitations on working hours and access requirements to adjacent properties will also impact the work. Compared to other reconstruction methods, FDR has significantly less impact on public traffic due to the high production rates and the ability to keep one-half of the roadway open during construction. If possible, it is advantageous to completely detour traffic to other roadways since this will permit the full width of the road to be treated at one time. If traffic must be maintained, one-half of the width can be treated while maintaining one-way traffic on the other half of the road. Obviously, if traffic is to be maintained the work zone must be adequately identified with temporary warning signs, delineators, flag people, and/or pilot vehicles. Poor signage and traffic control can lead to unsafe conditions and major disruptions on the site.

The condition or properties of the existing roadway materials have an influence on project planning. The consistency of the asphalt bound materials, in terms of thickness and intactness, significantly influences the production of the reclaimer. The moisture condition of the underlying materials will also influence production if aeration or additional moisture is required. The variability of the materials will have an influence on the application rates of any stabilizing agent(s), degree of compaction, and properties of the reclaimed mix.

The properties of the reclaimed mix influence how it should be placed, compacted and finished. The reclaimed mix properties dictate the type and length of curing required before the roadway can be opened to traffic and will also influence the type and timing of the wearing course placement.

Restrictions which dictate when traffic can use a section of reclaimed roadway will differ depending on the stabilizing agent(s) used and owner agencies' policies with respect to surface condition of the reclaimed mix or placement of the wearing course.

Typically, cementitious stabilizing agents require a period of moist curing so that they do not dry out and develop excessive shrinkage cracks. Moist curing could consist of periodic applications of moisture or placement of a temporary seal coat. If proper placement, compaction, and curing procedures are followed, light traffic can be allowed on the reclaimed mix without adversely effecting it.

For asphalt emulsion stabilization, the curing time will depend on the:

- type and quality of the asphalt emulsion
- moisture content of the reclaimed mix during compaction
- degree of compaction achieved or voids content of the reclaimed mix
- aggregate type including gradation and absorption properties
- amount of cement or lime added
- ambient conditions

The curing time could be as short as a few days or as long as a few months. Light traffic can be allowed on asphalt emulsion stabilized mixes shortly after final compaction has taken place.

Foamed asphalt stabilized mix can be opened to light traffic immediately after the completion of the compaction process. Foamed asphalt stabilized mix can be reworked without adversely affecting its ultimate strength, provided the moisture content is maintained at the same level as at the time of compaction. However, if the reclaimed mix is allowed to dry, reworking will significantly reduce its ultimate strength.

During the curing period, no matter what stabilizing agent has been used, heavy truck traffic should be restricted or at least limited, since the reclaimed mix is still developing strength. Excessive early heavy truck traffic may induce flexural or fatigue cracking which can lead to premature failure of the reclaimed mix.

Production rates, in order to meet construction schedules, will influence both the project planning and the type of equipment used on the project. In order to maximize the effectiveness of the construction equipment, the project is usually undertaken in sections. Ideally, these sections should be the full roadway width which can be processed in one working day. If required, a section could be the half the roadway width that can be processed in one working day, although this is less desirable. Processing half roadway widths can create problems for overnight traffic due to the differences in surface textures and in matching the joints when the second half of the roadway is processed. With the section approach, the total distance which can be processed in one day is divided into approximately 1/4 mile (400 meter) segments. The first pulverization pass of the reclaimer is along the outer edge of the roadway for the segment distance. The second pulverization pass is back to the starting point along the opposite outer edge of the roadway segment. The third and subsequent pulverization passes are inside the previous passes until the complete roadway width is pulverized. If no mixing passes of the reclaimer are required, it then moves to the next segment to begin the first pulverization pass. As soon as the reclaimer starts work on the next segment, the rollers begin the compaction process and the motor grader begins shaping the reclaimed material in the first segment. In this way, the equipment advances from one segment to the next, in two to three hour increments, until the daily section length has been completed.

The working speed of the reclaimer has the greatest influence in determining the length of section which can be processed in one day, and consequently the length of each segment. The working speed of the reclaimer is affected by:

- thickness of the asphalt layer
- hardness of the asphalt layer
- thickness of the underlying materials being incorporated into the reclaimed material
- top size, gradation, and density of the underlying materials
- gradation requirements of the reclaimed material
- production capabilities of the reclaimer

If stabilizing agent(s) are being added to the reclaimed material, more than one pass of the reclaimer is usually required. It may be possible to add the stabilizing agent(s) during the pulverization pass. However, on some projects may require the stabilizing agent(s) to be added during a second pass of the reclaimer in order to maintain a more consistent working speed obtaining a more accurate and uniform application of the stabilizing agent(s). On larger projects, utilizing more than one reclaimer, one for pulverization and a second for adding the stabilizing agent(s) and mixing, will significantly increase the overall production rates.

Since FDR is a high production, fast-track process, logistics need to be addressed in the planning process. To ensure that the reclaimed mix is uniform and productivity remains high, the project has to be continuously supplied with the necessary materials such as stabilizing agent(s), granular materials, and compaction water. Daily requirements for these materials need to be determined in advance and procedures need to be in place to see that they are supplied without interruption. On large projects or when supply lines are long, temporary storage facilities near the project are established to protect against supply delays and to increase production.

12.3 PULVERIZATION

The preferred way to start the very first pulverization pass of an asphalt surfaced roadway is to have the reclaimer make a preliminary cut from the roadway shoulder perpendicular to the direction of the succeeding passes. The cutting drum is lowered into the softer shoulder material, reducing cutting tool wear, and provides a vertical butt-joint in the pavement to work and compact against. Where this is not possible, the alternative is to line the reclaimer along one edge of the first segment and slowly grind through the asphalt surface and into the underlying materials. This method causes accelerated cutting tool wear, and some bouncing of the cutting drum can be experienced when the asphalt layer is thick and/or hard. If the reclaimer is allowed to creep forward very slowly while cutting through the asphalt pavement a reduction in the bouncing of the cutting drum may be noticed.

Figure 12-7: Reclaiming operation

To align the reclaimer longitudinally and to prevent strips of unpulverized materials being left between adjacent passes, a clear guide for the operator should be given. Typically, this entails painting guide marks on the existing pavement or by stringing a line which is easy to follow. With an experienced operator, only the first pass needs to be marked out since the previous pass is followed on subsequent passes.

Roadway and reclaimer widths do not normally match, and several passes are required to pulverize the roadway treatment width. This results in a series of longitudinal joints and some overlap between passes is usually required. Therefore, only the first pass will be the full width of the reclaimer, with the width of subsequent passes being reduced by the amount of the overlap. The minimum overlap width is normally 4 inches (100 mm) but this is sometimes increased to take into account:

- treatment depths in excess of 12 inches (300 mm)
- coarseness of the reclaimed materials
- type of stabilizing agent(s) being used
- time lapse between adjacent passes

The width of the overlap generally is increased with: increasing layer thickness; reclaimed material coarseness; when working with cementitious stabilizing agent(s) and; where the first pass was made more than twelve hours before the adjacent pass, particularly when using stabilizing agent(s).

With the size and horsepower of modern reclaimers, the need to rip the asphalt pavement in front of the reclaimer has been eliminated in all but very isolated instances. These could include very thick asphalt layers or very stiff asphalt pavements due to excessive oxidation hardening or low ambient temperatures. There is no standard or rule of thumb for the optimum size of the chunks that should be left after ripping.

The treatment depth or “depth of cut” is determined by the specifications in accordance with the desired finished product of the reclaimed mix. When the specified depth of cut requires the cutting drum to be kept at the bottom of the asphalt layer due to unsuitable material below, the condition of the cutting tools needs to be checked more often. This is due to the accelerated wear that may occur since the cutting tools are not cooled by the underlying granular material. The depth of cut can be controlled manually or automatically through the reclaimers on-board sensing systems. On most reclaimers, the depth of cut can also be controlled on each side of the cutting drum.

Depending on the opening of the rear door of the reclaimer’s pulverization/mix chamber and the materials being pulverized, the reclaimed material will be “bulked” or “fluffed” up and will be higher than the original pavement surface. As the rear tires of the reclaimer ride up on this fluffed up material the cutting drum may rise and the processing depth should be verified at this point. In addition, if the reclaimer is making subsequent mixing passes of the pulverized material, the mixing depth will be influenced by the amount of bulking that has taken place.

The gradation of the reclaimed material should be checked after pulverization to ensure it corresponds to the gradation used in the mix design. It is neither necessary, practical, nor economical to pulverize the existing asphalt layer to the maximum aggregate size used in the original HMA or underlying materials. Reclaimers are not crushers and will not reduce the pavement layers to sizes smaller than the original aggregates.

The gradation of the reclaimed material can be controlled by the operation of the reclaimer. The gradation of the reclaimed material is influenced by the:

- front and/or rear door opening on the pulverization/mixing chamber
- position and/or breaker bar setting of the pulverization/mixing chamber
- rotation speed of the cutting drum
- forward speed of the reclaimer
- condition of the existing pavement
- ambient temperature

The more the rear door is closed, the longer the pulverized material is retained inside the pulverization/mixing chamber. This increases the number of contacts with the cutting tools and the breaker bar under the hood of the pulverization/mixing chamber. This allows the larger chunks of asphalt pavement and underlying agglomerates to be broken down. The maximum size of the reclaimed material will be larger than the maximum aggregate size of the existing aggregates but it will be the smallest when the rear door is opened very little. It is important to remember that the existing material fluffs after being pulverized due to the increase in void content, and so the rear door cannot be completely closed.

The closer the breaker bar is to the cutting drum, the finer will be the gradation of the reclaimed material.

A lower cutting drum rotation speed, the one with the most torque, is typically used when pulverizing thick lifts of asphalt layers or when mixing dense granular base materials with the pulverized asphalt layers. A faster rotation speed is used when working with light or medium pavement thicknesses. The fastest cutting drum rotation speed is used when pulverizing very thin asphalt layers or for mixing passes.

A slow forward speed of the reclaimer means that as each cutting tool hits the existing material it dislodges or pulverizes a small piece of material. Generally, the slower the forward speed of the reclaimer, the finer the gradation of the reclaimed material.

When the existing asphalt layers are cracked and/or alligator cracking is present, sizing of the reclaimed material is more difficult. The cutting drum, operating in an up cut direction, tends to lift or flip up the asphalt layer in large chunks instead of being ground off or pulverized by the cutting drum. These large chunks of pavement are harder to size than if they had remained in place. Several operational techniques can be used in order to maintain the required size of the reclaimed material, including:

- reducing the forward operating speed
- increasing the cutter drum rotation speed
- reducing the rear door opening
- raising the cutting drum to the bottom of the asphalt layer

Reducing forward speed, increasing cutting drum rotation and closing the rear door will increase the number of impacts within the pulverization/mixing chamber, so the material has a greater chance of being broken down to the correct size. Raising the cutting drum reduces the angle of approach for the cutting tools to a more horizontal impact and there will be less of a tendency to flip up or dislodge chunks of asphalt. This will require that a second mixing pass be undertaken to ensure the full treatment depth has been achieved.

The physical properties of the asphalt layer are affected by the ambient temperature. If the pavement is cool, the asphalt layer is very stiff but also very brittle, and can be pulverized into small pieces. As the temperature of the asphalt layer increases, it becomes more plastic, and the risk of “slabbing” increases. Slabbing occurs when the asphalt layer lifts or breaks off in large chunks in front of the cutting drum and must be handled as noted previously. Typically, the most efficient temperature for sizing of the reclaimed material is between 50 and 90°F (10 and 30°C).

The reclaimed material tends to migrate down-slope when the reclaimer is operating on a cross-slope or superelevation. This phenomenon becomes more apparent, the greater the cross-slope and the thinner the treatment depth becomes. A motor grader is used to blade the reclaimed material back into place before the adjacent pass is made with the reclaimer thereby maintaining the roadway shape and ensuring an adequate longitudinal joint.

The up-cut rotation of the cutting drum tends to bury the larger pieces of reclaimed material at the bottom of the treatment depth. Likewise, a down cutting rotation of the cutting drum, as can occur during a mixing pass, tends to lift the larger pieces of reclaimed material to the top of the treated area. This must also be accounted for when adjusting the operation of the reclaimer for the proper sizing of the reclaimed material.

The occasional oversized chunk of asphalt pavement can elude pulverization. It is more economical to have these picked up and placed in front of the reclaimer for further reduction, than to make an additional pulverization pass with the reclaimer.

Figure 12-8: Reclamation of commercial/industrial site

12.4 MIXING AND PLACEMENT

When additional pulverization or mixing passes are required to obtain the required gradation or to increase uniformity, the reclaimed material should be lightly compacted and reshaped. This is required to more accurately control the mixing depth, since the rear wheels of the reclaimer compact or reduce the thickness of the fluffed up reclaimed material during the pulverization pass. With light compaction and then reshaping, the reclaimed material will be uniform in thickness allowing the treatment depth to be better controlled. On most FDR projects, the most frequent error made during the mixing passes is incorporation of subgrade soil into the reclaimed mix by operating the cutting drum at too great of a depth. Care should be taken to ensure that the depth of the pulverization pass is between 1 and 2 inches (25 and 50 mm) less than the final mixing pass. This will reduce the risk of a thin layer of untreated reclaimed material being left beneath the stabilized layer.

Light compaction and reshaping also should be undertaken when stabilizing agent(s) are being added. The light compaction will provide a solid working platform for the reclaimer, water truck, and/or stabilizing agent tankers, allowing for a more consistent working speed. Reshaping will permit more accurate control of the treatment depth and application of the stabilizing agent(s).

Various types of modern reclaimers will place the pulverized and mixed reclaimed material in different ways. Most often, the cutting tools on the reclaimer's cutting drum are arranged in a chevron pattern to promote mixing. Lateral movement of the reclaimed material is minimal. The reclaimed material exits from the pulverization/mixing chamber rear door, spread across the width of the pass being struck off and smoothed out by the bottom edge of the rear door. The shape of this initial placement of the reclaimed material is dictated by the reclaimer since the rear door is attached to the pulverization/mixing chamber.

Reclaimed materials that do not require aeration to adjust moisture content may be spread to the required thickness immediately after mixing. Reclaimed materials that require aeration are generally formed into a windrow after mixing. As there is a tendency to leave a hump in the roadway when blade spreading from a centerline windrow, and to improve traffic accommodation, it is better to move the windrow to one side.

The motor grader is used to move and place the reclaimed material to the desired longitudinal grade and cross-slope. The amount of motor grader work required to place the reclaimed material will depend on the original shape of the roadway, the specified final shape of the roadway, and on the type of wearing surface which will be used. If a thick layer of HMA is to be used as the wearing course, the final or surface smoothness tolerance is usually larger than if a single surface treatment is to be used.

The motor grader should be used judiciously and be carefully supervised. Some reclaimed materials have coarse gradations, particularly for projects in which the asphalt layers were very thick and these materials can be easily segregated.

Some highway or airport projects with very tight surface tolerances may require the use of sonic or laser controls on the motor grader. For even tighter grade control, a grade trimmer or cold planer, equipped with automatic grade and slope controls, and using a mobile reference point/ski or fixed reference point/stringline, may be required.

At the end of the tight blading or trimming of the reclaimed surface, any excess material should be removed. Extreme care must be taken to ensure that shallow depressions are not filled with thin lenses of uncompacted reclaimed materials which are not bonded to the underlying mix.

12.5 STABILIZING AGENT ADDITION

If stabilizing agent(s) are required to improve the physical properties of the reclaimed mix, they can be added in a number of ways and locations. How and when the stabilizing agent(s) are added depend primarily on the:

- type of stabilizing agent(s) being used
- form of the stabilizing agent(s), i.e., dry, liquid or slurry
- availability of equipment
- desired end result

There are no hard and fast rules on how and where to add the stabilizing agent(s), since each project has its own set of unique requirements.

Addition of the stabilizing agent(s) during the pulverization pass, using the reclaimer's onboard additive system, eliminates some or all of the subsequent mixing passes. This has a corresponding reduction in production costs and works well if the existing roadway is uniform in surface condition, material thickness, material composition, and no undetected buried utilities/castings are encountered.

Figure 12-9: Stabilizing Agent Addition

In order to maintain a uniform application of the stabilizing agent(s) the following three variables must be held as constant as possible:

- operating speed of the reclaimer
- volume or depth of the layer being treated
- amount of stabilizing agent(s) being added

If one or more of these variables changes, an adjustment to the others has to be made in order to achieve uniformity or consistency in the reclaimed mix. Notwithstanding the computerized interlock between the forward operating speed and the amount of stabilizing agent being added, separate pulverization and mixing passes are being used more often. Although more costly, this has the effect of increased, more consistent working speeds as undetected buried utilities/castings are exposed and dealt with prior to the addition of the stabilizing agent. Variation in material thickness and composition can be assessed and corrected, resulting in a more uniform application of the stabilizing agent.

Stabilizing agent(s) that traditionally have been added in a dry state are now more frequently being added in the form of a slurry. The dry stabilizing agent is premixed with water to form a slurry which has a water content at or slightly below the amount which would be required to bring the reclaimed material to the OMC or 75 percent saturation whichever is less. The slurry is then controlled and injected into the pulverization/mixing chamber by the reclaimer's onboard liquid additive system. Application of the dry stabilizing agent as a slurry eliminates the environmental effects, particularly wind and rain, and can be a more accurate application method.

12.6 COMPACTION

The degree of compaction achieved is one of the primary determinants of the future performance of the reclaimed mix. Reclaimed mixes which are poorly compacted:

- can densify under traffic which may result in rutting
- will not achieve early strength gain which may result in surface raveling
- will not achieve the ultimate strength gain which may result in premature failures

Hence, it is imperative that adequate compaction be achieved at the time of construction.

Typically, one or more compactors are needed to adequately densify the reclaimed mix. As with compaction of other construction materials, the size, type, and number of compactors used will depend on the material properties, lift thickness, percent compaction required, smoothness of the compacted area, and production requirements.

The characteristics of the reclaimed mix will determine whether padfoot, smooth drum, and/or pneumatic compactors should be used. The depth of the reclaimed mix being compacted and the desired degree of compaction will influence the weight and amplitude/frequency of vibration for vibratory compactors and the static weight and tire pressure of pneumatic compactors. A field test strip can be used to establish the best combination of amplitude and frequency or combination of rollers.

As with other construction materials, it is also possible to over-compact a reclaimed mix, particularly if stabilizing agent(s) have been used. This reduction in compaction is more prevalent when vibratory compactors are being used. Generally, it is not necessary to loosen or remix the over-compacted area, but a smaller pneumatic compactor or vehicle traffic is used to seal the transverse check-cracking associated with over compaction.

Obviously, the correct moisture or fluid content is critical in achieving adequate compaction with the minimum of effort. Due to the time delay between initial compaction, placement, shaping, and final compaction, a light application of water is usually applied to the surface of the reclaimed mix before final compaction takes place.

Uniform compaction needs to be achieved in order to ensure consistent performance of the reclaimed mix. Compaction must be uniform in not only the longitudinal and transverse directions but also throughout the depth of the reclaimed mix. The rear wheels of the reclaimer ride on the surface of the reclaimed mix, partially compacting the material in the wheelpaths, while leaving the remaining material uncompacted. Prior to initial blading, the uncompacted material needs to compacted to the same level as the material in the wheelpaths. If this is not done, the compactors, particularly if steel drum rollers are used, will tend to ride on the lightly compacted material in the wheelpath and bridge over the uncompacted area. This can lead to differential or non-uniform compaction.

If the reclaimed mix exhibits instability in the form of rutting, shoving or cracking under the action of the rollers, the compaction process should be suspended immediately. When the instability is due to an excessive moisture or fluid content in the reclaimed mix, it needs to be aerated prior to further compaction. If the excessive moisture is not released, the area will not achieve the required degree of compaction, will not have the same strength as the surrounding area, will be sensitive to disturbance by traffic, and will most likely lead to a failure.

Often the instability of the reclaimed material is not due to excessive moisture but to an underlying subgrade problem. If proof rolling or an excavation reveals a subgrade problem, it needs to repaired. The repair method will vary, depending on the type and severity of the subgrade problem, but whichever method is used it is important to ensure that the area will drain at the end of the repair process.

Experience has indicated that compaction of reclaimed mixes stabilized with asphalt emulsion should be complete at or just after the emulsion starts to break, or when the reclaimed mix starts to change from a brown to a blacker color. The moisture content of the reclaimed mix prior to the asphalt emulsion breaking is sufficient to act as a lubricant between aggregate particles, but does not fill the void space between the aggregate particles and prevent densification from occurring. In addition, after the asphalt emulsion breaks, the viscosity increases significantly, requiring additional effort to achieve the required compaction.

Compaction of reclaimed mixes stabilized with foamed asphalt can take place immediately after mixing, assuming it is at or near the optimum fluid content for compaction. Reclaimed mixes stabilized with foamed asphalt will remain workable, providing the moisture content stays at or above the moisture content at the time of the foamed asphalt injection and mixing. Ideally, the compaction process should be completed before the foamed asphalt stabilized mix starts to dry out.

Cementitious stabilized mixes need to be compacted in as short a period of time as possible since the hydration process begins as soon as there is moisture available. Specifications traditionally indicate that the total time for mixing, placing, compacting, and finishing the cementitious stabilized mix be less than a specific time period, usually between two to four hours. The two to four hours is usually measured from the time the stabilizing agent first is exposed to moisture to the time compaction is complete. With a modern reclaimer this time limit is usually not difficult to achieve, provided the length of the segment being treated is appropriate for the available equipment.

Depending on the characteristics of the reclaimed mix and the type of finished surface required, the initial or breakdown rolling is completed with a vibratory padfoot or single or tandem smooth drum vibratory roller. Intermediate rolling is then performed with a heavy pneumatic roller and final rolling is undertaken with a tandem static or vibratory steel drum roller. Depending on project specifics, other combinations of rollers can and are used.

12.7 CURING

Reclaimed materials that have been stabilized by chemical, bituminous or a combination of these stabilizing agents need to be properly cured to:

- achieve the ultimate strengths
- prevent raveling under vehicle traffic
- facilitate placement of the wearing course

Curing can be divided into three categories: initial; intermediate; and final. Initial curing is relatively short and permits the stabilized mix to gain sufficient cohesion to be less susceptible to surface disturbance. Time for initial curing can be shorter than half an hour for foamed asphalt stabilized mixes and an hour or more for asphalt emulsion stabilized mixes. Initial curing times for cementitious and combination stabilizing agents usually fall between these two limits. Initial curing times depend almost entirely on the amount and type of stabilizing agent(s) used and very little on the ambient conditions.

Generally, the surface of the reclaimed mix is dampened with a light application of moisture, and the surface tightened with a pneumatic roller, as the last stage of compaction and the first stage of initial curing. During the initial curing period, all vehicle traffic is kept off the area or it is severely restricted, depending on the characteristics of the reclaimed mix. At the end of the initial curing period, the roadway can be opened to light vehicle traffic.

Intermediate curing is more extensive in length, and depends almost equally on the amount and type of stabilizing agent used and ambient conditions. Intermediate curing is required, to allow the reclaimed mix to build up sufficient strength and/or to allow sufficient moisture or volatiles to escape to permit the wearing course to be successfully applied.

In the case of asphalt emulsion stabilizing agents, intermediate curing allows the excess moisture required for compaction to escape. Entrapment of excess moisture by placement of a chip seal or other type of seal coat may cause the seal to strip or be removed under traffic, and numerous spot patches will be required. If the excess moisture is trapped by a relatively thin HMA overlay, the surface of the overlay may begin to shove under traffic due to bonding problems.

A criteria for determining when adequate intermediate curing has taken place has not been established due to the wide variety of reclaimed materials and stabilization agents. A minimum moisture content of bituminous stabilized mixes has been used as a means of establishing the intermediate curing period. With the increased use of lime or Portland cement to accelerate initial curing and strength gain, it may no longer be an adequate measure, as field strength does not correlate well with moisture content. As a rule of thumb, whenever a core can be extracted from the reclaimed mix relatively easily, it usually has developed enough strength and lost sufficient moisture to be covered by the wearing course.

In the case of cementitious stabilizing agents, intermediate curing allows hydration to take place and strengths to increase. With cementitious stabilizing agents, proper intermediate curing is also critical, in order to prevent excessive shrinkage cracking. Typically, the two types of intermediate curing are moist curing and asphalt sealing. Moist curing consists of keeping the surface of the reclaimed mix damp by regular applications of a very light misting of moisture, using a water truck. In hot and/or windy conditions, moist curing will be difficult since the surface will dry quickly and the potential for excessive shrinkage cracking increases dramatically. When intermediate curing is with an asphalt seal, it typically consists of a slow setting asphalt emulsion, applied relatively thick with an asphalt distributor. In some instances, the asphalt emulsion may be slightly diluted. On some projects, the asphalt seal may be a low viscosity, medium curing cutback asphalt.

The criteria for determining when adequate intermediate curing has taken place with cementitious stabilized mixes, typically depends on the attainment of a specified strength or waiting a fixed period of time. Typically, the intermediate curing period for cementitious stabilized mixes is seven days.

Raveling can occur with reclaimed mixes. The amount of raveling will depend on the gradation of the material, tightness of the surface, the type and speed of traffic permitted, and amount of initial curing which has taken place. Some reclaimed mixes may need to have a very light fog coat of slow setting asphalt emulsion, diluted one to one with water, to prevent excessive raveling prior

Figure 12-10: Bituminous stabilization mat prior to placement of wearing surface.

to placement of the wearing surface. When the area is opened to traffic before the fog coat has completely cured, a sanding will be required to prevent pickup of the asphalt emulsion.

Adequate intermediate curing has a direct effect on both the long-term performance of the reclaimed mix, the wearing surface, and the pavement structure. Heavy truck traffic should not be allowed or at least limited, during the intermediate curing period. Early heavy truck traffic can produce severe flexural or fatigue cracking of the reclaimed material which can lead to structural failure.

Final curing is the time it takes the stabilized mix to reach its ultimate strength, and can be a very long period. Final curing takes place after the wearing course has been applied and is dependent on the amount and type of stabilizing agent and ambient conditions. For some stabilizing agent(s) it can be measured in months or years.

12.8 WEARING SURFACE

After the reclaimed mix has been adequately cured, it can be surfaced with a variety of different wearing materials. The selection of what type of wearing surface to use depends primarily on the anticipated traffic, structural requirements, local climatic conditions, type of stabilizing agent(s) used, and economics. Since reclaimed mixes can have significantly higher load-carrying capabilities, particularly if stabilizing agent(s) have been used, it may be possible to use a thinner layer of HMA or even a more economical surface treatment such as a double chip seal. No matter which wearing surface is selected, it is critical that it bond properly to the reclaimed mix.

In preparation for surfacing, the reclaimed mix is usually swept with a power broom to remove all loose material. The type of wearing surface to be used will dictate what happens next. For HMA or cold mix overlays on bituminous or combination stabilized mixes, a tack coat of asphalt emulsion is typically used to assist with bonding. The application rate of the asphalt emulsion will depend on the surface condition of the reclaimed mix. For chemically stabilized mixes which have been cured with a seal coat, a tack coat may not be necessary. A prime/tack coat is usually required if the chemically stabilized mix has been moist cured.

For surface treatments such as chip seals, micro-surfacing, etc., the surface preparation of the reclaimed mix will vary to suit the particulars of the surface treatment.

CHAPTER 13: FULL DEPTH RECLAMATION – PROJECT SPECIFICATIONS AND INSPECTION

As with all roadway construction processes, two key steps are required to ensure the satisfactory construction and performance of a Full Depth Reclamation (FDR) project. First, is the development of an adequate and equitable set of specifications, and second is inspection during construction to ensure that the intent of the specifications has been achieved.

Although there is a trend in the Hot Mix Asphalt (HMA) industry towards greater reliance on end result specifications, with some owner agencies introducing performance warranties in conjunction with end result specifications, this has not yet been implemented with FDR. The number of unknowns associated with the existing pavement structure, the difficulties in specifying the end result requirements, and the recent development of the process, have all resulted in most FDR projects being undertaken using method specifications. This is not to say that end results are not used for FDR projects but that they are contained within the framework of the method/standard specifications.

13.1 STANDARD SPECIFICATIONS

Standard specifications for FDR projects need to address a number of items, including:

- general description
- definitions and terminology
- material requirements
- equipment requirements
- construction methods
- inspection and Quality Control/Quality Assurance (QC/QA)
- acceptance requirements
- measurement and payment

The general description, usually one or two short paragraphs long, introduces the project, the FDR process, and construction methodology in broad terms. It may or may not identify other sections of the owner agency’s existing specifications that are related to the FDR specifications and the various documents that need to be submitted by the contractor.

Some method specifications include a section outlining the terminology and definitions used within the specifications. The terminology and definition section is more often included when FDR is being used for the first time and not everyone is familiar or comfortable with the terms used.

The section on materials includes requirements for the granular materials, chemical and/or bituminous stabilizing agents, and water. The granular materials are added when the gradation of the reclaimed material requires alteration for increased mechanical stabilization or to increase the amount of reclaimed material for shape or thickness corrections. The chemical and/or bituminous stabilizing agent(s) that are required are usually indicated by a specific product, an equivalent product, existing owner agency specifications or other published specifications such as those contained in the American Society for Testing and Materials (ASTM).

In a method specification, the owner agency, as part of the mix design process, selects the:

- granular material gradation and source
- stabilizing agent(s) type and source
- application rate of stabilizing agent(s)

The stabilizing agent(s) could be mechanical, chemical, bituminous, or a combination of one or more of these. The stabilizing agent(s) could be supplied and used in liquid or dry powder form. Water used to aid compaction must be compatible with the stabilizing agent(s). The materials section is therefore primarily to indicate to the contractor the types of materials that will be used on the project, as opposed to requiring the contractor to select the particular materials to be used.

The section on equipment requirements contains a fair amount of detail, and can be rather lengthy. It includes details for all equipment from the reclaimer through to the placement and compaction equipment. The specifications can include requirements for:

- age or operating condition of all equipment
- reclaimer output/treatment depth capability
- treatment depth controls on the reclaimer
- rotational direction of the reclaimer’s cutting drum
- mechanisms for controlling the reclaimed material gradation via breaker bar and/or door opening on the reclaimer
- water truck/distributor capacity and ability to control application rates
- liquid additive system, complete with microprocessor to control addition of water and/or liquid stabilizing agent(s), linked to forward operating speed of reclaimer
- a system on the reclaimer to accurately produce and sample foamed asphalt when it is being used as the stabilizing agent
- liquid stabilizing agent tanker and/or distributor
- bulk spreaders to accurately add granular materials and/or dry stabilizing agents
- placement control methods on the reclaimer or on the motor grader
- type, size, and number of rollers required for compaction
- asphalt emulsion distributor and application controls for fog/seal coats

In addition, requirements for pre-approval or acceptance of the equipment, particularly the reclaimer, prior to use are often included. In some instances, the specifications include the requirement for the proposed FDR equipment to undertake a test or demonstration section in order for the owner agency to evaluate and approve the equipment, construction methodology, contractor, and/or workmanship.

Construction methods included in the specifications address such issues as:

- weather limitations prior to and during construction
- production plan indicating: sequence and length of each treatment segment; estimated

pulverization, mixing, placement, and compaction times for each segment; layout of transverse and longitudinal joints; stabilizing agent addition rates per segment; and other pertinent information
- accommodation of traffic through the work zone
- determination of in-situ moisture content of the materials to be reclaimed
- preliminary surface preparations required
- surface shape and grade requirements
- addition of stabilizing agent(s)
- time limitations between addition of the stabilizing agent(s) and completion of the compaction process
- method of controlling moisture content of the reclaimed mix
- method of addressing materials with excessive moisture contents
- gradation requirements of the reclaimed material
- continuity of stabilized materials
- methods of dealing with subgrade instability problems
- placement requirements for cross-section shape and grade control
- compaction procedures
- curing requirements and methods
- opening roadway to traffic
- protection and maintenance of the reclaimed mix prior to application of the wearing surface

With method specifications, the owner agency is in control of the construction process, and therefore needs to have full time inspection and testing. The owner agency personnel on the project need to have the experience to evaluate the test results and authority to make field adjustments to the FDR process.

The specifications usually outline the frequency of sampling and the testing methods that will be used. Wherever possible, these should be published industry standards, such as American Association of State Highway and Transportation Officials (AASHTO) or ASTM methods or the owner agency's own adaptation of these procedures. Since the owner agency is essentially in control of the construction process, the QC and QA testing are usually one and the same and increased inspection is used to control the FDR process.

A section of the specifications outlining the acceptance requirements for the FDR work is also included. The acceptance requirements include such things as:

- treatment depth/layer thickness
- gradation of the reclaimed materials
- stabilization content or physical properties of the reclaimed mix
- moisture content of reclaimed mix
- reclaimed mix uniformity
- degree of compaction.
- surface level/grade

- surface texture
- surface smoothness

Some of these are obviously end result requirements, but are included in the method specifications for FDR.

The final section deals with measurement and payment issues for the FDR project. The specifications usually outline how items will be measured such as:

- mobilization/demobilization
- surface preparation prior to FDR
- FDR of existing pavement structure
- stabilizing agent(s) supply and addition
- subgrade instability repair

In addition, the specifications indicate what is to be included in each of the payment items.

Mobilization/demobilization is more commonly being included as a specific payment item. Some specifications fix the amount/lump sum or limit it to a percentage of the total contract price. Other specifications require that mobilization/demobilization be included as part of the other payment items.

Surface preparation prior to the start of the FDR process is usually paid for by the square yard (square meter) of surface area. It includes full compensation for all work necessary to clean the roadway, usually by sweeping. Removal of edge vegetation is particularly important for projects in which the roadway is to be widened by blending shoulder material into the reclaimed mix.

Surface preparation does not include any preliminary leveling or removal of high spots by cold planing or similar activities. When these are required, they are paid for as separate items using the standard units of measurement.

Compensation for FDR can be by the cubic yard (cubic meter) of reclaimed mix or by the square yard (square meter) for a specified treatment depth. In both cases, the payment is for the final treatment volume or surface area, independent of the number of passes to process a given area, regardless of the overlap widths required, and regardless of the hardness or type of material reclaimed.

Individual pay items for areas with identifiable differences in asphalt pavement layers, granular base thickness, and/or required treatment depths should be used with the pay-by-area method.

The FDR unit rate usually includes full compensation for:

- setting out of the work
- pulverizing
- sizing
- supply and addition of water
- mixing
- overlap areas
- placing
- compaction

- curing
- protection/maintenance of the reclaimed mix
- all labor, tools, and equipment

Traffic accommodation is also generally included but can be a separate payment item, particularly for higher traffic roadways with specific requirements.

The supply and addition of stabilizing agent(s) are usually by separate payment items. Granular materials are paid by the ton (tonne) although they could also be by the cubic yard (cubic meter). Liquid stabilizing agent(s) are paid by the gallon (litre), and chemical stabilizing agent(s) are paid by the tonne (ton) for dry materials and by the gallon (litre) for slurried materials.

The rates include full compensation for supply, and addition of the stabilizing agent(s), including all transportation, handling, storage, spreading or fluidizing into a slurry, and application in the FDR process, disposal of all packaging, for all wastage, and safety measures required during handing and application.

Compensation for subgrade instability repairs is made as an individual payment item, using standard measurement units.

Special Provisions, appended to the FDR specifications, are used to indicate specific project requirements such as:

- limits of work
- construction schedule, staging or limitation on hours of work
- trucking requirements
- particular traffic accommodation requirements
- interaction and cooperation with other contractors
- parking and storage of equipment
- mix design information
- any other site-specific requirements

The condition of the existing or in-situ materials, as determined from the investigations carried out, together with the results of testing conducted on representative samples are usually included in the special provisions. Typically, information included from the detailed project analysis consists of:

- existing pavement structure, including individual layer thickness
- type of asphalt binder used in asphalt layers
- gradation of aggregates used in asphalt layers
- presence of any paving fabrics or specialty mixes
- moisture content, gradation, and asphalt content of Reclaimed Asphalt Pavement (RAP) samples
- location of all utilities and roadway castings, both exposed and buried
- moisture content, gradation, and plasticity of underlying materials
- results of any preliminary mix designs
- condition of subgrade, including soil type, moisture content, and strength

Any information included is usually accompanied by a caveat which indicates there is no guarantee that conditions other than those indicated will be encountered.

The degree to which the various issues are addressed within the specification and the special provisions will depend on the owner agency's experience with FDR.

13.2 SPECIFICATION LIMITS

Specifications typically include limits and/or tolerances on a number of physical properties of the reclaimed mix and could include some or all of the following:

- treatment depth/layer thickness
- gradation of the reclaimed materials
- addition of stabilizing agent
- moisture content of reclaimed mix
- reclaimed mix uniformity
- degree of compaction
- surface level/grade
- surface smoothness

Treatment depth or layer thickness is typically indicated on the plans or in the specifications. Thickness of the treated layer is one of two critical variables that affect the long term performance of the reclaimed mix. Some variation in treatment depth is to be expected, depending on the thickness variability of the existing pavement structure. The specified treatment depth is usually somewhat shallower than the existing pavement thickness, in order to prevent contamination of the reclaimed material with subgrade soils.

Typically, a tolerance of plus or minus a given amount from the design thickness is allowed. A value such as +/- 3/4 inch (20 mm) for a design treatment depth of 10 inches (250 mm) could be specified for pavement with uniform thickness. Treatment depth tolerance can also be specified as a percentage of the design thickness, such as +/- 5 percent for a uniform pavement thickness.

Regardless of the method of indicating the tolerance value, the treatment depth should not to be uniformly high or uniformly low. When existing pavement thickness is highly variable, an increase in the treatment depth tolerance should be made.

As indicated in Chapter 12, the gradation or sizing of the reclaimed material can be somewhat controlled by adjusting how the reclaimer is being operated. Recognizing that there are physical and economic limits on how fine the existing pavement can be pulverized by the reclaimer, most specifications indicate the amount passing a preferred maximum particle size, the amount passing the next smaller sieve size, and an upper limit on the amount passing the No. 200 (0.075 mm) sieve.

In the FDR process, 100 percent of the existing asphalt pavement is used along with a predetermined percentage of the underlying materials. Therefore, the variation or consistency of the existing asphalt pavement and underlying materials will have the greatest influence on the variation or consistency of the reclaimed mix. Typically, there are no specified gradation requirements for the intermediate sieve sizes, since these are determined by the gradation of the existing materials.

Adjustment in the overall gradation is normally addressed by the incorporation of granular material, as determined in the mix design.

The maximum size that 100 percent of the particles must pass is normally listed as either 2 inches (50 mm) or 1 1/2 inches (40 mm). The decision to use one over the other will depend on characteristics of the existing materials and desired properties of the reclaimed mix. The smaller the maximum particle size, the finer the overall gradation, but this is achieved at an increased cost.

The amount passing the next smaller sieve size in the standard sieve series is usually 90 or 95 percent. If the maximum particle size were listed as 2 inches (50 mm), the specifications would indicate that 90 or 95 percent of the reclaimed material was to pass the 1 1/2 inch (40 mm) sieve size. The decision on the maximum amount specified to pass the next smaller sieve size also depends on the characteristics of the existing pavements and the required characteristics of the reclaimed mix.

The amount passing the No. 200 (0.075 mm) sieve is typically listed as a maximum value and is used to ensure that the subgrade soil is not being excessively incorporated into the reclaimed materials. Typically, a value of 20 or 25 percent is used depending on the gradation of the underlying materials.

As was noted in Chapter 11, when foamed asphalt is used as the stabilizing agent, the reclaimed materials must meet higher gradation and Plasticity requirements. The mix design will determine whether the reclaimed materials can be stabilized with foamed asphalt in a cost effective manner.

The types of stabilizing agent(s) and required application rates expressed as a percentage of the dry mass of the reclaimed material should be indicated in the specifications, typically the special provisions. The tolerance limits of the stabilizing agent addition rate will depend on the type of stabilizing agent and the form in which it is being used.

When mechanical stabilization by the addition of granular materials is used, the application rate is usually required to be controlled to within +/- 5 percent of that specified. Other tolerance values for the application rate can be used, depending on the maximum aggregate size, gradation, and quantity of granular materials being used.

Tighter control of the addition rate is required when chemical or bituminous stabilizing agent(s) are being used. Specifications typically require that the stabilizing agent be controlled to within +/- 0.5 percent or less of the application rate indicated by the mix design/specification.

The tolerance for moisture content of the reclaimed mix will vary, depending on the type of stabilizing agent(s) being used. For mechanical and/or bituminous stabilizing agents, the field moisture content is usually required to be controlled so that it does not exceed the Optimum Moisture Content (OMC) or Optimum Fluid Content (OFC) nor be more than 2 percent less than the OMC/OFC. For cementitious stabilizing agents the field moisture content is usually required to be controlled so that it does not exceed the OMC or 75 percent saturation whichever is lower. If specialized chemical stabilizing agents are used, the field moisture contents will need to be controlled to the stabilizing agent supplier requirements.

Uniformity of the reclaimed mix is generally assessed visually and by specification requirements, with respect to longitudinal and transverse joints. Specifications usually indicate that between adjacent longitudinal passes of the reclaimer there can be no gaps of unprocessed material. Some specifications address this issue by requiring a minimum overlap of 2 to 4 inches (50 to 100 mm) for adjacent passes.

To ensure the continuity of the reclaimed mix, specifications may also require that the exact location of the end of each processing pass be marked. Processing of subsequent segments is required to start a minimum of 1.5 to 3 feet (0.5 to 1.0 meter) behind the transverse mark of the previous pass.

To be uniform, the recycled mix must be free of segregation and surface defects. Conventional methods of assessing segregation and surface defects of granular base materials could also be used for reclaimed mixes.

The degree of compaction is the second of the two critical variables that affect the long term performance of the reclaimed mix. Degree of compaction influences both the rate of strength gain and the ultimate strength achieved. These in turn will determine the reclaimed mix's response to repeated loading and load-carrying capabilities and by inference, the long term performance. The degree of compaction is usually specified as a percentage of a corresponding reference density.

The reference density for reclaimed mixes stabilized by mechanical or chemical stabilizing agents is usually the Maximum Dry Density (MDD), as determined by the Standard or Modified Proctor test or other compaction method used during the mix design. The MDD is not a fundamental property of the reclaimed mix, as it is dependent on the compaction effort and moisture content.

The degree of compaction for reclaimed mixes that have been stabilized with a bituminous agent is usually calculated using the MDD, as determined by the Marshall, Hveem or other compaction method used during the mix design.

The degree of compaction is typically specified to be an average of 95 percent of whichever reference density is being used, with no individual areas less than 92 percent. The specified degree of compaction can range from a low of 92 or 93 percent to a high of 97 or 98 percent.

In addition, if the lift thickness being compacted is relatively thick, the specifications sometimes include a compaction tolerance limit for depth. Generally, the specifications indicate that the percent compaction of the bottom third of the lift be not less than 2 percent lower than the average percent compaction for the total lift thickness. This is to ensure that compaction is uniform not only horizontally but also vertically.

Specifications usually indicate that the reclaimed mix has to be placed and compacted to the design grade and cross-slope with a tolerance. The tolerance is related to the maximum particle size of the reclaimed mix and the type of wearing surface that will be used. Typically, the tolerance is +/- one half of the maximum particle size specified, with no areas being uniformly high or uniformly low.

Specifications usually indicate that the smoothness of the reclaimed mix surface is to be checked with a straightedge. Individual irregularities must be less than 3/8 inch (10 mm) when checked against a 10 foot (3 meter) straightedge placed on the reclaimed mix surface in any direction. Some specifications also indicate that if the irregularities are caused by factors that are outside the control of the contractor, the specification can be relaxed.

13.3 INSPECTION, QUALITY CONTROL AND QUALITY ASSURANCE

A generic inspection, Quality Control (QC) or Quality Assurance (QA) plan cannot be presented herein due to the wide range of projects in which FDR is used and to the wide variety of equipment. The inspection and QC/QA plan needs to be developed based on the FDR application, and then amended for the specific type of equipment and stabilizing agent(s) being used on the particular project.

During the FDR process the areas of concern that the owner agency/contractor QC/QA plan needs to address include:

- treatment depth
- gradation
- stabilizing agent application rate
- moisture content
- uniformity
- compaction
- smoothness

To ensure that the automatic treatment depth controls are working correctly on the reclaimer, the treatment depth needs to be physically measured. Depth measurements should be performed on a regular basis by removing the reclaimed material on each side of the reclaimer. Pulverizing the pavement structure fluffs up the material and this needs to be accounted for when determining the treatment depths of subsequent mixing passes. A good ground man is indispensable in controlling treatment depth, particularly if the thickness of the existing pavement structure is variable.

The gradation of the reclaimed material should be checked periodically. This is to verify the gradation assumptions used in the mix design process and to ensure that the existing asphalt layers are being pulverized to the required maximum particle size. Maximum particle size checks are usually made more often than determination of the overall gradation of the reclaimed material. Sampling of the reclaimed material needs to be undertaken with special care to ensure that only the pulverized/mixed materials are sampled. The sample must also be taken from the full treatment depth since a reclaimer operating with the cutting drum in a down cutting mode will bring more of the large sized particles to the surface. If the full treatment depth is not completely sampled, the gradation results will not be representative.

The application of the stabilizing agent(s) must be checked on a regular basis since variations in application rates result in variations in the material properties and ultimate strength. The application rates should be checked not only randomly throughout the day but also for average application rates, using daily bulk quantities and daily treatment area.

Liquid stabilizing agents added through the reclaimer can be checked by using the on-board metering system. The metering system should be equipped with a means of determining the liquid flow and displaying the amount being added per minute. It should also have a totalizer to keep track of the quantity of liquid stabilizing agent that has been used. Using these two readings, the stabilizing agent application rate can be checked for a known area and for the day's production. The application of liquid stabilizing agents by distributor truck should be checked with standard methods used to verify application rates. The application rate of dry stabilizing agents is usually checked by using a tarp of known area and weighing the material retained by the tarp.

To ensure that the moisture content of the reclaimed materials is within the range appropriate for compaction, periodic checks on the moisture content of the reclaimed materials need to be made. Moisture content checks need to be made during the pulverization and mixing passes and even more frequently during the compaction process. For adequate compaction and long term performance, it is important that the field moisture be controlled at or slightly less than the OMC or OFC.

The water used in the FDR process needs to be clean and free of detrimental concentrations of acids, alkalis, salts, sugars and other chemical and organic compounds. If the water is not from a potable supply, it will need to be tested to ensure it is suitable, particularly when stabilizing agent(s) are being used.

Uniformity of the reclaimed mix is initially checked visually for any segregated areas. Segregated areas can be remixed with the reclaimer or motor grader on an as-required basis. Uniformity is also checked by ensuring that a sufficient overlap between adjacent passes, both longitudinally and transversely, is being used. Uniformity can also be checked by a comparison of the reclaimed mix gradation in a suspected segregated area with the gradation in a typical area.

Compaction is one of the critical variables that influences the long term performance of the reclaimed mix and so must be continually checked. It is important to confirm the average degree of compaction for the total treatment thickness but also for individual layers. The importance of determining the variation in compaction between the upper and lower layers of the treated thickness increases with increasing layer depths.

Nuclear density gauges are commonly used to determine the moisture content and density of many construction materials. Use of the nuclear gauge to determine moisture content of reclaimed mixes must be undertaken with extreme caution, since the nuclear gauge typically overstates the moisture content which, in turn, understates the field dry density/compaction. Nuclear gauges use the difference between the number of fast moving neutrons to the number of slow moving neutrons to determine measured moisture of a material. Fast moving neutrons emitted from the radioactive source in the nuclear gauge are turned into slow moving neutrons when they encounter hydrogen atoms which are assumed to be the hydrogen atoms of water. The reclaimed mix contains pulverized pavements that contain asphalt binder. Asphalt binders also contain a significant number of hydrogen atoms and so a direct correlation between the neutron/hydrogen count and moisture content is not possible. Calibration of nuclear gauges to account for the hydrogen in the asphalt binder is possible but not practical, as the amount of pulverized pavement and associated asphalt binder varies in a reclaimed mix. To overcome this problem a sample of the reclaimed mix at each test location for compaction has to be obtained and tested for moisture content in the laboratory. Alternatively, the field moisture and density can be determined with volumetric measurement tests such as the sand cone or rubber balloon method.

Figure 13-1: Completed FDR with Hot Mix Overlay

Existing pavements vary in composition not only longitudinally but also transversely and consequently, so do the material properties of the reclaimed mix. Care must be used when selecting the appropriate reference MDD to calculate the percent compaction achieved in the field. On projects with a significant amount of variability in the reclaimed mix, a sample may be needed to determine the appropriate MDD at each density test location.

During tight blading or immediately afterwards, the surface of the reclaimed mix should be checked for smoothness with the 10 foot (3 meter) straightedge. A number of locations should be checked, with the straightedge placed parallel and perpendicular to the longitudinal direction of the roadway.

CHAPTER 14: COLD RECYCLING – DETAILED PROJECT ANALYSIS

Through the project evaluation, economic analysis, and preliminary selection process outlined in Chapter 3, the potential rehabilitation alternatives were narrowed down to one specific technique. The next step in the rehabilitation design is the detailed project analysis which will lead directly into the final project design, advertising, tendering or letting, and construction.

The Hot Mix Asphalt (HMA) overlay, hot recycling, and reconstruction rehabilitation methods will not be addressed, since they are routinely used by all agencies. The rehabilitation techniques of Cold Planing (CP), Hot In-Place Recycling (HIR), and Full Depth Reclamation (FDR) are covered in depth, in other chapters. It is recognized that many of the steps in the detailed project analysis are common to all the rehabilitation methods but are addressed in each process, for continuity.

14.0 COLD RECYCLING REHABILITATION

Cold Recycling (CR) is the rehabilitation of asphalt pavements without the application of heat during the recycling process. The two sub-categories of CR, based on the process used, are Cold Central Plant Recycling (CCPR) and Cold In-Place Recycling (CIR).

CCPR is the process in which Reclaimed Asphalt Pavement (RAP) is processed in a central location to produce a recycled mix which can be used immediately or stockpiled for later use. CCPR is most frequently used as part of a total reconstruction of an existing roadway or in new construction where an existing source of RAP is available. The project issues associated with CCPR are similar to any centrally produced material used on a new or reconstruction project.

The CIR process consists of the on-site rehabilitation of the asphalt pavement with a recycling train which can range in size from a single unit to a multi-unit train.

Pavement distresses which can be treated by CIR, include:

- raveling
- potholes
- bleeding
- skid resistance
- rutting
- corrugations
- shoving
- fatigue, edge, and block cracking
- slippage, longitudinal, and transverse thermal cracking
- reflection and discontinuity cracking
- poor ride quality caused by swells, bumps, sags, and depressions

It is noted that unless the cause or causes of the pavement distress are addressed during the rehabilitation process, the distresses will be mitigated but they will not be eliminated.

The expected design life, performance during the design life and future maintenance requirements, are related to the treatment depth of the CIR, and on the type and depth of the subsequent wearing course. Hence, the detailed project analysis will further refine the CIR treatment depth and subsequent wearing course requirements.

14.1 HISTORIC INFORMATION ASSESSMENT

In the detailed review of historic or existing information, the data which needs to be assessed includes:

- age of the roadway, including any surface treatments. Surface treatments tend to be high in asphalt binder content which must be accounted for in the mix design process
- past condition surveys, in order to assess the rate of pavement deterioration
- thickness of the existing pavement structure and HMA layers. A minimum of 2 inches (50 mm) of asphalt pavement is generally required for CIR but 3 to 4 inches (75 to 100 mm) is preferred. If the CIR treatment depth is 2 inches (50 mm) and the total asphalt pavement layer is also 2 inches (50 mm), there is an increased risk that portions of the underlying granular base may be incorporated into the CIR mix

  Incorporation of untreated granular materials has been successfully undertaken, but there is an upper limit that can be incorporated into the CIR mix. The upper limit must be established during the mix design process but should generally be less than 25 percent by weight of RAP. If the untreated granular base content is in excess of 25 percent, the overall costs increase due to the higher recycling additive demand. In addition, the risk of segregation increases during construction, particularly if the granular base has a large maximum aggregate size and/or a coarse gradation. Segregation has an impact on overall strength, since segregated mixes tend to have reduced strength
- thickness of the HMA lifts within the anticipated CIR treatment depth. Moisture in HMA, delamination and/or poor bonding of HMA lifts and stripped aggregates could be encountered. Pavements with moderate stripping problems have been successfully treated by adding lime, either dry or as a slurry
- type of asphalt binder used in surface lift. Softer asphalt binders tend to have reduced stability values which may need to be improved with the use of additional recycling modifiers such as Portland cement, lime or coarse aggregate. Chemical recycling additives such as type C fly ash have been successfully used as well
- top size of aggregates used in surface lift. Depending on the top size of the aggregate, large stone mixes may influence the CIR treatment depth
- presence of any paving fabrics or interlayers in the anticipated treatment depth plus 25 percent. Paving fabrics are difficult to recycle with CIR and the presence of an interlayer may need to be assessed further, depending on its characteristic and location
- presence of exotic or specialty mixes, such as Open Graded Drainage Layers, Open Graded Friction Courses, Stone Matrix Asphalt, etc., will have an effect on the mix design and construction due to their coarser gradations

The detailed review of existing information contained in the maintenance records which needs to be assessed includes:

- patching locations and ages. Weak pavement structures/failing subgrades can lead to the CIR equipment "breaking-through" the pavement structure. Weak pavement structure can also lead to reduced compaction of the CIR mix, due to the pavement deflecting under the compaction equipment which in turn can lead to raveling during the curing period or rutting after the wearing course has been placed
- patching material including HMA, cold mix asphalt, injection spray patching, etc. (if these areas are significant)
- crack sealing activities, product types and ages

The detailed review of the existing Quality Control/Quality Assurance (QC/QA) information, from construction of all pavement layers within the anticipated CIR treatment depth, includes:

- asphalt binder content
- aggregate gradation, angularity, flat/elongated particles, and/or petrographic analysis
- voids total mix (VTM), voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) properties
- field compaction
- recovered asphalt binder properties

In order to delineate or isolate areas of substantial difference and/or uniformity within the project limits, a comparison of the QC/QA test results should be undertaken. Two times the standard deviation of the QC/QA test results, compared to the construction production tolerances, will give a quick indication of whether or not the mix variability is high or low. High mix variability is less desirable, since 100 percent of existing materials within the treatment depth will be recycled in the CIR process. The construction specifications may have to be modified to account for projects with high mix variability, if other factors have indicated that CIR is a viable option.

14.2 PAVEMENT ASSESSMENT

In the detailed pavement assessment, the type, severity, and frequency of the pavement distress which needs to be corrected is determined. Although CIR can rehabilitate most types of pavement distresses, cracked pavements which are structurally sound and have well-drained bases are the best candidates. The CIR process destroys the existing crack pattern and produces a crack-free layer for the new wearing course such as a HMA or an asphalt surface treatment. For CIR to be effective in mitigating the cracking, as much of the existing asphalt pavement layer should be treated as possible. Typically, at least 70 percent of the existing asphalt pavement thickness needs to be treated in order to mitigate the reflection cracking. The treatment depth is also affected by the maximum depth that can be treated at one time. Generally, the treatment depth is 2 to 4 inches (50 to 100 mm) for mixes modified with liquid recycling additives such as asphalt emulsions and emulsified recycling agents. Using additional recycling modifiers such as lime or Portland cement or a chemical recycling additive such as type C fly ash, increases treatment depths to 5 to 6 inches (100 to 150 mm). Obviously, the thicker the untreated portion of the existing asphalt pavement relative to the CIR treatment depth, the higher the probability of reflection cracking eventually occurring. Wherever possible, paved shoulders should also be treated in order to

Figure 14-1: CIR Candidate Road

prevent propagation of shoulder cracks into the adjacent treated driving lane.

An unusual surface texture may indicate the presence of a specialty HMA mix in the upper layer of the pavement which will need to be assessed further during the material properties assessment.

The presence of large or frequent surface patches increases the variability or decreased homogeneity of the existing materials which will have an effect on the consistency of the CIR mix. Large patches may require their own specific mix design, since they are usually newer and contain materials different from the original roadway.

Rutting in the form of wear rutting is easily treated with CIR and the appropriate high quality HMA wearing course, to ensure that wear rutting does not return. Instability rutting can be corrected with CIR if the appropriate recycling additives, modifiers and/or granular materials are selected. The addition of recycling modifiers such as lime and Portland cement, with asphalt emulsions or emulsified recycling agents, have been used to correct rutting problems. The selection of the type and amount of asphalt emulsion or emulsified recycling agent is also critical to correcting rutting problems. The use of High Float emulsions with harder base asphalt cements and/or the addition of polymers is becoming more prevalent. A chemical recycling additive, such as type C fly ash, can address instability rutting, as well. If granular materials are used they should be coarse, crushed material with addition rates usually less than 25 percent by weight of the RAP. Structural rutting, provided it is not originating in a very weak/wet subgrade, can be addressed with CIR and the subsequent placement of the appropriate thickness of HMA.

14.3 STRUCTURAL CAPACITY ASSESSMENT

There are two aspects of the structural capacity assessment which need to be addressed. The first is the structural capacity required for the anticipated traffic during the design life of the rehabilitation. The second is the ability of the existing pavement structure to support the CIR equipment during construction.

The first step is to reassess the structural capacity of the existing pavement and determine what is required for the anticipated traffic during design life of the rehabilitation. If the existing structural capacity needs improving, a determination of the required strengthening thickness must be undertaken using the agency's normal overlay thickness design methods.

If a mechanistic-empirical design method is used to determine the required overlay thickness for structural strengthening, the structural layer coefficient of a CIR mix typically ranges from 0.20 to 0.44 with an average value of about 0.30. The range in structural layer coefficient values is related to the amount and types of stabilizing additives which are used. CIR mixes that have had lime or Portland cement added as a modifier to liquid recycling additives, and chemical additives such as type C fly ash, typically have higher values. In addition, CIR mixes usually have measurable increases in strength after construction, due to curing of the recycling additive and/or modifier, and a reduction in the field VTM with traffic. The rate of strength increase is greatest during the first few months after construction but may continue at reduced rates for up to 2 years. Comparison of CIR mixes with standard HMA mixes, at similar VTM contents, has indicated that the CIR mixes have slightly higher modulus values and significantly greater fatigue life, indicating that the CIR mix may behave more like an open graded material than a dense graded material. Each agency will have to determine an appropriate structural layer coefficient typical of the CIR mixes used in their jurisdiction.

When the existing structural capacity is sufficient to handle the anticipated design traffic, then the CIR processes can be assessed further. Since no increase in strength is required, a thin HMA overlay or a single or double asphalt surface treatment could be used as the surface course.

Even when the strengthening thickness required is high, or if poor or marginal base and subgrade conditions exist, CIR has been successfully undertaken. In these instances asphalt emulsions, emulsified recycling agents with the addition of modifiers such as Portland cement or lime or chemical additives such as type C fly ash are commonly used. The combination of liquid recycling additives and either the Portland cement, lime or type C fly ash, produces higher earlier mix strengths that may be capable of bridging over the weak underlying areas.

When the existing structural capacity requires significant strengthening, due primarily to the anticipated traffic and the existing roadway does not contain structural or base failures, then CIR could still be used to treat the existing pavement distress, such as cracking, etc. The overall structural capacity deficiency could then be addressed by a thicker HMA overlay.

Pavements with major or extensive structural and/or base failures will not be good candidates for CIR and other rehabilitation methods should be assessed. If the structural/base failures are less than 10 percent of the project area, it may be economically feasible to remove and repair the failed areas by deep patching prior to undertaking the CIR. Care must be taken to ensure that water is not trapped within the repair area by creating a "bath tub" condition within the subgrade. If the excavation in the failed area needs to be below the surrounding subgrade elevation, the excavation must have a drainage outlet provided or be filled with non-permeable stabilized material.

Whichever rehabilitation technique is chosen, the source/cause of any isolated structural problems within the pavement must be identified and corrected or they will likely reappear with time.

For the second case of structural assessment, a determination of the load-carrying capacity of the granular base and pavement remaining after cold planning is required and becomes more important for thinner overall pavement structures. The CIR equipment wheel loads are generally high and after the cold planing machine removes the existing pavement for treatment, the rear drive track of the cold planer and the subsequent equipment is only supported by the remaining pavement structure. If the remaining pavement structure is thin or weak, the vertical load and shearing force of the rear track of the cold planer, as it pulls the recycling train along, can punch/shear into the underlying materials, lose traction stopping the CIR train.

The two most useful methods of assessing the load-carrying capacity of the pavement structure are Dynamic Cone Penetrometer (DCP) and Falling Weight Deflectometer (FWD) testing. With the DCP, the underlying materials can be assessed by coring or drilling through the asphalt pavement layers to expose the granular base, subbase, and/or subgrade materials. Obviously, if water has been used in the coring operation, the resultant moisture may affect the DCP values of the upper portion of the underlying materials. Assessment of the load-carrying capacity is usually conducted at the same locations that samples of the asphalt pavement for material property assessment are obtained. However, for weak and/or thin pavement structures, additional DCP testing should be conducted to more fully assess the load-carrying capacity and/or isolate weak areas. This is critical since reduced compaction may lead to a reduction in the performance of the CIR material.

Each agency will need to establish its own DCP blow count profile versus feasibility of CIR construction evaluation criteria, since it will be sensitive to material types, soil, and groundwater conditions. In general, if there is a minimum of 2 inches (50 mm) of asphalt pavement remaining below the CIR treatment depth and 6 inches (150 mm) of granular base, the risk of equipment break-through is low even if relatively low DCP blow counts are noted. As the remaining asphalt pavement thickness and/or the thickness of the granular base is reduced, higher DCP blow counts will be required to ensure equipment break-through does not occur.

DCP results will change throughout the year in response to changes in base and subgrade moisture conditions. The DCP results should ideally be obtained when the moisture conditions in the base, subbase, and subgrade will be similar to those at the time of CIR construction. If this is not possible, then an adjustment of the DCP evaluation criteria, to account for the differences in moisture contents from the time of testing to time of construction, will need to be made.

The FWD can also be used to assess the load-carrying capacity of the existing pavement structure, including the base, subbase, and subgrade by back-calculating the subgrade resilient modulus and the effective pavement modulus. Other parameters such as the surface curvature index, base damage index and/or base curvature index can be determined from the deflection bowl measurements produced by the FWD. As with the DCP testing, each agency will have to establish its own evaluation criteria based on their local conditions.

14.4 MATERIAL PROPERTIES ASSESSMENT

Utilizing the results of the existing information reviewed and the pavement assessment, the project is divided into areas/segments of similar materials or performance. A field sampling plan is then established utilizing either fixed interval or random sampling methods to determine the location of the field samples.

Field sampling has traditionally been obtained by coring/sawing or small milling machines. The popularity of using small milling machines to obtain field samples is declining since the consistency of the samples between different types of small milling machines is highly variable and it is relatively expensive. The gradation of the samples obtained by small milling machines is not as coarse with smaller maximum particle size and more fines, i.e., passing No. 200 (0.075 mm) sieve size than what is produced by the large milling machines during the CIR process. The current trend is to obtain samples by means of coring, usually 6 inches (150 mm) in diameter, and then subsequently crushing the cores in the laboratory. With field coring and laboratory crushing, the sample gradation more closely resembles what is achieved in the field during the CIR process. Block sampling, by means of sawing, can also be used, but it is usually more expensive than coring. It is important that the full depth of the asphalt bound layers be cored in order to assess its condition. However, only the upper portions of the core, equivalent to the anticipated CIR treatment depth, are used for subsequent analysis.

The frequency of field sampling varies with the size of the project, size of the areas of similar materials or performance, and the variability of the existing materials, as determined from the review of existing QC/QA data. Generally, the number of sample locations ranges from 3 to 5 for smaller, consistent areas to 20or more for larger, less consistent areas. Samples are obtained at a frequency of approximately one location per 5/8 mile (kilometer) per lane direction. The number of cores obtained at each field sampling location will depend on the number of field sample locations, the amount of laboratory testing to be performed, whether or not samples will be needed for subsequent CIR mix designs, and what type of mix design method will be used. If a modified Marshall or Hveem mix design is planned, the total number of cores will depend on the anticipated CIR treatment depth and core diameter. Approximately 110 pounds (50 kilograms) of material is usually required for each mix design. If the effect of an additional modifier or chemical additive other than traditional liquid recycling additives is to be assessed, then more material will be required.

The core samples should be carefully examined in order to detect the different pavement layers, previous surface treatments, interlayers, geotextile paving fabrics, specialty mixes, evidence of stripping, friable or disintegrating mix, retention of excessive moisture, and any tendency to delaminate. Once the cores have been inspected, the observations recorded and selected cores photographed, the cores are trimmed to the depth of the anticipated CIR treatment and crushed. Representative samples are then tested to determine:

- moisture content (if dry coring has been used)
- gradation of the crushed RAP
- asphalt binder content
- aggregate properties including gradation, angularity, etc.
- recovered asphalt binder properties including penetration, absolute and/or kinematic viscosity, and perhaps Superpave PG grading

This information will assist in the selection of the type and amount of liquid recycling additive and with determining whether or not new granular materials are needed to improve the characteristics of the RAP or are needed to address a deficiency in the original asphalt pavement such as flushing, etc.

14.5 GEOMETRIC ASSESSMENT

In the detailed geometric assessment, determine whether the project:

- requires major realignment, widening or drainage corrections
- contains underground utilities/drainage structures
- requires upgrading of any underground utilities
- contains bridges/overpasses
- needs longitudinal/grade corrections
- requires cross-slope/fall corrections

If major realignments, drainage corrections or frost heave mitigation repairs are required, reconstruction may be the preferred rehabilitation alternative. The use of CIR could be included as a stage in the overall rehabilitation process or CCPR could be used, particularly if extensive base, subbase, and/or subgrade problems are present. The existing pavement can be cold planed off and stockpiled for future use. The underlying materials are either removed and replaced or improved by stabilization. The stockpiled RAP could then be processed by CCPR and placed as a stabilized base course material.

CIR has been successfully used on projects where existing granular shoulders have been paved in the rehabilitation process. In order to be successful, the existing shoulder area has to: have sufficient granular material; be of sufficient strength; incorporation of the existing uncoated granular material is limited to 25 percent by weight of RAP; the appropriate stabilizing additive(s) are used; and the wearing course is a HMA of sufficient thickness.

The presence, frequency, and elevation of utility covers (manholes and valves) needs to be assessed, particularly in the urban setting. Manholes and valves should be lowered to 2 to 4 inches (50 to 100 mm) below the CIR treatment depth and their locations accurately recorded. Manholes should be covered with a strong steel plate and the excavation backfilled with RAP. Treatment of the roadway can take place in an uninterrupted manner so that the CIR depth and material consistency can be maintained. After placement of the subsequent wearing course, the manholes and valves are located, neatly excavated, and raised to the appropriate level of the wearing course to provide a smooth profile. Obviously, if any upgrading of the existing underground utilities is required, it should be undertaken prior to rehabilitating the roadway surface. CIR will also help mitigate the cracking at the edges of the underground excavations.

Existing pavements on bridges and overpass decks are traditionally not treated with the CIR process. All bridges and overpasses must be checked for structural capacity to determine whether they can support the CIR equipment.

The cold planers used as part of the recycling train have cutting head widths of 10 to 12 feet (3.0 to 3.7 meters) with extension widths of 1, 2 and 4 feet (0.3, 0.6 and 1.2 meters) being available. Hence, a variety of CIR treatment widths is available from 10 to 16 feet (3.0 to 4.9 meters).

If existing paved shoulders are to be treated, the width of the shoulder will influence how and when it is treated. Paved shoulder widths up to 4 feet (1.2 meters) can be treated at the same time as the adjacent driving lane by using the appropriate width of cold planer in the recycling train. Paved shoulder widths greater than 4 feet (1.2 meters) and less than 10 feet (3 meters) are difficult to treat, but two methods are available, both of which increase the project costs. The first method would be to use a smaller cold planer to mill the shoulder material to the desired depth and cross-slope, and windrow the RAP on the adjacent driving lane in front of the recycling train. The recycling train would then process the shoulder and driving lane material but at reduced production rates due to the volume of materials being handled. This method may not be viable if the CIR treatment depth is over 3 inches (75 mm) due to the material handling capabilities of the recycling train. The second alternative would be to use the smaller cold planer to remove the shoulder material, have the RAP treated using a CCPR facility and then placed on the shoulder prior to treating the adjacent driving lanes.

Pavements that are not whole multiples of the treatment width of the CIR equipment will require some overlap to ensure full CIR coverage. Ideally, an overlap between adjacent CIR passes of 4 to 6 inches (100 to 150 mm) is desired. If the overlaps become significantly larger, there are potentially both economic and performance implications, particularly if significant amounts of new granular material, liquid recycling additive and/or an additional modifier or chemical additive is being used in the process.

The CIR equipment is very long due to the number of pieces in the train. Therefore, roadway geometry, particularly in an urban setting, will influence the types of areas which can be treated. The CIR equipment can handle moderate radius turns such as acceleration/deceleration lanes, turning bays, etc., provided there is sufficient room for the equipment to exit the area. Roadways containing “T” intersections cannot be treated all the way to the top of the “T.” However, small milling machines are effective in working in conjunction with CIR trains to facilitate recycling the entire roadway in urban settings. Paved driveway and other entrances, mailbox pullouts, and other short and narrow areas in the roadway cannot normally be treated. Varying the CIR treatment width for short sections along the length of the project is not practical or recommended.

The CIR process can correct most longitudinal and transverse profile deficiencies prior to placement of the wearing course. However, if the existing pavement profile is severely defective, one of the following corrective operations may be required:

- if the existing asphalt pavement is of sufficient thickness, cold plane the roadway to correct the profile deficiencies prior to CIR
- add either new granular material or RAP from an external source in the CIR process
- correct as much of the profile deficiencies as possible with the CIR process and then correct the remaining profile deficiencies with additional leveling and/or wearing course material

14.6 TRAFFIC ASSESSMENT

Originally, CIR was used on low to medium traffic volume roadways, but it is now routinely being used on higher traffic volume roadways. There is no upper limit to roadway traffic volumes if a proper pavement structural design is undertaken as part of the rehabilitation process to ensure that the effects of future traffic are accounted for.

The CIR process minimizes traffic disruptions and user inconvenience, due to the short construction time compared to conventional pavement rehabilitation methods. CIR can be undertaken in off peak hours to further reduce the traffic disruptions, but this results in reduced daily productivity.

Depending on the width of the existing roadway the CIR operation will occupy 1 1/4 to 1 1/2 lanes within the CIR construction zone. For narrow roadways, accommodation of large/wide truck or oversized loads will need to be addressed.

On two lane roadways, one-way traffic through the construction zone will need to be maintained, with appropriate traffic control such as flag people, lane demarcation devices and/or pilot vehicles. Very narrow two lane roadways increase the traffic accommodation difficulties, particularly if there is little or no paved shoulder.

Traffic control at intersections and at business approaches also needs to be addressed in an urban environment. Due to the speed of the CIR processes, the intersections and approaches are not out of service for very long, and traffic is usually controlled with flag people and lane demarcation devices.

14.7 CONSTRUCTABILITY ASSESSMENT

As the CIR equipment is relatively wide and long, overnight parking/storage of the equipment is a concern. A sufficiently wide overnight parking area is required or the equipment must be allowed to be park on the side of the roadway with use temporary traffic delineation devices, warning lights and/or temporary signals to direct traffic. The width of the roadway being treated will determine whether this is a viable alternative.

The location/spacing of these parking/storage areas are critical since a multi-unit recycling train can process approximately 2 lane miles (3.2 kilometers) per day. Typically, parking areas should be on the order of 1 3/4 to 2 1/2 miles (3 to 4 kilometers) apart, to reduce the amount of equipment travel during the daily mobilization and demobilization. The individual pieces of CIR train have good clearance, so access to the parking area is generally not a problem.

Very steep, long, uphill grades are difficult to process with a multi-unit recycling train since the cold planer will have a difficult time maintaining enough traction to pull the train up the hill. Downhill grades are routinely handled. Single or two-unit recycling trains will be able to handle steeper and longer uphill grades. Grades over 5 percent or 2,500 feet (750 meters) in length generally result in reduced production rates and increased traffic control requirements.

Clear span heights for bridges and underpasses must be checked for not only the CIR equipment but for the haul trucks, as well.

Generally, CIR equipment can process to the edge of a curb and gutter section. For straight-faced concrete sections (with no gutter), a portion of roadway will not be able to be treated. Those areas, not accessible by the large CIR train, can be pre-milled with a small milling machine and the area replaced with CIR mix by use of an extendable screed on the paver or by hand work, similar to what is done on conventional paving projects.

If granular material is required in the CIR process, then the availability of aggregates of suitable gradation and quality must also be assessed.

14.8 ENVIRONMENTAL IMPLICATIONS

Areas that are extensively shaded receive little or no direct sunlight to assist in the breaking and initial curing of the recycling additive, and therefore, take longer to cure and compact. Extended traffic control, for a day or more, will be required to ensure the extensively shaded area does not ravel when opened to traffic. Similar curing conditions/problems can occur if the work is being undertaken in cold, damp conditions typical of late fall or winter weather, when there are pavement areas with poor drainage or higher than average moisture content. In these types of conditions, the use of an additional modifier such as lime or Portland cement or a chemical additive such as Type C fly ash can prove beneficial. The above additives and modifiers usually reduce the curing period and accelerate the strength gain sufficiently to permit the areas to be opened for traffic within a couple of hours.

As with all rehabilitation construction projects, there will be a certain amount of noise associated with the process. Typically, due the speed of the CIR operation and the transient nature of the process the noise effects will be short term. Once again, this issue will have increased concerns is an urban setting.

14.9 ECONOMIC ASSESSMENT

The expected service lives of the various CR rehabilitation techniques, when undertaking a life-cycle economic analysis, generally fall within the following ranges:

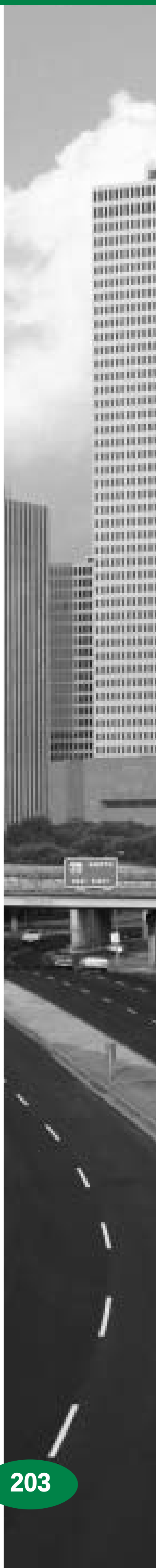
- CIR with surface treatment . . . . 6 - 8 years
- CIR with HMA overlay . . . . 7 - 15 * years
- CCPR with surface treatment . . . . 6 - 8 years
- CCPR with HMA overlay . . . . 12 - 15 * years

Note: * Equivalent to agency’s thick lift HMA service life.

The effectiveness and performance of the various CR rehabilitation techniques varies from agency to agency and is dependent on:

- local conditions
- climate
- traffic
- type of technique and quality of materials used
- quality of the workmanship

Figure 14-2: Completed CIR Project with a Hot Mix Overlay



CHAPTER 15: COLD RECYCLING – MIX DESIGN

Like Hot In-Place Recycling (HIR) and Full Depth Reclamation (FDR), there is no nationally accepted method for the design of Cold Recycling (CR) mixtures, and most agencies that use CR have their own mix design procedures. The Oregon Department of Transportation has an empirical procedure for estimating initial asphalt emulsion content for mixtures with 100 percent Reclaimed Asphalt Pavement (RAP). American Association of State Highway and Transportation Officials/the Associated General Contractors of America/American Road and Transportation Builders Association (AASHTO-AGC-ARTBA) Joint Committee Task Force 38 Report entitled “Report on Cold Recycling of Asphalt Pavements” (Task Force 38) contains mix design procedures for both Marshall and Hveem equipment and many states use it or modified Marshall or Hveem. There is also research underway to adopt Superpave technology to CR mixtures.

The mix design serves as an initial job mix formula, the same as in hot mix asphalt (HMA) construction. Adjustments are generally required for workability, coating, and stability.

Most mix design methods for CR mixes involve the application of asphalt emulsions, emulsified recycling agents or cutbacks as the recycling additive although foamed asphalt and chemical recycling additives have also been used. Three basic theories have been proposed for designing CR mixes with these recycling additives. The first theory assumes that the RAP will act as a black aggregate and the mix design consists of determining a recycling additive content to coat the aggregate. The second theory evaluates the physical and chemical characteristics of the recovered asphalt binder and adds a recycling agent to restore the asphalt binder to its original consistency. The assumption is that complete softening of the old asphalt binder occurs. The third and most prevalent theory is a combination of the first two, where some softening of the old asphalt binder occurs. This theory is referred to as the effective asphalt theory, where the recycling additive and the softened aged asphalt binder form an effective asphalt layer. The degree of softening is related to the properties of the old asphalt binder, recycling additive, and environmental conditions. Because the degree of softening is difficult to quantify, it is recommended that mechanical tests on the CR mix be a part of all mix designs.

Most State Highway Agencies that utilize CR have their own mix design procedures. The procedures range from simple to complex. The simplest methods entail empirical formulas based on the amount and consistency of the recovered asphalt binder to predict an initial recycling additive content. The complex methods include sophisticated testing such as resilient modulus, stability, and moisture sensitivity tests. Testing often includes short-term and long-term curing conditions. Adjustments are made in the field to the initial recycling additive content for optimum performance. The different methods generally address all or a portion of the following steps or procedures, as shown in Figure 15-1. The issues concerning each step of the general procedure are addressed in subsequent sections.

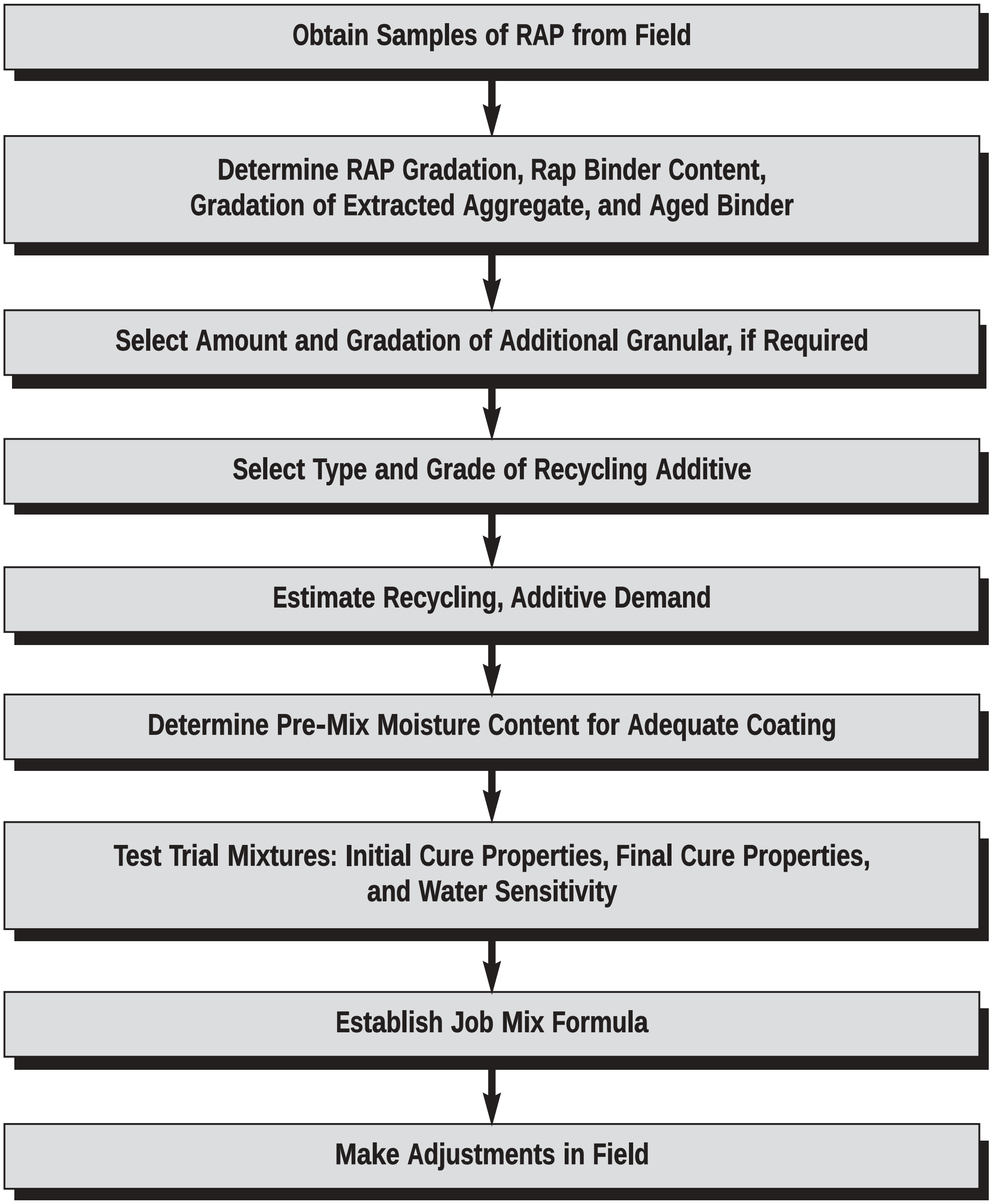


Figure 15-1: CR mix design flow chart

15.1 SAMPLING EXISTING PAVEMENT

Representative samples of the RAP should be obtained and evaluated to properly design a CR mixture. A sampling plan must be developed that adequately determines the physical properties of the RAP along the length of the project. A visual evaluation should be made along with a review of construction and maintenance records, to determine whether significant differences in materials will be encountered. Sections of the roadway with significant differences in materials should be delineated and treated as separate sampling units to ensure representative sampling. Areas with different mixtures and/or extensive maintenance mixtures should not be lumped together for design. After delineating representative sampling units, samples of the pavement should be obtained from each unit, using random sampling techniques. Stratified random samples are usually recommended, where a random sample or samples are obtained from each lot of the sampling area. The number of sampling lots and samples per lot vary with the length of the project and traffic. For larger jobs, length greater than 4 miles (6.4 kilometers), one random sample per lane 5/8 lane mile (kilometer), with a minimum of six samples per project, is often recommended. In urban locations, others recommend sampling frequencies of five samples per 5/8 lane mile (kilometer) or one per block due to the increased variability encounter with urban asphalt pavements.

Samples usually consist of cores. These should be obtained full depth, as the thickness of the pavement after milling must be evaluated to ensure that the remaining pavement can support the weight of the recycling train. It is generally recommended that a minimum of 1 inch (25 mm) and preferably 2 inches (50 mm) of asphalt material or 6 inches (150 mm) of aggregate base remain to support the weight of the recycling train.

The gradation of the RAP and extracted mineral aggregate will have an effect on the selection of the amount of recycling additive and on final mixture performance. Therefore, the importance of obtaining realistic field samples cannot be overemphasized. Representative samples of RAP are required. Field sampling has traditionally been obtained by coring/sawing or small milling machines. The popularity of using small milling machines to obtain field samples is declining since the consistency of the samples between different types of small milling machines is highly variable and it is relatively expensive. The gradation of the samples obtained by small milling machines is not as coarse with smaller maximum particle size and more fines, i.e., passing No. 200 (0.075 mm) sieve size than what is produced by the large milling machines during the CIR process. The current trend is to obtain samples by means of coring, usually 6 inches (150 mm) in diameter, and then subsequently crushing the cores in the laboratory. With field coring and laboratory crushing, the sample gradation more closely resembles what is achieved in the field during the CIR process. Block sampling, by means of sawing, can also be used, but it is usually more expensive than coring. It is important that the full depth of the asphalt bound layers be cored in order to assess its condition. However, only the upper portions of the core, equivalent to the anticipated CIR treatment depth, are used for subsequent analysis. Regardless of the method used to obtain RAP, it is recommended that agencies obtain samples of the RAP during construction to compare to mix design gradations. Based on this database, adjustments in gradations for mix design samples could be evaluated.

15.2 DETERMINATION OF RAP PROPERTIES

The properties of the RAP, extracted aggregate, and recovered asphalt cement should be evaluated. The gradation of the RAP should be determined in accordance with the American Association of State Highway and Transportation Officials (AASHTO) T 27 “Sieve Analysis of Fine and Coarse Aggregate” or the American Society for Testing and Materials (ASTM) C 136 “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate.” The asphalt content of the RAP needs to be determined, as well. For smaller projects, where it is not feasible to determine the properties of the recovered asphalt cement, the asphalt content may be determined in accordance with ASTM D 6307 "Test Method for Asphalt Content of Hot Mix Asphalt by the Ignition Method."

For larger projects, it is recommended that the properties of the recovered asphalt cement be determined, to assist in selecting the proper grade of recycling additive. The asphalt content of the RAP should be determined using AASHTO T164 "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures." Other extraction procedures can alter the properties of the recovered asphalt cement. Preheating the RAP for 3 hours at 250°F (120°C) prior to extraction is necessary, to determine the residual asphalt content of mixtures made from cutback asphalts or asphalt emulsions containing solvents.

The aged asphalt binder should be recovered from the RAP using the Rotovap procedure, as outlined in ASTM D5404 "Test Method for Recovery of Asphalt from Solution Using the Rotovapor Apparatus." If the equipment is not available, AASHTO T 170 "Recovery of Asphalt from Solution by Abson Method" may be substituted. The recovered asphalt binder should be tested to determine the effects of aging on the stiffness and consistency. At a minimum, the penetration at 77°F (25°C) and/or the absolute viscosity at 140°F (60°C) should be determined. The recovered penetration and viscosity data are useful in determining the proper grade of recycling additive for CR mixtures.

Current research is focusing on the use of the Superpave binder test property of G*/sin d (see Chapter 5 for an explanation of G* and d) for determining the grade of recycling additive. It is anticipated that the results from this study will be implemented in the future, replacing penetration and absolute viscosity.

15.3 SELECT AMOUNT AND GRADATION OF NEW AGGREGATE

Most CR projects are constructed without the addition of new aggregates, including some with fine gradations. The decision to add new aggregate should not be based on the gradation of the aggregate recovered from the RAP alone, because coarse angular particles of conglomerated fines can be manufactured by cold milling that are not broken down by traffic. However, the addition of new aggregate can be beneficial and justified in some cases, such as when excess asphalt binder is present or when it is deemed desirable to increase the structural capacity of the mix. Mixture testing should be performed to insure that the additional costs incurred result in measurable improvements in performance.

The gradation of the extracted aggregate, recovered from ASTM D 6307 or AASHTO T 164, should be determined, using a washed sieve analysis in accordance with AASHTO T 11 "Materials Finer Than 75-mm Sieve in Mineral Aggregates by Washing" and AASHTO T 27. Based on the gradation of the aggregate extracted from the RAP, the need for new aggregates can be evaluated. Many CR projects consist of upgrading lower volume pavements for higher traffic volumes. Many of these pavements contain local aggregates of lower quality, such as sand and gravel mixtures that may not provide adequate structural capacity. Increasing the percent coarse aggregate and the percent crushed material may improve the structural capacity of the pavement. RAP mixtures with excess asphalt binder can sometimes benefit from the addition of new aggregates, as well.

In areas where good quality coarse aggregates are not available, self cementing type C fly ash or type C fly ash/Portland cement blends, have been successfully utilized as a recycling additive to improve the structural capacity and reduce moisture damage potential of CR mixes.

Besides new aggregates, additional RAP may be added when a thicker section is desired but the depth of milling must be reduced because of the presence of a weak layer. RAP or new aggregate is recommended to prevent a reduction in the depth of the CR layer when roadway widening is undertaken.

New aggregates should be selected so that the blend of the new aggregate, and aggregate in the RAP, meets current specifications, in both gradation and quality. The Asphalt Institute has recommendations for aggregates for cold mix, but other agency specifications are suitable, as well. The Asphalt Institute recommends a minimum sand equivalent of 35 percent, a maximum Los Angeles Abrasion at 500 revolutions of 40, and a minimum percent crushed faces of 65 percent. Typical gradations for CR base mixes are shown in Table 15-1.

Sieve Size	A	B	C	D
	Percent Passing			
1.5” (40.0 mm)	100			
1” (25.0 mm)	90-100	100		
3/4” (20.0 mm)		90-100	100	
1/2” (12.5 mm)	60-80		90-100	100
3/8” (9.5 mm)		60-80		90-100
No. 4 (4.75 mm)	25-60	35-65	45-75	60-80
No. 8 (2.16 mm)	15-45	20-50	25-55	35-65
No. 50 (0.300 mm)	3-20	3-21	6-25	6-25
No. 200 (0.075 mm)	1-7	2-8	2-9	2-10

Table 15-1: Gradation Guidelines for CR Combinations of Aggregates from RAP and New Aggregates

Fine aggregates, especially natural sands, should not be added to CR mixtures unless the effect on performance is thoroughly evaluated. The milling process can increase the fines in the mix and the amount depends on many factors, including the type of existing aggregates. Adding new fines could lead to a loss of stability, difficulty in coating the RAP, reduced tolerance for water, and poor dispersion of the recycling additive.

15.4 ESTIMATE NEW RECYCLING ADDITIVE DEMAND

New or additional asphalt binder is necessary to facilitate compaction, improve the cohesion of the mix, and to reduce the viscosity of the aged binder. The recycling additives typically used to supply the new or additional binder are asphalt emulsions, recycling agents or cutback asphalts. The optimum recycling additive content for these additives is typically in the 0.5 to 3.0 percent range for CR mixtures using 100 percent RAP. For most mix designs this new recycling additive content is established based on previous experience or by using empirical formulas. The new or additional recycling additive demand is a starting point for mixture design purposes. For some jobs, the optimum recycling additive content is based on this initial estimate, with changes made in the field by experienced personnel.

The Oregon Department of Transportation has an empirical formula for estimating new or initial asphalt emulsion content, based on their experience. The formula is applicable to mixtures containing 100 percent RAP. The method is based on the gradation, asphalt binder content of the RAP and the penetration and absolute viscosity of the recovered binder. The procedure consists of adjusting a base asphalt emulsion content of 1.2 percent, based on the weight of the RAP, for properties of the RAP and recovered asphalt binder.

15.5 SELECTION OF RECYCLING ADDITIVE

The correct selection of the type and grade of recycling additive is necessary for the proper performance of CR projects. The most common recycling additives for CR mixtures are asphalt emulsions and emulsified recycling agents because they are liquid at ambient temperatures, and can be readily dispersed throughout the mix. Polymer modified versions of asphalt emulsions and emulsified recycling agents have been used to improve early strength, resist rutting, and reduce thermal cracking. Other modifiers, such as Portland cement or lime can also be incorporated to improve properties of the recycled mix. Portland cement or lime, both hydrated and slaked quicklime, has been used in combination with asphalt emulsions to improve early stiffening and improve moisture damage resistance.

15.5.1 ASPHALT EMULSIONS

The most common recycling additives are cationic and anionic mixing grade asphalt emulsions, both medium setting and slow setting, and high float emulsions, with and without polymers. Medium-setting (MS) asphalt emulsions are designed to mix well with open or coarse graded aggregates. They do not break on contact and will remain workable for an extended period of time. High float medium-setting (HFMS) asphalt emulsions are a special class of anionic medium-setting asphalt emulsions. They have a gel structure in the asphalt residue which allows for thicker films on aggregate particles, giving better coating in some instances, such as under high temperatures.

Slow-setting (SS) asphalt emulsions work well with dense graded aggregates or aggregates with high fines content. The slow-setting asphalt emulsions have long workability times to ensure good dispersion with dense graded aggregates. Slow-setting asphalt emulsions are formulated for maximum mix stability.

Some agencies recommend that a medium-setting asphalt emulsion with solvent be used when the penetration of the recovered asphalt binder is less than 30 and that slow-setting asphalt emulsions be used if the penetration of the recovered asphalt is greater than 30. Some agencies, such as the Pennsylvania DOT, use hard residue asphalt emulsions (CMS-2h, HFMS-2h and CSS-1h) when the recovered asphalt binder penetration is greater than 30. Other agencies require polymer modified asphalt emulsions when the recovered penetration is less than 10.

The asphalt emulsion selected should be compatible with the RAP and new aggregate, if utilized. The surface of an aggregate has an electrical charge, with siliceous aggregates having a more negative surface charge and calcareous aggregates a more positive charge. Cationic asphalt emulsions, those designated with a C in front of the grade, contain a negative charge and are selected for use with siliceous aggregates. Anionic asphalt emulsions, no designation before the grade, contain a positive charge and are preferred with calcareous aggregates. When new aggregates are incorporated into the CR mix, the type of asphalt emulsion should be selected based on the charge on the new aggregate. However, the charge on the RAP is not necessarily related to the charge on the surface of the aggregate in the RAP, and the selection should not be based on the type of aggregate alone. For CR mixtures with 100 percent RAP, the asphalt emulsion is selected to optimize coating and initial strength, and control breaking times. Field records from previous projects should be consulted for information on which types and grades of asphalt emulsions have worked well. AASHTO T 59 “Testing Emulsified Asphalts” can be used to evaluate coating as an aid in selecting the recycling additive.

15.5.2 RECYCLING AGENTS

Emulsified recycling agents are the normal means of using a rejuvenator in cold recycling of aged asphalt. The emulsified recycling agent is usually manufactured as a cationic asphalt emulsion. A growing trend is the use of custom or proprietary emulsified recycling agents. Suppliers custom blend recycling agents with various amounts of asphalt emulsion binders. The blended product is designed to restore some of the consistency of the aged asphalt binder while also adding additional asphalt to the mix.

The selection of recycling agent depends on the asphalt demand and on the desired reduction in viscosity of the aged asphalt binder. The effectiveness of recycling agents in reducing the viscosity of the aged asphalt is based on a number of factors. The reactions are complicated and depend on the time and temperature-dependent interaction between the recycling agent and the aged asphalt binder. The rate of softening is a function of the properties of the recycling agent and aged asphalt binder, mechanical effects such as mixing, compaction, traffic, and climatic conditions. Therefore, when determining the amount and type of recycling agent, it is recommended that the mechanical properties of the recycled mix be determined both before and after final curing, rather than simply relying on blending charts based on consistency.

15.5.3 CUTBACK ASPHALTS

Cutback asphalt cements have been successfully utilized in the past but are not currently preferred due to environmental and safety concerns, as the flash point of some cutbacks, could be at or below the CR application temperature. It is also noted that some jurisdictions have restricted or even prohibited the use of cutback asphalts.

15.5.4 FOAMED ASPHALTS

Foamed asphalt cements have been used in the past and there is renewed interest in their use. However, most 100 percent RAP mixtures contain an insufficient amount of fines for use with foamed asphalts.

15.5.5 CHEMICAL ADDITIVES

Type C fly ash, lime and Portland cement, added as a slurry, have been successfully utilized as a recycling additive in CR. These chemical additives can be used to improve early strength gain, increase rutting resistance, and improve moisture resistance of CR mixtures containing rounded coarse aggregates and a high percentage of natural sands. Lime and Portland cement contents used typically used have been 1 to 2 percent by weight of RAP. Fly ash contents in the 8 to 12 percent range have been reported. There is no standard method for determining fly ash content. Mix design methods are available from the American Coal Ash Association.

15.6 DETERMINE PRE-MIX MOISTURE CONTENT FOR COATING

For most recycling additives moisture will be required for adequate coating. The water required for coating is usually greater than that needed to facilitate compaction. The water may be in the RAP as free moisture or may be added to the CR mixture. The water may be added before the addition of the recycling additive, such as at the cutting head for lubrication and cooling or in the pugmill, along with the recycling additive. For slow-setting asphalt emulsions and the anionic grades of medium-setting asphalt emulsions, moisture is required during mixing for adequate coating. High float emulsions and cationic medium-setting asphalt emulsions can contain petroleum distillates and will perform better with drier aggregates than wet aggregates.

Regardless of the recycling additive used, it is recommended that a coating test be performed to determine whether mixing water is needed to disperse the additive. Coating tests generally consist of mixing 2.2 pounds (1000 grams) of RAP with the estimated initial amount of recycling additive and varying amounts of water. Water is added in equal increments, usually 0.5 percent, by weight of the RAP. The water is added and mixed briefly to dampen the RAP, maximum of 30 seconds. The recycling additive is added and the mixture is mixed for an additional 60 seconds. The dispersion is visually evaluated and the lowest moisture content that results in no additional increase in coating is selected. Hand mixing using a spoon and bowl is preferred over mechanical mixing because coating and workability are easily observed. For the typical recycling additives of asphalt emulsions and emulsified recycling agents, the sum of the mix water content, recycling additive and moisture content of the RAP is referred to as the total liquids content. The total liquids content will vary from project to project and must be established during the mix design.

15.7 TRIAL MIXTURES

The amount of mixture testing is dependent on the size and scope of the project. For smaller projects, mixture testing is sometimes omitted, although this is not recommended. There is no one universally accepted mix design method for CR. Some or all of the following procedures are usually preformed.

15.7.1 BATCHING

A representative portion of the RAP should be dried to a constant mass at 230°F (110°C) and the moisture content determined. The moisture content is needed in the coating test. The remainder of the RAP should be sieved over a series of sieves, starting with the maximum sieve size allowed in the specifications and ending with the No. 4 (4.75 mm) or No. 8 (2.36 mm) sieve. Material retained on the maximum sieve size should be reduced in size without creating excess fines or be discarded. Samples of the appropriate size, typically 2.4 pounds (1100 grams) for 4 inch (100 mm) diameter Marshall size samples or 8.8 pounds (4,000 grams) for 6 inch (150 mm) diameter Superpave Gyratory Compactor (SGC) samples, should be batched to the same gradation as the RAP. The number of samples required depends on the level of testing. It is generally recommended that triplicate samples be made at each recycling additive content for testing and evaluation.

15.7.2 MIXING

Prior to mixing the RAP with the recycling additive and mix water, the materials are brought up to the desired mixing temperature. Most mixing is accomplished at ambient temperatures of 68 to 77°F (20 to 25°C), and heating the materials is not required. Some agencies heat emulsified recycling additives to 140°F (60°C) for one hour prior to mixing. Preheating an emulsified recycling additive expedites breaking of the emulsion. The mix water can be heated to the same temperature as the emulsified recycling additive.

For 4 inch (100 mm) diameter Marshall sized samples, approximately 2.4 pounds (1100 grams) of RAP is mixed at the total liquids content previously determined. The recycling additive is varied above and below the initial additive content in 0.7 percent increments. For asphalt emulsions, this results in a change in the residual asphalt content of about 0.5 percent. The mix water is adjusted to keep the total liquids content the same for all samples.

15.7.3 COMPACTION

Mix design samples are compacted using a standard compactive energy. The compactive energy should produce a laboratory compacted sample with a comparable density to field produced mix. Compaction at elevated temperatures 140°F (60°C) using 50 blow Marshall compaction has been used by some agencies. This is somewhat undesirable, as the temperature of the mix never approaches this elevated temperature. Recent work has shown that 75 blow Marshall compaction at field mix ambient temperatures of approximately 100°F (40°C) resulted in densities comparable with field densities. Compaction using the SGC has been shown to work with CR samples. However, the Ndesign number of compaction gyrations must be reduced from those recommended for HMA to reproduce expected field densities. Efforts are currently underway to verify the number of design gyrations.

In the field, CR mixtures are typically compacted as the mixture begins to break. For asphalt emulsions and emulsified recycling agents, this is indicated by a change in color of the mixture from brown to black. Samples compacted at ambient temperatures can be compacted immediately after mixing or allowed to break prior to compaction. Breaking can take up to 2 hours for samples of loose mix placed in a pan. Heating the liquids, as previously described in Section 15.7.2 expedites breaking. For samples compacted at elevated temperatures, the loose mix is placed in an oven at the compaction temperature until the mixture reaches the compaction temperature, 1 to 2 hours. The mix should break during this time. Allowing the sample to break prior to compaction will result in a loss of some of the mix water to evaporation and it will not be available to assist compaction. Newer mix design methods are moving toward compacting samples at ambient temperatures and prior to initial breaking.

Compaction typically follows Marshall procedures AASHTO T 245 “Resistance to Plastic Flow of Bituminous Mixtures Using the Marshall Apparatus” or ASTM D 1559 “Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using the Marshall Apparatus” or Hveem procedures AASHTO T 246 “Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus” or ASTM D 1561“Test Method for Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus.” As previously discussed, the compactive effort must be adjusted to produce laboratory samples with densities comparable to field densities. Compaction temperatures, mix/material temperatures, and allowing mix samples to break will all effect the compacted density of the samples.

15.7.4 CURING

CR mixtures must lose their excess water and cure, to develop maximum strength potential. Mixture testing can be performed to evaluate initial placement conditions, short-term curing or final strength (final curing). Curing procedures vary by agency. Short-term curing is typically carried out by holding the compacted samples at an elevated temperature of 140°F (60°C) for 2 to 4 hours. The samples are left in their compaction molds and are placed on their sides. Samples can be damaged if removed from the molds too soon.

Long-term curing sometimes consists of holding samples at elevated temperatures of 230°F (110°C) until they reach a constant mass. Other agencies hold the samples at 140°F (60°C) for 24 to 48 hours to simulate long-term curing conditions. Samples can be removed from the compaction molds prior to long-term curing.

15.7.5 STRENGTH TESTING

Prior to strength testing and regardless of the type of curing, the samples usually undergo a bulk specific gravity test. Approximate volumetrics can be determined from compacted specimens, however the volumetrics of voids in total mix (VTM), voids in mineral aggregates (VMA), and voids filled with asphalt (VFA) are often not evaluated because of the difficulty of removing all of the mixing water from cured samples. The bulk density is usually determined by AASHTO T 166 "Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens" or ASTM D 2726 "Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures," or by dividing the mass of the sample by the measured sample volume. The bulk density is used to verify compaction of like samples and is used in construction quality control.

Strength testing has consisted of Marshall stability and flow, AASHTO T 245 or ASTM D 1559, Hveem stability, AASHTO T 246 or ASTM D1560, unconfined compression AASHTO T 167 "Compressive Strength of Bituminous Mixtures" or ASTM D 1074 "Test Method for Compressive Strength of Bituminous Mixtures," Indirect Tensile Strength (ITS), ASTM D 4123 "Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures" or Resilient Modulus, ASTM D 4123. There are no firm guidelines or threshold values for strength tests.

The optimum recycling additive content (ORAC) can be selected to optimize one or more of the above strength properties. A second approach to selecting the ORAC is to evaluate the compacted VTM. The VTM of the compacted samples are evaluated by determining the maximum specific gravity of a sample of loose mix at each recycling additive content in accordance with AASHTO T 209 "Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures" or ASTM D 2041 "Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures." The VTM is calculated in accordance with AASHTO T 269 "Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures" or ASTM D 3203 "Test Method for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures." The Asphalt Institute's publication MS-2 contains a good description of void calculations for asphalt mixtures. The ORAC is selected to give a VTM between 9 and 14 percent and/or at the peak density. The recycling additive content should not be artificially adjusted to reach the suggested VTM range. Suggested mix design procedures are available from the Task Force 38 Report on Cold In-Place Recycling.

In areas where there is a history of moisture susceptibility problems, some type of moisture conditioning test is warranted. AASHTO T 283 "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage" is the most common method used, although others have used the Index of Retained Resilient Modulus (IRRM). The IRRM is determined by dividing the resilient modulus of moisture conditioned samples by the resilient modulus of non-moisture conditioned, samples. The moisture conditioning is typically the same as described in AASHTO T283. Samples for moisture susceptibility testing are compacted to the mix design density, not 7 percent VTM as specified in AASHTO T283. Typical tensile strength ratios (TSR) for CR materials are greater than 70 to 80 percent. Portland cement and lime, both dry and slurry, have been shown to greatly improve TSR.

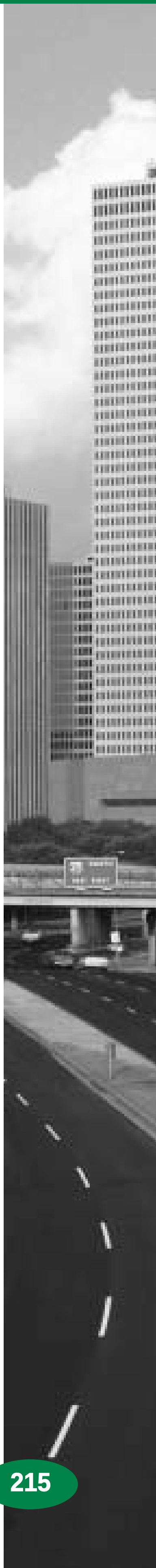
15.8 ESTABLISH JOB MIX FORMULA

At the completion of the mix design, the Job Mix Formula (JMF) is established. The JMF should specify the ORAC, type and grade of recycling additive, the mix water content, and laboratory compacted maximum density at the ORAC. These should be considered as starting points for construction and may need to be adjusted in the field by qualified individuals as conditions warrant.

15.9 FIELD ADJUSTMENTS

Adjustments to the JMF will be required as conditions warrant, and field personnel need the authority to make slight adjustments in mix water content and amount of recycling additive, based on changing field conditions. Slight adjustments in mix water of 1 to 2 percent and/or asphalt emulsion or emulsified recycling agent content of up to 0.5 percent or more could be necessary to ensure adequate dispersal of the recycling additive.

Field conditions that could warrant slight changes in mix water, asphalt emulsion or emulsified recycling agent are changes in the gradation of the RAP and changes in temperature. Changes in gradation of the RAP could result from non-uniformity of the pavement due to maintenance procedures or areas of non-uniformity of the original mix. A lowering of the pavement temperature can result in a coarsening of the RAP gradation and a lower compacted mat density. Increasing the recycling additive content to increase density could lead to an over asphalted mix and cause stability/workability problems. Changes in humidity levels and other environmental factors can effect the breaking of the asphalt emulsion or emulsified recycling agent, and affect dispersion and workability of the CR mixture. However, changes in the recycling additive content due to environmental conditions must be made with care or premature pavement failure could result.



CHAPTER 16: COLD RECYCLING – CONSTRUCTION

Cold recycling (CR) is not a new method of rehabilitating deteriorating roadways. For the past 50 years or more CR which was often called stabilization, has been practiced by various methods. These methods have included rippers, scarifiers, pulvimixers, and stabilizing agents to reclaim the existing surface and underlying materials. Asphalt emulsions, cutbacks and other recycling additives have been added and mixed by spraying the liquid on a windrow and mixing with a blade, with cross shaft mixers, and with various types of traveling plants. The CR material was blade laid and compacted with available compaction equipment.

There are two methods of CR asphalt pavements: Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR). CIR is faster, more economical, less disruptive, and environmentally preferable because trucking is greatly reduced. CIR is defined as an asphalt pavement rehabilitation technique that reuses existing pavement materials. CIR involves the processing, and treatment with bituminous and/or chemical additives, of the existing asphalt pavement without heat to produce a restored pavement layer. All work is completed while on the pavement being recycled. Transportation of materials, except for the recycling additive(s) being used, is not normally required. The depth of processing is typically 3 to 5 inches (75 to 125 mm). The process is sometimes referred to as partial depth recycling because the underlying materials and or some of the bituminous materials are left intact. In-Place recycling that incorporates untreated base material with the bound material is referred to as Full Depth Reclamation (FDR) and is discussed in Chapters 10 through 13.

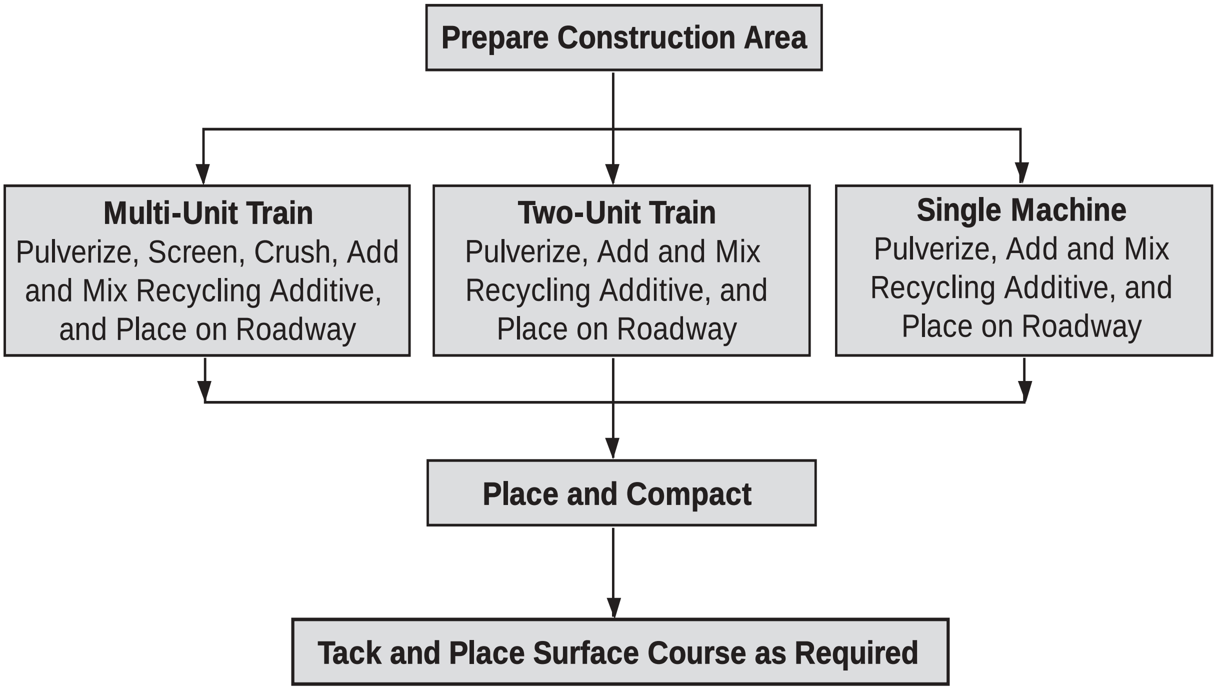


Figure 16-1: CIR construction flow chart

Today, through the innovations of equipment manufacturers, contracting agencies, and contractors, remarkable advancements have been made in the CIR process. The most important advancement was the development of the large cold planing machines. Modern CIR equipment can process up to 2 lane miles (3.2 kilometers) of roadway a day. The result is a stable, rehabilitated roadway at a total expenditure of 40 to 50 percent less than that required by conventional construction methods. The typical construction sequences for CIR are shown in Figure 16-1.

In many locations, high quality Reclaimed Asphalt Pavement (RAP) millings are available and CCPR can produce a high quality, economical paving material, preventing a valuable resource from being land filled. CCPR methods are appropriate when an existing pavement cannot be in-place recycled and must be removed to allow treatment of underlying materials. Typical construction sequences for CCPR are shown in Figure 16-2.

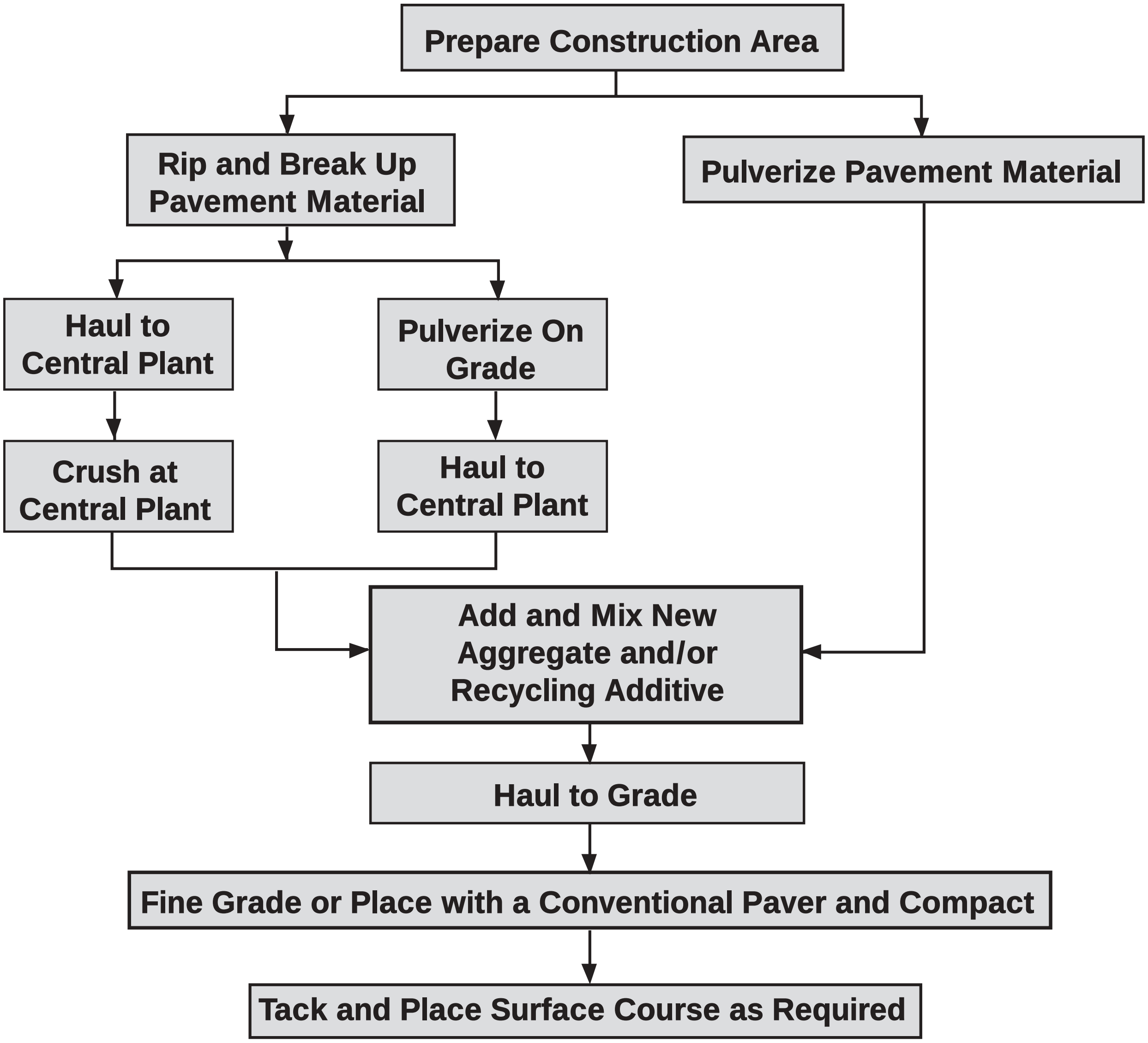


Figure 16-2: CCPR construction flow chart

Figure 16-3: Cold In-Place Recycling Arterial City Streets

The equipment and procedures for each method are discussed in the following sections.

16.1 COLD IN-PLACE RECYCLING METHODS

The use of the CIR train has become the rehabilitation method of choice since the greatest savings occur when trucking costs are eliminated. Both two-unit and multi-unit trains operate with high productivity, excellent quality control, and reliability.

When evaluating a project for CIR, several factors can influence the type of equipment best suited for the project. Milling machines currently used with CIR have 10 to 12 feet (3.0 to 3.7 meters) wide cutting drums with extensions up to 4 feet (1.2 meters) available. Pavements less than 20 feet (6.0 meters) wide could prove difficult to CIR and maintaining traffic could be a problem. Shoulders are often incorporated into the CIR mixture. This prevents existing distress in the shoulder, typically cracks, from propagating into the recycled mix and its overlay. Pavements with shoulders 4 feet (1.2 meters) wide or less can be recycled in one pass by using an appropriate sized extension to the milling machine. A second approach is to use a smaller milling machine to mill the shoulder and deposit the RAP in a windrow in front of the train. Pavements with 6 feet (1.8 meter) shoulders and 12 feet (3.7 meter) lanes, up to 18 feet (5.4 meters) total width, have been recycled in this manner. The windrow and full lane are then recycled in one pass. Shoulders wider than 10 feet (3 meters) can be recycled in one pass.

CIR has been successfully completed on all types of roads, ranging from low volume rural county roads, to city streets, to Interstate highways with heavy truck traffic. However, maintaining traffic through and around the construction zone needs to be considered, especially on roads with limited pavement and or shoulder widths and or few alternate or bypass routes. The single or two-unit trains are usually preferred in urban areas with numerous cross streets and business or residential access.

16.1.1 PREPARATION OF CONSTRUCTION AREA

Prior to construction, areas of non-uniform materials or pavement thickness should be identified. Areas with either insufficient pavement thickness or subgrade strength to support the weight of the recycling train should be identified. These areas of insufficient support must be corrected prior to recycling or risk the cold planing machine or other CIR equipment breaking through the pavement, causing construction delays and added expense. Weak material should be removed and replaced with suitable patching material. Areas of the project that exhibit frost heave should be identified and the frost susceptible materials removed and replaced with suitable patching material. RAP is an excellent choice for patching material. Aggregates may be used, as well. Large areas patched with aggregate could require increases in recycling additive for proper coating. The use of RAP eliminates this concern. Small aggregate patches are acceptable but will result in some uncoated aggregate.

Portions of the project that were identified during mix design as requiring different recycling additive content should be identified and construction personnel made aware of the situation.

16.1.2 RECYCLING TRAINS

16.1.2.1 SINGLE UNIT TRAIN

There are several variations of single unit trains available, with one variation shown in Figure 16-4.

With the single unit train the milling machine cutting head removes the pavement to the required depth and cross-slope, sizes the RAP and blends the recycling additive with the RAP. Single train units do not contain screening and crushing units, making control of the maximum particle size more difficult. Most single unit trains are capable of producing uniform RAP with a maximum size of 2 inches (50 mm) by operating the cutting head in the down cutting mode and controlling the forward speed. The forward speed of the machine can help control the coarseness of the millings since reducing the forward speed results in a finer RAP. Pavements that are badly alligator cracked, make controlling the maximum particle size difficult

A spray bar in the cutting chamber adds the liquid recycling additive. The liquid recycling additive is either self-contained in the unit or provided by a tanker truck which is often towed or pushed by the single unit train. The amount is based on the treatment volume, determined by the cutting depth and width, and the anticipated forward speed of the unit. Single unit trains provide the lowest degree of process control because the recycling additive application rate is not directly linked to the treatment volume. Roadways that are badly distorted due to rutting, edge drop-off, etc. are not good candidates for CIR with the single unit train, because proper recycling additive application rate would be difficult to ensure.

Figure 16-4: Single unit CIR train

Dry additives and or new aggregates can be applied by spreading the material on the pavement ahead of the milling machine prior to milling. One pass of the single unit train is sufficient to adequately pulverize and mix all ingredients. The recycled mix is placed with a screed attached to the cold planer, as indicated in Figure 16-4.

The advantages of the single unit train are simplicity of operation and high production capacity. The single unit train may be preferred over the multi-unit train in urban areas and on roads with short turning radius, due to its short length. The main disadvantages of this method are the limitations on RAP aggregate oversize, limitations on precise material proportioning, and minimal mixing times.

16.1.2.2 TWO-UNIT TRAINS

Many CIR trains now incorporate pugmill mix-pavers as an integral part of the train. These two-unit trains, as shown in Figure 16-5, consist of a large, full lane milling machine and a pugmill mix-paver. The pugmill mix-pavers are predominately cold mix pavers with an integral metered pugmill in the chassis. The milling machine removes the RAP. The two-unit train does not contain crushing and screening unit. Control of RAP maximum size and gradation is the same as with single unit trains. The mix is deposited into the pugmill of the mix-paver. The pugmill contains a feeder belt with a belt scale and a processing computer to accurately control the amount of liquid recycling additive. The mix leaves the pugmill directly into the paving screed auger system. The two-unit train provides an intermediate to high degree of process control, with the liquid recycling additive being added based on the weight of the RAP, independent of the treatment volume and forward speed of the train.

Figure 16-5: Two-unit CIR train

The advantages of the two-unit train are simplicity of operation and high production capacity. The two-unit train may be preferred over the multi-unit train in urban areas and on roads with short turning radius due to its short length. The main disadvantage of this method is the limitation controlling RAP aggregate oversize.

16.1.2.3 MULTI-UNIT TRAINS

The multi-unit train typically consists of a milling machine, a trailer mounted screening and crushing unit and a trailer mounted pugmill mixer, as indicated in Figure 16-6. The milling machine mills the pavement to the desired depth or cross-slope. The milling head can operate either in a down cutting mode which results in a finer RAP gradation or in the up cutting mode which results in higher capacity.

The RAP is deposited into the screening and crushing unit. All material is passed over the screening unit and oversize material sent to a crushing unit, typically an impact crusher. The crushed material is returned to the screening unit for resizing. The maximum size of the RAP is controlled by the opening size of the bottom of two screens.

The RAP proceeds from the screening and crushing unit to the pugmill mixer. A belt scale on the belt carrying the RAP to the pugmill determines the weight of the RAP entering the pugmill. The amount of liquid recycling additive is controlled by a computerized metering system, using the

Figure 16-6: Multi-unit CIR train

mass of material on the belt scale. Liquid recycling additive is added to the pugmill by a pump equipped with a positive interlock system which will shut off when material is not in the mixing chamber. A meter connected to the pump registers the rate of flow and total delivery of the liquid recycling additive introduced into the mixture. A twin shaft pugmill blends the liquid recycling additive and RAP into a homogenous mixture. Trains equipped with computerized metering systems have the highest degree of quality control and the highest productivity, about 2 lane miles per day (3.2 lane kilometers).

The material leaving the pugmill is deposited in a windrow or deposited directly into the paver hopper. The material from the windrow is picked up with a windrow elevator and is placed and compacted using conventional HMA paving equipment.

The multi-unit train provides the highest level of process control. The main advantages of the multi-unit train are high productivity and high process control. The major disadvantage is the length of the train which can make traffic control difficult in urban locations.

16.1.3 FIELD ADJUSTMENTS TO THE MIX

CR is a variable procedure. Changes in the gradation of the RAP result in changes in the workability of the mix. The Job Mix Formula (JMF), optimum moisture, and recycling additive contents developed in the laboratory are starting points for construction. Adjustments in the mix water content or recycling additive content may be necessary to promote good coating and workability. Changes to these values should be made judiciously and only by experienced personnel. Rigid adherence to the original JMF recommendations may result in less than optimum performance.

One of the first things to evaluate is the coating of the mix. Adequate coating is desired. If the mix is not sufficiently coated, the mix water content is increased first. Excessive mix water may cause the asphalt to flush to the surface, retarding curing. Too little mix water results in mix segregation, raveling under traffic or poor density. Reducing the asphalt emulsion one grade softer may improve coating.

If the recycled mix is adequately coated but lacks cohesion, the amount of asphalt emulsion or emulsified recycling additive is increased. Too much asphalt emulsion or emulsified recycling agent will result in an unstable mix, and too little may cause the mixture to ravel, although minor raveling is acceptable. The balling of fines is usually the result of excessive asphalt emulsion or emulsified recycling agent or excessive fines in the RAP.

The following field test has been used to evaluate cohesion. A ball of the material is made by squeezing the material in the fist. If the ball is friable (falls apart after the pressure is released), the mix lacks cohesion. The palm of the hand should contain specks of asphalt, indicating the proper asphalt emulsion or emulsified recycling agent content. If the hand is stained, the asphalt emulsion or emulsified recycling agent content could be too high.

Adjustments to the initial asphalt emulsion or emulsified recycling agent content should be made based on the appearance of the mat after initial compaction. With the proper asphalt emulsion or emulsified recycling agent content, the mat should be brown and cohesive. Excess raveling is an indication of too little recycling agent and a shining black mat is an indication of too much. Adjustments in asphalt emulsion or emulsified recycling agent are typically made in 0.2 percent increments and should only be made by experienced personnel. An increase or decrease in the recycling additive may be followed by an equivalent change in the mix water content to keep the total liquids content the same.

16.1.4 LAYDOWN AND COMPACTION

Either conventional asphalt pavers or cold mix pavers are used to place the mix. Some contractors use pavers with oversize hoppers to allow for RAP surges caused by fluctuations in the existing pavement section. The screed should be operated cold as a heated screed causes RAP to stick, tearing the mat, and will not promote extra density or reduced breaking time. The laydown machine should be operated as close to the milling machine as possible, reducing the fluids necessary for placement and the aeration time required before compaction.

Compaction is accomplished with heavy pneumatic and double drum vibratory steel-wheel rollers. CR mixes are more viscous than conventional HMA and require heavier rollers. It is not possible to compact CR mixes to the same density range as HMA. Well compacted CIR mixes could have a Voids in Total Mix (VTM) in the 9 to 14 percent range or higher.

Compaction commences as the mixture begins to break. If asphalt emulsions or emulsified recycling agents are used this could take from 30 minutes to 2 hours depending on environmental

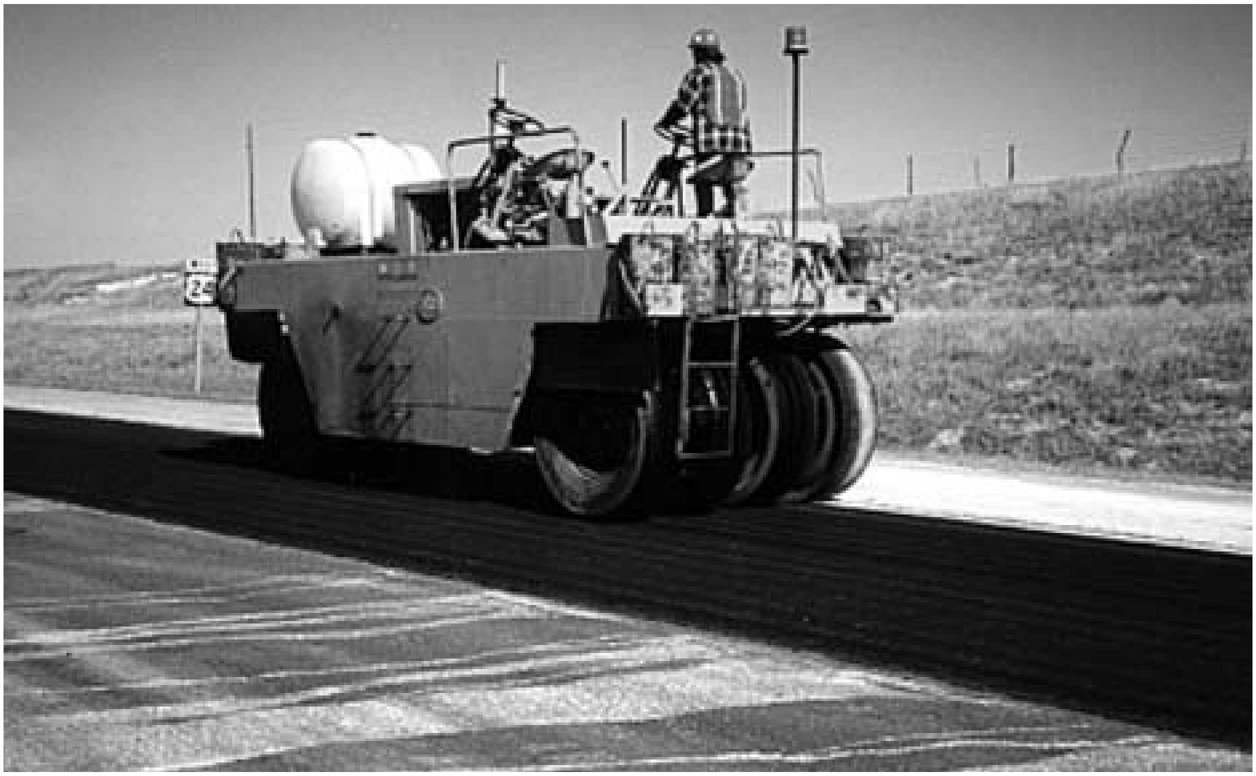


Figure 16-7: Heavy pneumatic tired roller

conditions. The mix will turn from a brown to a black color when the asphalt emulsions or emulsified recycling agent breaks. Some agencies heat the recycling agent and mix water to the 120 to 140°F (50 to 60°C) range to reduce curing or breaking problems in cool or damp conditions. Delaying compaction until after the mixture breaks can cause a crust to form on the top portion of the mixture. The formation of a crust will make compaction difficult and severe roller checking and cracking could result with steel-wheel rolling.

For mixes with type C fly ash, lime, or Portland cement as the recycling additive, rolling commences immediately after placement. A set retarder is often required to prevent rapid set and loss of strength.

Breakdown rolling can be successfully accomplished with either pneumatic-tired or vibratory steel-wheel rollers or a combination of both. Local mix and weather conditions will have an effect on the preference of which method to use. Many contractors begin breakdown rolling with one or two passes of a static steel-wheel roller. This can improve final smoothness of the compacted mat, prevents edge distortion, and prevents excessive distortion of the mat by pneumatic rolling. Additional breakdown rolling is accomplished with heavy pneumatic-tired rollers, 25 tons (23 tonnes) or more, as shown in Figure 16-7.

Breakdown rolling is continued until the roller “walks out” of the mix. This is followed by intermediate rolling with a 12 or more ton (11 tonne) double drum vibratory steel-wheeled rollers. Finish rolling, as shown in Figure 16-8 is with the vibratory steel-wheel roller to remove roller marks. Some report breakdown rolling should not be accomplished with a vibratory steel-wheel

Figure 16-8: Finishing rolling

roller alone due to the possibility of trapping moisture in the mix, delaying curing. For fly ash mixes, breakdown rolling is usually accomplished with a vibratory steel-wheel roller.

Rolling patterns should be established to determine the procedures that result in optimum compaction. Passes with various combinations of rollers should be evaluated. A nuclear density meter can be used to evaluate relative increase in density with roller passes. The number of passes that results in no further increase in density should be selected as the rolling pattern. The relative density of the mat, measured with a nuclear density meter, can be recorded to assist in compaction monitoring.

The rolling procedures should be followed and the recycled mix compacted to minimum of 97 percent of the relative density of the control strip. Difficulty in meeting this density could indicate a change in uniformity of the mixture and a new roller pattern or a new control density is needed.

The following rolling procedure is generally recommended. The longitudinal joint should be rolled first, followed by the regular rolling procedure established in the control section. Initial rolling passes should begin on the low side and progress to the high side by overlapping of longitudinal passes parallel to the pavement centerline. For static rollers, the drive drum should be in the forward position or nearest to the paver except on steep grades where the position may need to be reversed to prevent shoving and tearing of the mat. Drums and tires should be uniformly wetted with a small quantity of water or water mixed with very small amounts of detergent or other approved material, to prevent mixture pickup. Care should exercised in rolling the edges of the mix so the line and grade are maintained.

16.1.5 CURING

The compacted CR mixture must be adequately cured before a wearing surface is placed. The rate of curing is quite variable and depends on several factors. These include day and nighttime temperatures, humidity levels and rainfall activity after recycling, moisture content of the recycled mix before and after recycling, the level of compaction, in-place voids, the drainage characteristics of the material below the CR and the shoulders. Sealing the surface prior to adequate moisture loss may result in premature failure of the CR mix and/ or the surface mix.

Various agencies have differing moisture content requirements prior to placement of the wearing surface and these can be based either on the total moisture in the mix or the increase in moisture content from the pavement prior to recycling. Often curing times, generally 10 days to 2 weeks, are used as the acceptance criteria. It is commonly felt that if a dry cut core can be extracted essentially intact, then the mix has cured sufficiently to place the overlay. In any event, it is generally accepted as preferable to overlay a partially cured mix prior to winter shutdown rather than leave it exposed to the winter. Experience has indicated that these mixes will complete their curing in the following season. The addition of lime has been reported to greatly accelerate the curing process. Rolling with a steel-wheel roller several days after initial compaction, usually referred to as “re-rolling,” is sometimes done to remove minor consolidation in the wheelpaths as a result of densification by traffic. This re-rolling is best completed on warmer days or during warmer periods of the day, such as in the afternoon.

It is generally best to keep traffic off the pavement during curing. However, this can almost never be accommodated. A light application of a fog seal may be necessary to prevent raveling of the mix prior to placement of the wearing surface. The fog seal should consist of a light application of slow-setting asphalt emulsion or the asphalt emulsion used as the recycling additive. The asphalt emulsion should be diluted 50 percent with water prior to application. Typical application rates are between 0.05 to 0.10 gallons/square yard (0.23 to 0.45 liter/square meter). The fog seal will be necessary for fly ash mixtures, as well. Since tire pick-up of the recycled mix can occur, traffic should remain off the fog seal until it has adequately cured.

16.1.6 WEARING SURFACE

Due to the high VTM content, CR mixes need a wearing surface to protect the mixture from intrusion of surface moisture. For pavements with low traffic volumes, single and double chip seals have been successfully employed. For pavements with higher traffic volumes, conventional HMA wearing surfaces have been employed. A tack coat should be applied at a rate similar to the fog seal, to promote good bond between the CR layer and the HMA overlay.

The minimum recommended HMA overlay thickness is 1 inch (25 mm) with 1 1/2 inches (40 mm) preferred. Thin HMA lifts are hard to adequately compact and a poorly compacted surface mix will not protect the CIR from moisture intrusion. The thickness of the HMA overlay should be based on the traffic level and existing roadway strength. Some agencies use the Falling Weight Deflectometer (FWD) to evaluate the pavement section prior to designing the thickness of the HMA overlay. Others assign an “a” coefficient of 0.25 to 0.35 to the CR layer for use with the

Figure 16-9: Urban Cold In-Place recycled mat prior to placement of wearing surface

1986 AASHTO Thickness Design Guide. These coefficients are based on resilient modulus testing but each agency will have to develop their own coefficient.

16.2 COLD CENTRAL PLANT RECYCLING

CCPR may be a viable alternative when stockpiles of high quality (uniform) RAP are available or when it is not possible to in-place recycle the pavement. RAP may be from a nearby milling project or a pavement crushing operation. The RAP is hauled to a central plant or a portable unit can be hauled to the stockpile site.

The central plant may require a screening and crushing unit to control the maximum size of the RAP or a scalping screen may be used to remove oversize RAP. The central plant should have a RAP feed hopper and conveyor belts with a belt scale. The belt scale should be linked to a computerized liquid recycling additive and water system that accurately meters the recycling additive into the pugmill, based on the mass of the RAP. The liquid recycling additives should be metered into the pugmill using positive displacement pumps with interlocks to shut off the supply when the chamber is empty.

Asphalt emulsion and emulsified recycling agent mixes require shorter mixing time than conventional asphalt mixes. Asphalt emulsion mixes can be over-mixed resulting in a loss of asphalt coating caused by the premature breaking of the asphalt emulsion. Undermixing can cause poor coating of the mix. Complete coating of the coarse portion of the RAP or aggregate is not

Figure 16-10: CIR Train set up in a stationary plant mode

necessary at the time of mixing. Further coating takes place during spreading and rolling of the mix.

The screening and crushing unit and pugmill mixer from a recycling train are being utilized as central unit plants, as indicated in Figure 16-10.

Conventional asphalt drum mix plants and batch mix plants have also been utilized on occasion. However, continuous or stabilization plants, as indicated in Figure 16-11 are most often used.

16.2.1 LAYDOWN, AERATION AND COMPACTION

The CCPR mixture is discharged into surge bins, storage silos, deposited into stockpiles or directly into haul trucks for transport to the job site. The use of surge bins, storage silos or stockpiles results in a continuous operation which results in a more uniform mixture and more efficient trucking.

Aeration of the CCPR mix may be required, to reduce the water and volatile content prior to compaction. The laydown and spreading equipment for CCPR mixes are the same as for CIR and conventional HMA. The recycled mix can be placed in a windrow and spread to grade and cross-slope with a motor grader. The motor grader also can assist in aeration of the mix. Jersey spreaders attached to the front end of crawlers or rubber-tired tractors have been used to place the mix. Conventional HMA pavers and cold mix pavers with windrow attachments, the same as for CIR, are typically used. Compaction, curing, and placement of the wearing surface are the same as for CIR.

Figure 16-11: Conventional CCPR plant

CHAPTER 17: COLD RECYCLING – SPECIFICATIONS AND INSPECTION

The current trend in the construction industry is to move away from method specifications, where the owner agency describes in detail not only the scope of the project, but also how to construct the project, and to move toward end result specifications. In a true method specification, the owner agency describes in complete detail all equipment and procedures that must be used to obtain the desired quality of the project. Method specifications require continuous construction monitoring and require that the inspector work closely with the contractor to assure compliance with the specifications. If an inspector is not available, it will be impossible to determine later whether the contractor complied with the specifications. Writing a good set of method specifications requires that the agency preparing the specifications be experienced with all phases of the proposed construction.

With end result specifications, the owner agency tells the contractor what level of performance or end result it expects from the project, and how that performance level or end result will be measured. It is then up to the contractor to decide how to best meet the performance requirements. The contractor could select the construction method and equipment, job mix formula, recycling additives, and construction sequence. At the end of the project, the owner agency would perform testing to assure that the minimum performance level was obtained. Testing is usually statistically based. Therefore, reasonable construction variation of the test properties must be understood and allowed for in the specifications. The major difficulty in preparing end result specifications is in determining what properties to specify and what limits to set. The test properties specified should be directly or at least indirectly related to performance.

Cold Recycling (CR) is a variable process and the properties that relate to performance are not completely established at this time. The variability of the process makes setting statistically based specification limits difficult. The lack of a good understanding of the mix, material, and construction sequences that relate to performance makes selecting properties for testing suspect, as well. Therefore, most CR projects currently use a combination of method specifications and end result specifications.

In combination specifications, the owner agency typically specifies the required equipment and might specify a portion of the construction sequence. The owner agency would provide the job mix formula (JMF) and select the recycling additive and rate or have the authority to approve or modify the contractor's JMF. The minimum requirements for the size, type, and level of automation of the construction equipment are typically specified. The compaction sequence is sometimes specified; however, the contractor is usually required to meet certain testing requirements, as well. Specifying the compaction sequence can inhibit contractor efficiency and innovation. Testing requirements are typically specified for maximum size of the RAP, recycling additive and amount, final in-place density, and smoothness or cross-slope.

17.1 QUALITY CONTROL/QUALITY ASSURANCE

A good Quality Control/Quality Assurance (QC/QA) plan is essential to obtaining a satisfactory CR pavement, regardless of the type of specification used. As with any in-place construction, CR can involve the recycling of pavement sections with variability in gradation and asphalt content, due to areas of major maintenance such as patching and chip sealing. A good QC/QA plan must not be so complex as to prohibit changes due to this inherent variability, yet be sophisticated enough to determine the acceptability of the CR process and identify areas of non-uniformity where changes in the process are necessary.

The required material sampling and testing should be appropriate for the construction methods and should be related to process control and/or final product performance. CR is a variable process and changes in rolling patterns, moisture content, and recycling additive content will be necessary to obtain optimum performance. The testing and acceptance plan needs to be formulated to identify the need for slight changes in the above procedures and flexible enough to allow for changes without redesign of the mixture.

Tables 17-1 and 17-2 show the recommended field sampling and testing plan for CR and the accompanying notes, respectively, developed by the American Association of State Highway and Transportation Officials, the Associated General Contractors of America, American Road and Transportation Builders Association (AASHTO-AGC-ARTBA) Joint Committee Task Force 38 Report entitled “Report on Cold Recycling of Asphalt Pavements.” This report is available from AASHTO. The sampling and testing methods refer to American Society for Testing and Materials (ASTM) and AASHTO test methods. Other test methods from other government agencies could be substituted if proven acceptable. Guide specifications, developed by Task Force 38, are included at the end of the chapter. Comments to the test plan are in part from the Task Force 38 Report, as well.

17.2 INSPECTION AND ACCEPTANCE ISSUES

There are issues and concerns that must be fully understood and addressed when dealing with CR. These issues arise due to the inherent variability of recycling and to the special concerns related to compacted moist, cold, bituminous mixtures that are not a part of conventional HMA construction. These issues, as they relate to sampling, testing, and specifications, are discussed below.

17.2.1 RAP GRADATION

Most agencies limit the maximum size of the RAP to 1 1/2 inches (40 mm). Oversized material can result in increased segregation of the mix, excess voids, increased permeability, and difficulty in spreading and compacting the mat. For thin sections of CR, oversize RAP could cause tearing of the mat. A good rule of thumb is for the maximum RAP size to be no larger than 1/3 of the compacted layer thickness.

Table 17-1. Recommended Field Sampling and Testing for Control of CIR

Type of Testing	Purpose of Testing	Frequency	Sample Location & Size
Recommended for Control and Testing			
RAP gradation, 2, 1.5 or 1.25 inch (50, 37.5 or 31.5 mm) sieves	Specification compliance with maximum size determination	Each 1/2 mile (0.8 km) [1,6]	From conveyor belts, windrow or mat, minimum weight of 20 pounds (9.0 kilograms)[2]
Recycling Additive[3] (asphalt emulsion, emulsified recycling additive, Portland cement, fly ash, lime, etc.)	Check on specification compliance	Every load sampled, one test per day	From asphalt tank on recycling unit or transport truck, wide-mouth plastic bottle, 1 quart (1 litre) sample size[1]
Moisture added to the RAP[4]	Adjustment of water content for proper mixing and compacting	Each 1/2 mile (0.8 km) [1,6]	From belt into mixer or after spreading, minimum weight of 20 pounds (9.0 kilograms)[2]
Mat moisture content after curing (asphalt emulsions/ recycling agents only)	To determine when the new asphalt surface can be placed	Each 1/2 mile (0.8 km) [1,6] one each lane	Full cold recycled lift depth sample, minimum weight of 3 pounds (1.4 kilograms)[2]
Recycling additive content	Verify amount of recycling additive and also accuracy of meter readings	Minimum of one per day	By tank gauging, truck weighing or meter readings and RAP weight by belt scale
Recycled material compacted density by rolling control strips [5]	To establish rolling procedures and target density for specification compliance	Minimum of two strips and nuclear density testing each 1/2 mile (0.8 km) [1,6]	Strips at beginning of project and additional if major changes in the recycled mix properties occur, 400 to 500 foot (120 to 150 meter) length
Recycled material compacted density by field compacted specimens [5]	To establish the target for specification compliance	Material sample and nuclear density testing each 1/2 mile (0.8 km)[1,6]	Material sampled from windrow or mat after spreading, minimum weight of 20 pounds (9.0 kilograms)[2]

Table 17-1. (continued) Recommended Field Sampling and Testing for Control of CIR

Recommended for Control and Testing			
Depth of pulverization/milling	For specification or plan compliance	Each 1/8 mile (0.2 kilometer) or additional as needed	Measurements across the mat, adjacent to longitudinal joints and at the outside edge
Spreading depth of recycled material, Cold Central Plant Recycling only	Check of the lift thickness for specification or plan compliance	Each 1/8 mile (0.2 kilometer) or additional as needed	Measurements across the mat, adjacent to longitudinal joints and at the outside edge
Mixing equipment calibration	To assure proper content of the recycling additive(s) and moisture	Prior to beginning of work each year and additional, as required[7]	Material being processed from mixer into a truck and liquids into barrels, tanker or asphalt distributor for weighing by a scale
For Information Only			
Recycled material temperature	To determine the influence of temperature on compaction and temperatures for mix design	Minimum of four each day, two early morning and two late afternoon	Determined for the recycled material when mixing and the mat immediately prior to rolling
Recycled mat smoothness	To develop data on spreading procedures and for possible future specification requirements	Continuously or at selected locations of existing pavement and after cold recycling	By profilograph device (California or other)
Original pavement and recycled material asphalt contents[8]	To determine added and total asphalt contents	Randomly[6]	From selected locations in a stockpile or pavement before recycling and in the recycled mat, minimum weight of 20 pounds (9.0 kilograms)[2]

Table 17-2. Notes for Recommended Field Sampling and Testing, i.e., Table 17-1

1. Additional sampling and testing may be required if major changes in RAP characteristics are observed, such as a much coarser or finer gradation or a noticeable difference in asphalt content or when considerable variability is occurring in the field test results.

2. RAP sampling generally should be in accordance with ASTM D 979 or AASHTO T 168 procedures for Sampling Bituminous Paving Mixtures.

3. Asphalt Emulsion and emulsified recycling agent sampling should be in accordance with ASTM D 140 or AASHTO T 40 for Sampling Bituminous Materials.

4. The moisture content can be determined with ASTM D 1461 or AASHTO T 110 for Moisture or Volatile Distillates in Bituminous Paving Mixtures. Also, the moisture content can be adequately determined by weighing and drying a sample to a constant weight using a forced draft oven in accordance with ASTM D 2216 or AASHTO T 265 or by microwave oven drying according to ASTM D 4643.

5. Target densities for recycled mix compaction are being established by using rolling control strips or by the field compaction of density specimens using Marshall and Proctor compactors and recently gyratory compactors. The compacted density, when determined, normally is measured with a nuclear density/moisture gauge since it is generally not possible to obtain cores during construction. For control strips, backscatter measurement is typically used but for density checks for specification compliance, direct transmission measurement is preferred. The procedures generally followed are in accordance with ASTM D 2950 Density of Bituminous Concrete in Place by Nuclear Methods. The density obtained will be a “wet density” as conversion to a true “dry density” by the gauge is not possible with these types of mixes. A more accurate dry density may be obtained by sampling the recycled mix at the nuclear gauge test location, determining the moisture content by drying and correcting the gauge wet density using the sample moisture content.

6. For each length or lot size quantity specified, materials sampling can be completed on a random basis using the procedures of ASTM D 3665 for Random Sampling of Construction Materials.

7. Based on the mixer computer meter readings and other checks, additional calibration may be required. This calibration may require only checking and adjusting the belt scale system using weights.

8. The asphalt content in cold recycled mixtures can be determined by asphalt extraction using ASTM test methods D 2172 or D4125 or AASHTO test methods T 164 or T 287 or the ignition furnace using ASTM D 6307.

Figure 17-3: Cold Recycling Paver with Integral Pugmill. Microprocessor controlled aggregate and emulsion measuring systems provide accurate proportioning.

17.2.2 RECYCLING ADDITIVE(S) SAMPLING

The recycling additive(s) should be sampled to insure proper type and compliance with specifications. When using an asphalt emulsion as the recycling additive, the specifications should allow for the changing of the asphalt emulsion grade one grade to facilitate field coating and compaction. Changing the asphalt emulsion grade one grade softer can improve compaction and coating when difficulties are encountered with coating and compaction. The moisture content is generally adjusted first, to improve coating rather than adjusting the recycling additive content. Field methods to evaluate coating, and suggested remedial measures, are discussed in Chapter 16, Section 1.3. Changes in recycling additive content should be made judiciously and only by experienced personnel.

17.2.3 MOISTURE ADDITION

Proper moisture control is required for good recycling additive dispersion and CR mix compaction. Chapter 16, Section 1.3 discusses adjustments to moisture content to facilitate coating. Generally, more moisture is needed for dispersion than for compaction. For asphalt emulsions and emulsified recycling agents, compaction should not take place until the mixture begins to break, turning from brown to black in color. It may be necessary to delay compaction of CR mixes with asphalt emulsions or emulsified recycling agents 30 minutes to 2 hours, with the delay dependent on the recycling additive breaking properties, lift thickness, and weather. For final strength gain (curing), this mixing and compaction moisture must leave the mat. It is important that this moisture not be sealed in during rolling.

Figure 17-4: Connected Water (Front) and Emulsion (Rear) Tanks to permit Metered Addition of Both Liquids

17.2.4 RECYCLED MIXTURE MOISTURE CONTENT

CR mixtures with asphalt emulsions or emulsified recycling agents as the recycling additive must properly cure in order to reach their full strength potential. The rate of curing is quite variable and depends on several factors. These include day and nighttime temperatures, humidity levels and rainfall activity after recycling, moisture content of the recycled mix before and after recycling, the level of compaction, in-place voids, the drainage characteristics of the material below the CR, and the shoulders. Placement of a wearing surface on a CR mat with excessive moisture will delay strength gain of the CR and could cause premature failure of the wearing surface.

Various agencies have different moisture content requirements prior to placement of the wearing surface, and these are based on either the total moisture in the mix or the increase in moisture content from the pavement prior to recycling. Samples of the compacted mix are required to determine the moisture content, as nuclear density meters will not give accurate moisture content results with these types of materials. Rather than sample and patch the compacted CR mix, most agencies specify curing times, generally 10 to 14 days. Traffic is allowed on the mat during this time. A light fog seal may be required to prevent raveling of the CR. A light application, 0.05 to 0.10 gallons/square yard (0.23 to 0.45 liter/square meter) diluted 50 percent with water, of CSS-1 or the asphalt emulsion used for as the recycling additive has been reported as satisfactory.

17.2.5 RECYCLING ADDITIVE CONTROL

A proper recycling additive content is required for optimum performance and recycled mix workability. For asphalt emulsions and emulsified recycling agents, excess recycling additive will result in an unstable mix that is subject to rutting and shoving. The balling of asphalt emulsion with fines in the windrow is another indication of excessive recycling additive. Too little recycling additive can result in segregation and surface raveling when opened to traffic. Adjustments to the asphalt emulsion or emulsified recycling agent content should be made in 0.2 percent increments and should only be made by experienced personnel. For chemical additives, such as type C fly ash or Portland cement, too little recycling additive could result in a weak layer and/or poor durability, while too much recycling additive could result in a brittle mixture.

Modern CIR trains have microprocessor controlled weigh measuring systems for asphalt emulsions, emulsified recycling agents and RAP that when properly calibrated, give a very good record of the recycling additive rate. It is possible to determine the asphalt emulsion or emulsified recycling agent content by sampling the mix off the conveyor belt, prior to entering the mixer and by sampling the CR mix discharging from the pugmill. The asphalt content is determined for both samples using either solvent extraction or the ignition furnace. The difference in asphalt contents is the residual asphalt in the asphalt emulsion or the emulsified recycling agent. This residual asphalt content can be converted to an asphalt emulsion content using the residue content of the asphalt emulsion or the emulsified recycling agent.

17.2.6 COMPACTION PROCEDURES

CR mixes are more viscous than conventional HMA and it will not be possible to compact CR mix to the same density range as HMA. Well compacted CR mixes could have voids in total mix (VTM) in the 9 to 14 percent range or higher.

Compaction is accomplished with heavy pneumatic-tired rollers, 25 tons (23 tonnes) or more, and with double drum vibratory steel-wheeled rollers weighing 12 or more tons (11 tonnes). Compaction should begin as the mix begins to break. This is indicated by the mix beginning to turn from brown to black. Delaying rolling until after the mix breaks can result in a crust forming in the top portion of the mat making compaction difficult and causing severe roller checking or cracking.

Breakdown rolling can be successfully accomplished with either pneumatic-tired or vibratory steel-wheel rollers or a combination of both. Local mix and weather conditions will have an effect on the preference of which method to use. Initial breakdown rolling with one or two passes of a vibratory steel-wheel roller in the static mode can improve final smoothness of the compacted mat, prevent edge distortion and prevent excessive distortion of the mat during pneumatic rolling. Additional breakdown rolling is accomplished with heavy pneumatic-tired rollers until the roller "walks out" of the mix. Finish rolling is with the vibratory steel-wheel roller to remove roller marks.

The following rolling procedure is generally recommended. The longitudinal joint should be rolled first followed by the regular rolling procedure established in the control section. Initial rolling passes should begin on the low side and progress to the high side by overlapping of longitudinal passes parallel to the pavement centerline. For static rollers, the drive drum should be in the forward position or nearest to the paver except on steep grades where the position may need to be reversed to prevent shoving and tearing of the mat.

Drums and tires should be uniformly wetted with a small quantity of water or water mixed with very small amounts of detergent or other approved material to prevent mixture pickup. Care should exercised in rolling the edges of the mix so the line and grade are maintained. The roller should be kept 8 to 12 inches (200 to 300 mm) inside the outside edge of the mat on the initial pass when using a pneumatic roller. Constant monitoring of the mat is required when using vibratory compaction, to prevent roller checking or other cracking.

Rerolling after some period of curing may be advantageous when density has been hard to achieve, such as with cool temperatures and coarser RAP gradations. The rolling is usually accomplished with a steel-wheel roller or with a pneumatic roller followed by a steel-wheel roller. Rerolling serves several additional purposes including: removing wheel marks and minor consolidation caused by traffic while the mix is gaining strength; sealing the CR reducing moisture infiltration and; adding additional densification. The mat should be observed during rerolling and rolling ceased if roller checking or cracking occurs. Rerolling thin CR lifts could result in debonding.

17.2.7 COMPACTED MAT DENSITY

In general, the higher the compacted density, the better the material properties of the CR mixture. The gradation of the RAP is not as uniform as the aggregate in HMA and it may not be possible to achieve as uniform a compacted mat (same standard deviation). Because of this, HMA specifications and HMA QC/QA procedures should not be used with CR mixes, as specification compliance will not be achievable.

Three methods are available for determining the target density for compaction of CR mixtures. They are percent of laboratory compacted density, percent of field compacted density, and percent of control strip density. The latter two methods are preferred because percent of mix design density does not address normal changes in RAP gradation that affect the field compacted density.

When using percent of field compacted density, the target density is determined by compacting field samples using the mix design compactive effort and determining the bulk density of the sample. The bulk density is determined on either a dry or a wet mass basis. The wet bulk density is determined either by dividing the wet mass by the measured volume or by the saturated surface dry (SSD) mass minus the submerged mass (SSD basis).

Problems with sample tenderness can be encountered when using the SSD method. The wet density can be converted to a dry density by correcting the wet weight by the measured moisture content of a portion of the sample, or by oven drying the entire compacted sample. A second problem encountered with SSD bulk density determination is inaccurate measurements due to high void contents. AASHTO T 166 “Bulk Specific Gravity of Compacted Bituminous Mixtures using Saturated Surface-Dry Specimens” is not recommended for samples that contain open or interconnected voids or absorb more than 2 percent water by volume during testing. This will usually be the case with CR mixtures. Paraffin coating AASHTO T 275 “Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens” or sealing samples with a plastic wrap, either manually or vacuum sealing, has been used with limited success. A FHWA pooled fund study is currently underway to evaluate the use of “Corelok” to establish the bulk specific gravity of porous samples. It is hoped that the results of that study will minimize the difficulties with existing test methods and provide more accurate results. Typical specification requirements using field compacted target densities are 93 to 96 percent compaction, on a wet density basis.

Figure 17-5: Nuclear density meter

The major problem with the field compacted method is determining the proper compactive energy. Many agencies use 50 blow Marshall compaction with the samples heated to 140°F (60°C). Satisfactory results have been obtained although the CR mix will not reach this temperature in the field. Recent work has shown that CR field mix compacted using 75 blow compaction at ambient mix temperatures of 100°F (40°C) resulted in densities equivalent to field compacted densities. There is interest in using the Superpave Gyratory Compactor (SGC) for mix design and field control. As in the case for mix design, whatever compaction level/mix temperature is utilized, it must produce laboratory compacted densities that are achievable in the field.

To avoid the above problems with field compacted samples, many agencies use rolling control strips to determine the target density. The mix is rolled to a minimum number or passes with rollers of specified minimum weights. After the minimum number of passes, the density is monitored with each additional pass using a nuclear density meter. The wet density is recorded. The target density is the density obtained when additional passes result in an increase in wet density of less than 1 pound/cubic foot (16 kilograms/cubic meter). The rolling pattern is the number of passes of each roller that resulted in the target density. Specifications typically require 96 to 97 percent of the target density. The target density may have to be re-established if the uniformity of the mixture changes significantly.

The compacted density of the mat is the wet density, usually determined with a nuclear density meter as shown in Figure 17-5.

The nuclear density meter obtains the dry density by adjusting the wet density for hydrogen atoms. In CR mixtures, the aged asphalt binder and many recycling additives contain hydrogen atoms, as well as the mix water. The reported dry density is the wet density reduced by the hydrogen atoms found in all of these sources, not just the water, resulting in inaccurate readings. The dry density can be determined by obtaining a sample of the mix from the location of the density test and determining the moisture content. The wet density can be corrected to a dry density using this moisture content.

For QC purposes, testing in the backscatter mode can be used, although direct transmission is recommended. There can be a significant difference in density between backscatter and direct transmission, due to the coarse surface texture and lift thickness of CR mixes. For quality assurance and/or specification compliance testing, readings should be made in the direct transmission mode. Nuclear density measurements should be calibrated to the density, from cores from the pavement. This correlation is often not performed because it can be difficult to obtain cores in a timely manner. Several days may be required before satisfactory cores can be obtained. Success has been reported using specimens dry sawed from the CR shortly after placement.

17.2.8 DEPTH OF MILLING

The specifications can either require a constant depth of milling or the grade and cross-slope can be reestablished. It is not possible to do both. The depth of milling may need to be adjusted due to unexpected field conditions, such as a weak base or subgrade, a thinner pavement section, or to be the proper distance from the interface/boundary between two pavement layers. A pavement should be milled to just below the interface between pavement layers, or no closer than 3/4 inch (20 mm) above the interface boundary. Failure to heed these recommendations may result in chunks of the pavement being dislodged by the milling machine.

17.2.9 SPREADING DEPTH/CROSS-SLOPE

The spreading depth only applies to Cold Central Plant Recycling (CCPR). The spreading depth needs to be monitored to provide adequate pavement thickness for load-carrying capacity and for compliance with specification requirements. The cross-slope for all CR should be checked regularly with a level and straight edge behind the paver and after rolling. Typical specifications require no deviation greater than 1/4 inch (6 mm) when using a 10 foot (3 meter) straight edge. The edge of the mat should be rolled first and progress toward the center or high side to prevent excessive edge sloughing.

17.2.10 MIXING EQUIPMENT CALIBRATION

The mixing equipment should be regularly checked to determine whether the proper amount of recycling additive and moisture are being added. Modern two-unit and multi-unit CIR trains have microprocessor controlled weight measuring systems for liquid recycling additives. When properly calibrated a very accurate record of the recycling additive rate is available. Weigh belt scales, liquid metering systems, and other components should be calibrated at the beginning of each job and whenever problems are encountered

17.3 GUIDE SPECIFICATIONS

Many owner agencies have considerable experience with CR and they have developed their own specifications to fit their particular expectations based on local materials and environmental conditions. Based on the significant effect environmental conditions and local materials have on CR performance, specifications from one agency might not be applicable to another agency, in a different location.

The following guide specifications are from the Task Force 38 Report and are based on SECTION “411 Cold Recycled Asphalt Pavement” of AASHTO’s Guide Specifications for Highway Construction. Many of the requirements are general in nature due to the universal nature of guide specifications. Local experienced contractors and owner agencies should be consulted for specific recommendations. The specifications should be applicable to CCPR, as well as CIR.

COLD RECYCLED ASPHALT PAVEMENT – GUIDE SPECIFICATIONS

5.1 DESCRIPTION. This work shall consist of cold milling and pulverizing the existing asphalt pavement to a specified depth and maximum size or processing accepted stockpiled asphalt pavement, mixing a recycling agent(s), water and additives with the reclaimed material, and spreading and compacting the mixture.

5.2 MATERIALS. Recycling agent(s) shall include asphalt emulsions or asphalt emulsion rejuvenators. Materials shall meet the requirements of the appropriate specification Subsections:

Portland Cement	Specifications to be provided by the User Agency
Asphalt Emulsions	Specifications to be provided by the User Agency
Water	Specifications to be provided by the User Agency
Quicklime	Specifications to be provided by the User Agency
Fly Ash	ASTM C 618 and D 5239
Emulsified Rejuvenators	Specifications to be provided by the User Agency
Blotter Sand	Specifications to be provided by the User Agency

A. Composition of Mixtures. The cold recycled mixture shall be composed of Reclaimed Asphalt Pavement (RAP), recycling agent(s), and additives as specified. The composition of the mixture shall be established by the Contractor and approved by the Engineer and required shall be the following:

1. The sieve size where 100% passing is required __________ (1.25 inch (31.5 mm) sieve is recommended).
2. The beginning percentage of recycling agent _____, water _____ and additives _______ to be added to the RAP.

The cold recycled mixture shall be sampled for testing for job compliance at the spreading operation.

B. RAP Material. For Cold In-Place Recycling (CIR), the RAP shall be accepted by samples taken from the cold planer's conveyor, if there is no screening and crushing unit, and from the discharge conveyor of the screening and crushing unit if one is being used. RAP shall be accepted from a stockpile if Cold Central Plant Recycling (CCPR), without a screening and crushing unit, is being used and from samples from the discharge conveyor if screening and crushing unit is being used.

C. Recycling Agent(s). These materials shall be accepted under Specifications to be provided by the User Agency.

D. Additives. Additive sources shall be approved by the Engineer.

5.3 CONSTRUCTION REQUIREMENTS

A. Weather Limitations. Cold recycling operations shall be performed with asphalt emulsions when the atmospheric temperature in the shade is 50°F (10°C) and rising and it is not foggy. When using cement or fly ash, the atmospheric temperature in the shade shall be 39°F (4°C) and rising. Recycling operations shall not be performed when rain is occurring or night temperatures are forecast to fall below freezing.

B. Cold Milling Equipment and Mixing Plants. Cold milling equipment shall conform to Specifications to be provided by the User Agency.

A continuous pugmill mixing plant shall be equipped with a belt scale and automatic controls to obtain the proper amount of recycling agent and liquid additives, such as hydrated lime or cement slurry.

C. Hauling Equipment. Trucks used for hauling shall conform to Specifications to be provided by the User Agency.

D. Asphalt Pavers. Self-propelled asphalt pavers shall conform to Specifications to be provided by the User Agency.

E. Rollers. Rollers shall conform to Specifications to be provided by the User Agency except that a minimum of one 25 ton (23 tonne) pneumatic-tired roller and one 12 ton (11 tonne) or larger double drum vibratory steel-wheeled roller shall be provided.

F. Temperature of Recycling Agent. Recycling agent(s) shall be used within the temperature range specified for the mixing of the material being used. If required, the recycling agent(s) shall be heated to within the desired temperature range without overheating.

G. RAP Moisture Content. RAP for the cold recycled mixture shall have water added prior to mixing with the recycling agent(s), as specified or required by the Engineer to provide proper coating/dispersion and compaction.

H. Mixing Operation. The RAP, recycling agent(s) and additives shall be combined in the quantities required by the specifications or as directed by the Engineer. The mixing operation shall result in the RAP being thoroughly mixed with recycling agent(s) and additives, if used.

I. Spreading and Finishing. Asphalt pavers shall be used to spread the cold recycled mixture to the established grade and cross-slope.

The paving operations shall be conducted to protect existing and finished pavement sections. Traffic control and paving operations shall be completed according to the approved traffic control plan unless otherwise approved by the Engineer.

If blotter sand is required to prevent pick-up of the cold recycled mixture by traffic, it shall be applied by a mechanical spreader at a rate of from ____ to ____ (5 to 10 pounds per square yard, (2.7 to 5.4 kilograms per square meter) is recommended).

J. Rolling. After the cold recycled mixture has been spread and any surface irregularities corrected, the mat shall be uniformly compacted without undo displacement and cracking. The number, weight, and type of roller furnished shall be sufficient to obtain the required compaction of the cold recycled material. The sequence of rolling operations shall provide the specified degree of compaction. The longitudinal joint shall be rolled first followed by the regular rolling procedure. The initial passes for all regular rolling should begin on the low side and progress toward the high side by overlapping of longitudinal passes parallel to the pavement centerline. When using an asphalt emulsion, the initial rolling shall not begin until the asphalt emulsion has started to break (turning from a brown to a black color). The time of beginning initial rolling shall be determined by the Engineer. With Portland cement or fly ash the recycling agent, the initial rolling shall begin immediately after spreading of the cold recycled material and be completed as soon as possible.

Rollers shall be operated at speeds appropriate for the type of roller and necessary to obtain the required degree of compaction and prevent defects in the mat. For static rollers, the drive drum normally shall be in the forward position or nearest to the paver. However, on steep grades, the non-powered drum shall be nearest to the paver, if required to prevent the mixture from shoving and tearing. Vibratory rollers shall be operated at the speed, frequency and amplitude required to obtain the required degree of compaction and prevent defects in the mat.

To prevent picking up of the mixture by rollers, drums and tires shall be uniformly wetted with water or water mixed with very small quantities of detergent or other approved material.

Any pavement shoving or other unacceptable displacement shall be corrected. The cause of the displacement shall be determined and corrective action taken immediately and before continuing rolling. Care shall be exercised in rolling the edges of the cold recycled mixture so the line and grade of the edge are maintained.

A minimum density of _____ percent (88% recommended) of the Maximum Theoretical Density. AASHTO T 209 or a minimum density of ______ percent (93% recommended and method used in determining laboratory density specified) of laboratory specimens made of production materials should be obtained.

When the control strip method of density control is specified, the control strip shall be constructed of mixture produced with the cold recycling equipment and within the pavement section. The Contractor shall select compaction patterns from which the Engineer (assisted by testing results using nuclear gauge or other testing procedures) will select the coverage that provides the specified minimum percent of density (97% minimum recommended). Whenever there is a change in the cold recycled material or compaction method or equipment or unacceptable results occur, a new test control strip shall be constructed, tested, and analyzed. Revised compaction methods will be selected by the Engineer.

K. Joints. Adjacent recycling passes shall overlap the longitudinal joint a minimum of 4 inches (100 mm). Any fillet of fine, pulverized material which forms adjacent to the vertical face of longitudinal joints shall be removed prior to spreading the cold recycled material, except that such fillet adjacent to existing pavement which will be removed by a subsequent overlapping milling need not be removed. The cold recycling widths selected shall not result in longitudinal joints being located in wheelpaths.

L. PAVEMENT SMOOTHNESS. The surface shall be tested with a 10 foot (3 meter) straightedge at locations selected by the Engineer. The variation of the surface from the testing edge of the straightedge between any two contacts, longitudinal or transverse with the surface, shall not exceed ______ (3/16 inch (5 mm) recommended). Irregularities exceeding the specified tolerance shall be corrected by and at the expense of the Contractor by grinding/cold milling or leveling with cold or hot mix asphalt as directed by the Engineer. Following correction, the area shall be retested.

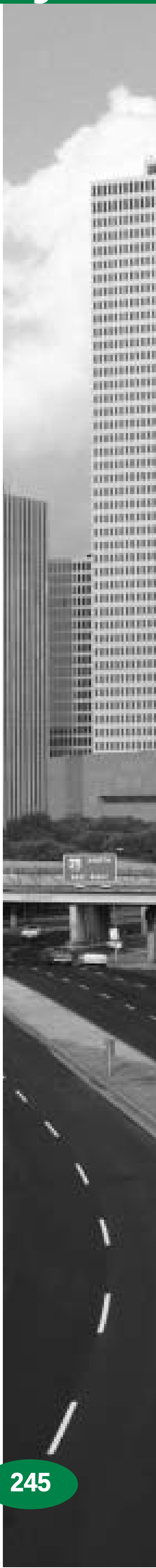
5.4 METHOD OF MEASUREMENT

- In-place cold recycling will be measured by the station along the centerline of the lanes or by the square yard (square meter).
- Water will not be measured for payment.
- Liquid recycling agent(s) will be measured by the U.S. gallon (litre) or ton (tonne). Cement and fly ash will be measured by the ton (tonne).
- Cement, when dry cement or cement slurry is specified, shall be measured by the ton (tonne).
- Quicklime, when hydrated lime slurry is specified, shall be measured by the ton (tonne).
- Blotter sand will be measured by the ton (tonne) or cubic yard (cubic meter) in the truck at the point of usage for the quantity applied on the pavement.

5.5 BASIS OF PAYMENT

Payment for accepted quantities will be made as follows:

Pay Item	**Pay Unit**
In-Place Cold Recycled Asphalt Material	Station or Square Yard (Square Meter)
Recycling Agent	U.S. Gallon (Liter) or ton (tonne)
Blotter Sand	Ton (tonne) or Cubic Yard (Cubic Meter)
Quicklime	Ton (tonne)
Cement	Ton (tonne)



GLOSSARY OF TERMS

ABRASION: the wearing away of a surface material of a pavement structure by tire friction or snowplow scraping.

ABSOLUTE VISCOSITY: a method of measuring viscosity using the poise (Pascal•second) as the basic measurement unit utilizing a partial vacuum to induce flow in the viscometer. Test temperature of 140°F (60°C) is typical for an asphalt binder.

AGE-HARDENED: decrease in the penetration and/or increase in viscosity of asphalt binder caused by loss of volatiles and oxidization of the asphalt binder during manufacture (predominately during mixing) and subsequent exposure to weather.

AGGREGATE: a hard, inert, granular material of mineral compositions such as sand, gravel, shell, slag or crushed stone.

ALLIGATOR CRACKING: cracks which occur in asphalt pavements in areas subjected to repeated traffic loading which develop into a series of interconnected cracks, with many-sided, sharp-angled pieces, characteristically with an alligator pattern.

ASPHALT: a dark brown to black cementitious material in which the predominating constituents are bitumens that occur in nature or are obtained by petroleum processing.

ASPHALT BINDER (CEMENT): a dark brown to black cementitious material, in which the predominant constituents (+99%) are bitumens which occur in nature or are obtained as residue in petroleum manufacturing, and are used as binder in asphalt-aggregate mixes.

ASPHALT CONCRETE: a high quality mixture of asphalt binder and carefully graded coarse and fine aggregates.

ASPHALT EMULSION: an emulsion of asphalt binder and water that contains a small amount of an emulsifying agent. A heterogeneous system containing two normally immiscible phases (asphalt and water) in which the water forms the continuous phase of the emulsion, and minute globules of asphalt form the discontinuous phase. Asphalt emulsion may be either anionic i.e., electro-negatively charged asphalt globules or cationic, i.e., electro-positively charged asphalt globule types, depending upon the emulsifying agent.

ASPHALT LEVELING COURSE: a layer of asphalt concrete, of variable thickness, used to eliminate irregularities in the contour of an existing pavement surface prior to a superimposed treatment or construction.

ASPHALT PAVEMENT: pavement consisting of asphalt concrete layer(s) on supporting courses such as concrete base (composite pavement), asphalt treated base, cement treated base, granular base, and/or granular subbase placed over the subgrade.

ASPHALT REJUVENATOR: a liquid petroleum product, usually containing maltenes, added to asphalt paving material to restore proper viscosity, plasticity, and flexibility to the asphalt.

ASPHALT-RUBBER: a blend of asphalt binder, reclaimed tire rubber, and certain additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt binder sufficiently to cause swelling of the rubber particles.

ASPHALTENES: the high molecular weight hydrocarbon fraction precipitated from asphalt by a designated paraffinic naphtha solvent at a specified solvent-asphalt ratio.

ATTERBERG LIMITS: soil moisture values used to define liquid and plastic conditions and thus to identify silty, clayey, and organic soils in the Unified Soil Classification System.

AVERAGE ANNUAL DAILY TRAFFIC (AADT): the average daily amount of vehicles in all lanes and both directions in a one year period.

BASE COURSE: a layer of specified or selected material of planned thickness constructed on the subgrade or subbase for the purpose of serving one or more functions such as distributing load, providing drainage, minimizing frost action, etc.. It may be composed of crushed stone, crushed slag, crushed or uncrushed gravel and sand, reclaimed asphalt pavement or combinations of these materials.

BATCH PLANT: a manufacturing facility for producing asphalt concrete that proportions the aggregate constituents into the mix by weighted batches and adds asphalt binder by either weight or volume.

BENKELMAN BEAM: a device for measuring the rebound deflection of a pavement surface, under a standard load, to assess/evaluate its structural adequacy.

BINDER: an adhesive composition of asphalt binder modifies asphalt binder, etc. which is primarily responsible for binding aggregate particles together.

BITUMEN: a class of black or dark-colored (solid, semisolid or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalts, tars, and pitches are typical.

BITUMINOUS: containing or treated with bitumen.

BLEEDING (FLUSHING): presence of excess asphalt material on the pavement surface caused by too much asphalt binder in the mix, too heavy of an application of an asphalt sealant, excessive crack or joint sealant, and/or low mix air void content. Traffic action and warm temperatures can contribute to the occurrence of bleeding.

CAPE SEAL: a surface treatment where a chip seal is followed by the application of either a slurry seal or micro-surfacing.

CATIONIC EMULSIONS: emulsions where the asphalt binder globules in solution having a positive charge.

CHIP: particles of crushed coarse aggregate that can be one size or uniformly graded.

CHIP SEALING: a surface treatment using one or more layers of chips and asphalt emulsion binder.

CLAY: a cohesive soil composed of very fine particles which is defined by the Atterberg Limits in the Unified Soil Classification System.

COARSE AGGREGATE: that portion of aggregate retained on the No. 4 (4.75 mm) sieve.

COLD IN-PLACE RECYCLING (CIR): a rehabilitation treatment involving cold milling of the pavement surface and remixing with the addition of asphalt emulsion, Portland cement or other modifiers to improve the properties, followed by screeding and compaction of the reprocessed material in one continuous operation.

COLD PLANING (CP): a process which uses equipment where a rotating drum with helical placed teeth grinds up the pavement into pieces to the desired depth.

CONSISTENCY: describes the degree of fluidity or plasticity of asphalt binder at any particular temperature. The consistency of asphalt binder varies with temperature so it is necessary to use a common or standard temperature when comparing the consistency of one asphalt binder with another.

COMPACTION: the densification or compressing of a given volume of material into a smaller volume of a soil or pavement layer by means of mechanical manipulation such as rolling or tamping, with or without vibration.

COMPACTION CURVE: the curve showing the relationship between the dry unit weight (density) and the moisture content of a soil for a given compaction effort.

COST EFFECTIVENESS: an economic measure defined as the effectiveness of an action or treatment divided by the present worth of life-cycled costs.

CRACK FILLER: a material, usually bituminous or silicon-based, used to fill and seal cracks in existing pavements.

CRACK REPAIR: maintenance in which badly deteriorated cracks are repaired through patching operations.

CRACK SEALING: a maintenance treatment in which a crack is filled with a sealant. This may or may not include prior routing and/or drying with hot compressed air.

CROSS SECTION: a profile cut or illustration taken at right angle to the centerline of the longitudinal axis of a roadway.

CRACK TREATMENT: maintenance in which cracks are directly treated through sealing or filling operations.

CRUSHED GRAVEL: aggregate produced from the crushing of gravel, with most particles having at least one crushed face.

CRUSHER: equipment that is used to reduce larger stone and gravel too smaller, usable sizes.

CRUSHED BASE EQUIVALENCY: a measure expressing the contribution of each pavement component in terms of an equivalent thickness of crushed granular base.

CRUSHED STONE: aggregate produced from the crushing of quarried rock, with all faces fractured.

CUPPING: a depression in the pavement profile along crack edges caused by damaged or weakened sub-layers.

CUTBACK ASPHALT: asphalt binder that has been blended with distillates.

DEEP PATCHING: a maintenance treatment where the asphalt concrete and granular layers are removed and replaced with asphalt concrete with or without granular material below.

DEEP STRENGTH PAVEMENT: a flexible pavement with at least 7 inches (175 mm) of asphalt concrete on 6 inches (150 mm) or more of granular base.

DENSE-GRADED AGGREGATE: an aggregate that has a particle size distribution such that when it is compacted, the resulting voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, are relatively small

DENSIFICATION: act of increasing the density of a mixture during the compaction process.

DENSITY: the degree of solidity that can be achieved in a given mixture that will be limited only by the total elimination of voids between particles of mass. The mass of material divided by the volume, expressed as pounds per cubic foot (kilograms per cubic meter).

DISTRESS MANIFESTATION INDEX (DMI): a numerical value representing the cumulative amount of various types and severity of pavement surface distress.

DRAINAGE LAYER: an open graded base, stabilized or unstabilized, for pavements, usually 4 to 6 inches (100 to 150 mm) in thickness, and connected to a positive drainage system.

DRYER: an apparatus that will dry aggregates and heat them to specified temperatures.

DRY MIXING PERIOD: the interval of time between the beginning of the charge of dry aggregates into the pugmill and the beginning of the application of bituminous material.

DRUM MIX PLANT: a manufacturing facility for producing asphalt concrete that continuously proportions aggregates, heats and dries them in a rotating drum, and simultaneously mixes them with a controlled amount of asphalt binder. The same plant may produce cold-mixed bituminous paving mixtures without heating and drying the aggregates.

DUCTILITY: the ability of a substance to be drawn out or stretched thin. Ductility is considered an important characteristic of asphalt binders. In many applications, the presence or absence of ductility is usually considered more significant than the actual degree of ductility.

DYNAFLECT: a device to measure the surface deflection of a pavement under a sinusoidal varying load in order to evaluate its structural adequacy.

EDGE DETERIORATION: secondary cracks and spalls that occur within a few mils (mm) of the edges of a primary crack.

END RESULT SPECIFICATION: the specification of an end result to be achieved in construction, as compared to a method type of specification.

EMBANKMENT: a raised fill structure whose surface is higher than the natural adjoining surface.

EMULSION: an abbreviated term for asphalt emulsion binder which is produced in a high shear mixing device using asphalt binder, water, admixture, and in some cases, distillates.

EQUIVALENT SINGLE AXLE LOAD (ESAL): a concept which equates the damage to a pavement structure caused by the passage of a non-standard axle load to a standard 18,000 pound (80 kiloNewton) axle load, in terms of calculated or measured stress, strain or deflection at some point in the pavement structure or in terms of equal conditions of distress or loss of serviceability.

EROSION: wear caused by the force of wind or moving water.

FALLING WEIGHT DEFLECTOMETER (FWD): a device to measure the surface deflection of a pavement under a dynamic load in order to evaluate its structural adequacy.

FATIGUE: decrease of strength due to repetitive loading.

FAULTING: a difference in elevation between opposing sides of a crack caused by weak or moisture-sensitive foundation material.

FILLER: general term for a fine material that is inert under the conditions of use and serves to occupy space and may improve physical properties.

FINE AGGREGATE: aggregate passing the No. 4 (4.75 mm) sieve and predominantly retained on the No. 200 (0.075 mm) sieve.

FINES: proportion of a soil or clay and silt particles in an aggregate, finer than No. 200 (0.075 mm) sieve size.

FLEXIBLE PAVEMENT: a pavement structure usually composed of one or more asphalt concrete layers over an unbound aggregate or stabilized base and prepared subgrade soil.

FLUSHING: see bleeding.

FRACTURED FACES: an angular, rough or broken surface of an aggregate particle created by crushing, by other artificial means or by nature.

FRICTION: resistance to the relative movement of one body (tire) sliding, rolling or flowing over another body (pavement surface) with which it is in contact.

FRICTION COURSE: open graded mix or surface treatment to improve road surface friction.

FRICTION NUMBER: the ability of an asphalt paving surface, particularly when wet, to offer resistance to slipping or skidding. Aggregates containing non-polishing minerals with different wear or abrasion characteristics provide continuous renewal of the pavement's texture maintaining a high friction number surface.

FROST HEAVE: the rise in a pavement surface caused by the freezing of pore water and/or the creation of ice lenses in the underlying layers.

FULL DEPTH PAVEMENT: a flexible pavement structure which has asphalt concrete layer(s), usually greater than 6 inches (150 mm) in total thickness, placed directly in contact with the subgrade.

GEOSYNTHETIC: woven or non-woven man-made materials designed for such applications as drainage, filtration, separation, and strengthening. They can be subdivided into various groups: geotextiles, geowebs, geocomposites, geogrids or geodrains.

GRADATION: the proportions by the mass of soil, rock, granular or other materials distributed in specified particle size ranges.

GRADE: the elevation of a surface or the slope of the surface.

GRADIENT: the amount of slope along a specific line or route, such as road surface, channel or pipe.

GRANULAR BASE EQUIVALENCY (GBE): a measure expressing the contribution of each pavement component in terms of an equivalent thickness of granular base.

GRAVEL: granular material predominantly retained on the No. 4 (4.75 mm) sieve and resulting from natural disintegration and abrasion of rock or processing of weakly bound conglomerate.

HEAT-PLANER: a device that heats the pavement surface and uses a stationary or vibrating flat steel blade or plate to shear off up to 1 inch (25 mm) of the heated surface.

HEAT-SCARIFIER: a device that heats the pavement surface and uses stationary steel tines/teeth or rotating milling drum to loosen or remove up to 1 inch (25 mm) of the heated surface.

HIGH FLOAT EMULSION: an emulsion with petroleum distillates that have a gel quality imparted by the addition of various chemicals.

HOT MILLER: a device that heats the pavement surface and uses a rotating milling drum that has cutting tools mounted over the cylindrical surface to mill off up to 2 inches (50 mm) of the heated surface.

HOT IN-PLACE RECYCLING (HIR): a rehabilitation treatment used to correct asphalt pavement surface distress involving heating, removal of old asphalt concrete, processing, mixing with new aggregates, new asphalt binder and/or recycling agents, relaying, and compacting to meet specifications for conventional asphalt concrete.

HVEEM METHOD: method to design hot mix asphalt concrete.

INFRARED HEATING: involves heating a pavement using invisible heat rays having wavelengths longer than those of red light, thus direct contact of flame on pavement surface is avoided. Sometimes referred to as radiant or indirect heating.

IMPERMEABILITY: the resistance to passage of air and water into or through a pavement.

IMPERVIOUS: resistant to movement of water or air.

INTERNATIONAL ROUGHNESS INDEX (IRI): a summary statistic which characterizes road surface longitudinal roughness, based on the simulation of a standard quarter car model moving over the longitudinal profile of the road.

KINEMATIC VISCOSITY: a method of measuring viscosity of an asphalt binder using the millimeters squared per second (stoke) as the basic measurement and is related to the absolute viscosity by the specific gravity of the asphalt binder. Test temperature of 275°F (135° C) is typical for an asphalt binder.

LIFE-CYCLE COST ANALYSIS: an investigation of the present and future costs of each repair alternative, taking into account the effects of both inflation and interest rates on expenses over the life of the project.

LIPPING: an upheaval in the pavement profile along crack edges. Lipping may be the result of bulging in underlying Portland cement concrete base or the infiltration and buildup of material in the crack.

LOAD EQUIVALENCY FACTOR: a ratio of relative pavement damage to the number of Equivalent Single Axes Loads (ESAL's) a particular loading on a vehicle axle assembly represents.

LONGITUDINAL: parallel to the centerline of the pavement or laydown direction.

LONGITUDINAL CRACK: a distress manifestation where the crack or crack pattern in the pavement is parallel to the direction of travel.

MAINTENANCE: well timed and executed activities to ensure or extend pavement life until deterioration of the pavement layer materials and subgrades is such that a minimum acceptable level of serviceability is reached, and/or it is more cost-effective to rehabilitate the pavement.

MAINTENANCE MIX: a mixture of bituminous material and mineral aggregate applied at ambient temperature for use in patching holes, depressions, and distress areas in existing pavements using appropriate hand or mechanical methods in placing and compacting the mix. These mixes may be designed for immediate use or for use out of a stockpile at a later time without further processing.

MARSHALL METHOD: a method to design hot mix asphalt concrete.

MARSHALL STABILITY AND FLOW: design properties (resistance and deformation) of asphalt concrete determined from specific laboratory tests on a test specimen.

MAXIMUM SIZE (OF AGGREGATE): in specifications for or descriptions of aggregate, the smallest sieve opening through which the entire amount of aggregate is required to pass.

METHOD BASED SPECIFICATION: a specification involving the methodology or technique to be applied to a construction item, such as number of passes of a certain weight of roller.

MICROWAVE: short electromagnetic waves sometimes used to heat asphalt paving mixtures for recycling.

MILLING: removing the surface of a pavement with a self-propelled machine equipped with a transverse rotating cutter drum.

MINERAL FILLER: a finely divided mineral product at least 70 percent of which will pass a No. 200 (0.075 mm) sieve. Pulverized limestone is the most commonly manufactured filler, although other stone dust, hydrated lime, Portland cement, and certain natural deposits of finely divided mineral matter are also used.

NOMINAL MAXIMUM SIZE (OF AGGREGATE): in specifications for or descriptions of aggregate, the smallest sieve opening through which the entire amount of the aggregate is permitted to pass.

OPEN-GRADED AGGREGATE: an aggregate that has a particle size distribution such that when it is compacted, the voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, remain relatively large.

OVERLAY: a new lift(s) of asphalt concrete placed on an existing pavement to restore the ride or surface friction or strengthen the structure.

PASS: a single passage of a reclaimer, motor grader or roller.

PATCHING: a maintenance treatment to repair failures or replace surface material.

PAVING GRADE: a classification system used to define asphalt binder types used for the production of hot mix asphalt for road, street, highway and other applications.

PAVEMENT: the layers above the subgrade.

PAVEMENT CONDITION INDEX (PCI): a composite measure of surface distress types, severity, and frequency.

PAVEMENT STRUCTURE: the subbase, base, and wearing surface layers.

PAVEMENT MANAGEMENT SYSTEM (PMS): a wide spectrum of activities including the planning or programming of investments, design, construction, maintenance, and the periodic evaluation or performance used to provide an effective and efficient road network.

PENETRATION: consistency of an asphalt binder expressed as the vertical distance that a standard needle penetrates a sample of the material under standard conditions of loading, time, and temperature.

PERFORMANCE BASED SPECIFICATION: a specification involving minimum or maximum levels of performance items at certain ages, such as roughness, surface distress, surface friction or structural adequacy.

PERMEABILITY: a property of a material measured in terms of the rate with which it allows passage of water or air.

PETROGRAPHIC ANALYSIS: a procedure to assess the durable qualities of aggregate through its petrology and structural fabric.

PLASTICITY INDEX (PI): the numerical difference between the liquid limit and the plastic limit of a soil.

PLASTIC LIMIT (PL): the lowest moisture content at which a soil remains plastic.

PLATE LOAD TEST: a method to determine the load bearing capacity of a subgrade, subbase or base, by measuring the deflection of a plate under a static load.

POISE: a centimeter-gram-second unit of absolute viscosity, equal to the viscosity of a fluid in which a stress of one dyne per square centimeter is required to maintain a difference of velocity of one centimeter per second between two parallel planes in the fluid that lie in the direction of flow and are separated by a distance of one centimeter.

POLISHING: the phenomena caused by the abrasive action of vehicle tires on aggregate particles that reduces the frictional properties of the surface.

PORTLAND CEMENT: a hydraulic cement comprised of very fine grains produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates and calcium sulphate.

PORTLAND CEMENT CONCRETE (PCC): the product of mixing Portland cement, mineral aggregates, water, and in some cases additives such as an air entering agent which result in a hardened structural material after hydration.

POTHOLE: localized distress in an asphalt-surfaced pavement resulting from the breakup of the asphalt surface and possibly the asphalt base course. Pieces of asphalt pavement created by the action of climate and traffic on the weakened pavement are then removed under the action of traffic, leaving a hole.

POTHOLE PATCHING: the repair of severe, localized distress in asphalt-surfaced pavements. This maintenance activity is generally performed by the agency responsible for the roadway and is intended to be a temporary repair at best. Pothole patching is not intended to be a permanent repair. Full-depth reconstruction of the distressed areas is necessary for a permanent repair in most instances.

PREVENTIVE MAINTENANCE: major maintenance treatments to retard deterioration of a pavement, such as chip seal, rout and crack seal, etc.

PRIME COAT: the application of low-viscosity liquid asphalt or asphalt emulsion to penetrate and bind a granular base prior to the placement of asphalt concrete.

PROFILE: (longitudinal) a chart line indication of elevations, grades, and distances and usually indicating the depth the cut and height of fill of the grading work commonly taken along the centerline of the proposed road alignment.

PROFILE: (transverse) a cross-sectional plot of surface elevations across a road.

PUGMILL: a device for mixing hot or cold aggregates and reclaimed asphalt pavement with an asphalt binder, recycling agent or stabilizing additive(s) to produce a homogeneous mixture.

QUALITY ASSURANCE (QA): a system of activities whose purpose is to provide assurance that the overall quality control job is in fact being done effectively. It involves a continuing evaluation of the effectiveness of the overall control program with a view to having corrective measures initiated where necessary. For a specific product or service, this involves verifications, audits, and the evaluation of the quality factors that affect the specification, production, inspection, and use of the product or service.

QUALITY CONTROL (QC): the overall system of activities whose purpose is to provide a quality of product or service that meets the needs of users. The aim of quality control is to provide quality that is satisfactory, adequate, dependable, and economic.

RAVELING: the wearing away of a pavement surface through the dislodging of aggregate particles and/or matrix of asphalt binder and fine particles.

RECLAIMED ASPHALT PAVEMENT (RAP): asphalt pavement or paving mixture removed from its original location for use in recycled hot mix asphalt, Cold Recycled mixes or for Full Depth Reclamation.

RECYCLING AGENT: a blend of hydrocarbons with or without minor amounts of other materials that is used to alter or improve the properties of the aged asphalt in a recycled asphalt paving mixture.

RECYCLED HOT MIX ASPHALT (RHM): a mixture of reclaimed asphalt pavement with the inclusion, if required, of asphalt binder, asphalt emulsion, cut-back asphalt, recycling agent, mineral aggregate, and mineral filler.

REHABILITATION: a term in pavement management involving the restoration of pavement serviceability through such actions as overlays.

REJUVENATOR: an additive used in the recycling of reclaimed asphalt pavement.

RIDING COMFORT INDEX (RCI): a measure to characterize the ride quality of a pavement on a scale of 0 to 10.

ROAD FRICTION: a general term related to the frictional or friction number properties of a road surface.

ROUT: a groove cut along a crack in asphalt pavements to act as a reservoir for crack sealant.

RUTTING: a distortion occurring in the wheelpaths of an asphalt concrete pavement.

SAND: granular material passing the No. 4 (4.75 mm) sieve and predominantly retained on the No. 200 (0.075 mm) sieve, either naturally occurring or the product of processing, i.e., manufactured sand.

SAND ASPHALT: a mixture of sand and asphalt binder, cutback or asphalt emulsion. It may be prepared with or without special control of aggregate grading and may or may not contain mineral filler. Either mixed-in-place or plant mix construction may be employed. Sand asphalt is used in construction of both base and surface courses.

SATURATES: a mixture of paraffinic and naphthenic hydrocarbons that on percolation in a paraffinic solvent are not absorbed on the absorbing medium. Other compounds such as naphthenic and polar aromatics are absorbed thus permitting the separation of the saturate fraction.

SCARIFICATION: ripping (usually with grader teeth), reshaping, and recompacting a pavement surface and/or base and/or subbase layer.

SCARIFICATION: removal of the top 1 to 2 inches (25 to 50 mm) of an asphalt pavement using a bank of tines/teeth or a rotating milling drum.

SCREEN: in laboratory work an apparatus, in which the apertures are circular, for separating sizes of material.

SECONDARY CRACK: a crack extending parallel to a primary crack.

SEGREGATION: a deficiency in pavement components where the coarse particles are separated from the fine matrix.

SERVICEABILITY: the ability, at time of observation, of a pavement to serve traffic that uses the facility.

SHALLOW PATCHING: a maintenance treatment where the surface layers(s) of asphalt concrete is removed and replaced with well compacted asphalt concrete.

SHOULDER: the non-travel portion of a road on each side of the pavement.

SHOVING: permanent, longitudinal displacement of a localized area of the pavement surface caused by the traffic-induced shear forces.

SIEVE: in a laboratory work an apparatus, in which the apparatus are square, for separating sizes of material.

SKID NUMBER (SN): a standard test measure of the friction between a tire and a wetted road surface.

SLAB: a load bearing layer of Portland cement concrete, with or without reinforcement, sized to control and minimize shrinkage cracking.

SLURRY SEAL: a surface treatment of asphalt emulsion, sand, Portland cement, and water, placed as a slurry. Single or multiple applications may be used.

SOIL: sediments or other unconsolidated accumulations of solid particles which are produced by the physical and chemical disintegration of rock and which may or may not contain organic matter.

SPRAY INJECTION: repair technique for potholes in asphalt-surfaced pavements and spalls in PCC-surfaced pavements that uses a spray-injection device. Spray-injection devices are capable of spraying heated asphalt emulsion, virgin aggregate or both into a distress location.

STABILITY: the ability of asphalt paving mixture to resist deformation from imposed loads. Stability is dependent upon both internal friction and cohesion.

STABILIZATION: a mechanical, chemical or bituminous treatment designed to increase or maintain the stability of a material or otherwise to improve it's engineering properties.

STABILIZING ADDITIVE: a mechanical, chemical or bituminous additive or material used to increase or maintain the strength, durability or moisture susceptibility of a material or to improve its engineering properties.

STANDARD PROCTOR: a test method where 12,375 foot-pounds per cubic foot (593 Kj/(cubic meter) of compactive effort is used to determine the optimum moisture content and maximum dry density of a soil aggregate.

STOKE: a unit of kinematic viscosity, equal to the viscosity of a fluid in poises divided by the density of the fluid in grams per cubic centimeter.

STRIPPING: a phenomenon in asphalt mixtures, where the asphalt binder film debonds or strips from the aggregate particles in the presence of water.

STRUCTURAL ADEQUACY INDEX (SAI): a measure that uses deflections and Equivalent Single Axle Loads to characterize the structural adequacy of a pavement on a sale of 0 to 10.

STRUCTURAL CAPACITY: the load-carrying capacity of a pavement that can be determined by evaluating the materials and/or layer thickness of the pavement structure or the surface deflections.

STRATEGIC HIGHWAY RESEARCH PROGRAM (SHRP): a comprehensive, multimillion dollar research program in the USA and other countries involving research in Long Term Pavement Performance, Asphalt, Concrete, Structures and Highway Operation.

SUBBASE: the layer of select compacted granular material placed on the subgrade and which is overlain by the base of a flexible pavement structure or the Portland cement concrete slab of a rigid pavement structure.

SUBGRADE: the soil prepared and compacted to support a pavement structure.

SUPERPAVE: a general term encompassing the methodology developed in the Strategic Highway Research Program for selecting asphalt binders, for designing hot mix asphalt concrete and for estimating the fatigue, rutting, low-temperature cracking and moisture damage performance of the asphalt concrete.

SURFACE RECYCLING: a general term that describes the Hot In-Place Recycling of the upper portion of an asphalt pavement.

SURFACE TREATMENT: a maintenance or rehabilitation treatment used to seal a road surface, improve its ride or surface friction. Multiple applications of bituminous material and mineral aggregate may be used.

TACK COAT: an application of liquid asphalt or asphalt emulsion to an existing asphalt concrete surface prior to the placement of an asphalt concrete lift or overlay.

TEXTURIZATION: grooving, milling or otherwise abrading the top of a pavement surface.

THERMOPLASTIC (MATERIAL): a material that becomes soft when heated and hard when cooled.

THROW-AND-GO: repair technique for cold-mix patching materials in which material is shoveled into pothole, with no prior preparation of the pothole, until it is filled: compaction of the patch is left to passing traffic, while the maintenance crew moves on to the next distress location.

Throw-and-roll: repair technique for cold-mix patching materials in which material is shoveled into pothole, with no prior preparation of the pothole, until it is filled: the material truck tires are used to compact the patch before the crew moves on to the next distress location.

TRANSVERSE: perpendicular to the pavement centerline or direction of laydown.

TRANSVERSE CRACK: a distress manifestation where the crack is perpendicular to the direction of travel.

TRAFFIC GROWTH FACTOR: a factor used to estimate the percentage annual increase in traffic volume.

TRUCK FACTOR: the number of Equivalent Single Axle Loads (ESAL's) represented by the passage of a truck.

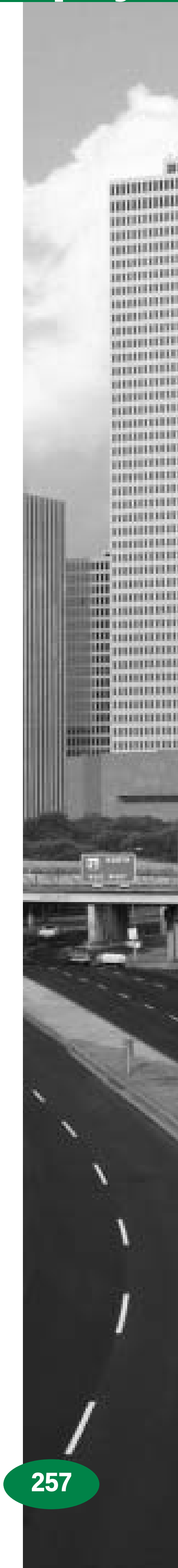
VIRGIN AGGREGATE: new aggregate added to recycled asphalt pavement in the production of recycled hot mix asphalt concrete, Cold Recycled mixtures and for mechanical stabilization using Full Depth Reclamation.

VIRGIN ASPHALT BINDER: new asphalt binder added during recycling to improve the properties of the recycled asphalt concrete.

VOIDS: empty spaces in a compacted mix surrounded by asphalt coated particles.

WARRANTY: guaranteed performance of a work or physical item; e.g. contractor guarantee that pavement rutting on a project will not exceed “x” mils (mm) at “y” years.

WORKABILITY: the ease with which mixtures may be placed and compacted.



BIBLIOGRAPHY

American Association of State Highway and Transportation Officials *Guide Specifications for Highway Construction*. Seventh edition, Washington, DC.

American Society for Testing and Materials *Annual Book of ASTM Standards, Volume 04.03 Road and Paving Materials; Vehicle-Pavement Systems*. West Conshohocken, Pennsylvania.

Asphalt Institute *Principles of Construction of Hot-Mix Asphalt Pavements*. Manual Series No. 22 (MS-22) Second Edition, Lexington, Kentucky, 1998.

Asphalt Institute *A Basic Asphalt Emulsion Manual*. Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky.

Asphalt Recycling and Reclaiming Association *An Overview of Recycling and Reclamation Methods for Asphalt Pavement Rehabilitation*. Brochure, Annapolis, Maryland, 1992.

Asphalt Recycling and Reclaiming Association *Technical Disciplines, Cold Planing, Hot Recycling, Hot In-Place Recycling, Cold In-Place Recycling, Full Depth Reclamation*. Brochure, Annapolis, Maryland, 1990.

Emery J. "Implementing End Result Specifications QC/QA/ERS/TQM". *Proceedings*, Canadian Technical Asphalt Association, 1993.

Emery J. "Asphalt Concrete Recycling in Canada". *Transportation Research Record 1427*, TRB, National Research Council, Washington, DC, 1993

Hicks, G.R. et al. "5 PM Treatments for Flexible Pavements". Better Roads, January, 2000.

Huffman, J.E. "Update on Asphalt Recycling, Reclamation". Better Roads, October, 1999.

Kandhal, P.S. and R.B. Mallick *Pavement Recycling Guidelines for State and Local Governments*. Publication No. FHWA-SA-98-042, FHWA, U.S. Department of Transportation, Washington, DC, 1997.

Mack, J. "State DOTs Update Life-Cycle Cost Analysis". Better Roads, July, 1998.

Palsat, D. and C. McMillan "End Product Specifications – 8 Years of Experience by Alberta Transportation & Utilities". *Proceedings*, Canadian Technical Asphalt Association, 1993.

Raza, H. *An Overview of Surface Rehabilitation Techniques for Asphalt Pavements, Instructors Guide*. Publication No. FHWA-SA-94-074, FHWA, U.S. Department of Transportation, Washington, DC, 1994.

Roberts, F.L. et al. *Hot Mix Asphalt Materials, Mixture Design and Construction*. Second Edition, NAPA Education Foundation, Lanham, Maryland, 1996.

Strategic Highway Research Program, National Research Council *Distress Identification Manual for the Long-Term Pavement Performance Studies*. Publication No. SHRP-LTPP/FR-90-001, Washington, DC, 1990.

Sullivan, J. *Pavement Recycling Executive Summary and Report*. Publication No. FHWA-SA-95-060, U.S. Department of Transportation, FHWA, Washington, DC, 1996.

Transportation Association of Canada *Pavement Design and Management Guide*. Ottawa, Ontario, 1997.

US Army Corps of Engineers *Hot-Mix Asphalt Paving Handbook*. Publication No. UN-13 (CEMP-ET), 1991.

U.S. Department of Transportation, Federal Highway Administration *Pavement Recycling Guidelines for Local Governments - Reference Manual*. Report No. FHWA-SA-90-042, Washington, DC, 1997.

U.S. Department of Transportation, Federal Highway Administration *Pavement Maintenance Effectiveness / Innovative Materials Workshop, Participants Handbook*, Report No. FHWA-SA-96-007, Washington, DC, 1985.

Zaniewski, J.P. and M.S. Mamlouk *Preventive Maintenance Effectiveness – Preventive Maintenance Treatments, Participants Handbook*. Publication No. FHWA-SA-96-027, FHWA, U.S. Department of Transportation, Washington, DC, 1996.

COLD PLANING

Asphalt Recycling and Reclaiming Association *Guide Specifications for Cold Planing*. Annapolis, Maryland, 1999.

Cameron, A. Personal communication, January, 2000.

Hansen, B. Personal communication, January, 2000.

Kandhal, P.S. and R.B. Mallick *Pavement Recycling Guidelines for State and Local Governments*. Publication No. FHWA-SA-98-042, FHWA, U.S. Department of Transportation, Washington, DC, 1997.

Murray, S.W. Personal communication, December, 1999.

Roberts, F.L. et al. *Hot Mix Asphalt Materials, Mixture Design and Construction*. Second Edition, NAPA Education Foundation, Lanham, Maryland, 1996.

Vuillaume, B.C. Personal communication, January, 2000.

Wirtgen GmbH *The various uses of small milling machines up to 40" (1m) working width*. brochure, Germany, 1995.

Wirtgen GmbH *Cold milling machines series 1300-2000 DC*. brochure, Germany, 1997.

Wirtgen GmbH *Cutter bits, Holder systems, Milling drums*. brochure, Germany, 1999.

HOT RECYCLING

Asphalt Institute *Principles of Construction of Hot-Mix Asphalt Pavements*. Manual Series No. 22 (MS-22 Second Edition, Lexington, Kentucky, 1998.

Asphalt Recycling and Reclaiming Association *Proven Guidelines for Hot-Mix Recycling*. Annapolis, Maryland, 1992.

Decker, D.S. and Young, T.J. “Handling RAP in a HMS Facility”. *Proceedings*, Canadian Techincal Asphalt Association, 1996.

Decker, D.S. “Producing and Placing HMA”. Journal, Association of Asphalt Paving Technologists, Volume 68A, Chicago, Illinois, 1999.

Emery J. “Asphalt Concrete Recycling in Canada”. *Transportation Research Record 1427*, TRB, National Research Council, Washington, DC, 1993.

Kandhal, P.S. and R.B. Mallick *Pavement Recycling Guidelines for State and Local Governments*. Publication No. FHWA-SA-98-042, FHWA, U.S. Department of Transportation, Washington, DC, 1997.

Kennedy, T.W. et al. “Optimizing Use of Reclaimed Asphalt Pavement with the Superpave System”. Journal, Association of Asphalt Paving Technologists, Volume 67, Boston, Massachusetts, 1998.

Paul, H. “Evaluation of Recycled Projects for Performance”. Journal, Association of Asphalt Paving Technologists, Volume 65, Baltimore, Maryland, 1996.

Roberts, F.L. et al. *Hot Mix Asphalt Materials, Mixture Design and Construction*. Second Edition, NAPA Education Foundation, Lanham, Maryland, 1996.

Sullivan, J. *Pavement Recycling Executive Summary and Report*. Publication No. FHWA-SA-95-060, U.S. Department of Transportation, FHWA, Washington, DC, 1996.

U.S. Department of Transportation, Federal Highway Administration *Pavement Recycling Guidelines for Local Governments* – Reference Manual. Report No. FHWA-SA-90-042, Washington, DC, 1998.

U.S. Department of Transportation, Federal Highway Administration *User Guidelines for Waste and By-Product Materials in Pavement Construction*. Report No. FHWA-RD-97-148, Washington, DC, 1998.

HOT IN-PLACE RECYCLING

Asphalt Recycling and Reclaiming Association *Hot In-Place Recycling, First in the Line of Pavement Maintenance*. Brochure, Annapolis, Maryland.

Bradbury, A.L. et al. “Performance of In-Situ Hot Mix Recycling as a Maintenance Technique in Canada”. XIIIth International Road Federation World meeting, Toronto, Ontario, 1997

Bauer, C. et al. *An Environmental Review of Hot In-Place Recycling in British Columbia*. unpublished report, Royal Roads University, British Columbia, August, 1998.

British Columbia Ministry of Transportation and Highways H.I.P. ’91. conference proceedings, Vancouver, British Columbia, 1991.

Button, J.W. et al. “Hot In-Place Recycling of Asphalt Concrete, A Synthesis of Highway Practice”. *NCHRP Synthesis 193 TRB*, National Research Council, Washington D.C. 1994.

Dunn, L. “Hot In-Place Recycling and Asphalt Hardening – Myth or Reality?”. unpublished presentation at the Asphalt Recycling and Reclaiming Association annual meeting, Florida, 1996.

Dunn, L. “A Study to Develop Guidelines for the Design of Hot In-Place Recycling (HIPR) Mixes Based on the Performance of HIPR Roadways in Alberta”. unpublished presentation at the Asphalt Recycling and Reclaiming Association semi-annual meeting, Minnesota, 1996.

Dunn, L. “End Result Specifications for Hot In-Place Recycling (HIR)”. unpublished presentation at the Asphalt Recycling and Reclaiming Association annual meeting, Texas, 1997.

Dunn, L. et al. “Guidelines for the Design of Hot In-Place Recycled Asphalt Concrete Mixtures”. *Proceedings*, Canadian Technical Asphalt Association, 1997.

Emery J. et al. “Asphalt Technology for In-Place Surface Recycling using the Heat Reforming Process”. Proceedings, Canadian Technical Asphalt Association, 1989.

Fyvie, K. and J. Van Valkenburg “Hot In-Place Recycling of Runway 15-33 Prince George Airport, B.C. – A Case Study”. *Proceedings*, Canadian Technical Asphalt Association, 1999.

Gavin, J. and C. McMillan “Alberta Transportation & Utilities Experience with Hot In-Place Recycling”. *Proceedings*, Canadian Technical Asphalt Association, 1993.

Heavy Construction News “Hot new machine helps smooth out problems”. Volume 41, No. 9, September, 1997.

Kandhal, P.S. and R.B. Mallick *Pavement Recycling Guidelines for State and Local Governments*. Publication No. FHWA-SA-98-042, FHWA, U.S. Department of Transportation, Washington, DC, 1997.

Kandhal, P.S. and K. Y. Foo ”Designing Recycled Hot Mix Asphalt Mixtures Using Superpave Technology”. NCAT Report No. 96-5, National Center for Asphalt Technology, Auburn University, Alabama, 1997.

Kandhal, P.S. et al. ”Evaluation of Recycled Hot Mix Asphalt Mixtures”. NCAT Report No. 95-1, National Center for Asphalt Technology, Auburn University, Alabama, 1995.

Kazmierowski, T.J. et al. “Seven Years Experience with Hot In-Place Recycling in Ontario”. *Proceedings*, Canadian Technical Asphalt Association, 1994.

Kennedy, T.W. et al. “Optimizing Use of Reclaimed Asphalt Pavement with the Superpave System”. Journal, Association of Asphalt Paving Technologists, Volume 67, Boston, Massachusetts, 1998.

Lee, S.Q.S. et al. “New Developments in Hot In-Place Recycling Technology and Specifications”. Proceedings, Canadian Technical Asphalt Association, 1998.

Maag, R.G. “Surface Recycling for Kansas DOT”. *Proceedings*, Asphalt Recycling and Reclamation Association, 1995.

Martec Recycling Corporation *Principles of Hot In-Place Recycling of Asphalt Pavements*. Draft No. 1, Vancouver, British Columbia, 1996.

Nevada Transportation Technology Transfer Center *Western States Round Table, Hot In-Place Asphalt Recycling*. conference proceedings, University of Nevada Reno, Reno, Nevada, 1994.

Pyrotech Asphalt Equipment Mfg. Co. Ltd. *Hot In-Place Asphalt Pavement Recycling, A Technical Training Seminar & Workshop*. Kamloops, British Columbia, 1994.

Rogge, D.F. et al. *Exploratory Study of Hot In-Place Recycling of Asphalt Pavements*. Transportation Research Report 94-23, Transportation Research Institute, Oregon State University, Corvallis, Oregon, November, 1994.

Taisei Rotec, Inc. *Hot In-Place Recycling Heat Reforming Process*. brochure, Japan, 1989.

Taverner, G. et al. "Hot In-Place Recycling of Airfield Pavements at Canadian Forces Base Edmonton, Alberta". *Proceedings*, Canadian Technical Asphalt Association, 1990.

Terrel, R. et al. "Hot In-Place Recycling: State-of-the-Practice". Journal, Association of Asphalt Paving Technologists, Volume 66, Salt Lake City, Utah, 1997.

FULL DEPTH RECLAMATION

Asphalt Recycling and Reclaiming Association *Full Depth Reclamation Guide*. brochure, Draft 2, Annapolis, Maryland, 1999.

Asphalt Recycling and Reclaiming Association *Guideline Specifications for Full Depth Reclamation*. Annapolis, Maryland.

Asphalt Recycling and Reclaiming Association *Full Depth Reclamation Around the World*. brochure, Annapolis, Maryland.

Asphalt Institute *A Basic Asphalt Emulsion Manual*. Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky, 1998.

Asphalt Institute *Asphalt Cold-Mix Recycling*. Manual Series No. 21 (MS-21), Second Edition, Lexington, Kentucky, 1986.

Better Roads "Pre-project evaluation aids reclamation". July, 1998.

Bomag, A United Dominion Company *Cold In-Place Recycling*. Kewanee, Illinois, 1987.

Bomag, A United Dominion Company *Soil Stabilization with Asphalt*. Kewanee, Illinois, 1987.

Caterpillar Paving Products Inc. *Full Depth Reclamation Manual*. Minneapolis, Minnesota, 1996.

Caterpillar Paving Products Inc. *Full Depth Reclamation, The Versatile Alternative*. Minneapolis, Minnesota, 1996.

CMI Corporation *A Practical Guide to Soil Stabilization & Road Reclamation Techniques*. Oklahoma City, Oklahoma, 1994.

Favretti, P. "Resistance to Freeze-Thaw Cycles of some Asphalt Cold Mixtures". *Proceedings*, Canadian Technical Asphalt Association, 1994.

Favretti, P. et al. "Deep Cold In-Place Recycling with Cement/Emulsion". *Proceedings*, Canadian Technical Asphalt Association, 1997.

Huffman, J.E. "Full Depth Pavement Reclamation: State-of-the-Practice". Journal, Association of Asphalt Paving Technologists, Volume 66, Salt Lake City, Utah, 1997.

Huffman, J.E. "Restoring distressed roads FDR can be a valuable rehab technique for cracked pavements". Asphalt Contractor, December, 1997.

Kandhal, P.S. and R.B. Mallick *Pavement Recycling Guidelines for State and Local Governments*. Publication No. FHWA-SA-98-042, FHWA, U.S. Department of Transportation, Washington, DC, 1997.

Kearney, E. and J. Huffman "Full-Depth Reclamation Process". *Transportation Research Record 1684* TRB, National Research Council, Washington, DC, 1999.

Loudon A.A. & Partners "Comparison of Stabilizing Agents Using the Deep Cold In-Place Recycling Process". Kloof, South Africa, undated.

Loudon A.A. & Partners *Cold Deep In Place Recycling, Technical Recommendations and Application Specifications*. Kloof, South Africa, 1995

Theriault, Y. "Some Laboratory and Field Investigations on Combining Lime or Cement with Foamed Asphalt". *Proceedings*, Canadian Technical Asphalt Association, 1998. Subsequent discussions *Proceedings*, Canadian Technical Asphalt Association, 1999.

Wirtgen GmbH *Cold-Mix Recycling and Soil Stabilization*, brochure, Germany, 1990.

Wirtgen GmbH *Cold In-Place Recycling Including Base Rehabilitation, An Economic and Environmentally Friendly Construction Process*. brochure, Germany, 1992.

Wirtgen GmbH *Wirtgen Cold Recycling, The method, the equipment and its application*. brochure, Germany, 1994.

Wirtgen GmbH *Wirtgen Cold Recycling Manual*. Germany, 1998.

Wirtgen GmbH *Laboratory-scale foamed bitumen plant WLB 10*. brochure, Germany, 1998.

Wise, P.W. "In Place Full Depth Cold Flexible Pavement Reclamation". Conexpo/Con-Agg, Las Vegas, Nevada, 1996.

COLD RECYCLING

American Association of State Highway and Transportation Officials *Guide Specifications for Highway Construction*. Seventh edition, Washington, D.C.

AASHTO-AGC-ARTBA Joint Committee Task Force 38 *Report on Cold Recycling of Asphalt Pavements*, AASHTO, Washington, DC, March 1998.

American Coal Ash Association *Soil and Pavement Base Stabilization with Self-Cementing Coal Fly Ash*. Washington, DC, 1999.

Asphalt Emulsion Manufacturers Association *Recommended Performance Guidelines*. Second Edition, Annapolis, Maryland.

Asphalt Institute *A Basic Asphalt Emulsion Manual*. Manual Series No. 19 (MS-19), Third Edition, Lexington, Kentucky.

Asphalt Institute *Asphalt Cold-Mix Recycling*. Manual Series No. 21 (MS-21), Second Edition, Lexington, Kentucky, 1986.

Badaruddin S.R. and R.S. McDaniel "Cold In-Place Recycling for Rehabilitation and Widening of Low-Volume Flexible Pavements in Indiana". *Transportation Research Record 1342*, TRB, National Research Council, Washington, DC, 1992.

Cross, S.A. “Experimental Cold In-Place Recycling with Hydrated Lime”. *Transportation Research Record No. 1684*, TRB, National Research Council, Washington DC, 1992.

Cross, S.A. “Evaluation of Cold In-Place Recycling”. K-TRAN: KU-93-1, Kansas Department of Transportation, Topeka, Kansas, 1995.

Cross, S.A. and G.A. Fager “Fly Ash in Cold Recycled Bituminous Pavements”. *Transportation Research Record 1486*, TRB, National Research Council, Washington, DC, 1995.

Cross, S.A. and D. Young “Evaluation of Type C Fly Ash in Cold In-Place Recycling”. *Transportation Research Record 1583*, TRB, National Research Council, Washington, DC, 1997.

Cross, S.A. “Experimental Cold In-Place Recycling with Hydrated Lime”. *Transportation Research Record 1684*, TRB, National Research Council, Washington, DC, 1999.

Croteau, J.M. and Stephen Lee “Cold In-Place Recycling: Performance and Practices”. XIIIth International Road Federation World meeting, Toronto, Ontario, 1997.

Epps, J.A. *Cold-Recycled Bituminous Concrete Using Bituminous Materials*. NCHRP Synthesis of Highway Practice 160, TRB, National Research Council, Washington, DC, 1990.

Jahren, T.J. et al. *Review of Cold In-Place Recycled Asphalt Concrete Projects*. Iowa DOT Project HR-392, Iowa Department of Transportation, Ames, Iowa, February 1998.

Kandhal, P.S. and R.B. Mallick *Pavement Recycling Guidelines for State and Local Governments*, Publication No. FHWA-SA-98-042, FHWA, U.S. Department of Transportation, Washington, DC, 1997.

Kearney, E. “Cold Mix Recycling: State-of-the-Practice”. Journal, Association of Asphalt Paving Technologists, Volume 66, Salt Lake City, Utah, 1997.

Kearney, E. “Cold Mix Recycling: State-of-the-Practice”. 5th Materials Engineering Conference, American Society of Civil Engineers, Cincinnati, Ohio, 1999.

Lauter, K.A. and M.C. Corbett “Developing Gyratory Compactor Guidelines for use with Cold In-Place Recycled Material”. *Proceedings*, Canadian Technical Asphalt Association, 1998.

Lee, S.Q.S. et al. “Low Temperature Cracking Performance of Superpave and Cold In-Place Recycled Pavements in Ottawa-Carlton”. *Proceedings*, Canadian Technical Asphalt Association, 1997.

McKeen, R.G. et al. “New Mexico’s Experience with Cold Insitu Recycling”. TRB, National Research Council, Washington, DC, 1997.

Murphy, D. and J. Emery “Evaluation of Modified Cold In-Place Asphalt Recycling”. *Transportation Research Record 1545*, TRB, National Research Council, Washington, DC, 1996.

Murphy, D. and J. Emery “Evaluation of Modified Cold In-Place Asphalt Recycling”. *Proceedings*, Canadian Technical Asphalt Association, 1997.

O’Leary, M.D. and R.D. Williams “In Situ Cold Recycling of Bituminous Pavements with Polymer-Modified High Float Emulsions”. *Transportation Research Record 1342*, TRB, National Research Council, Washington, DC, 1992.

Roberts, F.L. et al. *Hot Mix Asphalt Materials, Mixture Design and Construction*. Second Edition, NAPA Education Foundation, Lanham, Maryland, 1996.

Rogge, D.F. et al. “Use of Asphalt Emulsions for In-Place Recycling: Oregon Experience”. *Transportation Research Record* 1342, TRB, National Research Council, Washington, DC, 1992.

Rogge, D.F. et al. “Case Histories of Cold In-Place Recycled Asphalt Pavements in Central Oregon”. *Transportation Research Record 1337 TRB*, National Research Council, Washington, DC, 1992.

U.S. Department of Transportation, Federal Highway Administration *Pavement Recycling Guidelines for Local Governments - Reference Manual*. Report No. FHWA-TS-87-230, Washington, DC, 1987.

Zhou, H. and S.E. Nodes “Study of Lime vs. No Lime in Cold In-Place Recycled Asphalt Concrete Pavements”. Publication No. OR-RD-92-02, Oregon Department of Transportation, Oregon, 1991.

GLOSSARY OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AGC	Association of General Contractors of America
ARRA	Asphalt Recycling and Reclaiming Association
ARTBA	American Road and Transportation Builders Association
ASTM	American Society for Testing and Materials
BARM	Basic Asphalt Recycling Manual
BBR	Bending Beam Rheometer
C	Centigrade
CaO	Calcium Oxide
CBR	California Bearing Ration
CCPR	Cold Central Plant Recycling
CIR	Cold In-Place Recycling
CKD	Cement Kiln Dust
CP	Cold Planing
CR	Cold Recycling
DBC	Design Bitumen Content
DCP	Dynamic Cone Penetrometer
DMI	Distress Manifestation Index
DSR	Dynamic Shear Rheometer
DTT	Direct Tension Tester
ESAL	Equivalent Single Axel Load
F	Fahrenheit
FDR	Full Depth Reclamation
FHWA	Federal Highway Administration

FWD	Falling Weight Deflectometer
GBE	Granular Base Equivalency
GPR	Ground Penetrating Radar
HFMS	High Float Medium-setting asphalt emulsion
HIR	Hot In-Place Recycling
HMA	Hot Mix Asphalt
IRI	International Roughness Index
IRRM	Index of Retained Resilient Modulus
ITS	Indirect Tensile Strength
JMF	Job Mix Formula
LKD	Lime Kiln Dust
LTPP	Long Term Pavement Performance
m	Slope value from Bending Beam Rheometer test
MDD	Maximum Dry Density
mm	Millimeter
MTD	Maximum Theoretical Density
NCHRP	National Cooperative Highway Research Program
OFC	Optimum Fluid Content
OGFC	Open Graded Friction Course
OMC	Optimum Moisture Content
ORAC	Optimum Recycling Additive Content
PAV	Pressure Aging Vessel
PCC	Portland cement Concrete
PCI	Present Condition Index
PG	Performance Grade (asphalt binder)

PMS	Pavement Management System
PrI	California Profilograph Index
PSI	Present Serviceability Index
QA	Quality Assurance
QC	Quality Control
RA	Recycling Agent
RAP	Reclaimed Asphalt Pavement
RCI	Riding Comfort Index
RCR	Riding Comfort Rating
RTFOT	Rolling Thin Film Oven Test
S	Creep Stiffness Value from Bending Beam Rheometer test
SDI	Surface Distress Index
SGC	Superpave Gyratory Compactor
SHRP	Strategic Highway Research Program
SMA	Stone Matrix (Mastic) Asphalt
SN	Structural Number
SQA	Statistical Quality Assurance
SS	Slow-setting asphalt emulsion
SSD	Saturated Surface Dry
TFOT	Thin Film Oven Test
TSR	Tensile Strength Ratio
Va	Air Voids
VFA	Voids Filled with Asphalt
VMA	Voids in the Mineral Aggregate
VTM	Voids in Total Mix

NOTES

NOTES