Performance and Cost of Selected Hot In-Place Recycling Projects

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The objective is to summarize the extent of use and resulting performance of hot in-place recycled (HIPR) asphalt pavements. Most types of surface distress in an asphalt pavement can be corrected by HIPR provided the pavement has adequate structural integrity. When all factors are considered, a savings of up to 50 percent can be achieved when a 25-mm (1-in.) HPR layer is compared with cold milling and placement of a new 25-mm overlay. Careful consideration must be given to preparing specifications that are relevant to the intended construction program. Specifications should clearly describe an acceptable finished HIPR product. In some cases, it may be necessary to describe certain elements of the equipment required to furnish the desired product. A telephone survey of all 50 state highway agencies was conducted to determine the extent of use of HIPR and type of processes being used. The survey revealed that fewer than 10 state agencies are routinely using HIPR. Most states have tried HIPR but only experimentally. Many states have no experience with the new remixing processes.

This paper summarizes the performance of hot in-place recycled (HIPR) asphalt pavements and is based on information collected as part of the work reported by Button et al. (*1*).

HIPR is defined as a process of correcting asphalt pavement surface distress by softening the existing surface with heat; mechanically removing the pavement surface; mixing with a recycling agent, possibly adding virgin asphalt and/or aggregate; and replacing it on the pavement without removing the recycled material from the original site. HIPR may be performed as either a single-pass (one-phase) operation that recombines the restored pavement with virgin material, or as a two-pass procedure in which the restored material is recompacted and the application of a new wearing surface follows a prescribed interim period that separates the process into two distinct phases.

The Asphalt Recycling and Reclaiming Association recognizes three basic HIPR processes (*2–4*):

1. Heater-scarification: heating, scarifying, rejuvenating, leveling, reprofiling, and compacting;
2. Repaving: heating, scarifying, rejuvenating, leveling, laying new hot mix, reprofiling, and compacting; and
3. Remixing: heating, scarifying, rejuvenating, mixing (and/or adding new hot mix), mixing, leveling, reprofiling, and compacting.

All of these methods are sometimes referred to as surface recycling. Heater-scarification typically removes up to 25 mm (1 in.) of the existing road surface, rejuvenates it, and reshapes it in the final operation. The repaving process includes recycling to an approximate 25 mm (1 in.) depth, adding a recycling modifier to improve asphalt viscosity, and simultaneously applying a thin overlay over the recycled layer. The remixing process incorporates and blends virgin material with recycled material in a pugmill and then lays the blended material as a wearing course. Sometimes scarification is replaced or assisted by rotary milling.

As a result of relatively recent developments in Europe, Japan, and the United States, HIPR is experiencing a metamorphosis, that is, the heater-scarification process and some older repaving processes (particularly the multiple-pass methods) are being replaced by the newer single-pass repaving or remixing processes. The majority of published information available on long-term performance of HIPR is on heater-scarification and multiple-pass repaving methods. This is because these types of HIPR have been in use for the longest period of time (*5*).

The objective of this paper is to summarize the extent of use and resulting performance of HIPR asphalt pavements.

SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION

A telephone survey was conducted in 1992 to determine the extent of HIPR use by state departments of transportation (DOTs) (*1*). Normally, the state materials engineer or state bituminous engineer was contacted. Most of these survey results are summarized in Table 1. These findings should be considered subjective because they represent the opinions and knowledge of HIPR use in the state from a single individual.

In general, HIPR has been used by state DOTs on a very limited basis. Of the 50 states surveyed, 18 have not used HIPR at all. Many of these states reported that they would like to try HIPR, but the opportunity has not presented itself. Reasons some states are not using HIPR are cited as follows:

- HIPR equipment and operators are not located in the area.
- Most surfaces are open graded and are not suitable candidates for HIPR.
- Pressure from the hot-mix industry to use all new material is so strong that HIPR has been suppressed.
- HIPR was considered once for a 50-mm (2-in.) thick pavement, but it would have required placing the material in two lifts. For pavements 50 mm (2 in.) thick or more, it is cheaper to do central plant recycling.
- HIPR could only be cost effective for use on Interstate highways, and the quality of HIPR was not believed to be adequate for Interstates.
- Limited knowledge about HIPR and have no data on the process to assess cost effectiveness.
- Not impressed with HIPR primarily because felt that the process burned the asphalt.

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TABLE 1 Results of U.S. Survey on Hot In-Place Recycling

State	Extent of HIPR Use			Methods Used			Milling Depth Range, mm	Written Specs Available	Class of Highways for HIPR			Surface Seal or Overlay Common Placed Over HIPR Pavement	Performance of HIPR Pavements				Comments
	None	Experimental	≤ 5jobs/yr	Heater Scar.	Repave	Remix			Major	Secondary	Low Volume		Excellent	Good	Fair	Poor	
Alabama		X			X	X	50		X		X		X (Remix)				
Alaska		X		X					X					X			Tried one job 1 ½ years ago. Equipment not readily available in the area.
Arizona		X		X			25		X	X		X				X	Rejuvenating agent softened subsequent overlay above causing bleeding.
Arkansas			X			X	25-32	X		X				X		X	Poor performing jobs were probably not good candidates for recycling.
California		X		X		X	19-38	X	X	X	X			X		X	Early heater-scarification project were failures and not considered cost-effective. Projects are scheduled using newer equipment.
Colorado			X	X	X		38-50	X	X	X	X			X			
Connecticut		X			X		38-50		X								Advantage of HIPR would be to use at night and reduce user cost.
Delaware	X																Most surfaces are open-graded and are not good candidates for HIPR.
Florida			X	X	X	X	38	X	X			X		X			
Georgia		X				X		Developing		X							Used remix process 20 years ago with bad experience. Have spec. to allow recycling on any job.
Hawaii	X																Equipment not available in the area. Most of the construction jobs in Hawaii are too small for HIPR to be cost-effective.
Idaho		X		X		X	50	X	X								Emission controls limit HIPR use.
Illinois		X			X		25-38				X	X		X	X	X	
Indiana	X																
Iowa		X		X			< 25	X			X	X				X	Problems with reflective cracking, early rutting, loss of friction.
Kansas			X	X			19	X	X	X	X	X		X			Problems with reflective cracking after 2-3 yrs.

Kentucky	X																Hot mix industry is so strong, recycling seems unlikely.
Louisiana		X		X	X	X	19-38	X	X	X		X (for Heater Scar.)		X		X	No more heater scarification planned. Believed to not be cost effective.
Maine	X																HIPR equipment not available in the area.
Massachusetts	X																Two remixer jobs are planned for secondary roads.
Maryland			X			X	38-50	X	X	X				X			
Michigan		X			X					X				X			Repaving process hardens asphalt. In the future will specify no direct flame.
Minnesota		X			X				X			X		X		X	Hot-mix industry very strong.
Mississippi		X			X	X	38	X	X			X		X			Remix project too young to categorize performance.
Missouri	X																
Montana		X			X		25-44	X	X	X	X	X (Interstate)			X		Cost was high due to mobilization.
Nebraska	X																
Nevada		X			X		32					X		X			Tried to do a remix job but emissions too high. Would like to try again would like to be able to recycle at least 2 inches.
New Hampshire		X			X				X			X		X			HIPR hasn't been used since 1972.
New Jersey	X																
New Mexico	X																Considered HIPR once but would have required placing in two lifts. For 2-inch thick pavements, cheaper to do central plant.
New York			X			X	25-38	X	X					X			
N. Carolina	X																Would like to know more about cost-effectiveness of HIPR.
N. Dakota	X																No contractors in the area.

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TABLE 1 (*continued*)

State	Extent of HIPR Use			Methods Used			Milling Depth Range, mm	Written Specs Available	Class of Highways for HIPR			Surface Seal or Overlay Common Placed Over HIPR Pavement	Performance of HIPR Pavements				Comments
	None	Experimental	≤ 5jobs/yr	Heater Scar.	Repave	Remix			Major	Secondary	Low Volume		Excellent	Good	Fair	Poor	
Ohio			X	X		X	38	X	X (Remix)	X (Heater Scar.)		X (with Heat Scar.)		X (Heater Scar.)			Heater scarification is good if pavement structurally sound. Remixing will improve both structural and AC properties.
Oklahoma		X			X		25	X	X			X					
Oregon	X							X									Two repaving projects scheduled.
Pennsylvania		X				X			X	X					X		Performance may have been better if design were of a finer gradation and if a rejuvenator had been used.
Rhode Island	X																Would like to try HIPR but haven't had the opportunity.
S. Carolina		X				X	25		X				X				Only tried one HIPR job.
S. Dakota	X																Would like to try HIPR soon.
Tennessee		X			X	X			X	X		X		X			Roads recycled using Repave process were very rough.
Texas			X	X	X	X	25-38	X	X	X				X			
Utah			X		X		25	X	X	X		X		X			
Vermont		X				X			X			X				X	One remixing job was done and with a standard overlay control. HIPR will have to provide 16% longer maintenance free life to be as cost effective as standard overlay.
Virginia			X	X			38	X			X	X			X		
Washington		X		X						X				X			Pollution problems make HIPR prohibitive.
W. Virginia	X																
Wisconsin	X																
Wyoming	X																HIPR equipment not in the area.

25 mm = 1 inch

Twenty-two of the states interviewed reported using HIPR but only on an experimental basis. Ten additional states use HIPR on a somewhat regular basis but generally construct fewer than five jobs per year. None of the states commonly use HIPR on more than five jobs annually. Collectively, these 32 states have used at least one of the three HIPR processes: heater-scarification, repaving, and remixing. Thirteen states reported having used heater-scarification; several others have probably used the process but did not consider it recycling. Fifteen states reported having used the repaving process, and 16 states reported they have used remixing.

Most states did not specify a preference in HIPR methods, but of the nine states that did, all indicated a preference for the remixing process. This is primarily because of the added option of incorporating additional aggregate to correct deficiencies in the recycled mixture. One state reported that both heater-scarification and remixing have their place depending on the pavement condition: heater-scarification can be used only if the pavement is structurally sound, whereas remixing can improve both structural and binder properties.

HIPR is used primarily on major and secondary highways. Some states commonly place a surface seal or overlay on the HIPR pavement. This, however, can depend on the specific circumstance. For example, Montana places an overlay on the HIPR pavement if it is on an Interstate highway. Both Louisiana and Ohio construct an overlay if heater-scarification was the HIPR process used.

HIPR CASE HISTORIES

Based on a review of published case studies (Table 2), HIPR often presents an attractive alternative to conventional pavement leveling and resurfacing processes (*1*). When properly executed, HIPR can create a pavement no different in appearance or ride than a pavement that has been resurfaced by conventional methods. The process provides a recycled pavement that has improved mixture properties and cross slope. It yields excellent bonding at the interface between the old pavement and the new overlay and at the construction joint between the HIPR pavement and the adjacent lane by heating the adjacent pavement. It has been used successfully on city streets and highway and airport pavements that possessed adequate structural integrity. The single-pass operation is convenient to the motoring public and the agencies involved in the coordination of road surfacing. Time of construction, as well as the requirement for haul trucks and their contribution to congestion, is significantly reduced when compared with conventional paving operations. HIPR allows pavement maintenance funds to go further while contributing to the conservation of raw materials and energy and reducing landfill requirements.

Specific lessons learned from selected case histories are itemized as follows:

- A thorough and comprehensive preliminary investigation and testing program should be given a very high priority (*6*).
- Careful consideration must be given to preparing specifications that are relevant to the intended construction program and the specifications must clearly describe the type of equipment that will provide an acceptable finished product (*6*).
- One agency felt that for all in-place recycling projects, greater than normal resources are required for both inspection and materials testing (*7*). This is partly because the process is relatively new and also because it offers more opportunities for variability than conventional paving processes (*8*). HIPR equipment is inherently complex and is built so that many of the operations cannot be readily observed. Inspectors should be trained to analyze the consequences of various mechanical failures and operational malfunctions (*9*). Items specifically associated with HIPR might include: consistency of pavement being recycled (ensure proper mixture design), preheating operations (avoid charring of asphalt), recycling depth, and sampling and testing to ensure proper rejuvenation and no overheating.
- Heating and mixing of existing pavement during HIPR significantly increases the viscosity of the asphalt cement. Guidelines that account for asphalt hardening directly attributable to the HIPR process should be developed (*6*).
- Excess asphalt mastics used for joint and crack filling operations created flare-ups under the preheater. A conventional garden fertilizer spreader was used to distribute a 1- to 2-mm thick strip of hydrated lime along the heavily filled cracks, which reduced the flare-ups; sand was also considered (*6*). In some cases, the crack sealant material was removed before recycling (*7*).
- Isolated areas of an existing pavement with excessive asphalt content can be detected by bleeding following the preheaters. In these areas, the recycling agent application rate can be manually reduced, if deemed necessary, to avoid subsequent flushing under traffic.
- In cool northern climates or in winter, night work has sometimes been impractical because of low ambient and pavement temperatures (*7*).
- In some cases, it has been possible to achieve adequate compaction at mat temperatures more than 20°C (36°F) below that normally desired. One explanation of this is that the viscosity of the "effective" binder was actually close to the desired value. That is, in the brief interval of time between mixing and compaction, the recycling agent had an opportunity to diffuse only into the effective asphalt cement (the film surrounding the aggregate or clump of aggregates) but not into the pores of the aggregate where the rest of the aged asphalt resides (*7*).
- There can be considerable gaseous emissions (blue smoke) at times from heating and mixing equipment. Emissions can be especially high on pavements with excessive joint or crack sealer at the surface. Newer equipment has significantly reduced or eliminated this problem (*5*). Complete assessments of impact on the environment should include the fact that HIPR eliminates disposal of waste material.
- Attempts to push the heat deeper into the pavement result in excessive heat at the surface if either a greater exposure time or a higher source temperature is employed (*10*). Excessive heat and exposure time is a concern when considering durability of the recycled mixture (*11*).
- Conventional gradation specifications, design properties, and compaction requirements should be used when specifying HIPR or permitting it as an alternative.
- Strength equivalencies used in the pavement design process should be the same as those normally assigned to a similar standard mixture produced by conventional processes (*12*).
- Recovery of asphalt cement from recycled mixture should be made at regular intervals during the production process. Viscosity should be in a range comparable with that obtained from conventional asphalts (*12*).
- The maximum scarification depth for most successful HIPR operations is 50 mm (2 in.); however, 75-mm (3-in.) depths have been achieved using tandem scarifiers and/or rotary milling.

TABLE 2 Summary of Selected Case Histories of Hot In-Place Recycled Pavements

Agency/ Date Recycled	Cost Information	Description of Job	Condition of Old Pavement	HIPR Equipment Used	Milling Depth/ Overlay Depth	Rejuvenating Agent / Mix Temperature	Unique Features	Performance/ Remarks
Heater Scarification Process								
City of Richmond, Virginia 1988 (5)	Unknown	Various city streets	Fatigue cracking with some rutting	Natural, heater-scarify and 25 mm overlay later	25 mm/0 mm	Reclamite at 0.45 l/m^2 / Unknown	Steel wheels at rear of heating units. No mix testing prior to HIPR.	Some raveling of recycled layer prior to overlaying.
City of Grand Prairie, TX 1988 (5)	Unknown	Two-lane residential street with curb and gutter	Few transverse and longitudinal cracks	Dustrol, heater-scarify and overlay later	25 mm/0 mm	Reclamite at 0.45 l/m^2 / Unknown	Steel wheel at rear of heating units. Manually controlled screed.	Not available.
Louisiana DOT 1977 (35)	Unknown	14.2 km of U.S. 61	Rutting up to 38 mm deep	Benedetti heater-scarify and overlay later	19 mm/0 mm	Reclamite at 0.45 l/m^2 / 177°C	Scarification depth insufficient due to prolonged rainfall.	Extensive raveling prior to overlaying. Finished surface had open appearance. Did not eliminate all rutting. Skid numbers of recycled surface unacceptable.
Repaving Process								
FAA, Carrabelle, Florida 1990 (36)	$4.28/$m^2$	Thompson Field Airport. 30 m by 1212 m runway	Unknown	Repaver	25 mm/25 mm	Unknown / Unknown	Considered most environmentally acceptable option. Required 6 days.	Officials pleased that job met specs and appeared cost effective and had short down time.

Florida DOT 1979 (19)	\$2.99/m^2. A savings of 25% estimated (over milling + 25 mm overlay)	US 41, Ft. Myers, Fla. 3.9 km, 6-lane. ADT-39,000	Rutting, cracking, low friction. Pavement structure was OK.	Cutler Repaver	25 mm/19 mm	EA-SS-1, 0.27 l/m^2 79°C to 121°C	An FHWA demonstration project. Saved substantial energy.	PSI[2] increased from 3.53 to 3.89. After 14 yrs pavement has 12 mm ruts, hairline cracking, and fair ride quality. Overall performance good.
Louisiana DOT 1980 (26)	Unknown	Metairie Rd from US61 to IH-10. 5.8 km curb and gutter section	Cracking, rutting	Cutler Repaver	25 mm/20 mm	CSS-1, 0.45 l/m^2 Unknown	Numerous locations with open texture. No transverse distribution of scarified material.	Eliminated cracks, and restored cross slope, and minor improvement of longitudinal undulations. Began raveling in 6 mo. Generally, satisfactory after 5 yrs.
Louisiana DOT 1986 (20)	\$4.90/m^2 as compared to \$7.40/m^2 for conventional	11.4 km of US 71	Overlay on PCCP[3] had reflection cracks with severe spalling which gave poor ride quality.	Cutler Repaver	25 mm/38 mm	ARA-1 0.63 l/m^2 Mat 66°C to 130°C with 101°C avg. behind paver	Production 1.3-4.2 km/day. Most samples disintegrated during coring. New mix lost 11-22°C between haul truck and final screed.	Difficult to achieve density. Low mat temp. Recycled section performing about equivalent to control section.
City of Phoenix 1990 (24)	\$3.59/m^2	City collector street. 8,361 m^2	Severe alligator cracking with longitudinal cracking distortions, bleeding and raveling	Cutler Repaver	19 mm/25 mm	Yes. Type and quantity Unknown Unknown	Heated, stripped, and windrowed existing chip seal then heated remaining surface course.	Early performance good. Low pollution favorable to city officials.

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TABLE 2 *(continued)*

Agency/ Date Recycled	Cost Information	Description of Job	Condition of Old Pavement	HIPR Equipment Used	Milling Depth/ Overlay Depth	Rejuvenating Agent / Mix Temperature	Unique Features	Performance/ Remarks
Lee County, Iowa 1990 (22)	$3.41/m^2$	Rural roads X-38 and X-48	Oxidized surface, cracking, 13 mm ruts	Cutler Repaver	19 mm/25 mm	Elf ETR-1 at 0.36 l/m^2 / 105°C	Rejuvenator application rate geared to forward speed of machine.	Early performance good. Officials pleased with relatively little traffic disruption.
FAA Texarkana, Texas 1986 (17)	50 percent savings reported	Airport- 2011 m and 25 yr old	Aged, brittle mix. Low friction.	Cutler Repaver	25 mm/25 mm	Type unknown 0.54 l/m^2 / 110°C	Mix disintegrated when cold milling was attempted; could not control depth.	After 6 yrs a few surface cracks have appeared in isolated places. Otherwise, performance is excellent.
Connecticut DOT 1981 (9, 26)	$4.33/m^2$. 16% more than control	Rt. 15 at Westport, Connecticut 4.7 km, 4-lane divided	Rutting. Otherwise fairly good condition.	Cutler Repaver	25 mm/25 mm	AE-300R, 0.36 l/m^2 / 121°C ± 17°C by spec.	AE-300R was unsuitable for this job; too low in maltenes. Average scarified depth was < 13 mm.	Some reflection cracking. HIPR same as control. Recycling cost about 16% more than conventional.
Remixing Process								
Transport Canada[1] 1988 (6)	Unknown	Prince George Airport, British Columbia	Extensive longitudinal, transverse, and random cracking with raveling. Annual crack sealing no longer cost effective.	Taisei Rotec Remixer	50 mm/50 mm -- No new aggregate added to RAP.	Cyclogen-L at 0.36 l/m^2 Varied based on observed flushing during heating / 110°C-150°C was specified. Maintained at low end.	Thin layer (1-2 mm) of hydrated lime was applied to excess mastic at previously filled cracks to prevent flare-ups during the preheating process.	Extraction tests verified excellent control of rejuvenator application rate. Asphaltenes decreased by 24%; polar compounds increased 143%, which indicates improved durability.

Defence Construction Canada[1] 1989 (7)	$\$3.58/m^2$ for the 40 mm/19 mm -- $\$4.17/m^2$ for conv. 50 mm overlay	Airfield pavements at Canadian Forces Base, Edmonton, Alberta, 330,000 m^2	Severe raveling and thermal cracking. Badly weathered, oxidized appearance	Artec Remixer -- Only a small area was remixed	40 mm/50 mm and overlaid at a later date; or 40 mm/19 mm repave	RJO #3 at 0.4 l/m^2 120°C behind paver was targeted value	Specifications had stringent requriements for rideability and surface permeability. Removed striping and crack filler before recycling.	Equipment was capable of heater-scarification, repaving, and remixing. Early performance of pavement has been good. Author states that pavement flushing is a concern, and that more inspection and testing will be required for all HIPR.
Texas DOT 1991 (31)	$\$2.15/m^2$ for recycling portion only	IH-10 and SH-87 near Beaumont	Severe rutting, age-hardened mix. Raising elevation by overlaying was impractical	Wirtgen Remixer	25 mm to 31 mm	ARA-1 About 116°C	High traffic limited production to 1400 m/day.	No drop off during construction enhances safety. Early performance satisfactory.
Tennessee DOT 1990	Unknown	Northern-most 9.7 km of IH-75 in Tennessee	Severe rutting and other forms of distress.	Wirtgen Remixer	75 mm + 24 kg/m^2 of new mix	AES-300RP (polymer) at 0.63 l/m^2 107°C	Milling to 75 mm depth slowed production to 1.1 m/min. Added extremely coarse admixture to improve stability.	Officials pleased with density, stability, asphalt content, and gradation. Overall early performance very good.
Alabama DOT 1989 (16)	Unknown	6.44 km segment of US 78 near Fruithurst	Cracking and rutting. Unsightly.	Wirtgen Remixer	38 mm + 14 kg/m^2 of new mix	Unknown Near 150°C	First remixing project in the southeast.	Minimal traffic disruption was important. Early performance OK.

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TABLE 2 *(continued)*

Agency/ Date Recycled	Cost Information	Description of Job	Condition of Old Pavement	HIPR Equipment Used	Milling Depth/ Overlay Depth	Rejuvenating Agent / Mix Temperature	Unique Features	Performance/ Remarks
Mississippi SHD 1990 (15)	Unknown. 40% savings reported	55 lane-km of IH-59 in Lauderdale County	Highly polished with some rutting.	Wirtgen Remixer	38 mm + 15 kg/m^2 of new mix	Yes, unknown / 110°C	Pavement was 18 yrs old and was structurally sound.	Early performance OK DOT pleased with project.
Texas DOT 1990 (37)	Unknown	IH-35 in La Salle County near Cotulla	Surface was severely age-hardened with cracking and rutting.	Wirtgen Remixer	50 mm + 8 kg/m^2 of new mix	None used. Asphalt was in new mix. / Unknown	Surface was cold-milled then top 50 mm of base was recycled. Used 2 preheaters.	Officials believe process is promising. Early performance OK.
Canadian Dept. of National Defense[1] 1989 (38)	Acceptable economic alternative	Lancaster Park Airfield near Edmonton 4250 m	Unknown	Artec Repaver and Remixer	38 mm + 19 - 50 mm overlay; 38 mm + 41 kg/m^2 new mix	Shell RJO-3 at 0.19 l/m^2 / Unknown	Agency required close adherence to specifications.	Specs on density, temperature, penetration, scar, depth and smoothness of surface were met. An acceptable economic alternative.
British Columbia Ministry of Highways[1] 1989 (38)	$1.70/m^2 for recycling only	Trans-Canada Highway (Rt 1) near Vancouver, 126 lane-km	Rutting, surface cracking and other age-related distress	Artec and Taisei Remixers	38 mm to 63 mm (no new material added)	Unknown / 105°C minimum	Used a 2-stage milling/heating process.	All specs were met. Ministry was satisfied with final results. Appears to be an acceptable economic alternative. Reduced traffic disruption.
Texas DOT 1989 (39)	$2.57/m^2 including 30 kg/m^2 of new mix	IH-20 from Louisiana, border to FM450, 51 km, ADT-18,000 20% Trucks	Poor ride quality and some raveling. An other portion was overasphalted	Wirtgen Remixer	38 mm + 30 kg/m^2 new mix	ARA-1 at 0 to 0.71 l/m^2 / 110°C	Part of job designed to receive no rejuvenator, as it was already overasphalted.	Officials pleased with early performance. Pleased with safety aspects of process. Good ride quality.

Texas DOT 1987 (28)	$3.05/m² a savings of 34% over conventional	US 259 in Lone Star. Major arterial carrying heavy trucks	Oxidized, block cracking and 25 mm ruts at intersections	Cutler Remixer	38 mm + 17 kg/m² new mix	AC-5 used with new mix 93°C behind screed	Remixer had no pugmill. Curb and gutter sections.	Early performance OK. Pleased with economics.
Oregon DOT 1987 (29)	17% savings estimated	82nd Ave from N.E. Wasco to S.E. Division a 5-lane major arterial	Rutting, cracking, very poor drainage	Taisei Remixer	Up to 50 mm + various new mix	Non-emulsified product Unknown	Train averaged > 6 m/min. Various quan. new mix added to correct drainage.	Officials very happy with project outcome. Ride quality and early performance good.
Texas DOT 1986 (30)	Unknown	US 380 from Decatur to Bridgeport. 18,400m². Very heavy truck traffic.	Rutting, cracking, surface irregularities	Wirtgen Remixer	50 mm + 22 kg/m² new mix	None Unknown	Specially designed admix had only 3% asphalt.	HIPR equipment apparently caused 2 longitudinal cracks to appear at 3 yrs. Ruts near 1/2" at 7 yrs.
South Carolina DOT 1983 (40)	Unknown	S.C. 291 from U.S. 29 to N. St. in Greenville. 1.2 km, 6-lane ADT-37,300	Unknown	Wirtgen Remixer	41 kg/m² surface mixed with 18 kg/m² virgin mat	Exxon AC-2.5 used in virgin mix Mat behind screed 110°C	On occasion aged asphalt was heated to the fire point. Recovered asphalt viscosity was 41,000 poise.	Stability, density and workability compare well with virgin mix. Durability of mix is a concern.

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TABLE 2 *(continued)*

Agency/ Date Recycled	Cost Information	Description of Job	Condition of Old Pavement	HIPR Equipment Used	Milling Depth/ Overlay Depth	Rejuvenating Agent / Mix Temperature	Unique Features	Performance/ Remarks
Texas DOT 1981 (30)	$1.59/m^2$ for recycling a depth of 25 mm plus cost of new mix added	US 59 near Lufkin, 20,000 ADT	Severe rutting	Wirtgen Remixer	50-38 mm + 20% new mix	ARA-1 at 0.1 0.45 l/m^2 / 107°C	Existing mix was asphalt sensitive and overasphalted, a lean mix was used as admix.	Severe rutting reoccurred. HIPR again by same process in 1984. Rutted again. Mix was removed and replaced in 1988.
Louisiana DOT 1990 (13)	$4.59/m^2$ including recycling, rejuv. agent and admixture	US 90 from La 99 to Jennings	Poor ride quality due to spalling of cracks reflected from underlying PCCP[3]	Wirtgen Remixer	38 mm + 30 kg/m^2 new mix	ARA-1 at 0.9 l/m^2. Elf AES-300RP used in a short section / 107°C - 150°C	Averaged 1.4 lane-km per day. Reduced asphalt content of admixture to 4%.	Initial economic benefit realized. Early performance OK.

[1] Cost for jobs in Canada given in Canadian dollars.

[2] PSI - Present serviceability index.

[3] PCCP - Portland cement concrete pavement.

• The mean viscosity of the recovered binder from recycled mixtures can be closely controlled. However, considerable variation in viscosity throughout the job may result. Sometimes it is difficult to add enough rejuvenator without overasphalting the mixture (*13,14*).

• The contractor should furnish a representative responsible for observing and adjusting the infrared heaters as they pass over the existing pavement to avoid overheating and thus minimize excessive hardening of the asphalt cement (*14*).

• Typical average construction rates may range from 610 to 2,800 lane meters/day (2000–9200 lane ft), depending on depth of scarification, pavement materials and temperature, recycling equipment, and traffic.

• Direct flame contact with the existing pavement surface should be avoided because this has caused excessive hardening and even charring of the asphalt. Specifications should require radiant preheating.

• HIPR is acceptable on roads with one seal coat; however, two or three seal coats at the surface may cause the material to smoke and even catch fire. The seal coats act as insulation that prevents heat from penetrating the pavement below (*15*).

• The ideal candidate for HIPR is a pavement that is not excessively oxidized (*16*), that is, the existing asphalt cement must be capable of being rejuvenated to its original, as-placed consistency.

• None of the HIPR methods currently in use are designed to provide for corrections in grade. They can smooth out some surface irregularities such as rutting or corrugations (*5*) but they cannot remove large undulations caused by volume changes in the base or subgrade.

• Heater-scarification alone can provide an acceptable intermediate or leveling course but is not acceptable as a surface course. An overlay for heater-scarified pavements is normally recommended (*5*).

• Where cold milling has destroyed a hard, brittle, cracked asphalt pavement down to the unstabilized base, HIPR was used successfully to recycle the top 25 mm (1 in.) and add an additional 25 mm of new surface (*17*).

RELATIVE PERFORMANCE OF HIPR PAVEMENTS

Correction of Pavement Distress

Heater-scarification, which has been in use for many years, has demonstrated reduced reflective cracking in a subsequent overlay. The older machines often had difficulty leveling severely rutted or rough surfaces. Ride quality specifications often had to be waived.

Only short-term performance data have been published for the modern HIPR techniques. Many of the modern HIPR processes are capable of virtually eliminating high-frequency surface irregularities caused by corrugations, shoving, and rutting in the surface mixture; however, low-frequency undulations in a pavement surface normally caused by movement in the substrate are not removed by the process. As with conventional virgin or recycled mixtures, if the source of the problem (aggregate grading or quality, binder quantity or quality, moisture susceptibility, or surface texture) is not eliminated in the HIPR process, the problem will again manifest itself in the recycled mixture.

For well-designed and properly executed HIPR pavements, performance regarding cracking, rutting, raveling, stripping, and skid resistance should be approximately equivalent to that of a conventionally constructed pavement. With existing HIPR operations, there is typically more variability within a finished pavement and between paving projects than with conventional paving operations.

Serviceability

In the early years, performance of heater-scarified pavements varied considerably because specifications were not effectively prepared. Many projects were constructed without proper design and quality control was lacking. Yet many lane miles of excellent work were constructed and have performed well beyond the early expectations of a stop-gap measure designed to gain 3 to 5 years of life. There are numerous projects that have served for more than 10 years (almost equivalent to the normal life expectancy of a 50-mm overlay) (*2*).

Service lives of 8 to 12 years for pavements produced by the repaving process have been reported. Shoenberger and Voller (*5*) concluded that the repaving procedure should provide a surface course equal to that produced by conventional overlays. They also concluded that the process will probably be cost effective only in limited circumstances such as locations where it is used in conjunction with other procedures. Placement of an overlay by a conventional paver may be more economical than passing a virgin mixture through a recycling train for placement over the recycled asphalt concrete.

Shoenberger and Voller (*5*) further concluded that the advantage purported by equipment manufacturers, that of providing a greater bond between the surface course and the underlying pavement, is not considered a significant benefit for most paving applications. However, work by Ameri-Gaznon and Little (*18*) demonstrates that the degree of bond has a substantial influence on rutting potential in surface layers, particularly under high tire pressures where braking and cornering action is common. Their work estimates that the ratio of induced shear stress within the pavement surface to shear strength of the surface layer under the stress state actually induced may drop drastically as bonding is reduced (even slightly, e.g., 10 percent).

On one occasion, the initial pavement serviceability index for a surface produced by the repaving process was reported to be about 0.5 less than that of a conventionally resurfaced pavement (*19*). Others have reported good to excellent serviceability (*20*).

Because the remixing process is only about 10 years old, serviceability of remixed pavements has not been established. Based on early performance, it is anticipated that service life of remixed pavements will be about the same as conventional pavements (*21*).

Structural Value

Most of those who have reported a structural value or layer coefficient for HIPR mixtures have given them the same value as conventional hot-mix asphalt concrete (*22*).

During the phone survey of the 50 state DOTs, only 17 states said they had considered a structural value for HIPR pavements. Fourteen of these stated they considered the structural value of a HIPR pavement layer about the same as virgin hot-mix asphalt. Three indicated they assigned a structural value of slightly less than virgin hot-mix asphalt.

Comparative Cost

Because of wide differences in processes, equipment, and reasons for choosing a particular rehabilitation process, direct comparisons between different HIPR processes or between HIPR and conventional methods are difficult and are project-dependent. Actual costs and cost savings realized will, of course, depend on many local factors. Total cost will vary depending on rejuvenator requirements, additives and admixtures used, local material and fuel costs, and location.

In 1990, it was reported that the cost of heater-scarification to a depth of 25 mm (1 in.) and incorporation of a recycling agent was approximately \$1.20/m^2 (\$1.00/yd^2) (*5*). An additional 25-mm (1-in.) overlay cost approximately \$1.97/m^2 (\$1.65/yd^2). Therefore, to recycle and overlay a pavement in this manner using the two-pass method would have cost approximately \$3.17/m^2 (\$2.65/yd^2).

Based on published figures (*17,20,23–26*), the cost of recycling the top 25 mm (1 in.) of a pavement surface and simultaneously placing an additional 25-mm (1-in.) overlay using the repaving process varies around \$3.50/m^2 (\$2.93/yd^2). When compared with cold milling and overlaying using conventional procedures, cost savings up to 25 percent are reported.

When the remixing process is compared with cold milling and applying a new overlay, cost savings of 5 to 50 percent are reported (*13,27–33*). A reasonable estimate for remixing when a 25-mm (1-in.) cut is made and 10 to 20 percent virgin material is added is approximately \$2.15/m^2 (\$1.80/yd^2).

Cost alone does not tell the whole story because HIPR offers options not available from conventional paving techniques, such as rejuvenating a pavement or correcting a mixture deficiency in an existing pavement, as well as conservation of materials and energy. HIPR can be specified to address specific problems or may be included as an alternative to conventional bid items (such as cold milling plus plant recycling). Because of the limited number of contractors presently in the HIPR business, such alternate bidding may be beneficial to obtain competitive bids. A conventional overlay may require covering shoulders to maintain profile, whereas HIPR would not raise the travel lane enough to require adjustments in shoulder height.

Energy Savings

In 1981 Servas (*34*) concluded that although energy savings obtainable through recycling have been overemphasized, quantifiable energy conservation benefits should lead to actual cost savings to the producer or contractor, which, in turn, will lead to lower prices for the consumer.

On a 101,000 m^2 (121,000 yd^2) repaving job in Florida (*19*), every effort was made to account for all energy expended. The amount of energy that would have been consumed on an equivalent job using conventional construction methods was estimated. It was found that the conventional method would have used 2.6 trillion J (2.5 billion Btu) more energy than the HIPR technique. This is equivalent to an energy savings of 32 percent!

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on a review of published information and a survey of state DOTs, the following conclusions regarding HIPR are proffered:

- When recycling a pavement to address a performance problem, the source of the problem must be identified and corrected or the problem is likely to manifest itself again after rehabilitation.
- Single-pass HIPR processes can be used to minimize traffic disruptions. Time required for lane blockages is less than for conventional pavement rehabilitation methods. Safety is enhanced because motorists do not have to contend with a pavement-edge dropoff for long periods.
- HIPR is a viable and economic rehabilitation alternative for asphalt pavements, particularly those with a thickness of at least 75 mm (3 in.) of hot-mix asphalt. The candidate pavement must be structurally sound because HIPR is limited to surface rehabilitation.
- The maximum recycling depth for most successful HIPR operations is 50 mm (2 in.); however, in Canada, where soft asphalts are normally used, two machines in tandem have achieved depths up to 75 mm (3 in.) (*27*). Machines with rotary milling heads can typically cut deeper than those with stationary scarifier teeth.
- Sometimes it is difficult to add enough rejuvenator without overasphalting the mixture.
- When all factors are considered, a savings of 10 to 50 percent can be achieved when a 25-mm (1-in.) HIPR layer is compared with a new 25-mm (1-in.) overlay. Benefit-cost data for HIPR pavements are scarce.

Recommendations

Based on the foregoing study of HIPR, the following recommendations appear warranted:

- General HIPR specifications should allow for all three options, that is, heater-scarification, repaving, and remixing. This gives more versatility to the individual planning engineer and a higher probability to cost effectively solve a particular problem. Whenever feasible, HIPR should be allowed as an alternative rehabilitation method.
- Specify equipment that gears application rate of recycling agent and virgin bituminous mixture (if any) to the forward movement of the applicator to maximize probability of uniform percentages in the recycled mixture.
- The same quality control tests used for hot-mix asphalt plant production should be performed for HIPR production. This includes quality control tests on aggregate gradation, asphalt cement content, and compacted density (air void content) of recycled materials. Quality control tests should also include recovering of binder from the recycled mixture and measuring absolute viscosity and penetration.

Research Needs Statements

This study of the state of the art of HIPR has revealed that the process is worthy of further investigation in certain areas.

- An overall physical characterization of HIPR mix as compared with conventional hot mix is needed. The study should address comparative resistance to rutting and cracking, as well as durability, moisture susceptibility of the mixtures, and importance of the bond at the interface between the old and new pavement layers.

• Life-cycle costs (first costs, life cycles, required rehabilitation periods, and maintenance alternatives) for HIPR should be better defined and compared with alternative maintenance and rehabilitation techniques.

• When recycling agents are used for laboratory mixture design, neither the importance of nor procedures for proper curing of hot recycled asphalt mixtures are known. What time period should be required between compaction and testing in the laboratory? How long do properties of mixtures change after final compaction? Are the changes significant? What laboratory curing procedure best simulates field conditions?

• Heating and mixing of the existing pavement during HIPR significantly increases the viscosity of the asphalt cement. Further studies of field data compared with laboratory prediction and accurate mixture temperatures and temperature profiles within the preheated layer should be conducted to develop guidelines to deal with asphalt hardening directly attributable to the HIPR process.

• Comprehensive guidelines for the overall HIPR process need to be developed to aid maintenance engineers and design engineers in their decision making process. The following should be addressed: optimum time during a pavement's service life to perform HIPR, preparation of specifications, types of pavements that are and are not viable candidates for HIPR, selection of type and quantity of recycling agent, mixture design and structural design specifically for HIPR, selection of optimum HIPR method, quality control, and quality assurance.

• Because the use of asphalt rubber in pavements has been mandated by the federal government, research should determine the effects of HIPR on asphalt rubber pavements.

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REFERENCES

1. Button, J. W., C. K. Estakhri, and D. N. Little. *NCHRP Synthesis of Highway Practice 193: Hot In-Place Recycling of Asphalt Concrete.* TRB, National Research Council, Washington, D.C., 1994.
2. Burgin, E. W. Asphalt Pavement Recycling and Rejuvenation. *Proc., 32nd Annual Conference of Canadian Technical Asphalt Association,* Vol. 32, Nov. 1987, pp. 2–13.
3. *Hot In-Place Recycling—First in the Line of Pavement Maintenance.* Hot In-Place Recycling Technical Committee, Asphalt Recycling and Reclaiming Association. Annapolis, Md., 1992.
4. Emery, J. J., J. A. Gurowka, T. Hiramine. Asphalt Technology for In-Place Surface Recycling Using the Heat Reforming Process. *Proc., 34th Annual Conference of Canadian Technical Asphalt Association,* Vol. 34, 1989.
5. Shoenberger, J. E., and T. W. Voller. *Hot In-Place Recycling of Asphalt Pavements.* Technical Report GL-90-22. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., 1990.
6. Fyvie, K. R., and J. V. Valkenburg. Hot In-Place Recycling of Runway 15-33 Prince George Airport, B. C.—A Case Study. *Proc., 34th Annual Conference of Canadian Technical Asphalt Association,* Vol. 34, Nov. 1989, pp. 258–277.
7. Taverner, G., Thompson, and W. Doering. Hot In-Place Recycling of Airfield Pavements at Canadian Forces Base Edmonton, Alberta. *Proc., 35th Annual Conference of Canadian Technical Asphalt Association,* Vol. 35, Nov. 1990, pp. 60–79.
8. Goodsall, D. A. *In Situ Recycling of Asphalt Wearing Courses in the UK.* Special Report 65. Transport and Road Research Laboratory, Crowthorne, Berkshire, UK, 1981.
9. Lane, K. R. *Placement of an Experimental Heater-Scarified In-Place Recycled Pavement.* Report FHWA-CT-RD-647-2-81-14. Connecticut Department of Transportation, Wethersfield, Nov. 1981.
10. Carmichael, T., R. E. Boyer, and L. D. Hokanson. Modeling Heater Techniques for In-Place Recycling of Asphalt Pavements. *Proc., Association of Asphalt Paving Technologists,* Vol. 46, 1977, pp. 526–540.
11. Thompson, E. A. Chemical Aspects of Asphalt Pavement Rejuvenation. *Proc., Canadian Technical Asphalt Association,* Nov. 1981, pp. 84–96.
12. Page, G. C. Florida's Experience in Hot Mix Asphalt Recycling. *Hot Mix Asphalt Technology,* 1988, pp. 10–16.
13. Doucet, R. J., Jr., and H. R. Paul. *Wirtgen Remixes Surface Recycling.* Report FHWA-LA-91-235. Louisiana Transportation Research Center, Baton Rouge, Feb. 1991.
14. Fletcher, M. O. *Asphalt Pavement Recycling Using the Wirtgen Remixer Process.* Research and Materials Laboratory, South Carolina Department of Highways and Public Transportation, Sept. 1984.
15. Robb, C. It's All in the Mix. *Construction News,* Southham Company, June 1990.
16. Hudson, S. Experimental Paving on Alabama's U.S. 78. *Dixie Contractor,* Nov. 1989.
17. Aging Asphalt Runway Gets In-Place Rehab. *Roads and Bridges,* Vol. 25, No. 1, Jan. 1987.
18. Ameri-Gaznon, M., and D. N. Little. Octahedral Shear Stress Analysis of and ACP Overlay on a Rigid Base. *Proc., Association of Asphalt Paving Technologists,* Vol. 59, 1990.
19. Potts, C. F., and K. H. Murphy. *Surface Recycling of Asphalt Concrete Pavements.* Materials Research Office, Florida Department of Transportation, Gainesville, Sept. 1979.
20. Breckwoldt, E. J., J. W. Lyon, Jr., and S. C. Shab. *Intradepartmental Correspondence on S. P. Numbers 826-04-09 and 836-05-04.* Louisiana Department of Transportation and Development, June 4, 1980 and February 26, 1981.
21. Marini, R. New Recycling Technology from Asphalt Pavements. *Proc., 3rd Eurobitume Symposium.* The Hague, The Netherlands, Sept. 1985.
22. Bandyopadhyay, S. S. Structural Performance Evaluation of Recycled Pavements by Using Dynamic Deflection Measurements. In *Transportation Research Record 888,* TRB, National Research Council, Washington, D.C., 1982.
23. Rathburn, J. R. One-Step Repaving Speeds Country Work. *Roads and Bridges,* March 1990.
24. Perry, G. M. Repaving . . . One More Time. *Southwest Contractor,* Vol. 52, No. 10, June 1990.
25. Paul, H. R. *Surface Recycling Route U.S. 71 Construction and Initial Evaluation.* Report FHWA-LA-86-189. Louisiana Transportation Research Center, Louisiana Department of Transportation and Development, Aug. 1986.
26. Ganung, G. A. *Performance Evaluation of Heat-Scarified In-Place Recycled Bituminous Pavement, Rt. 15, Westport.* Report FHWA-CT-RD 647-5-87-2. Division of Research, Connecticut Department of Transportation, 1987.
27. Kuennen, T. Hot In-Place Recycling Gets Nod in Provinces. *Roads and Bridges,* Vol. 27, No. 10, Oct. 1989.
28. Baker, J. Economics Prompt Texans to Use In-Place Recycling. *Roads and Bridges,* Vol. 25, No. 10, Oct. 1987.
29. In-Place Recycling Rids Roads of Ruts. *Roads and Bridges,* Vol. 25, No. 10, Oct. 1987.
30. Hot In-Place Recycling Saves Texans Money. *Roads and Bridges,* Vol. 24, No. 10, Oct. 1986.
31. Klemens, T. L. Upgrading IH-10 to First Class. In *Highway and Heavy Construction,* Cahners Publishing, Sept. 1991.
32. Taylor, M., and E. Dillmann. Airport Saves With Hot In-Place Recycling. *Public Works,* Vol. 119, No. 10, 1988, pp. 118–119.
33. Marini, R. Considerations in Hot Mix Recycling of Asphalt Pavements in the Domain of Road Maintenance. *Proc., 3rd IRF Middle East Regional Meeting,* Riyadh, Saudi Arabia, Feb. 1988.
34. Servas, V. P. Resource and Energy Savings Through the Recycling of Bituminous Pavement Materials. *Proc., PTRC Summer Annual Meeting,* University of Warwick, England, July 1981, pp. 107–117.
35. Carey, D. E., and H. R. Paul. *Surface Recycling of U.S. 61 from Norco to Jefferson Parish Line.* Research and Development Section, Louisiana Department of Transportation, Aug. 1980.

36. Johnson, J. K. *Results of Hot In-Place Recycling at Thompson Field.* Interagency Memorandum/Report, Aviation Office, Florida Department of Transportation, 1991.
37. Kuennen, T. Hot In-Place Recycling Revitalizes Texas Road. *Roads and Bridges,* Vol. 28, No. 10, Oct. 1990.
38. Kuennen, T. Hot In-Place Recycling Gets Nod in Provinces. *Roads and Bridges,* Vol. 27, No. 10, Oct. 1989.
39. Patyk, S. Road Mixer Revitalizes Texas Asphalt Pavement. *Roads and Bridges,* Vol. 27, No. 10, Oct. 1989.
40. Fletcher, M. O. *Asphalt Pavement Recycling Using the Wirtgen Remixer Process.* Research and Materials Laboratory, South Carolina Department of Highways and Public Transportation, Sept. 1984.

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