

Investigation of Current Practice on Hot In Place Recycling (HIR) in USA: Literature Review

현장가열재생 아스팔트 포장의 현재 미국 내의 적용 현황 연구: 문헌조사

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ABSTRACT

PURPOSES : The objective of this study is to investigate the current state of the practice, examining the steps in the process recommended by various agencies and the Asphalt Recycling and Reclaiming Association (ARRA)-namely mix design, structural design, structural capacity evaluation, and material characterization-in order to better understand the implications of hot in-place recycling (HIR).

METHODS : In addition, the current practice of state departments of transportation (DOTs) is here reviewed with the purpose of learning from successful past experiences so as to forestall any difficulties that may emerge under similar circumstances. Also, HIR benefits, including reduced costs, improved construction processes, and environmental friendliness are presented, as well as advantages and disadvantages of HIR application.

RESULTS : Most of the United States highway system is now deteriorating so that rehabilitation or reconstruction techniques are required for the most distressed roads, taking into account ways to increase the effectiveness of existing budgets. Several options are available in rehabilitating distressed roads, and the choice among these depends on many factors, including pavement distress condition, funding, and design life. Among these techniques, Hot In-Place Recycling (HIR) has emerged as a cost-effective treatment for deteriorated pavements, and has been proven an effective long-term strategy for pavement rehabilitation.

Keywords

asphalt pavement, pavement rehabilitation or reconstruction, hot in-place recycling (HIR)

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1. INTRODUCTION

Pavement recycling is a practical way to conserve our diminishing supply of construction materials and to reduce the cost of preserving our existing pavement network. When properly designed and constructed, recycled pavements have been found to

perform as well as pavements made of all-new materials (Epps, J.A et al., 1980 and Brown, D., 2000).

The growing demand for a safer, more efficient, and more cost-effective roadway system; the significant increase in the cost of bituminous materials (a jump of up to 70% in the past few years);

the difficulty in finding virgin aggregates; and decreasing budgets have led to a dramatically increased need to rehabilitate existing pavements. Accordingly, many recent changes in recycling rehabilitation strategies have raised the profile of the concept of recycling asphalt pavements. Not only has pavement recycling become more widely accepted and practiced, but related technology, equipment and procedures have advanced as well. Major developments in heavy duty equipment and construction procedures have been a vital part of the rehabilitation technique evolution. Powerful milling equipment has been developed that allows contractors to reclaim material from distressed asphalt pavements and to combine it with virgin aggregate and asphalt. Hot mix asphalt plants have been modified to handle reclaimed asphalt pavements (RAP). Mix design, structural design, and construction practices have been altered, where needed, to accommodate the use of RAP.

The recycling of asphalt pavement is not new. Cold recycling/rehabilitation of roadways with asphalt binder 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 (Bejarano et al., 2003). Subsequently, several recycling techniques, such as hot mix recycling, hot in-place recycling, cold mix recycling, cold in-place recycling, and full depth reclamation, have evolved, especially over the past 35 years. In-place recycling not only reduces the use of new materials but also reduces emissions, traffic, and energy associated with the transport and production of these materials (Larry Santucci, 2007).

Several options are available in rehabilitating distressed roads, and the choice of these depends on many factors, including pavement distress condition, funding, and design life. Among these techniques, Hot In-Place Recycling (HIR) has emerged as a cost-effective treatment for deteriorated pavements, and has been proven an effective long-term strategy for pavement rehabilitation. Although a recent FHWA policy statement has recommended recycled materials be considered for all paving projects, pavement recycling continues to face problems with performance reliability—specifically the lack of a nationally accepted protocol and defined design procedure—and problems with raveling, thermal cracking, compaction, low early strength and limited structural improvement. Such issues have prevented several agencies from pursuing HIR.

The objective of this independent study is to investigate the

current state of the practice, examining the steps in the process recommended by various agencies and the Asphalt Recycling and Reclaiming Association (ARRA)—namely mix design, structural design, structural capacity evaluation, and material characterization—in order to better understand the implications of HIR. In addition, the current practice of state departments of transportation (DOTs) is here reviewed with the purpose of learning from successful past experiences so as to forestall any difficulties that may emerge under similar circumstances. Also, HIR benefits, including reduced costs, improved construction processes, and environmental friendliness are presented, as well as advantages and disadvantages of HIR application.

2. BACKGROUND

Most of the United States highway system was built between 1950 and 1980 using pavements designed to last 20 years before rehabilitation or reconstruction. Many of the roads of that system are now deteriorating. New pavement construction and some cases of reconstruction require virgin material sources. However, these are becoming scarce, resulting in increased construction costs stemming from mining costs, hauling distances, and environmental protection requirements. Asphalt rehabilitation techniques represent a way to increase the effectiveness of existing budgets in order to maintain, preserve, rehabilitate and reconstruct more miles of roadway for each dollar spent. The re-use of existing in-situ road materials through rehabilitation techniques will also minimize traffic disruption, a further advantage over the use of virgin materials.

Flexible pavement rehabilitation alternatives include HMA overlay and recycling. Reconstruction is required when a pavement is more severely damaged. A HMA overlay atop prepared existing pavement is the conventional rehabilitation method. Reconstruction, the process of replacing the existing pavement structure, typically requires the complete removal and replacement of the existing pavement structure. Reconstruction is required when a pavement has either failed in layers below the HMA or has become functionally obsolete.

In-place recycling, another rehabilitation method, includes the re-use of existing HMA, or of both the existing HMA and base layer, to create a new layer. On top of the recycled layer, it is common to apply a new thick or thin HMA layer. Possible in-place flexible pavement recycling options include hot mix asphalt

recycling, hot in-place recycling, cold in-place recycling, and full-depth reclamation. In-place recycling is defined as recycling in which the entire process is conducted during the construction. Over the years, recycling has become one of the most attractive pavement rehabilitation alternatives, given that recycling of existing pavement materials to produce new pavement materials results in considerable savings in materials, money, and energy (National Center for Asphalt Technology, 1997).

2.1. Asphalt Pavement Recycling Methods

The use of asphalt cement to stabilize recycled asphalt pavement probably dates back only to the 1930s or 1940s. During this period the first heater-planer machines were developed. Thus, recycling of asphalt pavements has been practiced in the United States for approximately 80 years.

Asphalt pavement recycling can be divided largely into two categories. One is in-place recycling and the other involves the stockpiling of recycled material for future use. In-place recycling options for asphalt pavements include hot in-place recycling (HIR), cold in-place recycling (CIR), full-depth reclamation (FDR) with asphalt emulsion, cement, foamed asphalt, or combinations of cement with emulsion or foam, and the pulverization strategy. Typically, in both hot and cold in-place recycling, only part of the HMA layer is reused. By contrast, in full-depth reclamation and the pulverization strategy, the entire HMA layer and a portion of the underlying layer are recycled.

Current pavement recycling and reclamation methods answer a range of needs, as listed and discussed below:

- Hot in-place recycling (HIR)
 - Re-surfacing (Surface Recycling)
 - Re-paving
 - Re-mixing
- Cold in-place recycling (CIR)
- Full-depth reclamation (FDR)
- Pulverization strategy

The online survey to ascertain the status of in-place recycling use across the United States reveals that not all states have had experiences with in-place recycling. A total of 34 of the 45 states and one Canadian province (Ontario) surveyed indicated experience with both HIR and CIR projects, and 33 of the 45 indicated experience with FDR projects. Of the states with experience using HIR processes, HIR remixing was the most

frequently used (NCHRP, 2011). The survey revealed that even though the use of HIR and FDR is distributed across the United States, CIR is noticeably missing from use in the Southern and Southeastern states. The non-use of CIR in the Southern and Southeastern states likely stems from weather conditions (e.g., humidity, temperature, rainfall).

Different methods of recycling are applicable to different types, levels, and severity of problems, and hence to different periods of pavement life (see Figure 1). Typically, HIR is recommended when the majorities of pavement distresses are minimal, and are limited to the upper few inches of the surface of the roadway with no evidence of structural problems. CIR is used when there is a higher number, type, and severity of non-load-related distresses that may extend farther down from the surface. CIR with an overlay can be used to address some load-related distresses. FDR is an in-place rehabilitation process that can be used for reconstruction, lane widening, minor profile improvements, and increased structural capacity, addressing the full range of pavement distresses.

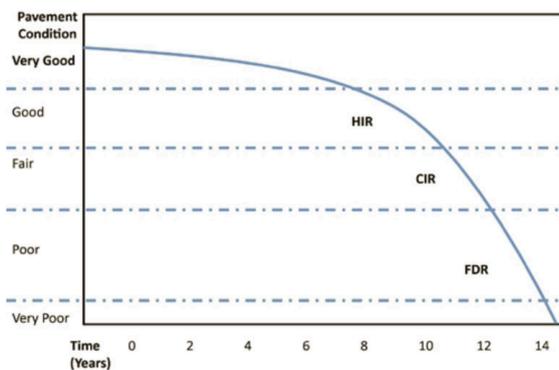


Fig. 1 Pavement Condition and In-Place Recycling Method (NCHRP, 2011)

Today, asphalt pavement recycling is commonly performed on highways and airport runways using a variety of methods, both hot and cold, for both central plant and in-place recycling operations. Of these four methods, the most remarkable changes and innovations in North America over the last ten years have been associated with hot in-place recycling.

2.1.1. Hot In-Place Recycling (HIR)

Hot in-place recycling requires preheating the existing surface immediately before milling, mixing the RAP with asphalt binders, recycling agents, new aggregates, or other additives to

improve the properties of the RAP, then placing and compacting the new mix in one continuous operation (NCHRP, 2011). With HIR, 100% recycling of the existing asphalt pavement is completed on site. Generally, use of virgin aggregates or HMA addition rates are limited by equipment constraints to less than 30% by mass of the HIR mix. The addition rates of the various additives are determined based on an analysis of existing asphalt pavement properties and subsequent laboratory mix designs, to confirm compliance with the required mix specifications. HIR has been utilized on low to medium traffic volume roadways.

With the HIR method, the existing pavement is heated and softened, and then scarified/milled to a specified depth of 3/4 to 1-1/2 inches and mixed (Asphalt Recycling and Reclaiming Association, 2001). New hot mix material (with/without RAP) and/or a recycling agent are added to the scarified RAP material during the recycling process. A new wearing course (new overlay) may or may not be placed in the recycled mix with an additional pass after compaction. This approach requires several pieces of equipment, including pre-heaters, heaters, scarifiers, mixers, pavers, and rollers. This combination of equipment is often referred to as a "train."

HIR can be performed as either a single-pass operation that recombines the restored pavement with virgin material, or as a two-pass operation, wherein the recycled material is re-compacted, followed by the application of a new HMA wearing surface. In single-pass operation, the scarified in-place material can be combined with new material if needed or desired. In two-pass operation, the restored RAP material is re-compacted first, and a new wearing surface is applied later. The treatment depth of the method varies from 3/4 to 2 inches. Pavement distresses which can be treated by HIR include raveling, potholes, bleeding, decreased friction number, rutting, corrugations, shoving, and slippage, as well as longitudinal, transverse, and reflection

cracking (Brown, D., 2000). Figure 2 shows the pavement conditions which may be addressed using HIR.

The Asphalt Recycling and Reclaiming Association (ARRA) has recognized three basic HIR processes (ARRA, 1992): A surface recycling, B remixing, and C repaving.

A. Surfacing recycling: Surface recycling has been known by a number of different names over the years including heater-scarification, heater-planing, reforming, resurfacing, and more. Surface recycling is an HIR process in which softening of the asphalt pavement surface is achieved using heat from a series of pre-heating and heating units. The heated and softened surface layer is then scarified to the desired treatment depth using either a series of spring activated teeth or "tines," or a small-diameter rotary milling head. A recycling agent may then be added, and the loose material is mixed, placed, and compacted. Treatment depths are normally 3/4 to 1 1/2 inches. No new asphalt mix or virgin aggregate is added in the surface recycling process. However, the surface recycled mix is generally overlaid with a chip seal or hot mix asphalt. In other words, surface recycling is often used in preparation for a subsequent HMA overlay.

B. Remixing: Remixing is used when the properties of the existing pavement need to be improved via the addition of new materials. In the remixing process, virgin aggregate, new asphalt binder, recycling agent, and/or new asphalt mix are added to the material recovered from the heated and scarified pavement surface. The composite recycled mix is then placed in one layer using the equipment train. The recycled mix from this process can be used as a wearing surface or overlaid with a chip seal or new asphalt mix. Treatment depths are normally 1 to 3 inches depending on whether the remixing process is done in a single- or multiple-stage operation. 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. Treatment depths for single-stage remixing are generally between 1 to 2 inches. 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

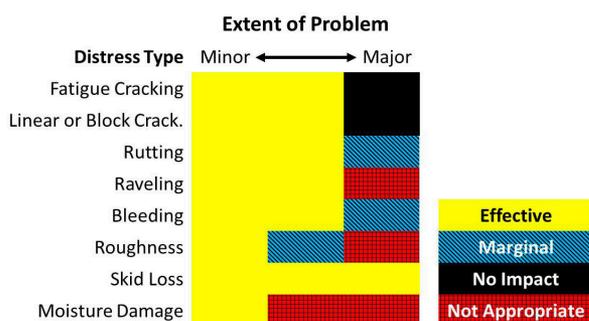


Fig. 2 Allowable Pavement Conditions for HIR Use (Scott Metcalf, 2006)

heating and scarification of the underlying layer. The specified treatment depth for multiple-stage remixing is generally between 1 1/2 to 3 inches.

C. Repaving: The repaving process essentially combines the surface recycling or remixing process with the addition of a new hot mix asphalt overlay. The surface recycled or remixed layer and the new hot mix 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. The recycled mix acts as a leveling course and the new hot mix serves as the wearing course over the recycled pavement. Since the asphalt overlay can be anywhere between 3/4 and 3 inches thick, the overall pavement thickness is increased significantly. 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. Single-pass repaving employs one unit equipped with two screeds. 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. The two layers are then compacted with a series of rubber-tired and vibrating steel drum rollers.

All three methods are sometimes referred to as surface recycling or HIR. As a result of relatively recent developments in Europe, Japan and the United States, HIR is experiencing a metamorphosis. The surfacing recycling (heater-scarification) process and some older repaving processes (particularly the multiple-pass methods) are being replaced or supplemented by the newer single-pass and multi-stage repaving or remixing processes.

The advantages of HIR are that surface cracks can be eliminated, ruts, shoves and bumps can be corrected, aged asphalt can be rejuvenated, aggregate gradation and asphalt content can be modified, hauling costs can be minimized and traffic interruption can be reduced due to short construction time, as

compared to conventional pavement rehabilitation methods. Disadvantages include the necessity of specialized equipment, the low recycling rate of a maximum of 2 in. of existing hot asphalt concrete pavement, the high mobilization costs, and the method's unsuitability for local streets with limited space. Moreover, the HIR process can compromise air quality due to the use of high bituminous material (National Center for Asphalt Technology 1997). Also, it cannot address reflective cracking problems of underlying layers, only pavement surface problems. The HIR operation with application of overlay is illustrated in Figure 3.

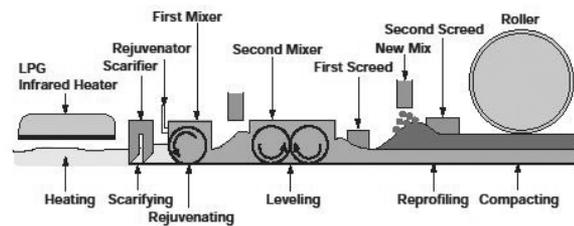


Fig. 3 Hot In-Place Recycling Process
(Asphalt Recycling and Reclaiming Association, 2001)

Over the past twenty years or so, several approaches to HIR have been attempted with varying degrees of success. These have ranged from simple direct-flame heating, heater-scarifying, combined cold milling/hot mixing, and more recently both infrared heating (IR) and IR combined with hot air. Key goals in improving this technology have included recycling to greater depths, the ability to add new materials, reduction of damage to existing pavement (overheating asphalt, aggregate degradation), and reduction of air pollution to acceptable levels.

2.1.2. Cold In-Place Recycling (CIR)

Cold in-place recycling (CIR) is undertaken on site, and generally uses 100% of the RAP generated during the process. This method involves reuse of the existing pavement material without the application of heat. Except for any recycling agent used, no transportation of materials is usually required, and aggregate can be added; therefore hauling cost is very low. Normally, an asphalt emulsion is added as a recycling agent or binder, proportioned as a percentage by weight of the RAP. The process includes pulverization of the existing pavement, sizing the RAP, application of the recycling agent, placement, and compaction. The use of a recycling train, which consists of pulverizing, screening, crushing and mixing units, is quite common. The processed material is deposited in a windrow from

the mixing device, where it is picked up, placed, and compacted with conventional hot mix asphalt lay-down and rolling equipment. The depth of treatment is typically from 75 to 100mm (Asphalt Recycling and Reclaiming Association, 2001). An additional layer, such as a chip seal, or 1 to 3 inches of hot-mix asphalt, is optional. The advantages of cold in-place recycling include significant structural treatment of most pavement distress, improvement of ride quality, minimum hauling and air quality problems, and pavement widening capability. According to the Asphalt Recycling and Reclaiming Association (ARRA), cost savings can range from 20 to 40% over conventional techniques. Because no heat is used, energy savings can be from 40 to 50%. Disadvantages include that the result is not typically used as surface course; experienced personnel and equipment are required; construction is subject to weather limitations; and the method will not remove the full depth of cracking in the original hot asphalt concrete pavement. In addition, CIR materials require a curing period before the HMA is placed. Typical curing periods are several days to 2 weeks, depending on the moisture characteristics of the mix, as well as environmental conditions and drainage (National Center for Asphalt Technology 1997). The CIR operation process is illustrated in Figure 4.

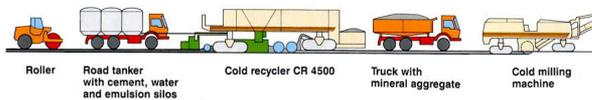


Fig. 4 Cold In-Place Recycling Process (National Center for Asphalt Technology, 1997)

2.1.3. Full Depth Reclamation (FDR)

Full Depth Reclamation (FDR) is a method of recycling in which a predetermined amount of the underlying base or subbase material is blended with the entire thickness of the distressed asphalt pavement to produce an upgraded, uniform base material.

FDR is used primarily for solving base course problems such as lack of structural capacity. The procedure requires curing, and will result in a new base. It is basically a cold mix recycling process without the addition of heat in which various additives, including asphalt emulsions and such chemical agents as calcium chloride, Portland cement, fly ash, and lime, are added to obtain an improved base. The four main steps in this process are pulverization, introduction of additive, compaction, and application of a surface or wearing course. If the in-place material is not sufficient to provide the desired depth of treated base, new

materials may be imported and included in the processing. New aggregates can also be added to the in-place material to obtain a particular gradation of material. This method of recycling is normally performed to a depth of 4 to 12 in (Epps, 1990). The advantages of FDR are that most pavement distresses are treated, hauling costs are minimized, significant structural improvements can be made (especially in the base), material disposal problems are eliminated, and ride quality is improved. Also, frost susceptibility may be decreased. The disadvantages are that traffic control can be problematic, the moisture content must be carefully monitored, and the addition of a wearing course is usually required. The FDR process is illustrated in Figure 5.

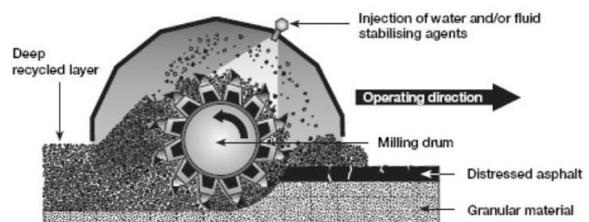


Fig. 5 Full Depth Reclamation Process (Wirtgen, 2004)

2.1.4. Pulverization Strategy

The pulverization strategy requires that the HMA layer be pulverized and mixed with a portion of the existing underlying base material to create a new base layer. This work consists of scarifying and pulverizing the existing HMA surfacing and a portion of the underlying base material; mixing, spreading, and compacting this mixture; and applying an asphaltic emulsion curing seal. In the pulverization process, a rubber tire reclaimer is used. Typical depths for pulverization range from 150mm to 200 mm, although the depth can exceed 300mm. At least 25mm of the existing base is pulverized to ensure complete pulverization of the HMA layer and to add more fines to the resulting material. The pulverized HMA is between 60% and 85% by mass of the pulverized aggregate base. The thickness of the new HMA layer typically ranges from 120mm to 165mm. The most suitable sites for this application have pavement with serious distress and requiring a large number of digouts, pavement with large deflections due to a weak underlying base layer, or pavement needing significant corrections in profile or cross slope. Pavements with bad drainage may not be suitable because the pulverization strategy cannot address drainage problems. The pulverized material creates lower stresses in the subgrade that could result in better rutting performance (Bejarano and Harvey,

2004). An initial analysis of the pulverization strategy showed that it was cheaper than traditional overlay in both the short term and over the life of the pavement (Bejarano and Harvey, 2004). However, because this analysis relied on short-term field testing and limited laboratory testing, comprehensive laboratory testing, including permanent deformation testing and long-term monitoring of field behavior, were noted as being required before final conclusions could be drawn regarding this question.

The pulverization strategy might be viewed as full depth reclamation since the two methods employ similar rehabilitation strategies. However, there is a difference between them, namely the introduction of a stabilizing additive such as cement and/or emulsion, or foamed asphalt. Most full depth reclamation projects reported (Kearney and Huffman, 1999; Mallick et al., 2002a; Bemanian et al., 2006) have used stabilizing additives.

3. Evaluation of HIR PROPERTIES

3.1. Material Properties Evaluation

Utilizing information gathered during visual assessments of pavement surfaces, a review of historic documents, and a pavement property assessment, a given pavement rehabilitation project is divided into sections based on shared performance characteristics or homogeneous /uniform conditions. Field samples are usually taken by means of coring to determine the following (Asphalt Recycling and Reclaiming Association, 2001):

- In-situ asphalt bulk specific gravity/density, asphalt binder content, extracted aggregate gradation, aggregate angularity, flat and elongated particles, and petrographic analysis
- In-situ asphalt pavement air voids, 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 temperature susceptibility or Superpave PG characterization/grading
- Gradation, field moisture content, angularity, Plasticity Index, and resilient modulus of the base and sub-base aggregates
- Subgrade soil type, Plasticity Index, moisture content, and strength
- Groundwater conditions

- Maximum Theoretical Density of the existing mix

Core samples in the order of 150mm to 200mm (6 inches to 8 inches) in diameter are preferred. However, 100mm (4 inch) diameter cores could be used for some laboratory testing, such as determination of field density, Marshall Stability, and so on. Generally, the number of sample locations ranges from 3 to 5 for smaller, consistent areas, to 20 or more for larger, less consistent areas. Samples are obtained at a frequency of approximately one location per 5/8 mile 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.

Some of the field samples should be obtained using compressed air as opposed to water during the coring/sawing process, so as to accurately determine the moisture content of the asphalt pavement. Moisture content significantly influences the production rates of the various HIR processes. As the moisture content of the pavement increases, there is a corresponding increase in the heat energy required to remove the moisture and heat the asphalt pavement to the desired temperature. Consequently, in order to achieve the desired mix temperature, the HIR train must move slower, reducing productivity.

3.2. Structural Capacity Evaluation/Design

Structural design considerations are very important in recycling techniques. Recycling processes can be used to correct structural deficiencies in the existing pavement and to address future traffic needs. In evaluating the structural capacity of pavements, two conditions need to be assessed: the structural capacity required for the expected traffic volume during the service life of the pavement, and the ability of the existing pavement structure to carry the load of the HIR equipment during construction.

The evaluation of pavement 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 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 executed either by destructive or non-destructive methods.

Destructive methods, including test pits or coring:

- Determine the existing pavement layer thicknesses
- Assess the existing strength by means of the Dynamic Cone Penetrometer (DCP) test, the field California Bearing Ratio (CBR) test, and so on

Knowing the thickness of the pavement layers and the results of the laboratory testing, this information can be mathematically converted, by means of material equivalencies, into a single value, such as the Structural Number (SN).

Non-destructive methods evaluate existing structural capacity, usually by determining the pavement response or deflection to an imposed load. Non-destructive deflection testing devices include the Falling Weight Deflectometer (FWD).

Typically, the HIR process requires a minimum of 75mm (3 inches) of existing asphalt pavement to ensure that the process will be successful. If the existing structural capacity requires enhancement, 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. Roadways with existing structural capacities requiring more than 50mm (2 inches) of strengthening should be treated with other rehabilitation methods, such as combined rehabilitation methods, staged rehabilitation, or HMA overlays. If the existing roadway needs to be strengthened after the HIR process, such can be done with an appropriate HMA overlay. Figure 6 provides a flow chart depicting the HIR rehabilitation selection process.

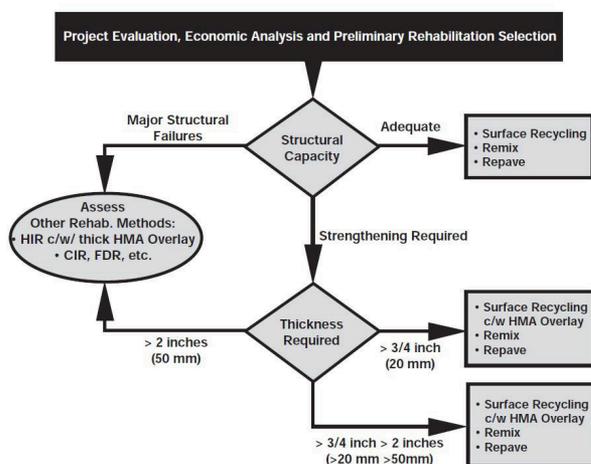


Fig. 6 HIR Rehabilitation Selection Process

3.2.1. Falling Weight Deflectometer (FWD)

In-place measurements of deflection have been used to evaluate the structural capacity of pavements. They can be used to back-calculate the elastic moduli and to evaluate the performance of pavements. Many devices are used to measure deflection in the non-destructive testing of pavements. The Falling Weight Deflectometer (FWD) is the most widespread non-destructive testing device used to back-calculate the field elastic moduli. FWD tests are generally performed in the morning and afternoon to evaluate the stiffness of the HMA and of the pulverized material at different temperatures.

Jeon (2009) reported that surface temperature differences between the morning and afternoon were significant, but that stiffnesses in the morning and afternoon were almost the same. He explained that this finding implies that there is no temperature sensitivity in the stiffness of pulverization material even when the pulverized HMA is between 60% and 85% of the mass of the pulverized aggregate base.

3.2.2. Dynamic Cone Penetrometer (DCP) Testing

The Dynamic Cone Penetrometer (DCP) is an instrument designed to provide a measure of the in-situ strength of fine grained and granular subgrade, granular base and subbase materials, and weakly cemented materials. The equipment consists of a 60° metal cone attached to a rod, and an 8-kilogram hammer that is dropped from a height of 575mm to drive the cone into the in-situ base material, typically through a core hole. A tape measure is secured to the rod so that the technician can record the depth of penetration with the increasing blow count. The associated DCP penetration in the base is plotted against the

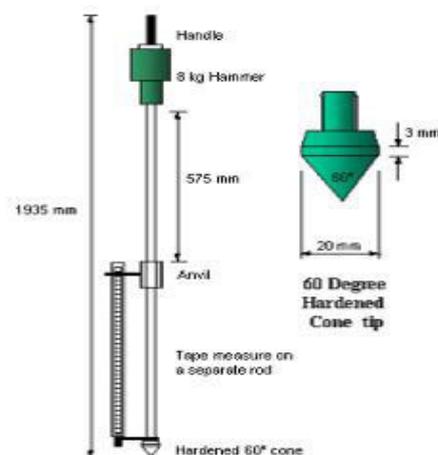


Fig. 7 A Schematic of DCP

number of blow counts. Changes in the penetration rate (DN = slope of the penetration-blow count relationship in mm/blow count) are used to determine the thickness of layers. In general, lower penetration rates are indicative of stronger materials. A schematic of the DCP is shown in Figure 7.

DCP tests are carried out both before and after rehabilitation in order to estimate the thickness of each layer, as shown in Figure 8. The data have shown that penetration blow counts before rehabilitation are typically greater than those after rehabilitation. This result could indicate that the material is stiffer after construction.

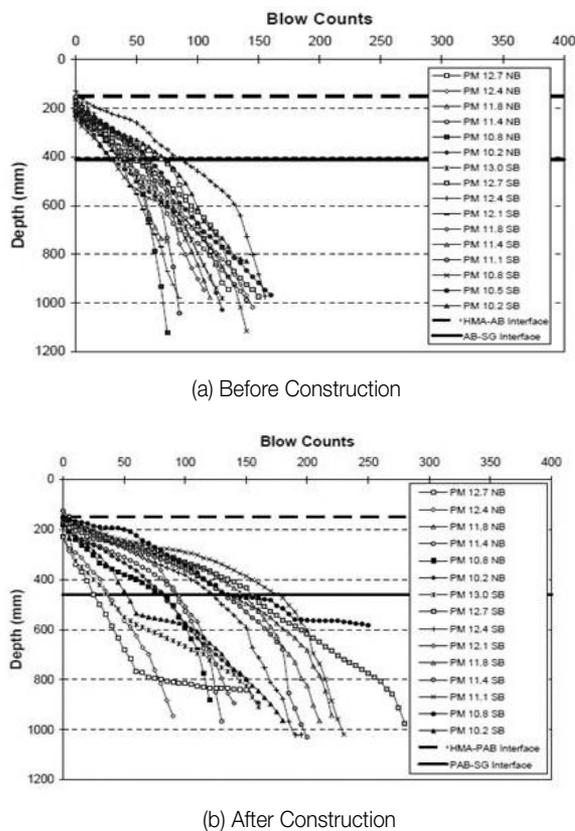


Fig. 8 DCP Test Results (Alturas Project Section)

4. MIX DESIGN CONSIDERATIONS

A number of HIR mix design methods have been used by various agencies due to the lack of a single accepted protocol for the mix design of HIR. In general, the philosophy underlying HIR mix designs has been to restore the properties of the existing aged asphalt pavement to those 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.

Mix design should be determined based on whether the original HMA mix design was adequate, and whether restoration of the existing HMA pavement is achievable. If not, a mix design should be considered which upgrades and improves the mix properties during the HIR mix design process to ameliorate the shortcomings of the original mix.

4.1. Mix Design Process

The mix design process for Hot In-Place Recycling is, in many ways, similar to that used for high content RAP Hot Mix Recycling. HIR generally involves the use of 70% - 100% RAP.

The asphalt binder plays a vital role in the performance of asphalt pavement. Recycling agents or very soft asphalt binders may be used to upgrade the overall quality of the asphalt binder in the recycled mix. HIR mix designs, especially for higher RAP contents (>25%), are more complex than standard virgin HMA mixes. Consequently, the mix designs take more time and incur increased costs.

The HIR mix design process is divided into largely two methods. The first is the traditional design, which takes into account not only the rheological properties of the asphalt binder but also those of the recycled mix. The second method is the Superpave design. At present, no documentation or confirmation exists that the Superpave technology is universally applicable to HIR mixes. In Superpave design, a three-tiered system for selecting the PG grade of the new asphalt binder is used for hot recycled mixes.

- If the amount of RAP is equal to or less than 15%, the selected PG grade of the new asphalt binder should be the same as the Superpave-required PG grade.
- If the amount of RAP is more than 15% but equal to or less than 25%, the selected PG grade of the new asphalt binder should be one grade below, i.e., softer, than both the high and low temperature grade required by the Superpave system.
- If the amount of RAP is more than 25%, the specific grade blending chart should be used to select the high temperature grade of the new asphalt binder. The low temperature grade should be at least one grade lower than the binder grade specified by the Superpave system.

The overall HIR mix design process, whether traditional or

Superpave, involves some or all of the following steps (Asphalt Recycling and Reclaiming Association, 2001):

- Evaluating the existing HMA, including asphalt binder, aggregates, and mix properties
- Determining whether the existing asphalt binder requires 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

The complexity of the mix design process varies with the level and type of recycling selected. The mix design process for Hot In-Place Recycling is similar to that used for high content RAP Hot Mix Recycling. A simplified flow chart (see Figure 9) captures the key steps in an HIR mix design process. The binder properties of the asphalt recovered from RAP are penetration and viscosity. However, Superpave performance graded (PG) binder properties can also be measured and used in blend charts to determine the desired final asphalt grade in the recycled mix.



Fig. 9 Hot Recycling Mix Design Flow Chart

The percentage of recycling agent required to meet the target viscosity is initially determined on a weight basis. Usually, the target viscosity is selected to be close to the asphalt binder

properties that were observed when the roadway was originally constructed. Use of the viscosity blending chart for mix design 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. Also, the penetration value can be used to determine whether the existing asphalt binder needs to be rejuvenated during the HIR process.

4.2. Evaluation of the Existing Pavement

Just as the gradation of aggregate stockpiles and the properties of asphalt binder must be evaluated in designing an HMA mixture, the gradation and binder properties of the existing HMA pavement must be evaluated in designing an HIR mixture. Determination of the gradation and binder properties of the existing pavement requires testing of samples from the roadway. Regardless of the sampling method used, care should be exercised to minimize cutting or breaking the aggregate as doing so affects the gradation.

4.3. Determination of Rejuvenation Requirements

The asphalt binder in the existing pavement will have aged as a result of exposure to air and water during its service life. Aging is a process by which oxygen reacts with molecules in the binder, making it stiffer and less ductile. The loss of ductility makes the pavement more susceptible to cracking, thus affecting pavement life. The purpose of rejuvenation is to restore the properties of the aged asphalt to the desired binder properties. Rejuvenation involves adding recycling agent or soft asphalt to the recycled mixture. Recycling agents are a mixture of hydrocarbons that are mixed with the aged asphalt binder to modify or improve its properties. Adding soft, new asphalt binder to aged asphalt binder produces an “average” binder.

4.4. Selection of Optimum Mix

The conventional HMA mix design process consists of testing several trial mixes prepared with varying amounts of asphalt to determine the asphalt content that yields the specified volumetric properties. However, additional variables make the HIR mix design process more complicated. The amount of recycling agent, the percentage of admixture, the admixture asphalt content and admixture gradation all need to be selected to produce a mix with the desired qualities. Properties of the existing HMA pavement

can also change from location to location, further complicating the process. There is no established procedure for HIR mix design, so that the proportioning of trial mixes must depend on the experience of the mix designer. The trial mixes are tested to determine whether they meet project requirements. If none of the trial mixes does so, more trial mixes with different proportions must be tested. Additional testing for such characteristics as moisture susceptibility should be performed after the final mix design is selected.

5. CONSIDERED LABORATORY TESTS

5.1. Laboratory Index Test

Index testing is carried out to ascertain the basic properties of the material. Index tests include sieve analysis, Atterberg limits, compaction testing, permeability testing and aggregate shape testing. Atterberg limits can be obtained using the ASTM test protocol D4318. The Atterberg limits are a basic measure of the nature of a fine grained soil. Depending on the moisture content of the soil, it can appear in one of four states: solid, semi-solid, plastic or liquid. In each state the consistency and behavior of a soil are different, and thus so are its engineering properties. Based on the test results, the plasticity of the material can be evaluated. Al-Rousan et al. (2005) developed the methodology for shape classification of aggregates based on the distribution of their shape characteristics. A method for characterizing aggregates as measured and analyzed by the aggregate imaging system (AIMS) was developed by Masad (2004). The AIMS is equipped with an autofocus microscope and lighting that projects and captures black and white and grayscale images for the analysis of all shape characteristics.

5.2. Resilient Modulus Test

Due to repeated traffic loading, permanent deformation and recoverable vertical strain may occur simultaneously in the HIR construction layers. In order to evaluate performance, stiffness and permanent deformation, resistance should be determined. To that end, the resilient modulus test is an applicable laboratory test. Resilient response is dependent not only on stress state but also on material properties. Kim et al. (2007) conducted the resilient modulus test on various ratios of reclaimed asphalt pavement (RAP) and crushed aggregate. They found that the combination consisting of 25% aggregate and 75% RAP material had the

largest resilient modulus. They also found that the stiffness of the 50% aggregate and 50% RAP specimens was equivalent to that of the 100% aggregate specimens at the lower confining pressures. At higher confinement, the 50% aggregate and 50% RAP specimens were stiffer. Jeon (2009) applied resilient modulus test results to demonstrate that the stiffness of a base obtained via pulverization, one of the HIR techniques, is generally equal to or greater than that of the typical aggregate base.

6. CONSTRUCTION

6.1. Weather Conditions

A number of specifications contain weather restrictions on when recycling projects can be constructed. In HIR, weather conditions such as variations in temperature, humidity, and wind, all of which will affect breaking and curing times, must be considered; specifications will typically require that fog not be present during construction. In addition, the ambient air temperature must meet specifications, typically a minimum of 7°C (45°F) in the shade. Opening to traffic criteria should be in place to ensure that prior to opening the roadway to traffic, the surface temperature of the HIR treated pavement is 66°C (150°F) or less.

6.2. Surface Preparation and Compaction

The equipment used in preparation for recycling and for compaction after recycling is that typically used in conventional maintenance and HMA overlay placement projects. Surface preparation is not specific to a particular recycling process. Roller selection is typical of that used in standard roadway construction. Various recommendations for surface preparation are archived in ARRA (2009) presentations and Wirtgen (2004) project summaries. The most commonly cited practice is to remove any vegetation in cracks, scrub away dirt deposits, and broom the surface before recycling. When lane widening is to be completed, any vegetation along the shoulder must be removed. Wirtgen (2004) provides guidance on selecting the appropriate type of primary roller based on the general gradation of the mix.

7. ECONOMIC ASSESSMENT

An economic analysis, specifically a life cycle cost analysis (LCCA), is undertaken to compare the various rehabilitation techniques, in order to determine the most monetarily effective.

Such analysis typically necessitates comparing the life-cycle costs of the various rehabilitation alternatives being considered. A life-cycle cost encompasses all costs/expenses and benefits related to the roadway occurring over a fixed analysis period. 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, and 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, and so on, but these are difficult to quantify and are usually dealt with subjectively.

HIR costs vary with methods and treatment depths, but it normally costs less than \$35,000.00 per lane mile, or \$4.97 per yard (Scott Metcalf, 2006). For the projects reported by one study, the cost savings of HIR as compared to a 50mm (2in.) HMA overlay ranged from 19% to 45%. In all, cost savings of the method over conventional milling and resurfacing approach 50%, amounting to a potential savings of 18 billion dollars a year for the United States (Hesham Ali et al, 2011).

Denver, Colorado, has 5 years of experience using HIR on its 1,800 centerline miles of roadway network (Udelhofen 2006). Over these 5 years, Denver has used HIR to preserve approximately 1.1 million square yards of HMA, saving the agency more than \$5 million as compared to conventional mill and fill.

8. ENVIRONMENTAL IMPLICATIONS

Unlike conventional paving, fugitive emissions from HIR mix production occur on the project site instead of at an asphalt plant. Thus, when evaluating a project for HIR, designers must consider the affects these emissions may have. 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
- Ambient conditions, including temperature, wind velocity, and direction

Such factors as new HIR equipment, adequately maintained

and operated, 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, a certain amount of noise is associated with the HIR process. Typically, due to the speed of the HIR operation and its transient nature, the noise effects are short term. The noise issue is of greater concern in an urban setting.

The possibility of flammable substances near the work site needs to be assessed. In general, accidental fires do not represent a problem, but overhanging trees and vegetation can be scorched during the HIR operation. Immediately prior to the HIR equipment passing over or near any manholes, catch basins, vaults, and so on, these 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.

9. CASE STUDIES

Projects completed in Canada are the best documented, since most recent innovations in HIR have been developed there. Long-term performance is not yet well documented, although numerous HIR projects were constructed as early as 1987. More recent and short-term behavior or performance data are available for some projects.

The considerable experience with HIR in Canada has led to a government-sponsored project to evaluate the performance of HIR pavements constructed in Alberta since 1990. The ten projects studied were recycled using single-pass-two-stage HIR trains at a 50mm depth. The study focused on assessing binder rheology and mixture volumetric properties before and after construction. In addition, these same properties (binder and mixture) were compared at the time of construction and again in 1996 to evaluate the effects of time and traffic. Among other things, the data from the Alberta study indicated that adding a recycling agent increased penetration by about 30% and was thus effective in restoring the binder. For those projects in which no recycling agents were used, the HIR process reduced penetration by about 20%.

Another study (Kandhal and Foo, 1996) addressed the problems of recycling HMA using SHRP graded asphalt binders and how to adjust for these grades as compared to the older

approach using viscosity. Although the research was aimed at central-plant recycled HMA in which up to 30% RAP was used, the same principles could be used to extrapolate to HIR mixtures containing 70-100% RAP.

Reports on earlier projects noted that the water sensitivity of the recycled mixture can change unexpectedly. A pavement that exhibits stripping may not be improved by HIR even though the initial coating may appear to be adequate. Test results in several studies have shown that there is often a loss in resistance to water damage after HIR, probably because the binder is typically softened, thus resulting in a more water-susceptible mixture. Therefore, it may be prudent to consider anti-stripping measures such as using liquid agents or lime as additives.

9.1. Washington State Department of Transportation

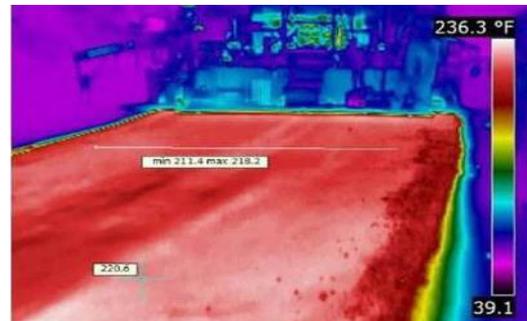
(Evaluation of Hot In-Place Recycle, Mark Russell et al., 2010)

This experimental feature report documents the construction of a section of SR 542 rehabilitated using the HIR process. HIR project selection, mix design, construction and testing are described.

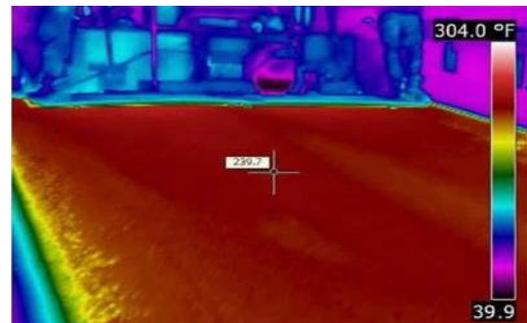
This report explains that the traditional method of recycling HMA pavement in Washington State in the past was to grind the top layer of the existing pavement. However, this method requires trucking the ground material back to the asphalt plant, stockpiling it, and then incorporating it back into the new HMA. The HIR technique is considered a sensible alternative because it eliminates the trucking and handling of the recycled HMA by completing the process in one pass. Moreover, a successful HIR process will provide the Washington State Department of Transportation (WSDOT) with an additional rehabilitation technology that can potentially save money and conserve resources.

In this project, the goal of mix design was to obtain an admixture with an air void specification of 2.5% to 5.5% when compacted to 75 gyrations in a Superpave gyratory compactor. The amount of recycling agent used was determined by comparing the viscosity testing of asphalt recovered from the existing pavement to that of the new asphalt binder typically used on WSDOT projects. The recycling agent assists in making the mix more compactable, allowing for adequate compaction at lower temperatures than with conventional HMA. This aspect of superiority is proven by results showing that the lay-down temperature for the HIR using a recycle agent is lower and more uniform than that for conventional HMA paving. As shown in

Figure 10, thermal images show a temperature range of 90.6°C (195°F) to 115.6°C (240°F) behind the screed. In mixing test results, voids in mineral aggregate (VMA) were within WSDOT's specifications, but air voids (Va) were lower, and consequently the voids filled with asphalt (VFA) were higher.



(a) Thermal Image Showing Uniform Temperature across the Mat



(b) Maximum Mat Temperature: 240°F

Fig. 10 Thermal Images Behind the Screed

The total project cost was \$5,670,000, including design, administration, safety, HMA paving, pavement marking and incidental work required to complete the project. However, the cost of the HIR items was only \$1,860,000 (Table 1), resulting in a cost of \$58,500 per lane mile. The total cost per lane mile for a conventional HMA rehabilitation on a highway in Washington State is generally \$200,000. Therefore, the initial cost of HIR was 15 percent less than that of traditional HMA mill and fill. However, although the initial cost of HIR is less than that of a

Table 1. Contract 7648 HIR Costs

Item	Unit of Measure	Final Quantity	Unit Price	Total Cost
Hot In-Place Recycled HMA	S.Y.	227,863.2	\$6.30	\$1,435,538.16
Asphalt Binder	Ton	157.99	\$521.00	\$82,312.79
Recycling Agent	Ton	51.34	\$1,800.00	\$92,412.00
Aggregate For Hot In-Place Recycled HMA	Ton	3,823.5	\$65.00	\$248,527.50
Total Cost				\$1,858,790.45

traditional HMA project, its service life must be determined to confirm whether its life cycle cost is lower than that of traditional HMA.

The HIR process successfully rehabilitated the pavement on SR 542 using less new material than a traditional HMA mill and fill. Pavement performance over time will determine whether HIR is a viable alternative to traditional HMA.

9.2. Mississippi Department of Transportation

(Evaluation of Hot In-Place Recycling, Gary Browning, 1999)

The objective of this study was to monitor and evaluate the performance of a mixture and surface over five years. Properties of the HIR-recycled layer, such as AC content; aggregate gradation; and binder properties of viscosity, penetration and ductility were determined and compared with those of an overlay project. The performance evaluation was conducted based on ride quality measured using a South Dakota Profiler (SDP), and the overlay thickness was computed via Dynamic Deflection Determination System (Dynalect) and Falling Weight Deflectometer (FWD) deflection data.

The HIR section consisted of 12.37km (7.688miles) of Interstate 55 in Pike County from about 16.1km (10miles) south of McComb to the Louisiana State line. In this project, a remixing technique of three basic HIR processes-surface recycling, repaving, and remixing-was used on roads with asphalt which had a minimum penetration value of 15-20, rutting of less than 25.4mm (1 in.) in depth, and no structural deficiencies. The existing pavement was first heated and milled to a depth of 31.75mm (1.25 in.). A rejuvenator and virgin mix were added, and the 38.10 mm (1.5 in.) of recycled mix was re-laid and compacted. The first pre-heater heated the surface to 87.8°C (190°F) and the second heated the surface to about 115.6°C (240°F). The use of infrared heating did not overly oxidize the existing asphalt cement. Mix temperatures were maintained between 115.6°C (240°F) and 135°C (275°F) after the screed.

The study's findings showed that the pavement using recycled asphalt material in the wearing course mixes demonstrated a performance competency comparable to that of conventional hot-mix. However, each type of pavement was found to cost almost the same in terms of dollars/SY (Square Yard).

9.3. Canal Point, Palm Beach County, Florida

(Evaluation of Binder Grade and Recycling Agent Blending

For Hot In-Place Recycled Pavement, Hesham Ali et al., 2011)

In this paper, material obtained from a large HIR project constructed in March 2010 by HIP Paving, LLC on SR 700 in Florida was used to conduct laboratory testing to evaluate binder PG grade and mixing effectiveness by comparing the dynamic modulus of the mix to the theoretical modulus.

Prior to heating and recycling the existing pavement, 6inch(15.2cm)-diameter core samples of the pavement to be recycled were obtained using a diamond core drill. After recycling but prior to compaction, a 54.4kg (120lb) sample of the hot in-place recycled loose mix was obtained. The binders from the pavement cores and the loose mix were extracted and recovered. The shear modulus of the binder was then measured using a Dynamic Shear Rheometer.

Table 2 presents the results of the performance grading of the recovered binder from the hot in-place recycled loose mixture. The binder from the hot in-place recycled loose mixture graded as PG 76-22 based on AASHTO M320, Performance Grade Asphalt Binder. This result is acceptable for the environmental conditions in Florida. Table 3 summarizes the performance grading of the recovered binder from the existing pavement prior to recycling. The binder from the existing pavement graded as a PG 88-10 based on AASHTO M 320. Based on these results, the

Table 2. Results of Recovered Binder Grading from the Hot-In Place Recycled Loose Mix

Condition	Test	Temperature, °C	Result
Recovered	G*/sin δ, kPa	82	1,28
		76	2,48
PAV Residue	G* sin δ, kPa	19	4670
		16	6263
	Creep Stiffness(MPa)/Slope	-12	92.1/0,324
		-18	169/0,283
Grade	AASHTO M 320	PG 76-22	

Table 3. Results of Recovered Binder Grading from the Existing Pavement

Condition	Test	Temperature, °C	Result
Recovered	G*/sin δ, kPa	94	1,45
		88	2,76
PAV Residue	G* sin δ, kPa	31	3955
		28	5230
	Creep Stiffness(MPa)/Slope	0	62.4/0,340
		-6	119/0,299
Grade	AASHTO M 320	PG 88-10	

recycling agent added was effective in modifying the properties of the binder of the existing pavement and making it acceptable for Florida environmental conditions.

In addition, dynamic moduli of samples made from the hot in-place recycled loose mix were compared with dynamic moduli estimated via the Hirsch model for the properties of the binder recovered from the loose mix. Replicated 100mm diameter by 150mm high dynamic modulus test specimens were prepared from the hot-in place recycled loose mix for dynamic modulus testing. Figure 11 compares the measured and estimated mixture modulus values.

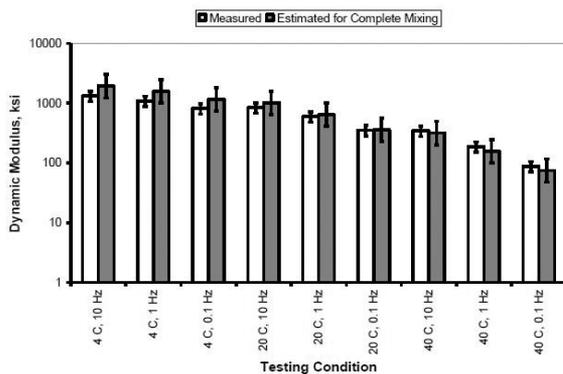


Fig. 11 Comparison of Field Mixed and Estimated Fully Blended Dynamic Moduli

The dynamic modulus mixing analysis conducted on the samples of the hot in-place recycled loose mix confirmed that a high degree of mixing of the recycling agent and the binder in the existing pavement occurred in the process used by HIP Paving, LLC.

The results suggest that mixing the binder with recycling agents can restore the original binder PG grade. Moreover, the results demonstrate that the hot in-place pavement recycling process has the potential to replace the milling and resurfacing process, with substantial financial and environmental savings, in the range of 30%-50% of the cost of milling and resurfacing. In addition, emission reductions of about 70% and 100% reuse of existing material can be realized.

10. CONCLUSIONS and RECOMMENDATIONS

10.1. Advantages and Disadvantages

The benefits of asphalt recycling (HIR) include:

- Conservation of energy and materials, including aggregates,

asphalt, and fuel (less truck hauling)

- Construction improvements realized through shorter construction periods, fewer traffic delays and control needs, safer site conditions, easy mobilization, absence of milling disposal costs
- Preservation of existing roadway geometry and clearances and cost savings over traditional rehabilitation methods
- Rejuvenation of oxidized asphalt binder with the use of recycling agents to restore pavement flexibility
- Pavement improvements through correction of surface conditions at up to 50mm (2in.) depths, correction of mix deficiencies, unaffected elevation and curb lines, improved ride and skid resistance
- Environmental concerns addressed through improved air quality due to less trucking and the reduction of smoke emissions on site through the use of afterburners on recent equipment upgrades

The disadvantages of asphalt recycling (HIR) include:

- Compaction problems resulting in segregated and open textures and low density.
- Cracks reappearing, smoothness deficiencies, inadequate milling depth, and insufficient mixing
- Generation of excess aggregate fines caused by milling to a depth at which the pavement was too cold, thus causing aggregate fracture
- Equipment-related problems, including frequent breakdowns, excessive smoke and steam, and unwieldy length of the paving train
- Poor performance of HIR equipment in windy or cool weather or when the pavement was damp
- Poor longitudinal joint matches and undersized paver and failure of the re-mixer to accept sufficient virgin HMA admix to upgrade the pavement (These concerns may have been due to factors other than the HIR equipment itself.)

10.2. Conclusions and Recommendations

Most of the United States highway system is now deteriorating so that rehabilitation or reconstruction techniques are required for the most distressed roads, taking into account ways to increase the effectiveness of existing budgets. Several options are available in

rehabilitating distressed roads, and the choice among these depends on many factors, including pavement distress condition, funding, and design life. Among these techniques, Hot In-Place Recycling (HIR) has emerged as a cost-effective treatment for deteriorated pavements, and has been proven an effective long-term strategy for pavement rehabilitation.

Over the past several years, acceptance of the HIR concept has steadily and rapidly grown. In addition, the techniques and equipment developed by pioneers in organizations such as Artec and Wirtgen have incrementally approached the goal of being able to recycle at depth and put down an asphalt pavement of sufficiently high quality that it can directly compete with other HMA pavements. However, HIR continues to face problems having to do with limited potential for structural improvement and uncertain performance reliability—specifically the lack of a nationally accepted protocol and defined design procedure. In short, there are shortcomings that require further attention, but it appears that many of these are gradually being overcome. The following recommendations can be drawn from this study:

- Different methods of recycling are applicable to different types, levels, and severities of problems, and hence to different periods of pavement life. Typically, HIR is recommended when the majorities of pavement distresses are minimal, and are limited to the upper few inches of the surface of the roadway with no evidence of structural problems.
 - A number of HIR mix design methods have been used by various agencies due to the lack of a single accepted protocol for the mix design of HIR. Therefore, specific mix design methods, such as Superpave, need to be developed for the design of recycled mixes.
 - Structural design considerations are fundamentally important in recycling techniques. Thus, structural design parameters need to be assessed before construction so that the final product meets or exceeds the desired performance.
 - The barrier cited most often by contractors as compared to agencies, the lack of project selection criteria, must be established concretely.
 - Further education and training are required to facilitate the expansion of the HIR industry.
 - Climate conditions must be considered in considering whether to select an in-place recycling process.
- A Life Cycle Cost Analysis is recommended to ascertain construction costs for various rehabilitation alternatives, given that these impact performance. Also, service life of HIR pavements should be determined to confirm whether their life cycle cost is lower than that of traditional HMA.

References

- Al-Rousan, T., Masad, E., Myers, L., and Speigelman, C. (2005), "New methodology for shape classification of aggregates," Transportation Research Record No. 1913, TRB, National Research Council, Washington, D.C., pp. 11-23.
- Asphalt Recycling and Reclaiming Association, (1992), "Hot In-Place Recycling--First in the Line of Pavement Maintenance," Hot In-Place Recycling Technical Committee, Annapolis, Maryland.
- Asphalt Recycling and Reclaiming Association, (2001), "Basic Asphalt Recycling Manual," Annapolis, MD.
- Bejarano, M. O., Harvey, J. T., and Lane, L., (2003), "In-situ recycling of asphalt concrete as base material in California," Transportation Research Board, 82nd Annual Meeting, Washington D.C..
- Bejarano, M. O. and Harvey, J. T., (2004), "Deep in-situ recycling of asphalt concrete pavements as granular base-design, construction and performance evaluation experience in California," Proceedings of 8th Conference on asphalt pavements for South Africa, Sun City, North West Province, South Africa.
- Bemanian, S., Polish, P., and Maurer, G., (2006), "Cold in-Place recycling and full-depth reclamation projects by Nevada department of Transportation: state of the practice," Transportation Research Record No. 1949, TRB, National Research Council, Washington, D.C., pp. 54-71.
- Brown, D., (2000), "Recycling Practices for HMA," Special Report No. 187, National Asphalt Pavement Association, Lanham, MD., pp. 7-9.
- Epps, J.A., D.N. Little, and R. J. Holmgren, (1980), "Guidelines for Recycling Pavement Materials," NCHRP Report No. 224, Transportation Research Board, Washington, D.C.
- Epps, J. A., (1990), "Cold-Recycled Bituminous Concrete Using Bituminous Materials," NCHRP Synthesis of Highway Practice 160, TRB, National Research Council, Washington, D.C.
- Gary Browning, (1999), "Evaluation of Hot In-Place Recycling," Final Report, Mississippi Department of Transportation.
- Hesham Ali et al., (2011), "Evaluation of Binder Grade and Recycling Agent Blending For Hot In-Place Recycled Pavement," Transportation Research Record No. 2011, TRB, Washington, D.C.
- Jeon, E., (2009), "Comprehensive Performance Evaluation of In-Place Recycled Hot Mix Asphalt as Unbound Granular Material," Dissertation, University of California.

- Kandhal, P.S., and Foo, K.Y., (1996), "Hot Mix Recycling Design Using Superpave Technology," Draft report, National Center for Asphalt Technology, Auburn, Alabama.
- Kearney, E.J., and Huffman, J.E., (1999), "Full-Depth Reclamation Process," Transportation Research Record 1684, TRB, National Research Council, Washington, D.C., pp. 203-209.
- Kim, W., Labuz, J.F., and Dai, S., (2007), "Resilient modulus of base course containing recycled asphalt pavement." Transportation Research Record No. 2005, TRB, National Research Council, Washington, D.C., pp. 27-35.
- Larry Santucci, (2007), "California Asphalt Magazine 2007 Environmental Issue," Publication of the Asphalt Pavement Association of California, p.15.
- Mallick, R.B., Bonner, D.S., Bradbury, R.L., Andrews, J.O., Kandhal, P.S., and Kearney, E.J., (2002), "Evaluation of Performance of Full-Depth Reclamation Mixes," Transportation Research Record No. 1809, TRB, National Research Council, Washington, D.C., pp. 199-208.
- Mark Russell et al., (2010), "Evaluation of Hot In-Place Recycle," WSDOT Research Report, Washington State Department of Transportation.
- Masad, Eyad A., (2004), "Aggregate Imaging System (AIMS): Basics and Applications", FHWA/TX-05/5-1707-01-1, Texas Department of Transportation Research and Technology Implementation Office, Austin, Texas.
- National Center for Asphalt Technology, (1997), "Pavement Recycling Guidelines for State and Local Governments," FHWA-SA-98-042, Washington, D.C.
- National Cooperative Highway Research Program (NCHRP), (2011), "Recycling and Reclamation of Asphalt Pavements Using in-Place Methods," National Cooperative Highway Research Program, Report 421.
- Scott Metcalf, (2006), "Hot In Place Recycling," Southern California Pavement Preservation Conference, April 25th, Diamond Bar, CA.
- Udelhofen, G., (2006), "Hot-in-Place Recycling Key to Denver's Street Maintenance," Asphalt Contractor, Vol. 20, No. 5, June/July, pp. 32-37.
- Wirtgen, (2004), "Wirtgen Cold Recycling Manual," Wirtgen GmbH, Windhagen, Germany.