Basic Asphalt Recycling Manual

U.S. Department of Transportation
Federal Highway Administration

ASPHALT RECYCLING AND RECLAIMING ASSOCIATION

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Cover Photo: Downtown Houston, Texas

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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.

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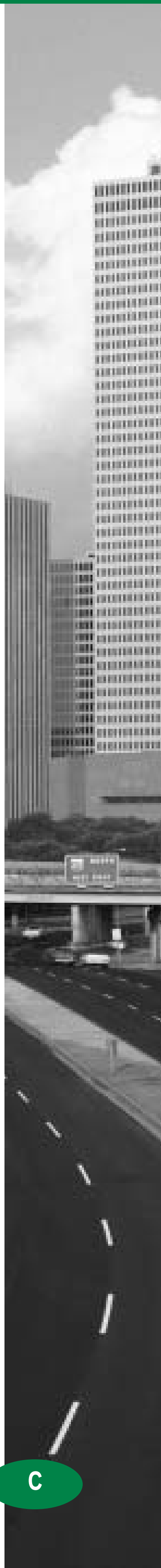

ARRA has published this first edition of the Basic Asphalt Recycling Manual (BARM). The BARM was prepared by Mr. Leonard Dunn, P.Eng. under contract with ARRA. Dr. Stephen Cross, P.E. (University of Kansas) was subsequently retained to assist in the preparation of Chapters 15 to 17, on Cold Recycling.

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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.

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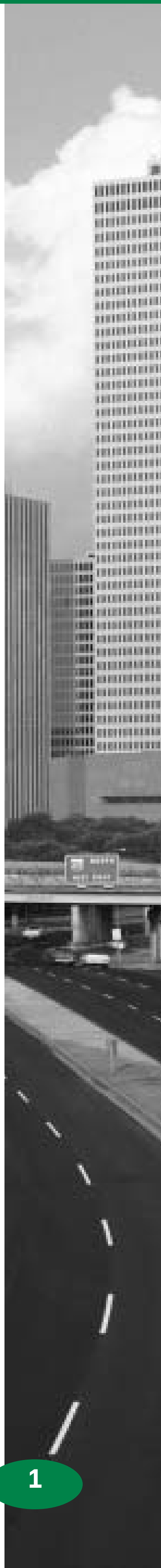
Chapter 1



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.

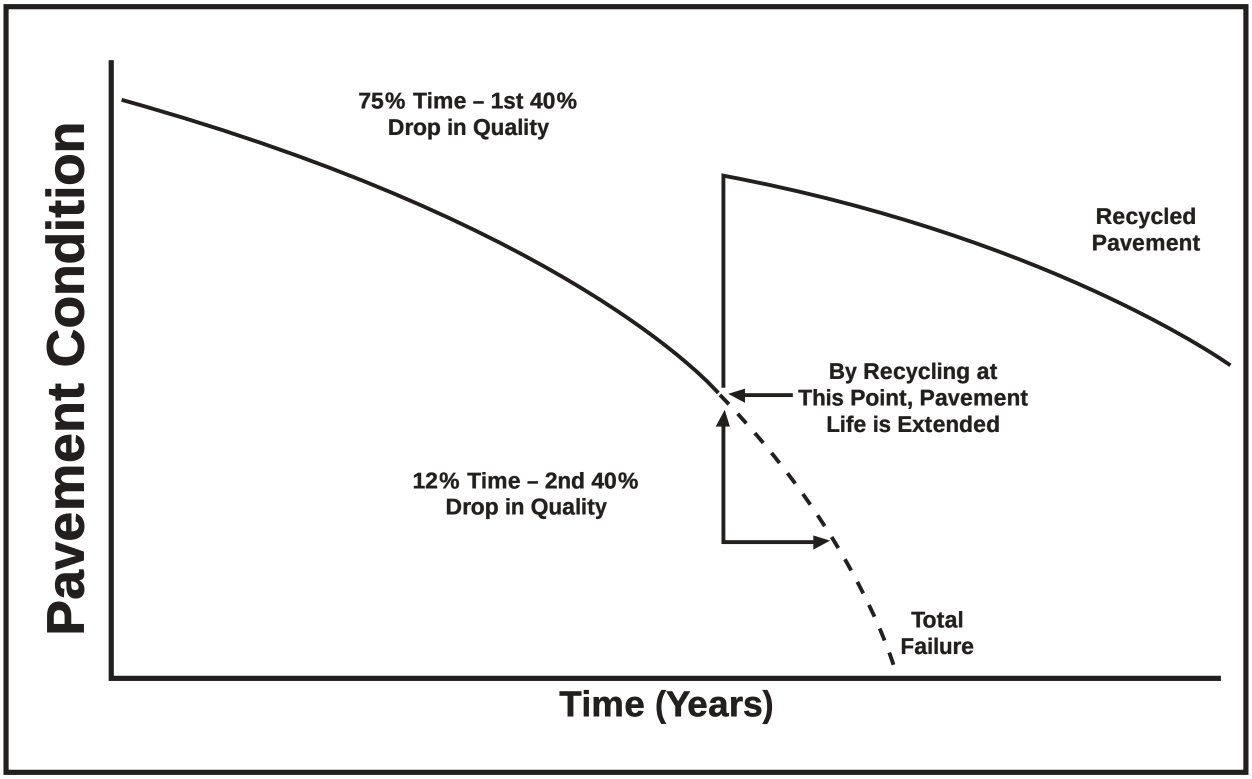


Figure 1-1: Pavement deterioration and recycling rehabilitation vs. time

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.

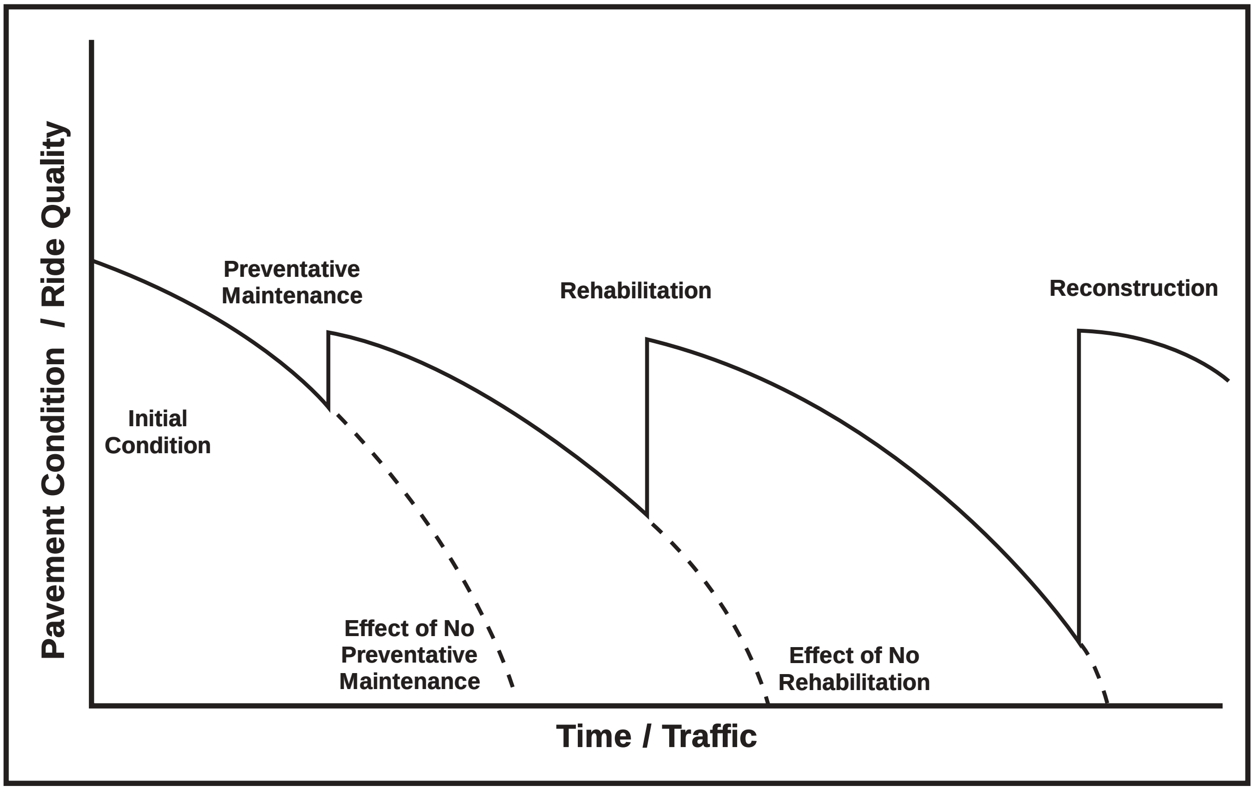


Figure 2-1: Pavement Deterioration vs. Time

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.

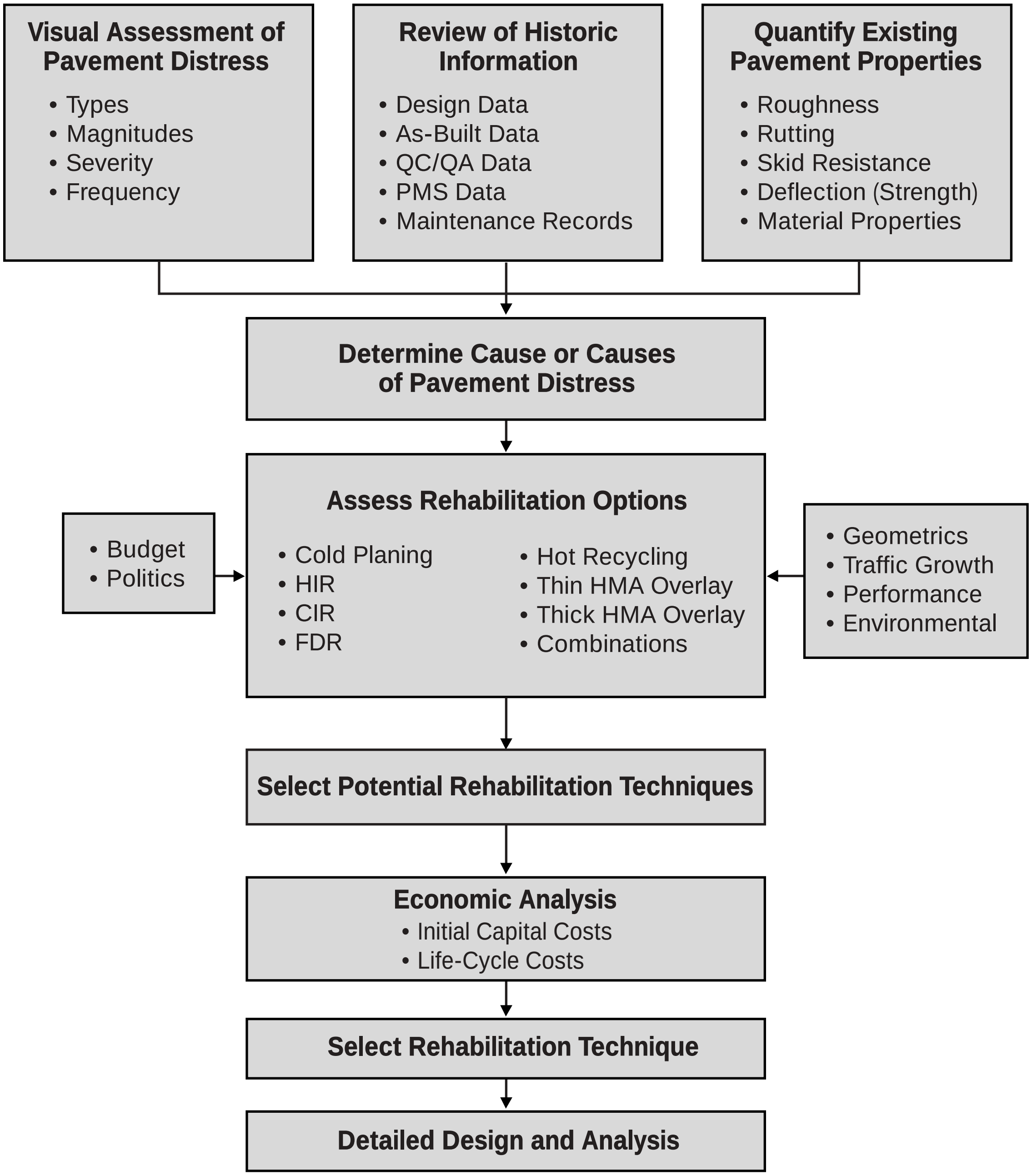


Figure 2-3: Rehabilitation technique selection process

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.

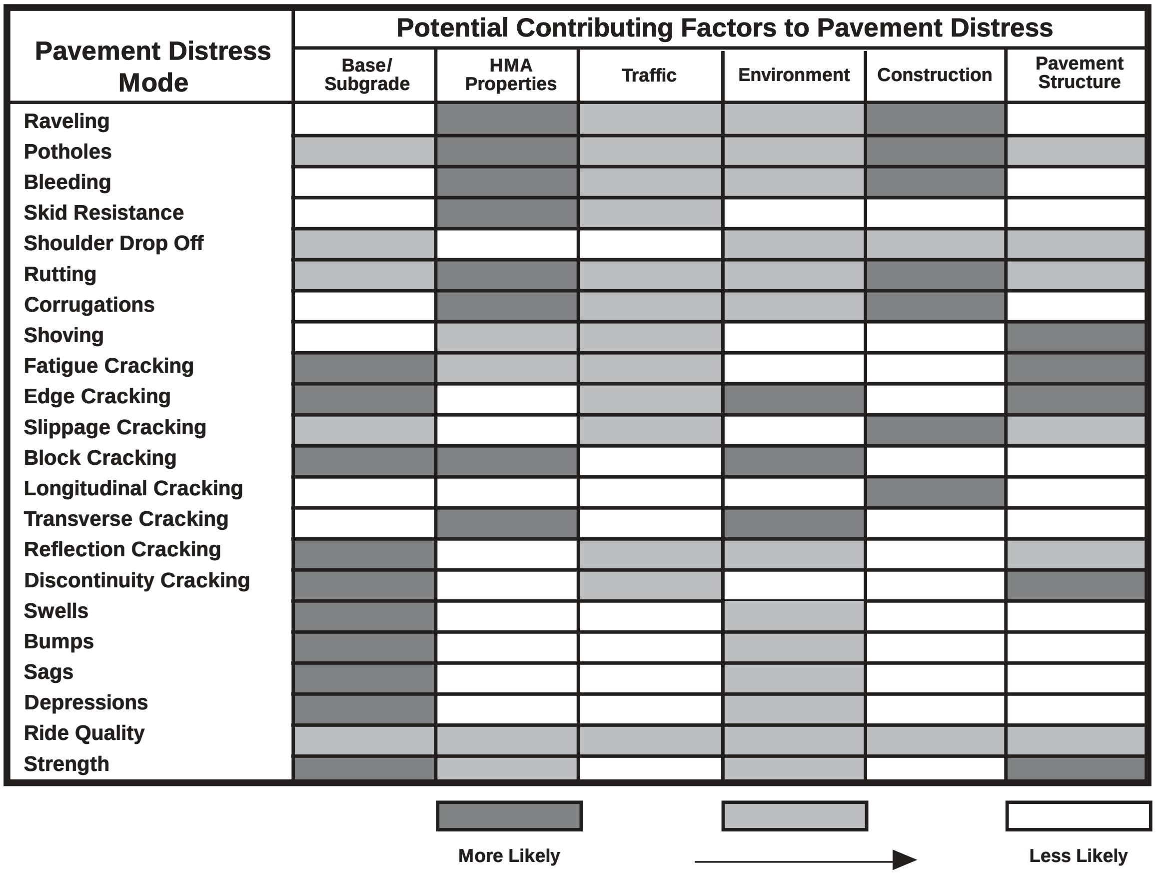
3.4 DISTRESS EVALUATION

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:



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.

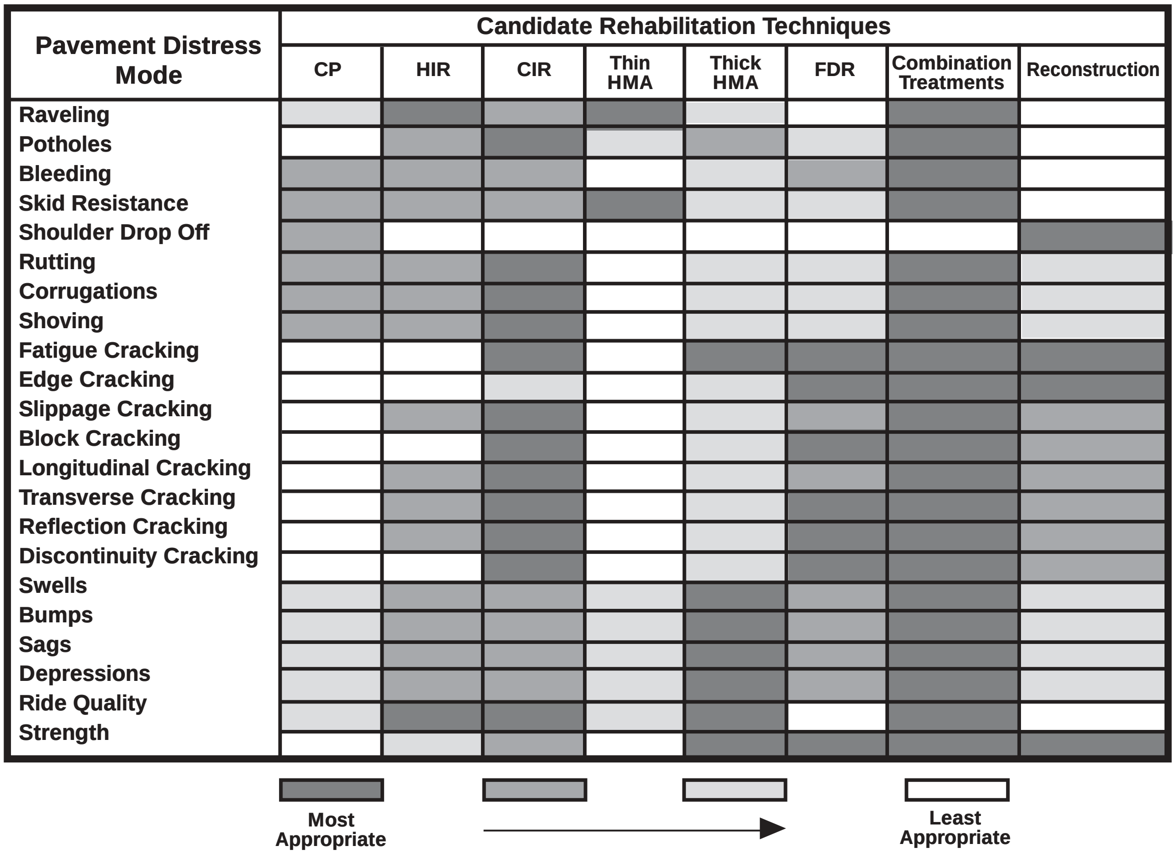
There are a considerable number of rehabilitation techniques which can be used either individually or in combination to rehabilitate a pavement. Rehabilitation techniques include:

- 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.



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.

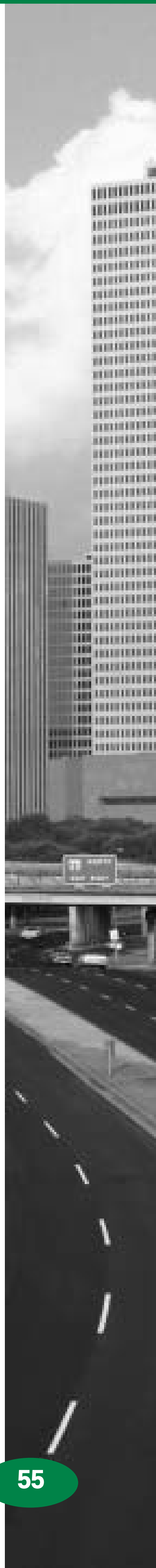
4.0 HOT IN-PLACE RECYCLING REHABILITATION

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	[dark]	[dark]	[dark]
Potholes	[light]	[dark]	[dark]
Bleeding	[light]	[dark]	[light]
Skid Resistance	[white]	[light]	[dark]
Shoulder Drop Off	[white]	[white]	[white]
Rutting	[light]	[dark]	[light]
Corrugations	[light]	[dark]	[light]
Shoving	[light]	[dark]	[light]
Fatigue Cracking	[white]	[light]	[dark]
Edge Cracking	[white]	[light]	[dark]
Slippage Cracking	[light]	[light]	[dark]
Block Cracking	[light]	[light]	[dark]
Longitudinal Cracking	[light]	[light]	[dark]
Transverse Cracking	[light]	[light]	[dark]
Reflection Cracking	[light]	[light]	[dark]
Discontinuity Cracking	[white]	[white]	[light]
Swells	[light]	[light]	[light]
Bumps	[light]	[light]	[light]
Sags	[light]	[light]	[light]
Depressions	[light]	[light]	[light]
Ride Quality	[dark]	[dark]	[dark]
Strength	[white]	[white]	[light]

[dark]	[light]	[white]

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.

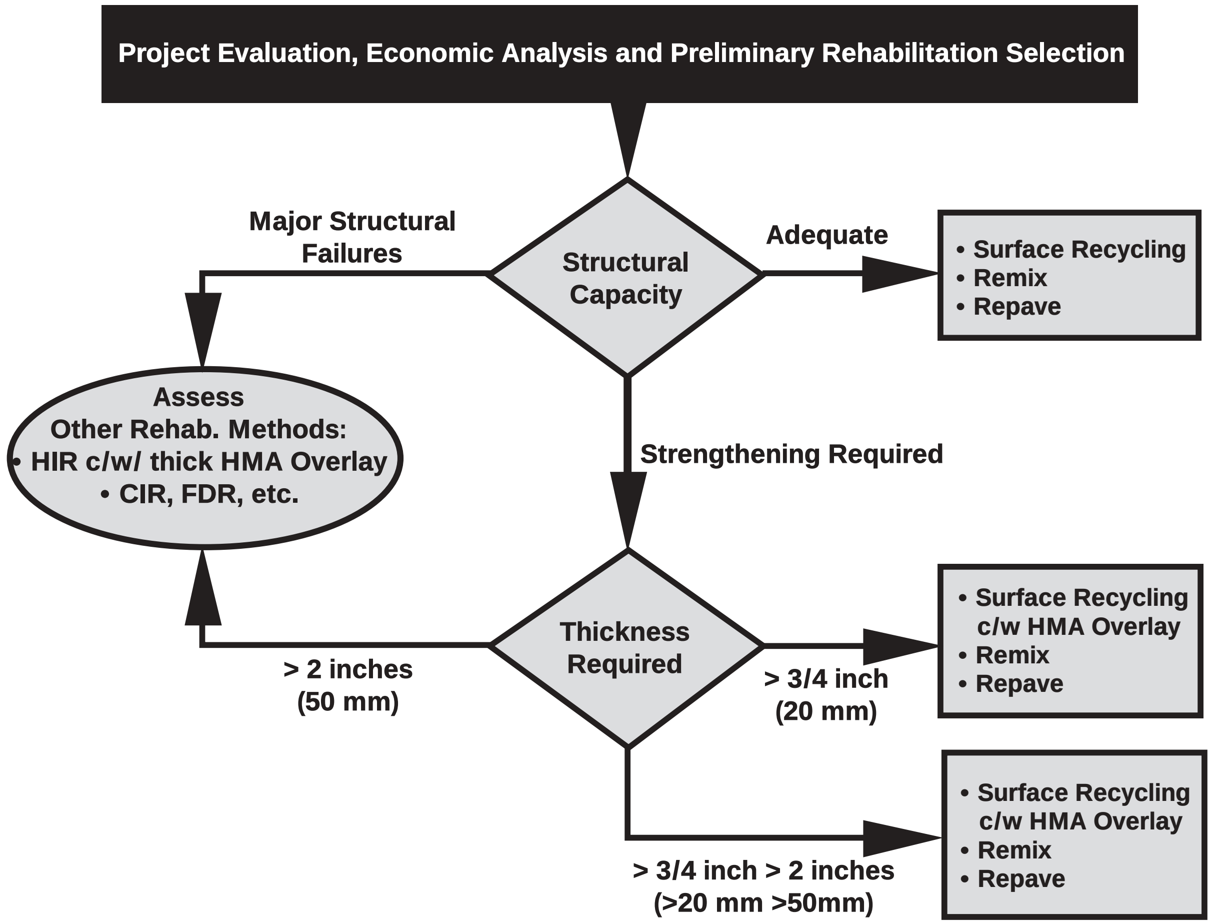
Typically, the Repaving process can include an integral HMA overlay of around 2 inches (50 mm) in thickness. The maximum thickness of the integral HMA overlay is related to the treatment depth of the Surface Recycling or Remixing process—which precedes the placement of the integral HMA overlay. When 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

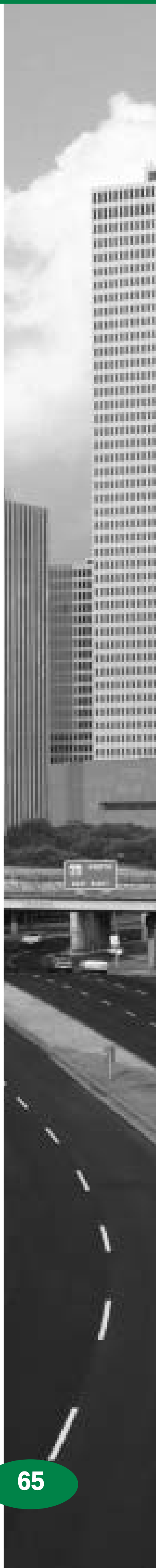
The expected service lives of the various HIR rehabilitation techniques, when undertaking a life-cycle economic analysis, generally fall within the following ranges:

- 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:

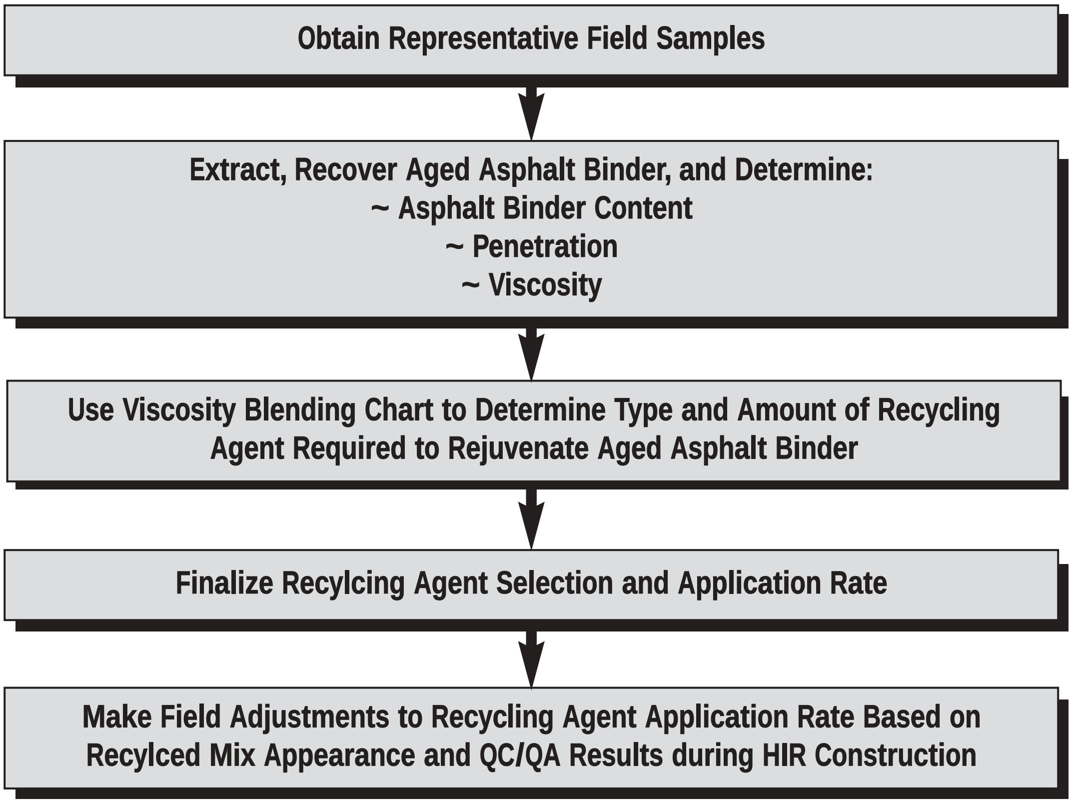


Figure 5-1: Blending chart design flow chart

- 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.

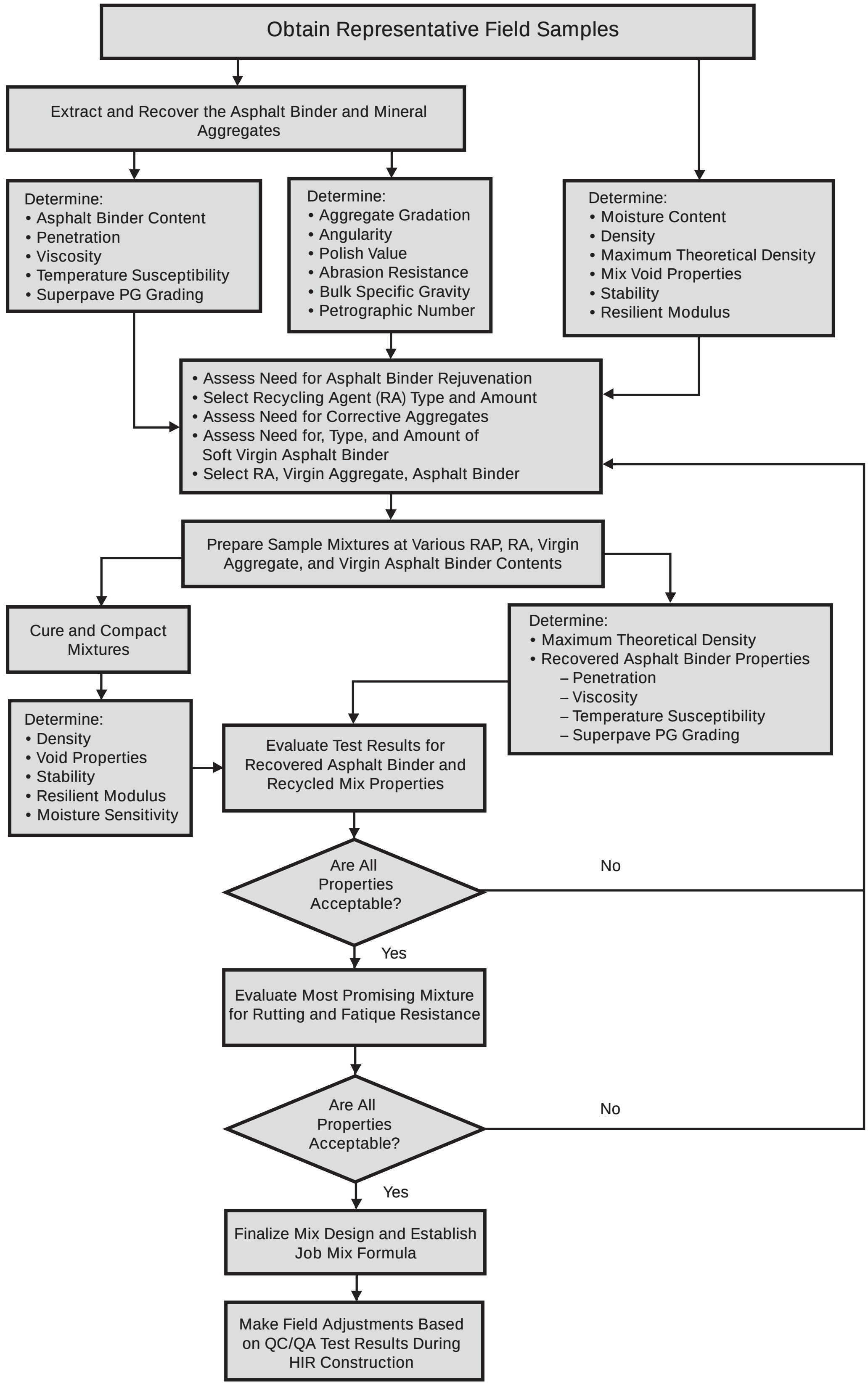


Figure 5-2: Comprehensive mix design flow chart

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.

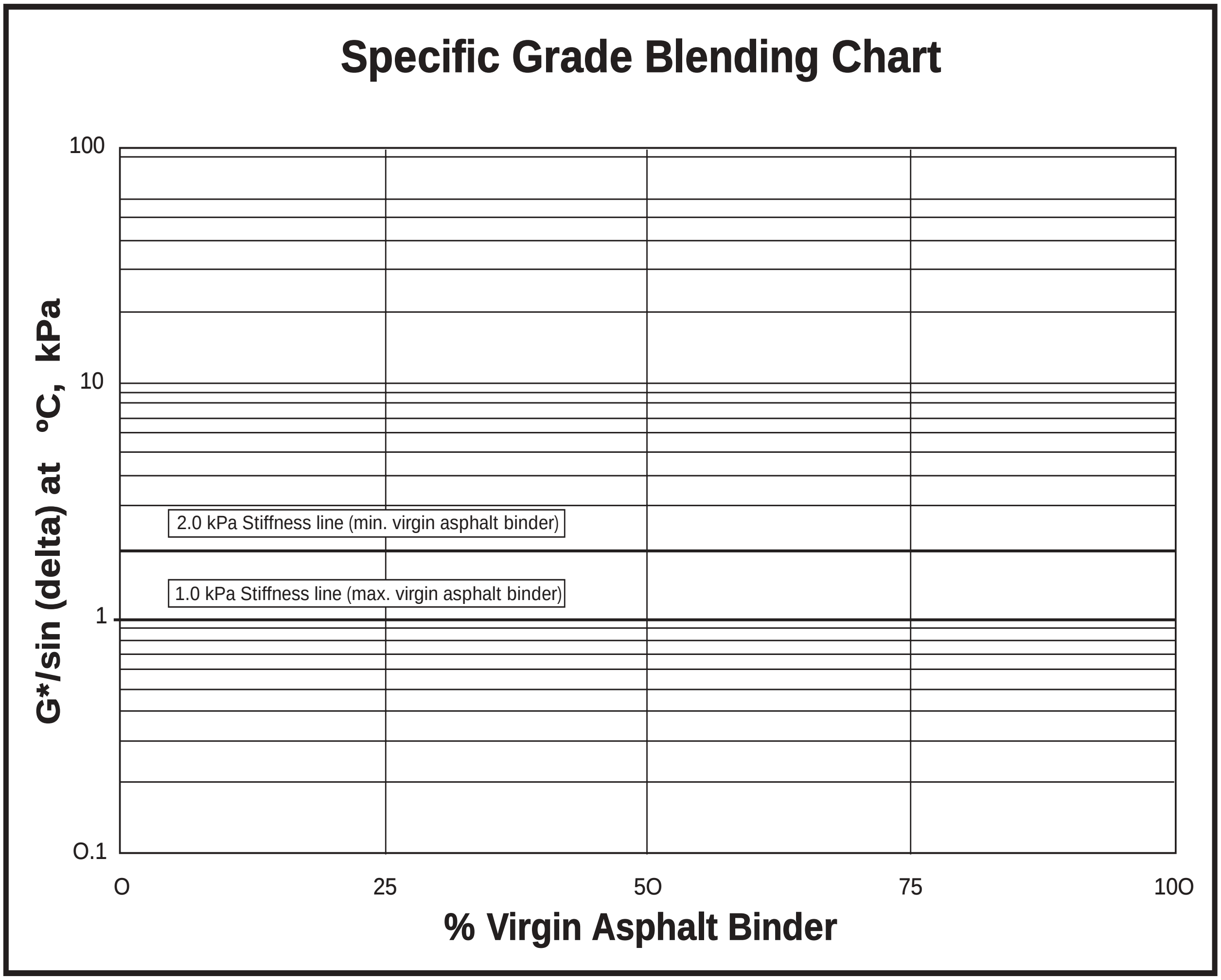


Figure 5-3: Specific grade blending chart

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

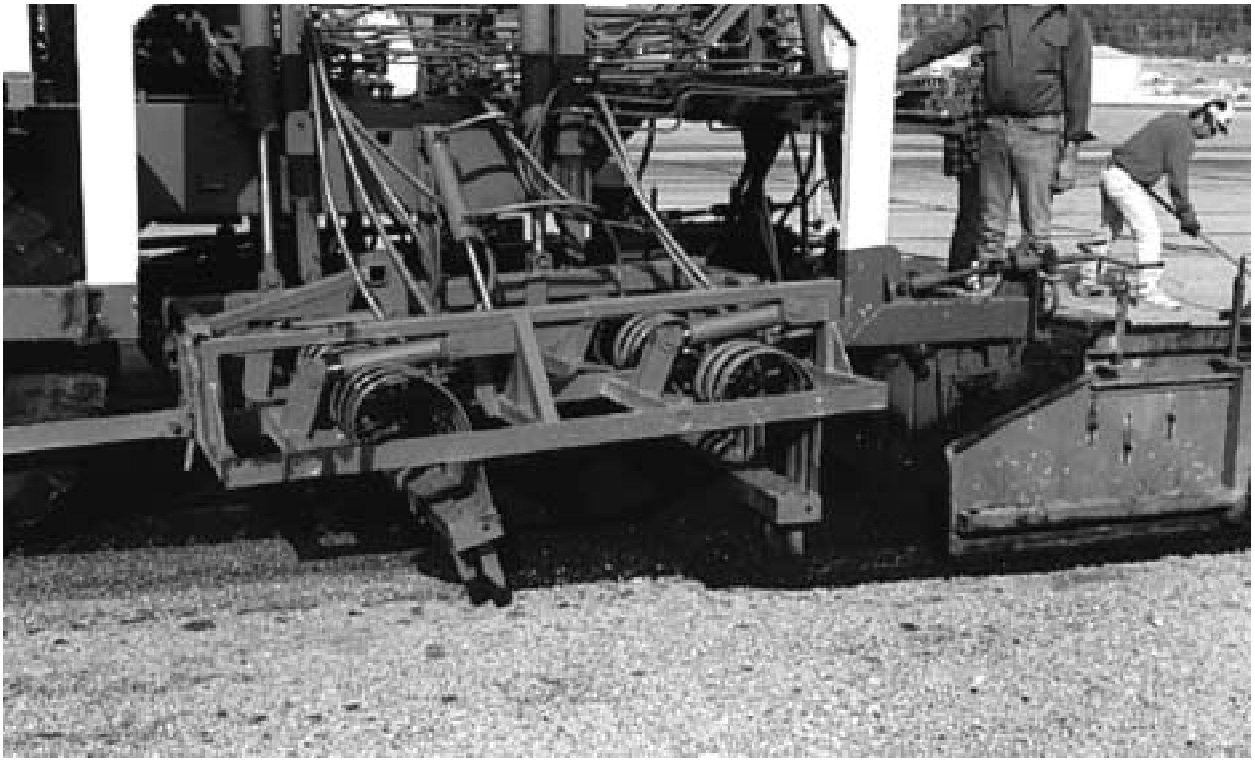


Figure 6-3: Spring loaded scarifying tines

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

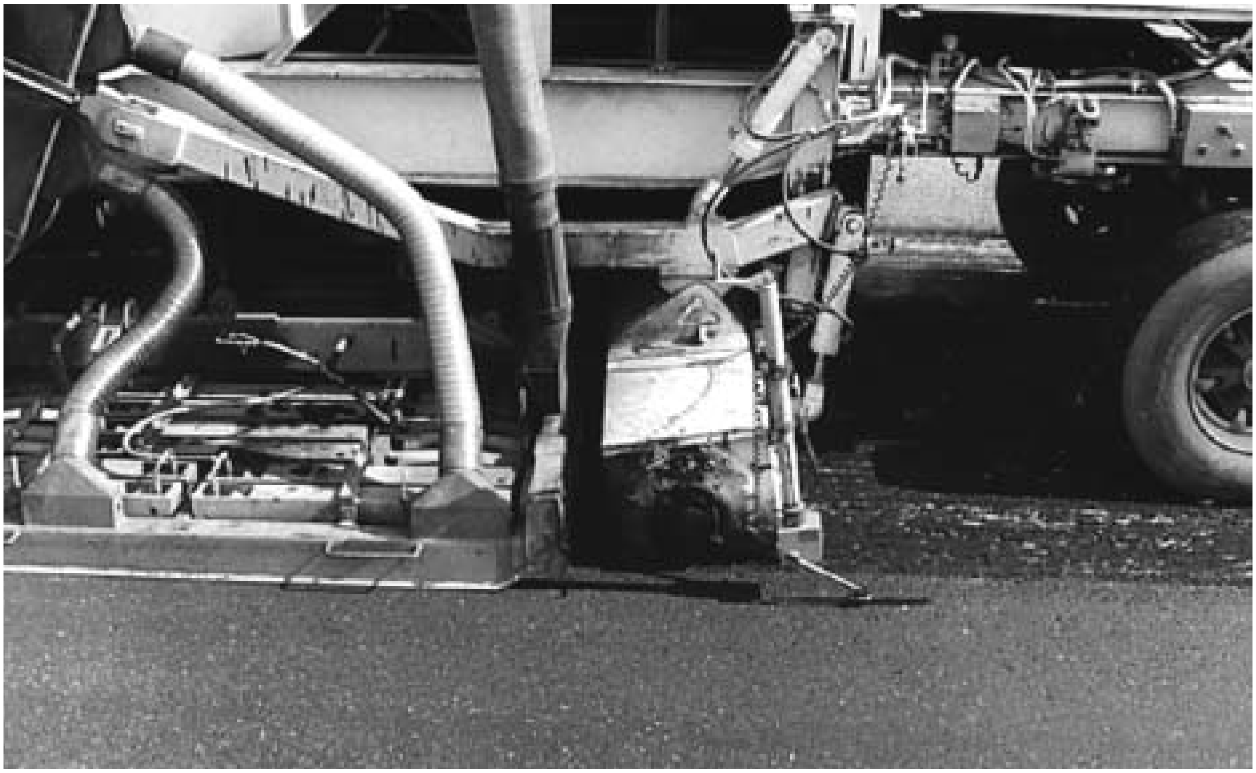


Figure 6-13: Hot milling drum and matching shoe

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).

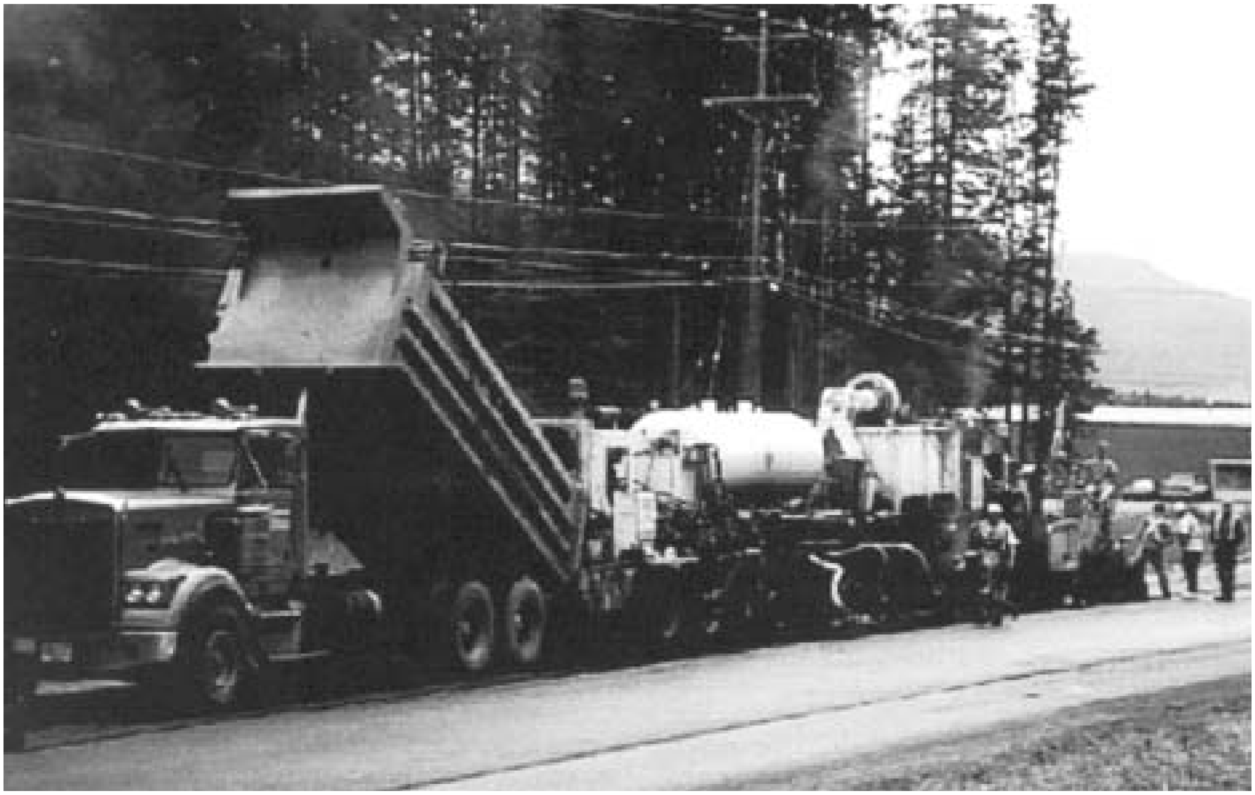


Figure 6-15: Haul truck supplying admix to HIR train

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.

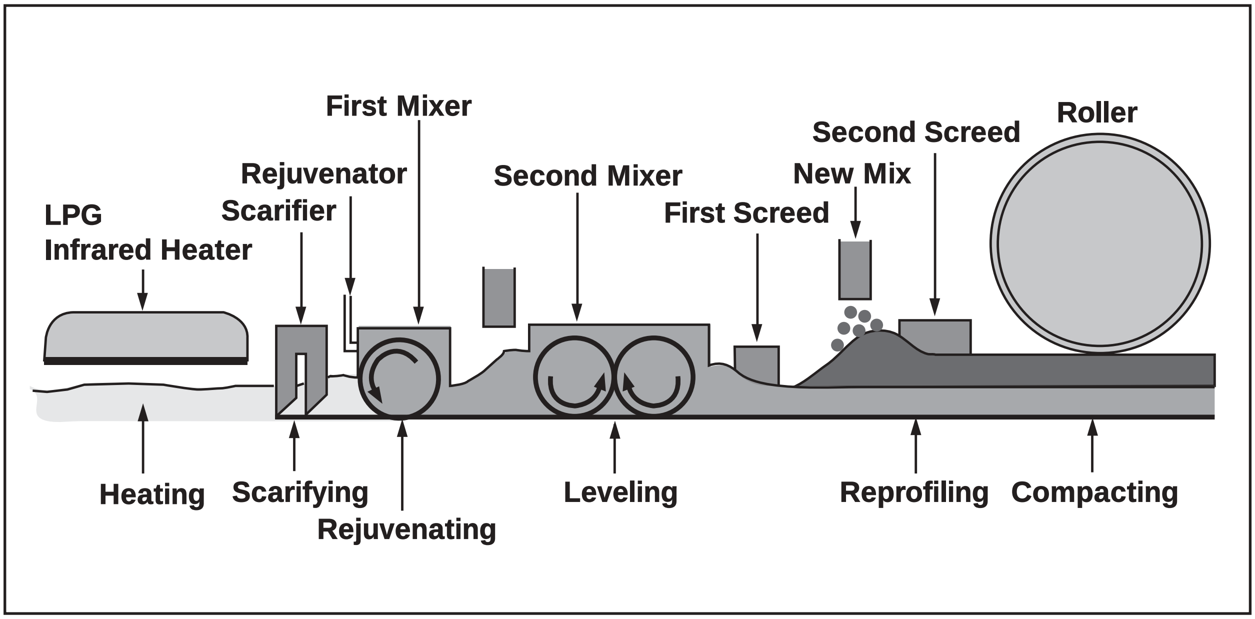


Figure 6-22: Admix movement through Repave equipment

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