Viability of Hot In-Place Recycling as a Pavement Preservation Strategy

The current Martec AR 2000 Hot Air HIR Train After Re-Laying the Recycled Pavement

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PROJECT SUMMARY PAGE	**Tech Report: 2008-xx**
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Abstract:

The poor state of the infrastructure throughout the U.S. and elsewhere is showing considerable need for repair due to wear and the deferred maintenance. Although recycling pavements is certainly not a new concept, the timing is right to reconsider this option as a viable treatment for pavement preservation.

Current recycling methods include two basic approaches: (a) inclusion of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) in a central plant operation, and (b) surface recycling, both at ambient or cold in-place recycling (CIR) or hot in-place recycling (HIR). In-place recycling is accomplished on the road by a train of specialized equipment that travels over the roadway, milling the surface, adding some materials and repaving the surface of the pavement as it goes. The HIR process is to soften the existing surface with heat, and mechanically loosen the reclaimed asphalt pavement (RAP), mix the loosened material with a recycling agent, aggregate, or virgin HMA, and relay the recycled material without removing it from the pavement site.

HIR is one option for recycling that is becoming more viable because of the rising cost of crude oil, resulting in more opportunities to save fuel, asphalt, aggregates, and the resources needed to produce them. This paper is an evaluation of two types of HIR: infrared heating and hot air heating and their differences, and assess the attributes of each. The factors used to evaluate the HIR methods include: environment (emissions such as smoke), energy, cost, productivity, performance, project selection, and construction. The advantages of both types are evaluated, and recommendations for implementation of current technology and future improvements in the technology are discussed.

Keywords: Surface Recycling, emission, HIR technologies

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DISCLAIMER

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1. Introduction

Background

The state of the infrastructure throughout the U.S. and elsewhere is showing considerable need for repair due to wear and the deferred maintenance caused by economic conditions has spurred engineers to seek new approaches. Although recycling pavements is certainly not a new concept, the timing is right to reconsider this option as a viable treatment for pavement preservation.

During the 1970s, there was a worldwide increase in the cost of crude oil that caused the highway industry to rethink how pavements were built. At that time, the prediction was that the cost of petroleum would continue to rise, the asphalt that was normally derived from crude would be in short supply, and that alternatives to asphalt as a paving material should be investigated. As a consequence, several materials were studied as alternatives or extenders of asphalt, including materials such as sulfur, wood lignin, slag, waste tires, etc. In addition, recycling of asphalt pavements was studied as a means of preserving the asphalt that was already in place. Eventually, the price of crude oil resumed its previous levels, and the interest in the alternative approaches waned.

In more recent times, the rapid rise in costs of fuel and aggregate, as well as asphalt, have put pressure on public and private highway maintenance budgets around the world. Pavement managers everywhere are seeking environmentally friendly ways to repave more highways with less money. Further, there is a concerted effort to conserve energy and reduce the carbon footprint of any and all activities. As a result, we are seeing a renewed interest in the same topics as were studied in the 1970s, but there seems to be a new urgency to making significant changes that will impact energy conservation and environmental concerns, and, using the latest catchword, going green.

Preservation of the existing network of roads and streets has taken on a more significant role since there is decreased financial ability to build new roads. There are numerous methods for preservation and rehabilitation, many of which are discussed in detail in the recently updated Caltrans Maintenance Technical Advisory Guide (MTAG) (Caltrans 2008). For example, the systematic approach to determining the most appropriate options is summarized in Figure 1. In this figure, as well as in the minds of highway engineers, recycling has taken on a much higher importance, and comparison of some alternative recycling methods is the purpose of this paper.

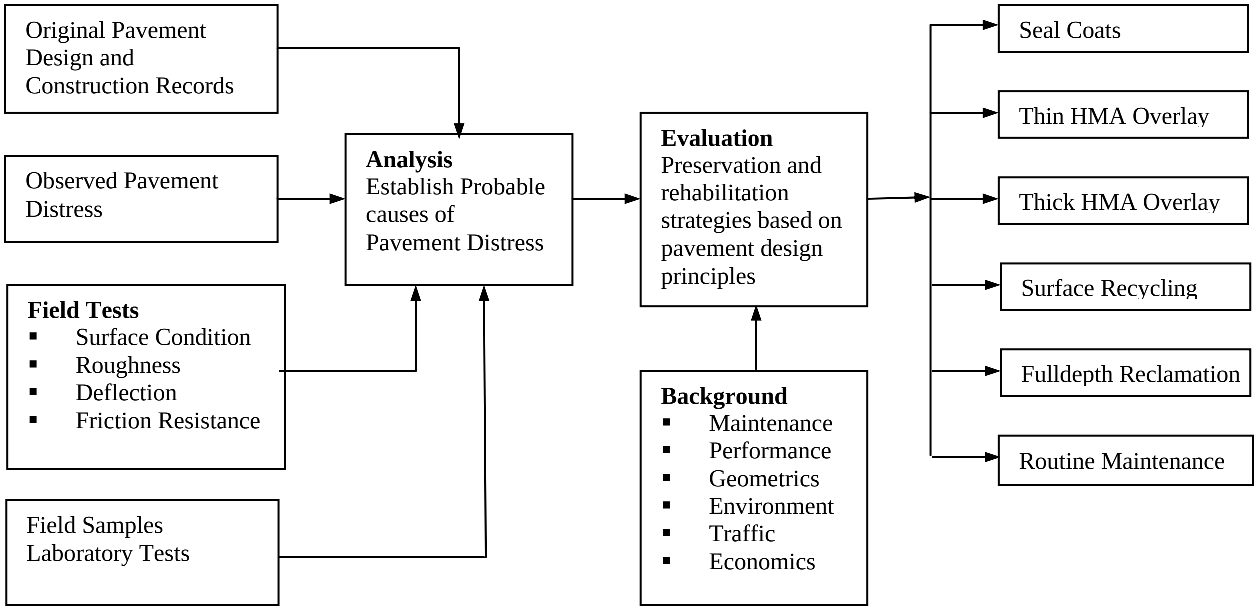

Figure 1 Summary of process to arrive at the best option for pavement preservation and rehabilitation (Modified from Epps, et al, 1997)

As noted in Figure 1, surface recycling fits into the pavement preservation strategies. Caltran has used CIR, but is now considering using HIR on projects in the 2009 construction season. Full depth recycling (or reclamation) is more of a rehabilitation strategy. It is also being considered as a strategy for rehabilitation roads in California.

Purpose

There are currently several types of asphalt recycling that are in various stages of development and use. These include two basic approaches: (a) inclusion of RAP (reclaimed asphalt pavement) that has previously been milled from the road, and using it as an aggregate and binder replacement in HMA (hot mix asphalt) in a central plant operation, and (b) surface recycling, both at ambient or cold in-place recycling (CIR) or hot in-place recycling (HIR), that is accomplished on the road by a train of specialized equipment that travels over the roadway, milling the surface, adding some materials and repaving the surface of the pavement as it goes.

This paper is aimed at comparing current types of HIR that are in use, as well as consideration of alternatives or improvements that are under consideration for the future. The main points are:

- Discussion of the types of HIR, including hot air, infrared (IR), and others,
- Comparison of HIR technologies, and
- Methods of evaluating pavements suitable for HIR and mix design approaches.

The paper focuses on one stage operations for depths up to 40 mm and multiple stage operations for greater depths

2. HIR Technologies

The focus of this paper is to compare hot air and infrared methods for HIR, as both of these methods are aimed at warming the surface of the existing HMA and then restoring the damaged or worn surface to new-like condition.

The HIR process is to soften the existing surface with heat, and mechanically loosen the reclaimed asphalt pavement (RAP), mix the loosened material with a recycling agent, aggregate, or virgin HMA, and relay the recycled material without removing it from the pavement site. The depth of milling typically does not extend beyond the HMA, and no underlying unbound material is included. The HIR recycled pavement may be used as a new pavement surface without the need for overlay or seal coat. The steps in HIR include:

- Heating and milling of the asphalt layers to a depth from 1 to 2 inches.
- Sizing the RAP, mix with recycling additives, and relaying the mix.
- If needed, add virgin aggregates or HMA, before remixing, and relaying.

The HIR process can be performed as either a single-pass operation that combines the restored pavement surface material with virgin material, or as a two-pass operation, in which the restored pavement surface material is re-compacted and the application of a new wearing surface follows at a later time.

Three different processes are commonly used in HIR, including:

- Surface recycling (heater scarification).
- Repaving and remixing.
- Remixing.

Currently, Caltrans has a specification for only HIR remixing (Caltrans, 2006), and this is the main interest at this time. Air pollution concerns using current technology may preclude the heater-scarification method from being used in California, and this method will not be discussed in this paper.

The HIR Remixing option is the most straightforward, and the most widely used in North America. From an engineer's point of view, the HIR concept is a practical solution to resurfacing highway pavements. It is a one-step process, minimizes the downtime of the roadway by repairing the pavement with the least disruption to traffic, and also addresses the economic, energy, and environmental concerns, all in one package.

History and Development

Although there have been some research, trials, and development of HIR in many countries, the seat of modern HIR is British Columbia, Canada (Oliver 2007). This development has been accomplished by innovative contractors (Wiley 2006) in several stages or phases. In addition, the British Columbia Ministry of Transportation & Infrastructure has been intimately involved and a leader in introducing the HIR concept into the public highway industry. Engineers in B.C. Highways have worked hard to provide projects to be recycled, and worked closely with the contractors to improve the results and to develop specifications that allowed for improved results. As a result, HIR is currently an ongoing part of the highway maintenance and rehabilitation program with numerous projects awarded each year.

The cooperation between the contracting agencies and the contractors doing the development work has had an on-going impact on innovation and positive, incremental improvements in HIR over the years

Early Development of HIR. The first asphalt pavement was placed in the United States in 1870 (The Asphalt Institute 2006). By 1915, reuse of asphalt pavements in road structures was recognized as an important option for pavement rehabilitation (NAPA 1977). Use of asphalt cement to stabilize recycled asphalt pavement probably dates back to only the 1930s or 1940s (Epps 1980, Shoenberger 1990). During this time period, the first heater-planer machines were developed. However, the total quantity of pavement materials recycled by all methods from 1915 to 1975 is small in comparison to the amount that has been recycled since 1975 (Epps 1980). Today, asphalt pavement recycling is commonly performed on highways and airport runways using several methods, including both hot and cold methods for both central plant and in-place recycling operations. Some sweeping changes and innovations in North America in the last 10 years have been associated with hot in-place recycling (HIR).

A chronological record of the evolution of HIR shows an increasing understanding and improvement on the concept. As indicated earlier, the modern era of recycling was initiated in the mid 1970s, but trials and experiments were tried much earlier. Several manufacturers have developed equipment with variations in the details and approach to HIR, but most are similar in a broad sense. One or more pre-heater units that are usually the infrared type are used to warm and soften the pavement ahead of the other units. Some manufacturers utilize stationary tines or teeth to scarify the warm pavement, but most currently use rotating milling heads. These are similar to those used for cold milling, but require less power because the warm pavement is softer. Most systems can mill to a depth of 25-40 mm, however for a target depth greater than 40 mm, a multi-stage system is recommended to achieve consistency in terms of developing sufficient heat and without too much emissions.

New Developments in Remixing. Variations of the repave and remix process were developed in the mid and late 1980s to early 1990s and this technology is being used in North America. The HIR systems are often called multi-stage, a terminology coined in B.C. to indicate two-stage, three-stage, or four-stage, because of the progressive stages of preheating, hot milling, remixing, and paving. But also, they are single step, meaning that the preheating was followed by a single milling operation, and the full depth of milling was done in one pass of the cutting heads. These single stage equipment styles were utilized by several manufacturers, including Rorison-Wiley Blacktop, Wirtgen, Taisei Rotec, and others.

Two-step and four-step process were developed by three companies: Rorison-Wiley Blacktop (now called Green Roads, Inc.), Pyrotech, Inc. and Artec, Inc., all of British Columbia, Canada. These companies realized that heating and milling to greater than a 40 mm depth in a single stage resulted in reduced production and a greater chance of breaking the aggregates or creating excessive smoke. Through trial and error they developed multi-stage systems whereby the pavement was heated and removed in 12.5 (four-stage) or 25mm (two-stage) layers. The idea was to take advantage of the ability to heat the top 12 or 25 mm of the pavement effectively. An improvement was introduced by Pyrotech when an afterburner was added to incinerate the smoke and vapors generated by high temperatures at the pavement surface as noted in Figure 1 (Terrel, et al 1997b, c).

Through the early 1990s, the further development of HIR technology seemed to reach a plateau. There were a number of HIR trains operating in the U.S. and Canada and they were using the various technologies. Because of the enormous potential of HIR, several user agencies began to seriously evaluate the effectiveness and conducted surveys of projects through key people who were directly involved.

As a result of these evaluations, the industry began to recognize the need for improvements. Among these, was the obvious need to improve air quality since many processes caused excessive smoking. The equipment and processing was needed to provide higher mix temperatures and deeper recycling in order to obtain quality results. Details of the needed improvements to the equipment operation included more power to climb grades, adjustable width, quieter operation, better ability to add virgin aggregates and mixtures as well as recycling agents, along with good instrumentation to monitor it all for improved quality control. Developing better procedures for selecting suitable projects would include more site evaluations and core sampling, and criteria to preclude those pavements unsuitable for HIR.

Beginning in 1994, Artec International began addressing many of the issues noted above, particularly the smoking issue, as well as improved heating of the pavement (Oliver 1994, Terrel, et al, 1996, 1997a). This new approach used hot air and infrared at the same time to heat the pavement surface by blowing hot air through a series of holes drilled in stainless steel tubes. Under pressure, the hot air impinged directly on the pavement surface, heating it. At the same time, the tubes were heated by the hot air passing through them which caused them to emit infrared radiation. Side skirts contained the hot air, which was vacuumed back into the burner, re-heated, and re-used. This single stage system generated less smoke than the infrared recycling trains because the returned hot air, which often contained some smoke and emission, was then incinerated during the reheating step. But because this was a single stage operation, it too struggled to reach depths of 50 mm or more without creating too much smoke. Later, Artec sold the technology to Martec, and did numerous trials and projects with their train known as the AR-2000.

Currently Used HIR Trains

Several different technologies have been developed that were aimed at recycling the asphalt in place, by first heating the surface and then recycling the existing pavement. These included at least the following companies who manufacture HIR equipment, and not specifically contractors who operate the equipment:

- **Cutler Repaving, Inc.** Lawrence, KS**,** does considerable pavement recycling using their single pass repaving and remixing process with IR propane fueled heaters.
- **Dustrol, Inc.** Towanda, KS does HIR as well as other recycling using IR heaters.
- **Taisei Rotec,** Tokyo**,** Japan, does HIR using propane fired IR, and has done several projects in North America.
- **Wirtgen Group,** Germany and Nashville, TN manufactures HIR equipment to do repaving, and utilizes propane for IR heating.

- **Green ARM Company, Ltd,** Japan, manufactures AR 2000 HIR machines under license from Martec Recycling Corporation and has developed a new type of HIR called HITONE, that transforms conventional pavement into an open graded surface over a mastic gap graded layer using IR heaters in one pass, and will demonstrate this process in California in 2008.
- **Pyrotech, Inc**., British Columbia, Canada manufactures HIR equipment.
- **Martec Recycling Inc**., based in British Columbia, Canada, licenses other companies abroad to manufacture and operate HIR trains.
- Several others who are no longer active manufacturers.

Infrared (IR) and Hot Air Systems for HIR

From the previous discussion, and list of possible options for HIR, this report will be limited to only IR and Hot Air. The following table summarizes these options:

Table 1 Summary of the chronological development of HIR in British Columbia (Wiley 2008)

Year Technology	Developing Company	Current Mfr. Model Name	Technical Positives	Technical Negatives
1985 Single-Stage Infrared heat	Rorison-Wiley Blacktop	No longer produced	None	Smoke 1 in max depth
1987 Two-Stage Infrared heat	Rorison-Wiley Blacktop	No longer produced	Good heat Transfer 1st 2 inch achieved	Variable smoke Variable quality Max 25% admix Large size
1990 Four-Stage Infrared heat	Artec Equipment	No longer produced ARC operates one in BC	Optimized Heat transfer 2 inch depth	Variable smoke Variable quality Max 25% admix Large size
1990 Two-Stage Infrared with Emissions Incinerator	Pyrotech Asphalt Equipment	Pyrotech Asphalt Equip. Pyropaver 300E		Variable smoke Variable quality Max 25% admix Large size
1995 Single-Stage Hot air/infrared	Artec International	Martec Recycling AR 2000	Less smoke at depths up to 40 mm. Diesel fuel	Variable smoke at depths > 40 mm Max 25% admix Very large size

The following paragraphs include descriptions of the two main types of HIR that are currently operating, infrared (such as the Pyrotech train) and hot air (such as the Martec train). A summary of the development of these technologies is shown in Table 1, along with the incremental improvements with each new generation of equipment. Note that this summary addresses only those technologies that have been developed in British Columbia, Canada, because that is considered the seat of HIR technology. Also, it appears to be where new ideas and improvements are being addressed. One or more of these systems may be appropriate for operation in the U.S., particularly in the western states. Currently, three HIR trains are operating in British Columbia:

- One Pyropaver 300E train operated by Green Roads, Inc.
- One Artec four-stage train operated by Peters Brothers Paving.
- One Martec AR 2000 train operated by ARC Asphalt (bought out by Pyrotech in 2007)

Pyrotech Pyropaver 300E

This two-stage HIR recycling train uses infrared energy to heat the pavement surface. This is an early example of the remixing process and diagrams of each unit can be seen in Figure 2. The first machine is preheating only, and heat is applied directly by IR heaters by lowering them to near the pavement surface. The second machine also heats the pavement using the same size and type of heater unit, but also has a milling head that removes up to 25 mm of warmed RAP from the surface and places it into a windrow. The third machine lifts the first windrowed material over the third heater and then repeats the heating and warm milling process to achieve a total depth of up to 50 mm. At this point, the first and second removed layers of RAP are combined and other materials such as rejuvenators, fresh HMA admix can be added. The RAP may be picked up directly into the paving hopper along with any rejuvenator. If there is need for adding additional HMA (admix), a truck can end dump the virgin HMA directly into the admix hopper. The combined RAP and HMA are then blended in a pug mill, and then placed into the hopper of a conventional paving machine**.**

Figure 2 Pyrotech Pyropaver 300E showing the vacuum system for reducing smoke

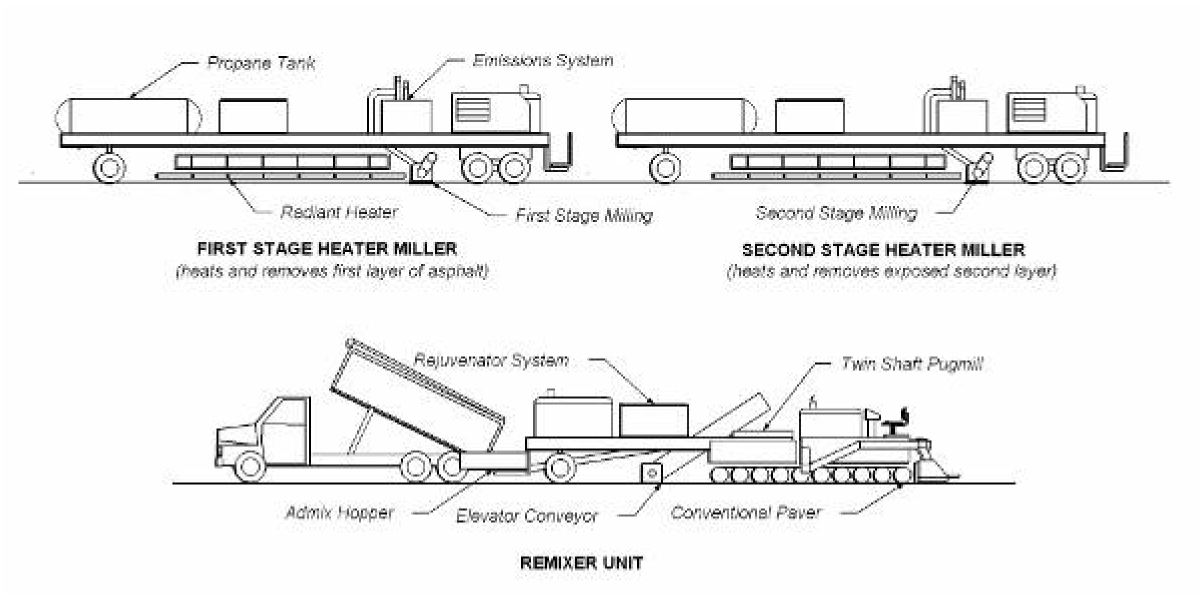

Figure 3   Diagram the Pyrotech 300E HIR Train showing the individual units (Wiley 2007)

Figure 4   Multi-stage HIR train developed and manufactured by Artec and Pyrotech, but currently operated as the ARC Supertrain in British Columbia

Figure 5 is a close-up of one infrared heater unit as seen from the bottom. These heaters are about 1000°C (1800°F) at the surface and the pavement surface can be rapidly heated to temperatures exceeding the burning point of asphalt under certain conditions. Although the temperature can be too high and one would expect that the asphalt binder could overheat or

char, this may occur only in the top few millimeters. Oxidative hardening is minimized because of the low level of oxygen near the surface; however the high temperatures may cause hardening due to other processes such as volatilization

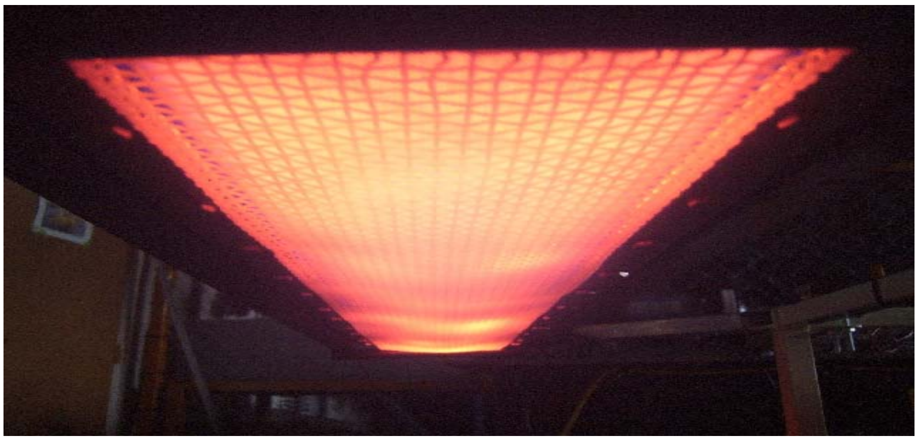

Figure 5 The HIR systems described in Figures 1 and 2 utilize infrared heaters that radiate heat directly onto the pavement surface.

Martec AR 2000

The AR 2000 Super Recycler was originally developed by Artec, and the technology was later sold to Martec. The idea of the AR 2000 was to improve the overall heating and recycling process by addressing several key issues (Terrel, et al 1997b). The system uses hot air in combination with low level infrared heating to warm the pavement. It is fueled by diesel rather than propane or butane, making the fuel much more available without the re-fueling hazards in populated areas. Removal of moisture from the RAP is difficult for any system, but the hot air and stirring action achieved in the AR 2000 may do a better job than IR only. An added benefit is less smoking because the hot air (at about 600°C) is a much lower temperature than that for IR and the cooler air is then returned by vacuum to the heating chamber where the smoke and emissions are incinerated. This system is a single stage recycler, meaning that it is heated and milled in one step. (Terrel, et al 1997b)

Figures 6 and 7 show the AR 2000 trains on projects and illustrates both the Artec and Martec versions which are quite similar. Figure 6 shows the heater units extended to their full width, which vary from 10 to 13 feet. The underside of the heating system shown in Figure 8 is a series of steel tubes with holes that allow the hot air to pass through and impinge on the pavement surface. Because the tubes are heated, it also serves as a supplemental low-level infrared heater. In an attempt to be more efficient, the AR 2000 operates as single stage system as seen in Figure 6. The steps in this HIR system include:

preheating using two identical heater units, a heater miller unit, and a heater mixer unit (with heated pugmill) where any needed additives, HMA, or aggregates are added, and finally into the traditional paving machine where it is laid back down.

Figure 6 The original Artec AR 2000 train working

Figure 7 The current Martec AR 2000 Hot Air HIR Train After Re-Laying the Recycled Pavement

Figure 8 Close-up of the underside of the AR 2000 hot air heating system.

3. Comparison and Discussion of the HIR Technologies

When one studies Table 1, it becomes readily apparent that the latest technology for HIR (Martec) was developed at least 13 years ago. As mentioned earlier, there has been a plateau in the development of technology. This lull has been caused by the lack of need because the price of asphalt has remained relatively stable until recently. Therefore, there has not been a lot of economic incentive to take the risk of embarking on new ventures. However, we are now feeling the pressure of environmental concerns such as global warming and energy conservation, and this may lead to renewed interest as well.

However, most of the early HIR trains are still operating in British Columbia on a regular basis. This is because the B.C. Ministry of Transportation has become familiar and comfortable with the equipment and the contractors operating in B.C., and projects that are designed for HIR are contracted on a regular basis for the past several years (Oliver 2005). The Province of Ontario also has continued interest in HIR and has an ongoing program (Kazmierowski 2008). Several States in the U.S. have ongoing interest and trial projects to evaluate this promising concept.

In recent times, the price of crude oil has spurred renewed interest in recycling. Even though there are promising energy and cost savings to be had by adopting HIR, there are lingering issues that tend to limit the outright embracing of HIR by highway agencies in a way that they have accepted Cold In-Place Recycling (CIR) on a much wider basis. The following discussion is an attempt to address the issues and discuss options for making improvements to the system.

Cost is a factor that is always important. The recent rise in the price of crude oil has affected all aspects of highway construction, including the cost of asphalt, fuel, aggregate, and others. Based on prior experience, considerable cost savings are to be realized with HIR, for example about 40% savings over mill and fill. However, most agencies have done limited projects, so the true cost is not reflected because of special one-time factors that enter into the equation. British Columbia (Oliver 2006) is one agency that has a sustained program in HIR that backs up this notion with hard information, and has compiled sufficient data to list the savings with confidence as follows:

- More than 160 projects completed to date
- Recycled 2.6 million tonnes of asphalt or 24 million $m^2$of highway since 1990
- $10 million + annual program.
- Costs through 2005 have shown that HIR rehabilitated pavements are about 40 to 50% less than for mill and fill (Oliver 2005).

Ontario is another Province that has done considerable work with HIR (Kazmierowski, 2008a). Since 1995, Ontario has recycled 1,009,607 m^2 using the remix process, but did not provide any cost data. The State of Colorado has included HIR in their program and from 2000 to 2008 have completed 37 projects for a total of 7,704,631 yd^2 (9,245,557 m^2) (Goldblum 2008). The weighted average cost was $3.74 per yd^2 ($4.49 m^2 for pavements recycled 37.5 to 50 mm deep.

The **durability** of pavements that have been recycled has been reported to be as good as or better than for traditional rehabilitation, based on limited data in Canada. In the 8-year study in Ontario (Kazmierowski 2008a) the recycled pavements using the IR system (Taisei Rotec) has life expectancy of 7 to 8 years, while those using the hot air system has 9 to 10 years life expectancy, and are similar to conventional HMA. In British Columbia (Oliver 2006), following a 2001 study and overall evaluation in the Province, the normal procedure is to use both recycling agent and admix, and the expected pavement life is more than 10 years. In milder climates such as California, one might expect a longer life with similar traffic conditions. This strategy is being considered for low volume roads in California.

Environment

Since asphalt pavement is one of the most recycled in the U.S., it provides an opportunity to save considerable energy, reduce the carbon footprint, and reduce such factors as air pollution in general.

HIR has not enjoyed a clean reputation when it comes to smoke generation. The early attempts at HIR that used direct flames were essentially a disaster. However, local highway agencies were tolerant and were optimistic that the technology would improve and smoke and emissions would be reduced. With the introduction of IR heaters for HIR, the pavements could be heated too much higher temperatures than for open flame heating. But problems with emissions still persist today. When conditions are good, which means good weather, low moisture in the RAP, and a uniform pavement to recycle, then productivity and associated smoke levels are tolerable, as seen in Figure 7. But much of the time, the pavement conditions are not ideal and smoke persists, as seen in Figure 8. General observation of smoke could be categorized as follows: (1) white smoke is mostly steam, and is usually harmless; (2) blue smoke is the result of overheating asphalt, crack sealers, etc., and can be hazardous to health and environment, and (3) black smoke would indicate burning of asphalt and is very hazardous to both health and the environment. Other emissions may also be hazardous, but are not visible.

Infrared radiation is sensitive to color, in that it is light sensitive. If the entire pavement surface is one uniform color, then the surface heats evenly. For example, if a patch or crack sealant is encountered, the asphalt binder may bubble up and turn black, and the temperature increased at that location, probably causing blue smoke or even some black smoke if flames develop. An example of this occurrence can be seen in Figures 9 and 10, where a patch rich in asphalt binder may have been encountered.

Figure 9 Example of HIR project with smoke being produced at an unacceptable level, indicating some overheating of the asphalt binder.

Figure 10 Localized hot spot caused by overheating RAP with crack filler or patching.

The hot air heating system has the advantage of being insensitive to the color and uniformity of the pavement surface. The circulating hot air, although not at nearly as high a temperature as the IR, still provides sufficient heat transfer to the pavement. The spent hot air is vacuumed back into the heating chamber where it is incinerated, thus reducing the smoke produced. The localized hot spots that are sometimes encountered with the IR system are not seen with hot air heating. However, if the HIR system is operated in windy conditions, especially cross winds, some of the heat is lost because the hot air is blown out from under the heating units, even when skirts are used.

With some highway agencies, such as Caltrans**, "smoke is not an option"** becomes a policy that must be dealt with. The definition of no smoke may mean many things, and will depend on the regulating agency. One suggestion is to define no smoke as the same level as that generated by conventional paving operations using HMA. If this level of air quality is acceptable, then the HIR system can most likely become a viable option for recycling, since HIR reduces total emissions (Terrel, et al, 1997b).

The HIR systems that heat with IR radiation typically use **propane** fuel, while the hot air system uses **diesel** fuel. Internationally, there is some concern about the use of propane because of safety in refueling in populated areas. Also, the availability of diesel is better, particularly in remote locations. In other U.S. locations, however, the choice may be dictated by local regulations such as difficulty in getting permits to use diesel. The convenience of using only one fuel for all needs at the jobsite makes it easier to manage. In California, the use of diesel may be limited when an alternative fuel is available, as may be dictated by local air quality regulations.

Energy consumption by various construction operations has been under consideration as part of the overall environmental improvement of the industry. The concept of reducing the energy use, particularly fossil fuels, and thus the carbon footprint is a reasonable goal. One Canadian study (CCA 2005) has focused on road construction options as a means to point out where improvements may be realized. From this study, data in Table 2 were extracted to show the potential savings when using HIR.

Table 2 Summary of Energy Consumption for Selected Pavement Preservation and Rehabilitation Methods (modified after CCA 2005)

Strategy	Thicknesses	Energy consumption (MJ/tonne)
Overlay	50 mm overlay HMA	680
Mill and Fill	40 mm cold mill then 50 mm fill HMA	819
HIR	50 mm hot mill + 50 mm recycle relay	570

Performance and Productivity of the HIR Technologies

The **productivity** of HIR systems is of some concern when comparing it with resulting quality of final pavement. The usual goal of HIR is to recycle the pavement to a depth of 50 mm and resulting in a pavement of at least the same quality as the original. From the beginning, this has been a challenge. Early attempts were aimed at heating the full depth in one pass of the heaters, followed by tining or milling. But in order for the IR heater (for example) to raise the temperature sufficiently at 50 mm depth, the surface would need to be intolerably hot, resulting in burning of the asphalt binder and smoking. Depths of 40 mm or less seem to be acceptable for HIR processes.

When it becomes desirable to recycle to depths greater than 40 mm (British Columbia typically specifies 50 mm depth), a two-stage HIR train may be required in order to achieve consistent results. For example, the contractor that operates the Martec train may be considering conversion of the train to two-stage. This would allow for better achieving adequate heating of the RAP and would have less potential for creating smoke and aggregate fracture.

Past experience has shown the speed of HIR to vary greatly with the weather and condition of the pavement, in particular, the moisture content. Most asphalt pavements may have about 6 to 10% air voids, and the amount of moisture will depend on climate and recent weather. However, it has been found that an average of about 2% moisture in the existing pavement is about right, even in dry climates (Terrel et al 1997c). In order for the RAP to reach a temperature above the vaporization point of water (212°F) the moisture must be heated and removed. While the IR heater can reach higher surface temperatures, there is no easy means of removing the water vapor. The hot air HIR heater, with its continuously circulating air, has a much better chance of drying the RAP, so that it can be heated adequately for remixing and compacting. As part of the project pre-evaluation, the moisture situation must be investigated in order to estimate expected production rate.

Another advantage of the HIR system is that by warming pavement, the RAP is more gently removed from the pavement without excessive aggregate breakage. This feature is beneficial to the mix design in that the aggregate gradation does not have to be radically adjusted by adding new aggregate or HMA to restore the pavement to desired quality. Cold milling has been around for a long time and is very good at aggressively removing pavement, but the resulting RAP may be fractured to the point where is best used for RAP that can be added to HMA in central hot mix recycling plants. With insufficient heating to depth, the milling step in HIR requires more powerful grinders to reach the required depth, with some aggregate fracture, and the average temperature of the resulting RAP is lower than desired, making it difficult to re-compact into a quality pavement. A solution to this problem was described earlier as multi-step HIR. The idea is to heat and remove the RAP in stages or steps by heating the surface, removing say ½ to 1-in of RAP, then heating again and repeating until the full depth is reached. By way of contrast, the Martec AR 2000 system using hot air, heats in one step, but a more powerful milling head is required to remove the RAP. With the hot air, additional heating is provided after the milling step has loosened the RAP, allowing the air to circulate within the stirring action of the on-grade mixing, resulting in additional heat transfer.

Much of the early work in HIR has been aimed at recycling 100% of the pavement into RAP that is immediately placed back on the roadway. The merit of this approach is to minimize the complexity of recycling, but the problems this approach makes it unworkable. The reasons for not attempting 100% include the possibility of burning or aging the asphalt binder excessively, and the inability to adjust the aggregate gradation that would otherwise improve the mixture. A key goal of HIR is to construct an asphalt pavement layer with properties at least as good, or better than, previously existed.

One method that HIR systems can increase the temperature of RAP and simultaneously change the gradation of the final mix, is to add virgin HMA (admix). Most of the systems now in use provide for this option. Typically, it means that a nearby HMA facility will need to produce a mix with special gradation and binder to be mixed with the RAP at the jobsite in order to meet the mix design requirements. Although it has been suggested, it may not be feasible nor a good idea to over-heat the HMA to provide additional temperature increase once the two materials are blended. However, most HIR systems, particularly those developed in Canada, have a maximum limitation of 25% virgin HMA that can be added. This limitation has been the result of some equipment designs, but primarily the desire by highway agencies to not increase the volume or thickness of the recycled pavement because of its potential impact on underpass height limitations as well as meeting curbs or shoulders without excessive increase in the crown or cross slope. There is no reason a higher percentage of virgin HMA could not be added which would provide for more flexibility in controlling temperature and mix quality, as well as geometrics.

A method that would permit the addition of more HMA admix to improve heat transfer without increasing volume is to first remove some of the old pavement using cold milling and disposing of it elsewhere, such as at a central hot mix plant where it can be recycled as part of the HMA. The volume of RAP thus removed would provide space for more virgin HMA to be added. In this manner, as shown in Figure 11, RAP/HMA ratios as high as 70/30 or 60/40 might be used without the necessity of increasing pavement thickness. A factor to consider, however, is the cost of additional hauling of materials that this approach would add to a project. It might seem that milling a portion of the RAP prior to recycling would be best done by milling a shallow depth over the full width of the pavement lane. However, it is easier and more accurate to cold mill deeper and narrower to remove a uniform amount of RAP. Preliminary testing (Wiley 2008) has shown that there is a net reduction in smoke resulting from the process of adding some heat through the addition of more HMA rather than heating it more on the grade.

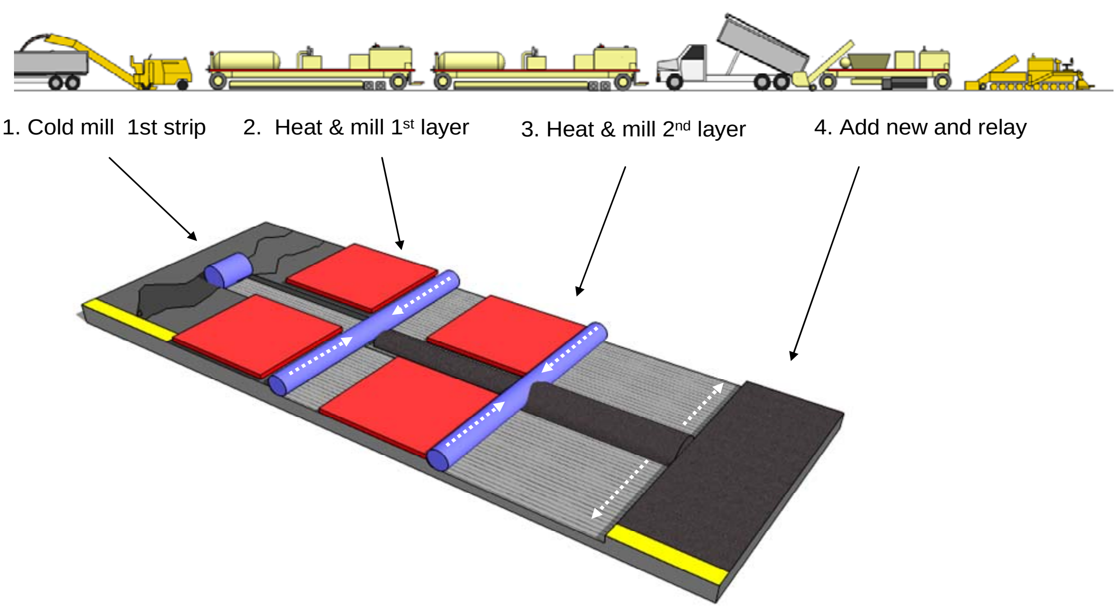

Figure 11 The concept of pre-milling and removing RAP from the pavement to make room for additional HMA Admix (pat. pend.) (P.C. Wiley)

The above approach of adding more virgin HMA may contradict the realities of RAP utilization, however. There is a current move to use more RAP in central plant mixed HMA by highway agencies because of the economic value of the RAP and resulting cost savings in re-using asphalt binder and aggregates. Most state highway agencies allow the use of RAP in HMA, but rarely more that 15 to 20%. Research is underway (NCHRP 2008) that will attempt to show how more RAP can be used, and the measure required for doing so, such as preserving the overall quality of the binder and mixture in general. The goal seems to be able to add as much as 50% RAP. Contrary to this approach is that of HIR, which is often recycled at 100% RAP, but with a desire to reduce the RAP content to improve other factors such as higher mix temperatures.

A further factor in the HIR equation is that far more RAP is produced by cold milling in urban areas than in rural areas. This imbalance, because of the extensive street network and need to maintain the recycled pavement flush with curbs, results in nearly as much RAP being produced as new HMA. As a result, it may be disposed of in ways that are less economical and a waste of resources such as asphalt binder and aggregate. In rural areas, there is less need to maintain curb lines, so any RAP produced might readily be put back into the pavement. However, the greater haul distance to take cold milled RAP back to the hot mix plant, blend it into the final mix with HMA, and haul it back to the jobsite makes the process more costly. The HIR option provides an opportunity to use more RAP, and without the excessive hauling costs.

A final comment on the HIR equipment relates to the very **large size** of each unit in the train such as pre-heaters and heater-mixers. The advantage is efficiency of operation, and the width of each pass can typically be varied from 10 to 13 feet to accommodate lane variance, etc. But these units are very heavy and cumbersome, making it more difficult to move from job to job without special hauling permits. Further, they are not very nimble when need arises to recycle in tight quarters such as turns, city streets, etc. This factor has made it less able to recycle in urban areas, along with the loud noise. Even though other in-place rehabilitations (CIR and FDR) may also be loud, they all seem to be a nuisance to the public. There is also the danger of damage to roadside vegetation and other features. It may be beneficial to the contractors as well as pavement agencies if the HIR units were smaller in size, and this may well become possible as future generations of HIR equipment are developed.

4. Design Considerations

Project selection and evaluation

Caltrans has included a detailed description and discussion of how a project is selected for preservation in their new edition of MTAG (Caltrans 2008). It is important that all the available data and resources are utilized to determine the most appropriate method for a given project. Figure 1 in this paper is a summary of the process and incorporates the existing pavement condition, including tests to help with the cause of distress analysis, the past history of this project as well as other projects that might have used the same materials in the vicinity, thus could experience the same problems.

A key part of this process shown in Figure1 is the sampling and evaluation of materials used in the asphalt pavement that needs preservation. A detailed evaluation of the HIR recycling option is beyond the scope of what can be presented here, but Chapter 3 (Caltrans 2008) does include more details. For HIR, the proper selection of materials is dependent on a thorough evaluation of the existing in-place materials. It is important to identify the characteristics of the existing pavement materials so that the correct types and amounts of additives can be determined (i.e., recycling agents and/or binders) and the need for additional materials such as virgin aggregate can be ascertained (FHWA 2001, Kendhal et al, 1997). The key elements in the decision process for assessing a pavement for possible HIR treatment include at least the following:

- Types of pavement distress. Thermal and fatigue cracking may be readily treated, but the presence of fatigue may warrant further structural evaluation such as FWD testing. Rutting due to mix design deficiencies, and age hardening due to poor quality asphalt both be treated by HIR, but the depth of distress and the presence of stripping will also have an influence on the decision.
- Thickness of existing HMA. Need to make sure there is sufficient depth to recycle.
- Uniformity of the pavement along the centerline. The HIR project may straddle two previous HMA contracts that have different mix designs, for example.
- Smoothness, skid resistance. HIR can smooth a rough ride (but not always), and the friction value can be increased with proper admix design
- Presence of chip seals, patches, and crack sealant. These materials may influence how well the HIR equipment can heat and process them into a uniform recycled mix.
- Excessive asphalt such as bleeding can be reduced with proper mix adjustments
- Asphalt binder and HMA mixture properties need to be tested in the laboratory as part of the mix design
- Environment. Weather and the time of year will influence the success of the project, as well as its location. For example, recent rains may have saturated the HMA, making it more difficult to heat and dry. An unexpected amount of moisture can slow production and decrease quality of the final pavement. Similarly, cold and windy weather will slow progress.

Just as important as the learning of the details noted above for evaluating a project for possible HIR, is the **time to say no**. For example, if the HMA is too thin, the moisture content is too high, the weather is too cold (late in the season), or the previous HMA has shown to be stripping, then is the time to perhaps change strategies and methodology

Mix Design

The purpose and philosophy of the mix design is to put as much asphalt binder as possible into the mix to provide waterproofing and durability, but not so much that there is loss in stability and stiffness required to carry the intended traffic. In theory, the concept of mix design for HIR projects is similar to that for new HMA, with the added steps of designing both the binder (by rejuvenation) and the mix by combining RAP and new materials such as virgin HMA so that the end result is essentially the same as HMA.

There are two main goals in doing mix design for HIR projects: (a) determine the properties of the aged asphalt binder in the RAP and add the optimum amount appropriate rejuvenator material to restore the old binder to the like-new desired condition appropriate for the climate and location, and (b) determine the properties of the RAP, and add aggregate, virgin HMA, and then test the material for comparison to the desired goals of expected performance, such as density, resilient modulus, water resistance, and other properties.

The detailed steps are described in the MTAG (Caltrans 2008), and the Asphalt Institute MS-2, for designing mix using RAP (The Asphalt Institute 2006) but the key steps are included as follows:

- Obtain representative samples of the old pavement, either from cores or sawed slab samples of pavement. Ideally, hot-milled samples would be best, but larger chunks or core samples can be heated in an oven and broken down by hand to represent the HIR process without the excessive aggregate breakage if cold milling were used to obtain samples. Note the presence of old seal coats, patching, etc., and their distribution along the pavement, and how these will affect the variability of the newly recycled pavement.
- Evaluate the material to determine mix properties such as binder content and aggregate gradation. This step includes the determination of cause of pavement failure, such as age-hardened binder, if possible.
- Determine the method of rejuvenation by testing the aged binder, selecting appropriate type and amount of additive materials for rejuvenation.
- Prepare and test mixture specimens in the laboratory for evaluation of the optimum proportioning of material.
- Establish a job mix formula (JMF).

The details of the mix design process are beyond the scope of this paper, but the key end result is the JMF, and it should include at least the following information:

- Asphalt binder content (%), penetration at 25ºC and viscosity at 60ºC of the asphalt binder contained in the RAP. Alternatively, the properties used to classify asphalt binder using the PG system may be used, for both the recovered and rejuvenated binders.
- Gradation of the aggregate in the asphalt pavement to be recycled (after extraction of binder).
- Gradation of aggregate and percent asphalt binder of the virgin HMA to be added to the mixture.
- Proposed asphalt binder grade, source, and properties (after rejuvenation).
- Source and properties of the aggregates proposed for use in virgin hot mix asphalt, separately as required.
- Source, type, amount, and properties of recycling agent.
- Aggregate gradation (including recycled pavement plus virgin hot mix asphalt) and asphalt content of the recycled asphalt concrete mixture (including recycled pavement, virgin hot mix asphalt, and recycling agent).
- Stability and volumetric analysis information of the recycled mixture.
- Penetration at 25ºC and viscosity at 60ºC and 135ºC of the binder in the combined recycled mixture (includes recycled pavement, virgin hot mix asphalt, and recycling agent), and other properties such as those used for PG grading of the binder.

As part of the mix design process, there is ample opportunity to explore alternative materials and concepts for the pavement to be restored by HIR. For example, the earlier traditional approach has been to make the HIR mixture the same as the previous design. But one must consider the cause of failure, if it was something other than normal wear due to traffic, and perhaps design a mix with improved properties. One example would be to make the recycled layer more open-graded to improve drainage and reduce noise. Another alternative would be to reduce the voids to make the mix less susceptible to water damage and aging. The presence of polymers, rubber, and other materials may make it difficult to design a traditional mix, but these materials may provide additional benefits to the recycled pavement. The usual approach with conventional HMA recycled in central hot mix plants is to “hide” relatively small amounts of RAP in the mix, minimizing the effect of RAP. However, with the HIR process, very high percentages of RAP are used, so the properties of the RAP have a large influence and may introduce some unintended consequences on the outcome of the design and performance.

Since the pavement will be exposed to high temperatures during HIR, possible sources of smoke, break down of polymers, and other unintended consequences must be anticipated when possible during the mix design process. The advent of new technology, equipment, and processes may provide good opportunity for change; for example the introduction of the warm mix asphalt concept into HIR. A further consideration is to make the recycled pavement with the possibility of recycling again in the future, such as with perpetual pavements, where the top 2-in might be milled and replaced repeatedly.

Coupled with the materials and design considerations, are the specifications that would be required to assure the construction of a quality HIR project as intended. Many states (Caltrans, 2006) and other highway agencies already have construction specifications, but because they have had limited experience, they may be inadequate, or aimed at the wrong issues.

One simple approach would be to specify that the recycled pavement should have the same properties as a new HMA, and let the contractor decide how to do it. This makes some sense since there is only limited experience, and the techniques are changing with time, and the more innovations that can be brought forward, the more benefit to the agency and the taxpayer. Based on experience of some agencies to date, and observations, a few comments may be helpful (Epps 2008); the following should be considered when writing the specifications:

Equipment and operations

The key steps in the operations of an HIR project are as follows. More details can be found elsewhere (MTAG, and ARRA):

- All loose material must be removed from pavement
- Heating and mixing equipment should be self contained and self propelled
- The combustion area must be enclosed
- No direct flame in contact with pavement
- Hot air is preferred, but infrared may be acceptable in some cases
- Heating does not char the asphalt surface
- Must be capable of heating to the desired temperature:
  (Min.190 to 230°F), and (Max. 300 to 315 °F) for adequate mixing and compactibility
- Must be capable of scarifying or loosening to the desired depth with minimum aggregate fracture
- Materials must be uniformly mixed and spread
- Rolling and compaction operation must be adequate to meet density requirements

Because all the operation is done in the field, there are considerations for when it is not appropriate to proceed with construction, and these may include:

Weather

- Ambient air temperature should be above 40°F (4°C)
- Pavement temperature should be above 50°F (10°C)
- Wind may be a factor in heat loss, so provision to stop work may be required
- Pavement surface should not be wet, nor should it be raining
- Weather otherwise prevents placement
- Depending on the location, elevation, etc., may want to limit HIR to only certain times of the year.

Payment

Payment for work completed should be on a square yard basis for a particular depth of recycling. Rejuvenating agents can be paid separately, as can admix in the form of virgin HMA. A smoothness requirement may be difficult to include, because the HIR operation largely follows the existing surface, but some general guidelines may be appropriate.

5. Summary and Recommendations

Summary

The concept of HIR has been shown to be viable through various studies and reviews (Terrel, et al, 1997b), and this paper is an update and evaluation of two types of HIR: infrared heating and hot air heating of the old pavement using single stage operations up to 40 mm (1.6 in) depths. However, there seems to be a consensus among contractors and the British Columbia Ministry of Transportation & Infrastructure that the multi-stage heating and milling process is just as important as the type of heating (Wiley 2008) for depths over 40 mm. HIR was pioneered at least 30 years ago, and more current technology began to be improved beginning more than 20 years ago, with incremental improvements made by various developers and equipment manufacturers. This development reached a plateau in the mid-1990s, and no significant improvements have been made since. The reason for the lag in interest in the technology is lack of economic incentive. In the 1970s, the oil shortage and rise in prices prompted highway agencies to look for alternatives such as recycling, but then interest and economic incentive waned when oil prices settled down. Now, with very high prices of fuel and asphalt, there is again considerable interest in recycling, and HIR is getting more attention.

This paper attempts to describe the differences, and assess the attributes of each. Very early HIR used direct flame and current HIR uses infrared or hot air, but only in a few select states and provinces. British Columbia, Ontario, Kansas, Colorado, and others, are currently using

HIR as part of their pavement rehabilitation strategy, while other agencies are not doing HIR at all.

Infrared heating, as in the Pyrotech system, has the advantage of using IR heaters that are readily available, and can provide high temperatures at the pavement surface. This means that the differential between the IR source and the pavement temperature is high and seemingly can heat at depth more readily. The disadvantage is that the asphalt binder may become overheated and even burned or charred. A further disadvantage is the tendency to create smoke from this overheating. Some of the smoking is caused by the presence of multi-colored areas such as patches, crack sealer, etc., because the IR is sensitive to color. Most HIR trains currently working in North America are using IR, and some (Pyrotech) have retrofitted the trains with vacuum systems to reduce smoking. The currently operating IR heaters use propane as fuel.

Hot air heating, as in the Martec system, supplies heat to the pavement (600°C) through a large manifold of tubes with holes for the hot air to impinge on the pavement surface, plus there is some low level IR heating from the hot manifold. The hot air system heats the pavement more evenly, since it is not sensitive to color. This lower temperature does not overheat the pavement surface, and smoking is reduced, and the hot air is vacuumed, and incinerated during re-heating and re-circulating, further reducing smoke. The Martec HIR also uses diesel fuel, considered to be a safety and convenience advantage as well as more fuel efficient. However, in California, there may be an issue with getting regulatory permission to use diesel fuel in some districts. There is one Martec HIR train working in British Columbia now (2008), as indicated earlier.

Some models of both HIR types of trains have used multi-stage recycling, meaning that the heating and milling take place in two or more steps. This process has proven to be important to reduce smoke and aggregate damage when recycling at depths greater than 40 mm.

Documented trial projects using HIR have shown that both infrared and hot air HIR can produce acceptable recycled pavements. However, there are many instances where the quality of pavement (due to insufficient heating of RAP, and resulting poor compaction), inadequate depth, and smoking would not be acceptable on a routine basis. A key factor is to select the appropriate type of projects to be recycled with HIR by proper evaluation through testing, and do not specify HIR if the pavement is not suitable. This process is the dual responsibility of the contractor and the specifying agency.

Recommendations

It would appear that both IR and hot air heating can do an adequate job of heating, but the tendency to create smoke at unacceptable levels tips the advantage to hot air. There have been adequate trials and projects to show that positive outcomes are possible by carefully controlling the equipment, selection of projects appropriate for HIR, and monitoring the weather such as ambient temperature, wind, and moisture, thus reducing the number of projects with marginal quality. The highway industry is ready for HIR, but there still needs to be some added innovation and improvement including:

- Develop specifications to encourage innovation in the next generation of HIR technology. Consider using the same end-result requirements as for HMA and allow for end-result options. These would include such factors as density, stiffness, and durability of the final asphalt mix, such as aging and water sensitivity.
- Require the option of adding more than the current limit (25%) of admix (virgin HMA) that will help improve quality and heat transfer, and reduce smoke emissions, when needed. This may need to be done through the pavement design process rather than equipment design, since most equipment would be able to physically utilize more admix.
- Focus on reducing smoke and other emissions that will be acceptable to the public and agency policy. Single stage hot air systems appear to have the advantage for recycling depths up to 40 mm. But heating beyond 40 mm in one stage is less viable and may result in milling relatively cooler RAP , causing aggregate breakage. Caltrans should initially require a strategy of milling 40 mm and putting back 50 mm. This option will add 20 % admix (virgin HMA)
- Improve heat transfer through better equipment, multi-stage milling and heating. Pre-heating the pavement before milling reduces aggregate breakage and improves overall quality.
- Ultimately strive to attain 50 mm depth of recycling, a target that is reasonable and can add structural improvement to the pavement as well as significantly extended life.
- Consider placing a limit on the size of future heater units in a HIR train to accommodate hauling on the highway, operation, safety, and make it useful in more situations, such as urban locations as well as rural highways.

Finally, Caltrans should consider implementing pilot projects using hot air technology to monitor the emissions and performance of the mix. Plans for this should begin immediately so construction can take place in 2009.

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