EXPLORATORY STUDY OF HOT IN-PLACE RECYCLING OF ASPHALT PAVEMENTS VOLUME I

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16. Abstract

Hot in-place recycling (HIR) is a method for rehabilitation of asphalt pavements. Potential for cost savings and resource preservation are high because existing pavement materials are processed on-site, with only the addition of small amounts of recycling agent.

The Oregon Department of Transportation (ODOT) constructed HIR projects in 1992 and 1993. In September 1992, ODOT contracted with Oregon State University (OSU) to evaluate the HIR projects, synthesize existing information on HIR, and develop guidelines for HIR use. This report summarizes the information developed during the study:

a) Construction equipment used on ODOT HIR projects is discussed.
b) Field data from six HIR projects are presented.
c) Results of a limited laboratory investigation of HIR are presented.
d) Proper project selection was found to be extremely critical to HIR success. A selection procedure is presented.
e) Based on information from the field studies and a limited laboratory testing program, a recommended mix design procedure is presented.

This report is in two volumes. Volume I includes the body of the report, Volume II includes the appendices.

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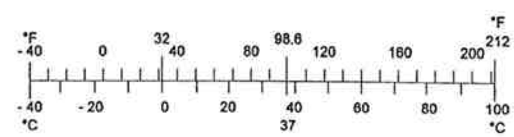
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy presented herein. The contents do not necessarily reflect the official views or policies of the Oregon Department of Transportation.

EXECUTIVE SUMMARY

In 1992 the Oregon Department of Transportation (ODOT) contracted for six hot in-place recycling (HIR) projects for rehabilitation of asphalt concrete pavements. Five projects were constructed in 1992; the sixth was constructed in 1993.

In September, 1992, ODOT contracted with Oregon State University (OSU) to

1. synthesize existing information regarding HIR,
2. evaluate the effectiveness of ODOT HIR projects,
3. refine the HIR mix design process in light of ODOT experience,
4. determine the most critical design inputs,
5. and develop guidelines for HIR use in Oregon.

This report summarizes the results of this research.

Research efforts included an extensive literature review, organization and analysis of available field data from the six ODOT HIR projects, limited field observation of the HIR process, and a laboratory testing program. HIR equipment and process are discussed. Construction challenges for each project and results achieved are reported and discussed. A flow chart for selection of HIR candidate projects is presented and discussed. A flow chart for HIR mix design for selected candidates is presented and discussed.

Challenges sometimes faced during HIR construction were

1. stripped pavements,
2. pavements with extensive delaminations, sometimes with water present,
3. very severely aged RAP,
4. heavily patched and highly variable pavements,
5. marginal, non state-of-the-art equipment,
6. smoke control, and
7. night paving requirements.

For three of six projects the challenges were too severe to provide fair evaluation of HIR equipment and methods.

One of ODOT's four wearing course HIR projects illustrated that if a suitable HIR candidate is chosen and a competent recycling contractor with state-of-the-art equipment is utilized, the HIR process can produce acceptable pavements. Three of ODOT's four wearing course HIR projects showed that pavements with stripping, extensive delaminations, or free water present in the pavement are not good HIR candidates.

Two of the HIR projects were designed to be base course for overlays. These projects show no signs of distress after HIR, but data indicate that rejuvenation of binder may have been spotty on one project, and that binder was actually hardened on the other. The project with apparent spotty rejuvenation had an average recycling agent (RA) add rate of about 0.2% compared to a design recommendation of 1.0%. The reasons for this difference are not fully understood -- fear of instability and metering equipment difficulties were factors. The project where binder was hardened experienced out-of-specification rejuvenating agent in less than design amounts, and probably over-heating.

Twenty conclusions and five recommendations for implementation are presented. Among the most significant of these are the following:

1. ODOT should continue to consider HIR as a rehabilitation option for asphalt pavements on carefully selected projects.
2. HIR for stripped pavements or for RAP which shows stripping potential is not recommended at the current stage of development of HIR technology.
3. If RAP binder absolute viscosity is greater than 200,000 poises, HIR to serve as a wearing course without addition of coated aggregate or virgin hot mix is not recommended.
4. ODOT should consider implementation of the HIR selection procedure presented in the report.
5. Critical inputs for HIR design come from testing RAP properties and from testing remolded specimens with RA added. These test properties are presented below:
   a) For RAP, properties are
      i) % asphalt,
      ii) penetration (25°C) of recovered asphalt,
      iii) absolute viscosity (60°C) of recovered asphalt, and
      iv) RAP gradation.
   b) For remolded specimens with RA added, properties are
      i) % air,
      ii) stability (Hveem or Marshall), and
      iii) Index of retained resilient modulus (or other stripping indicator).
6. ODOT should consider implementation of the HIR mix design procedure presented in the report.

EXPLORATORY STUDY OF HOT IN-PLACE RECYCLING OF ASPHALT PAVEMENTS VOLUME I

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1.0 INTRODUCTION

1.1 Background

As the nation shifts from new construction to preserving the existing highway system, recycling asphalt pavement materials is becoming increasingly important for both economic and environmental reasons. Transportation authorities estimate that for the next 10 to 15 years, it will cost approximately 16 billion dollars annually to maintain the present level of serviceability (FHWA, 1993). The staggering expense makes it imperative that cost effective alternative rehabilitation methods be investigated, developed, and utilized to their fullest potential. Recycling asphalt pavement materials is one of the most promising alternatives and has developed remarkably in recent years.

There are three methods of recycling currently in use, cold in-place, hot in-place, and in-plant recycling, primarily hot. Cold in-place recycling is the in-place milling of pavement followed by addition of an emulsified asphalt or rejuvenator, mixing, relaying, and compaction. Hot in-place recycling (HIR) is heating and scarification of the existing pavement, mixing with additional asphalt, aggregate, and/or rejuvenating agent, relaying and compacting. Hot in-plant recycling is milling the existing pavement, transporting it to a central plant where it is heated and mixed with additional asphalt, aggregate, and/or rejuvenator, transporting it back to the site, and placing it using conventional methods. With both "in-place" processes, everything is done on the highway saving the transportation costs of hauling the reclaimed asphalt pavement (RAP) back to a central plant. Table 1.1 presents the Asphalt Recycling & Reclaiming Association (ARRA) descriptions of the three recycling processes.

Table 1.1 Comparison of Recycling Alternatives (After ARRA literature.)

	Hot In-place	Cold In-place	Hot In-plant
Process:	Hot In-place recycling provides a very low-cost maintenance strategy that enables the public works official to effectively reuse existing materials. This process demonstrates that asphalt is a rather unique construction material in that it can be effectively and economically restored. Rather than bury the deteriorated pavement with inordinate depths of new material conventionally applied, or lose it to the grinder, proponents of Hot In-place recycling encourage restoration.	Cold In-place recycling is a road construction technique that reuses existing pavement structure. All work takes place on the existing pavement surface and requires no transportation of material. Cold In-place recycling results in a very stable road at a total expenditure less than that required by conventional methods.	The mixer heat transfer, where RAP materials are heated by "superheated" new aggregates, is the most common and most accepted method for hot mix recycling in a central mix asphalt plant. The process can be done in either a batch-type plant or a drum mix plant. The end result is the same, but the techniques to produce the end result are significantly different, depending upon the process selected.
Application:	Today there are many thousands of miles of asphalt pavement that are excellent candidates for Hot In-place recycling. These roadways are structurally adequate and possess a stable base, but exhibit the classic symptoms of pavement distress. Their surfaces are cracked, brittle and irregular, and they are deteriorating at a rapidly accelerating pace.	Cold In-place recycling is not a new method of rehabilitating deteriorating roadways. For the last 50 years or more, cold recycling has been practiced by various methods on a wide variety of roadway types. These methods have included the use of rippers, scarifiers, pulvimixers and stabilizers to reclaim existing surface and base materials. Emulsions, cutbacks and other additives have been added and mixed by spraying liquid on windrow and mixing. Today cold planing machines are being used to pulverize the roadway to the required size while at the same time cutting to a specified depth in preparation for liquid addition. In addition, one of the more recent types of equipment developed for Cold In-place recycling is the recycling train. This consists of a cold planer and a screening and crushing unit, which is followed by a mixing and proportioning unit.	Hot recycling provides the method by which reclaimed asphalt pavements can be reused or recycled. The process can be applied to many reclaimed materials. However, factors such as the materials to be used, the mix design requirements, the reclaimation process for the RAP, stockpiling techniques, and the equipment used, all have a major impact on the application of the process and the quality of the end result.
Advantages:	Hot In-place recycling effectively addresses the classic symptoms of deteriorated pavement: 1. Cracks are interrupted and filled. 2. Aggregate stripped of bitumen is remixed and recoated. 3. Ruts and holes are filled, shoves and bumps are leveled, drainage and crowns are re-established. 4. Flexibility is restored by chemically rejuvenating the aged and brittle asphalt. 5. Aggregate gradation and asphalt content may be modified by some variations of this process. 6. Highway safety is improved through skid resistance.	Cold In-place recycling has a number of advantages, including low mobilization costs, reduced haul costs, a very productive process and the use of materials in place. In addition, traffic can be maintained through the project, the roadway can be open to traffic very quickly, pollution is kept to a minimum,and projects can be completed in a minimal number of working days.	Hot recycling can transform old, deficient pavements into good, functional roadways. Asphalt or gradation programs can be corrected with aggregates and asphalt added to the new mix. Recycling can also help correct and maintain vertical and horizontal geometrics. Where curb and bridge clearances are a problem, old overlays can be planed and recycled in a cost effective rehabilitation alternative. Hot-mix recycling eliminates the disposal problems inherent in conventional methods, requires only minor modifications to existing equipment, can be performed in compliance with existing air pollution control standards, and can be done repeatedly, using the same materials.
Economics:	In a period of rapidly increasing costs and limited funding, Hot In-place recycling presents the opportunity to spread available dollars over a much wider area. Roadway deterioration can be suspended, pavements preserved and upgraded, and costly reconstruction avoided.	Cost savings have been realized on Cold In-place projects in the range of 20 to 40 percent lower than conventional construction techniques. The major areas of savings are utilization of the existing aggregates in the roadway, reduction of haul costs, and the maintenance of the way geometry eliminating rework of associated structures.	The economics of the hot recycling process can be influenced by a number of factors which will vary from project to project. The major areas of cost saving potential are: 1) The value of the asphalt cement in the RAP versus the cost of all new aggregate, 2) The value of the asphalt cement in the RAP versus new, and 3) The potential savings to adjacent structures that may not need rework if the existing pavement is removed and replaced, such as curbs, shoulders, guardrails, etc.

The focus of this study is hot in-place recycling. While HIR has been used since the 1930's, problems with depth control, mixture properties, safety, and gaseous emissions limited its scope and range of applicability. Marked improvements in preheating and scarification equipment and the development of air quality controls during the 1980's have made HIR a more attractive alternative to virgin hot mix overlays and inlays and to hot in-plant recycling. HIR also may be used in weather conditions where cold in-place recycling would not work.

The Oregon Department of Transportation (ODOT) began using HIR during the 1992 construction season. In 1992-93, six HIR projects were constructed.

1.2 Objectives

The study objectives were to:

1) Synthesize existing information regarding HIR.
2) Evaluate the effectiveness of ODOT HIR projects.
3) Refine the HIR mix design process in light of ODOT experience.
4) Determine the most critical design inputs.
5) Develop guidelines for HIR use in Oregon.

1.3 Study Approach

To accomplish the objectives the following steps were performed:

1) Information Gathering. A thorough literature review of the current knowledge regarding hot in-place recycling equipment, project selection, and mix design procedures was undertaken. Particular attention was given to information from British Columbia where the

HIR technology used for the ODOT projects was developed and applied.

2) Laboratory Testing Program. After completion of step 1, preliminary laboratory testing was begun. The goal was to accurately determine the properties required to characterize mix and binder before and after HIR. This was accomplished using conventional ODOT dense-graded mix design tests. With ODOT's approval, the following test procedures were utilized:

- Hveem Stability
- Index of Retained Strength
- Index of Retained Resilient Modulus
- Fatigue testing in the diametral mode

The laboratory tests also included testing of recovered asphalt for penetration and viscosity. Chapter 5 presents and discusses the laboratory methods, procedures and test results.

3) Field Studies. Field results in terms of material characteristics, ride data, and visual observations, both before and after HIR, are presented in Chapter 3. Also described are the construction processes, equipment, field control procedures, test results, and cost data for the projects studied.

4) Analysis. Data from the 3 steps above were compared and analyzed to determine:

a) Critical design inputs.

b) Preferred mix design procedures.

c) Expected field mix procedures.

d) Effectiveness of ODOT HIR projects.

e) Guidelines for HIR use in Oregon.

Based upon the literature review, laboratory testing, and the field study, suggested guidelines for project selection are put forth in Chapter 4 and a proposed mix design methodology is presented in Chapter 5. Finally, overall study conclusions and recommendations are discussed in Chapter 6.

2.0 HIR PROCESS AND EQUIPMENT

2.1 Introduction

While hot in-place recycling (HIR) of asphalt pavements has been used since the 1930's, readily available resources and cheap energy sources made it an unrealistic and rarely used rehabilitation alternative. Little research was conducted on HIR prior to the late 1970's when increasing asphalt costs mobilized research in all forms of pavement recycling. Several technological innovations were developed in the 1980's that have increased interest in HIR as a rehabilitation alternative for asphalt pavements. Canadian transportation officials have developed and applied this new HIR technology, especially in British Columbia where it gained popularity in the late 1980's and early 1990's.

2.2 HIR Process

The National Cooperative Highway Research Program Synthesis 193 "*Hot In-place Recycling of Asphalt Concrete*" defines the HIR process as consisting of the following steps:

1) Softening the existing pavement with heat,

2) mechanically removing the pavement surface,

3) mixing it with recycling agent, possibly adding virgin asphalt or aggregate,

4) replacing it on the pavement without removing the recycled material from the original site.

The Asphalt Recycling and Reclaiming Association, a non-profit international trade association of contractors, equipment manufacturers, suppliers, public officials, and engineers, defines three basic methods of HIR (ARRA, 1988):

- Heater-Scarification. A rehabilitation process that restores cracked, brittle and irregular pavement in preparation for a final thin wearing course as selected by the awarding authority.
- Repaving. This technique utilizes the same elements of heating, scarifying and rejuvenation as heater-scarification but combines these with the simultaneous overlay of new hot mix to form a thermal bond between the new and recycled layers. This single multi-step process is capable of achieving recycled depths of between 1 and 2 inches.
- Remixing. The existing roadway is thoroughly heated to a depth of 1-1/2 to 2 inches, then collected into a windrow by rotary scarifiers. Onboard mixing chambers then rework the material and combine it with controlled amounts of virgin mix and/or rejuvenation agents (RA). The virgin material can be specifically designed to modify aggregate gradation as well as asphalt content and characteristics. The equipment then lays the mix as a single homogenous course.

Of these three methods, only remixing was used on the six Oregon HIR projects.

While hot in-place recycling of asphalt pavements makes sense environmentally and economically, early technologies experienced problems with depth control, limited range of depth, and inconsistent mixture properties. Additional concerns were fire safety and air pollution.

Beginning in the mid-1970's, improvements in recycling equipment addressed these problems and made HIR more cost-effective. More efficient heating devices were developed, allowing scarification to depths of two inches. Other innovations gave more control over depth, density, and cross slope. The introduction of multi-stage HIR equipment, in which the existing pavement is heated and milled in layers, eliminated many of the scorching problems associated with "single pass" equipment. A brief and excellent historical account, with photographs, of the development of HIR is presented in, "Hot In-Place Asphalt Pavement Recycling -- A Technical Training Seminar & Workshop" (Pyrotech, 1993).

2.3 Hot In-Place Recycling Equipment

2.3.1 Equipment Used in the Pacific Northwest

Pyrotech, Artec, and Taisei have manufactured all HIR equipment used in the Pacific Northwest since the mid-1980's. Each company's equipment is discussed below. The Pyrotech and Artec equipment are examined more closely because they were used on the six HIR projects in Oregon. As HIR equipment seems to be changing every construction season, special emphasis was placed on the most recent field studies using state-of-the-art technology.

2.3.1.1 Pyrotech

The Pyrotech Pyropaver 300E is a two stage system consisting of a preheater, two heating/milling units, and a pugmill mixer. Conventional paving and compaction equipment follows. Pyrotech equipment was used on five of the six 1992-93 Oregon HIR projects.

Figures 2.1 through 2.13 present the HIR process using Pyrotech equipment. The recycling train is shown schematically in Figure 2.1, and in operation in Figures 2.2-2.3. In Figure 2.3, smoke from HIR is visible. The preheater (unit one), shown in Figures 2.4-2.5, starts the heating of the pavement surface and removes any moisture present. The first

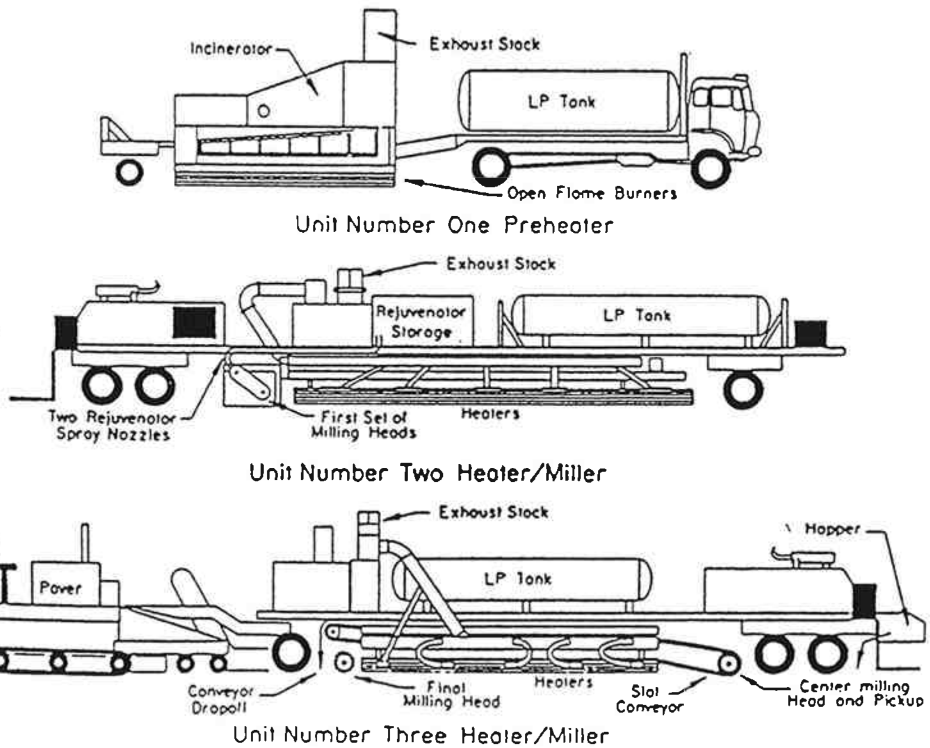


Figure 2.1 Schematic of Pyrotech PYROPAVER 300E (after Gavin & McMillan, 1993).

Figure 2.2 Pyrotech PYROPAVER 300E recycling train in operation.

Figure 2.3 Pyrotech PYROPAVER 300E showing "smoke cloud".

Figure 2.4 Pyrotech PYROPAVER 300E preheater (unit 1).

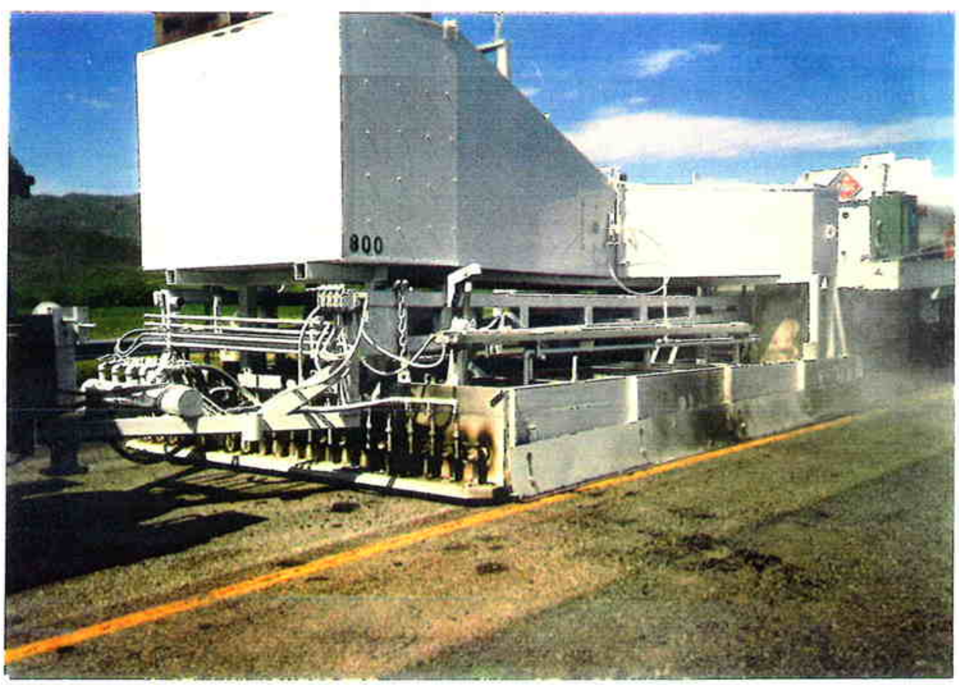


Figure 2.5 Close-up of Pyrotech PYROPAVER 300E preheater (unit 1).

heater/miller (unit two), shown in Figure 2.6, uses infrared heat to heat the surface before milling the top inch and adds the rejuvenating agent to the milled RAP. Figure 2.7 shows the milled RAP, with RA added, being windrowed into the center four feet of the lane. Figure 2.8 is a close-up of the windrow showing what can happen if too much RA is added. If additional aggregate is to be added, it is added here. Figure 2.9 shows the hopper for addition of virgin mix, and Figure 2.10 shows a truck dumping add-mix into the hopper. The combined material is conveyored over unit three's heater/miller which mills the pavement (similar to unit two) to an additional 1 to 1 1/4 inch depth. Figure 2.11 shows the second miller/grinder, just ahead of where all material (conveyored RAP from first milling, virgin mix, and RAP from the second milling) is combined. Figure 2.12 shows the combined RAP/virgin mix as it enters the pugmill before being placed in the paver hopper. Placement continues as with a normal hot mix pavement. Figure 2.13 shows rolling and compacting of the recycled mix behind the paver. The working width is 12 feet at typical speeds of 11 to 16 feet per minute.

2.3.1.2 Artec

The Artec recycling equipment shown schematically in Figure 2.14 differs significantly from the Pyrotech equipment. The HIR process using an Artec equipment train is shown in Figures 2.15 through 2.27. Unit one, the preheater, is shown in Figures 2.16-2.18. It heats the pavement to 300°F surface temperature. Figure 2.17 shows smoke which can result from the HIR process. Figure 2.18 shows the preheater from a rear view.

Figure 2.6 Close-up of Pyrotech PYROPAVER 300E first heater/miller (unit 2).

Figure 2.7 Milled RAP being windrowed into the center four feet of highway lane.

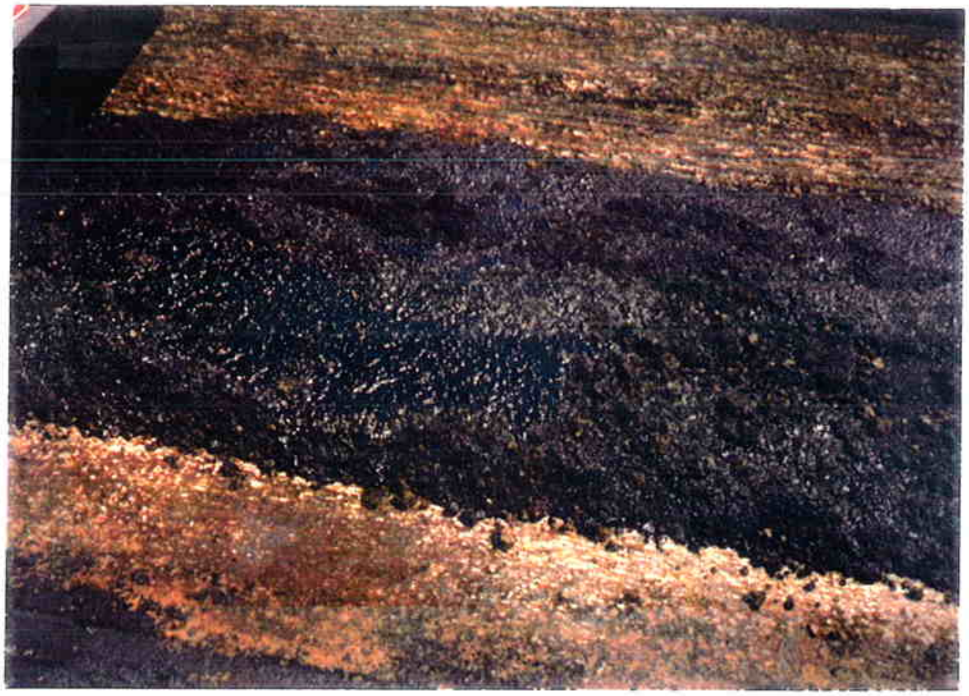


Figure 2.8 Close-up of windrow with excess rejuvenating agent added.

Figure 2.9 Hopper at the front of unit 2 for addition of virgin mix.

Figure 2.10 Truck dumping virgin mix into hopper.

Figure 2.11 Close-up of second miller/grinder, just before RAP and virgin mix are combined.

Figure 2.12 Combined RAP/virgin mix as it enters the pugmill.

Figure 2.13 Rolling and compacting of recycled mix behind paver.

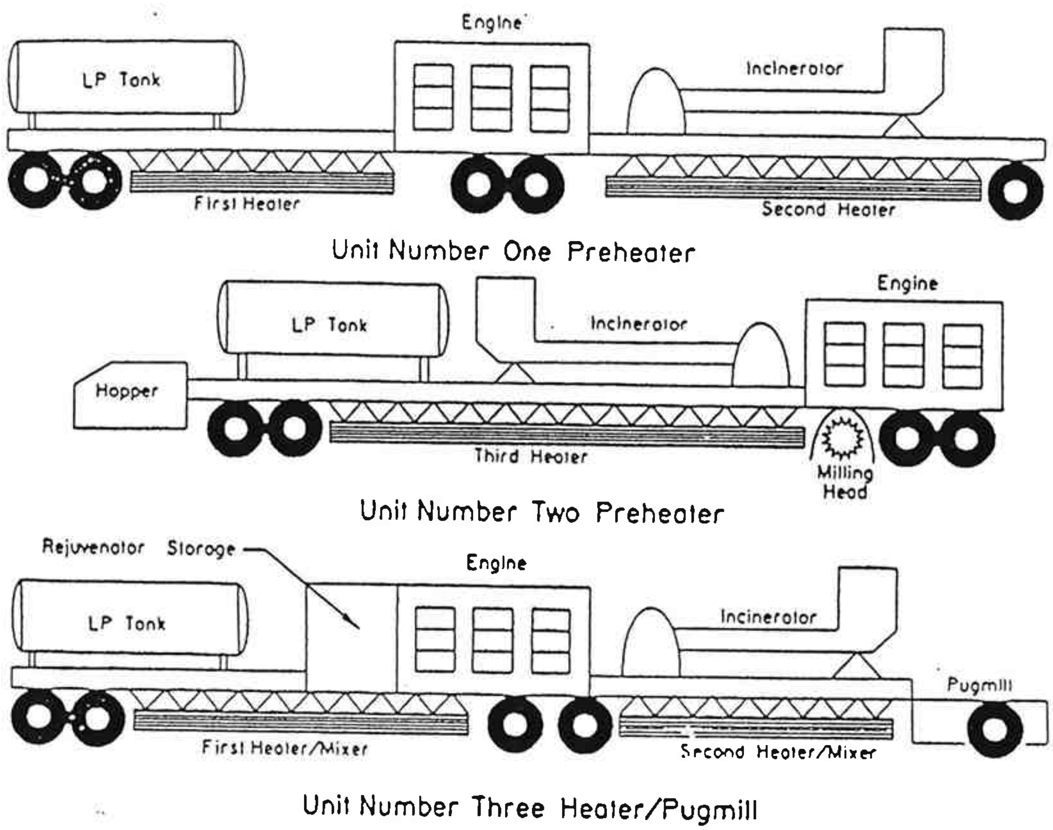


Figure 2.14. Schematic of Artec multi-stage recycling train (after Gavin & McMillan, 1993).

Figure 2.15 Artec multi-stage recycling train in operation. (Courtesy, ARTEC)

Figure 2.16 Artec multi-stage preheater (unit 1). (Courtesy, ARTEC)

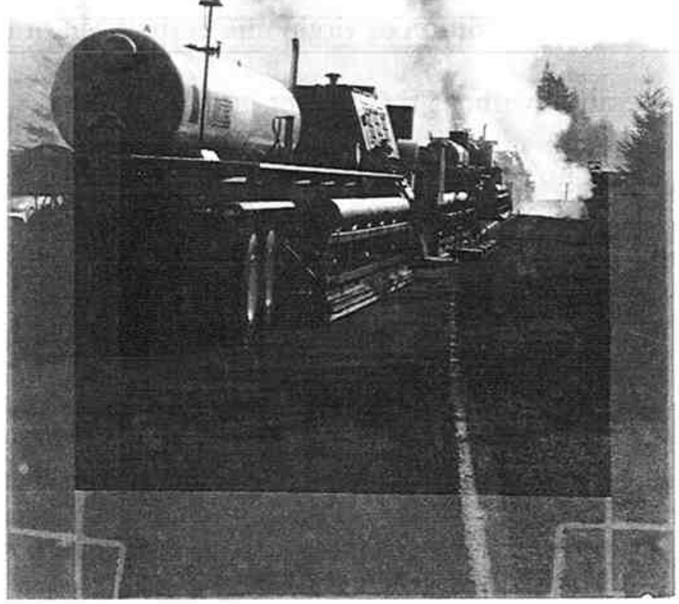


Figure 2.17 Artec multi-stage preheater with HIR smoke in background.

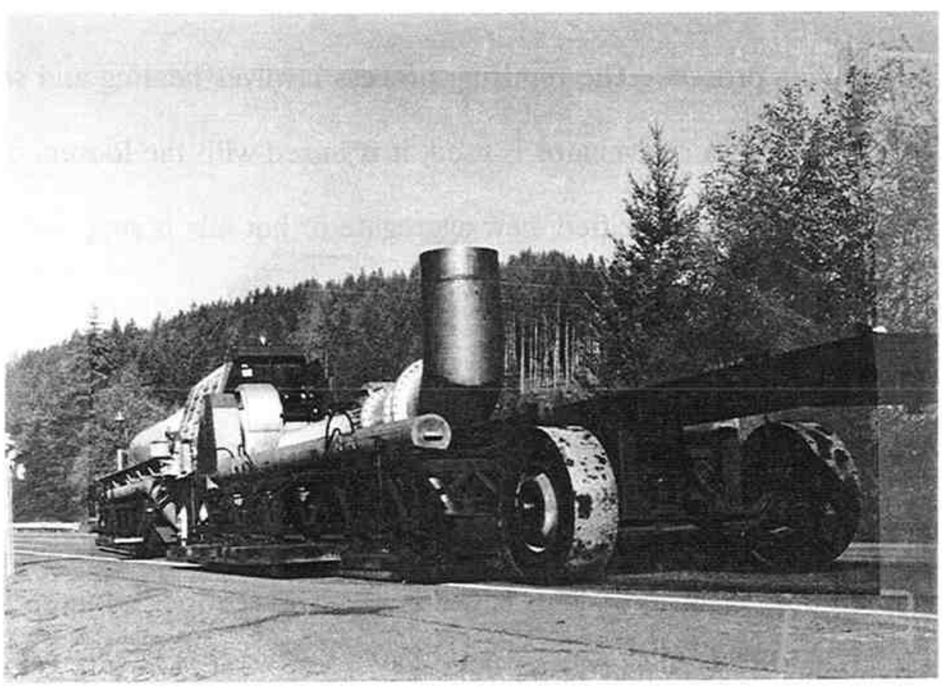


Figure 2.18 Back side of Artec multi-stage preheater (unit 1).

Unit two, shown in Figures 2.19-2.20, supplies more heat to the pavement and mills to the desired depth, up to 2 inches, depositing the millings across the lane width. Figure 2.19 shows the hopper for the addition of virgin mix at the front of unit two and Figure 2.20 shows unit two in operation without the hopper attached.

Figure 2.21 shows unit three and the paver in operation. Figure 2.22 is a close up of the heaters on unit three. Unit three "stirs" and further mixes the millings prior to collecting the RAP into a pugmill where RA is added (Figures 2.23-2.24). The rejuvenated mix is deposited in a windrow which is then placed using a "pickup machine" paver shown in Figure 2.25. Finally, Figures 2.26-2.27 show the recycled mat being compacted using conventional methods. Working widths and speeds are similar to the Pyrotech equipment.

2.3.1.3 Taisei

The Taisei equipment, shown schematically in Figure 2.28, uses two infrared preheaters, units one and two, and a single reforming unit, unit three. It can be either a remixing or a repaving process. The remixing process involves heating and scarifying the surface, up to 2 inches. If a rejuvenator is used, it is mixed with the loosened material by a single hot milling mixer. If specified, new aggregate or hot mix is supplied to unit three by trucks which dump the new materials into a hopper located on the front of the unit. A second mixer then mixes the first mix with the new mix, which is then screeded to grade and compacted. In the repaving process, the same equipment is used, but the secondary mixer is usually not used, and is raised above the working surface. A new hot mix is overlaid on top of the recycled mix. Typical working speed is about 13 feet per minute. The working width is adjustable between 10 and 14 feet.

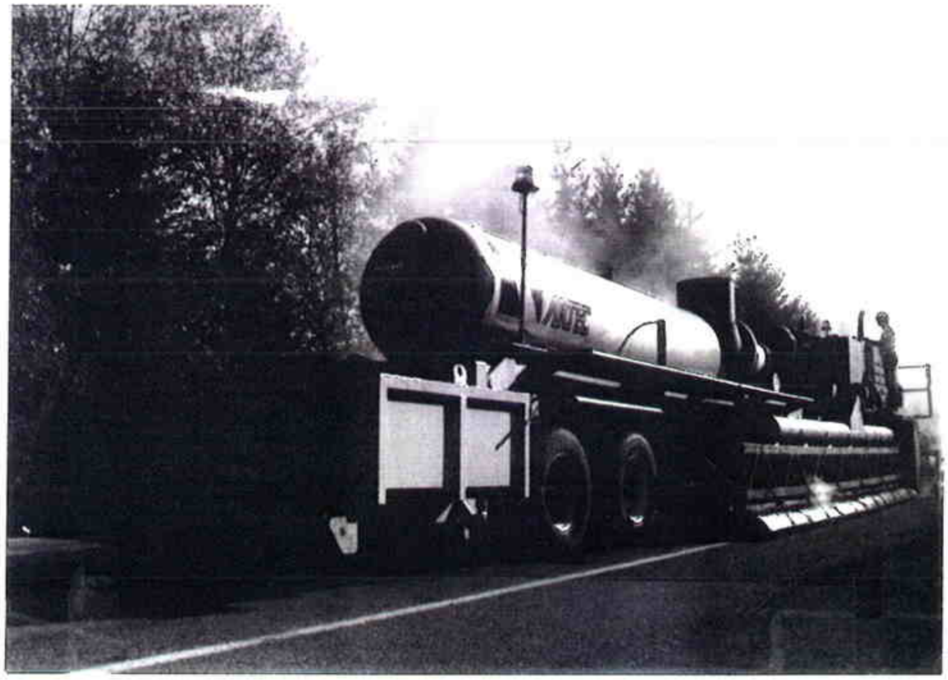


Figure 2.19 Hopper at front of unit 2 for addition of virgin mix.

Figure 2.20 Close-up of Artec multi-stage first heater/miller (unit 2).
(Photo courtesy of ARTEC.)

Figure 2.21 Close-up of Artec multi-stage second heater/miller (unit 3) and paver.
(Photo courtesy of ARTEC.)

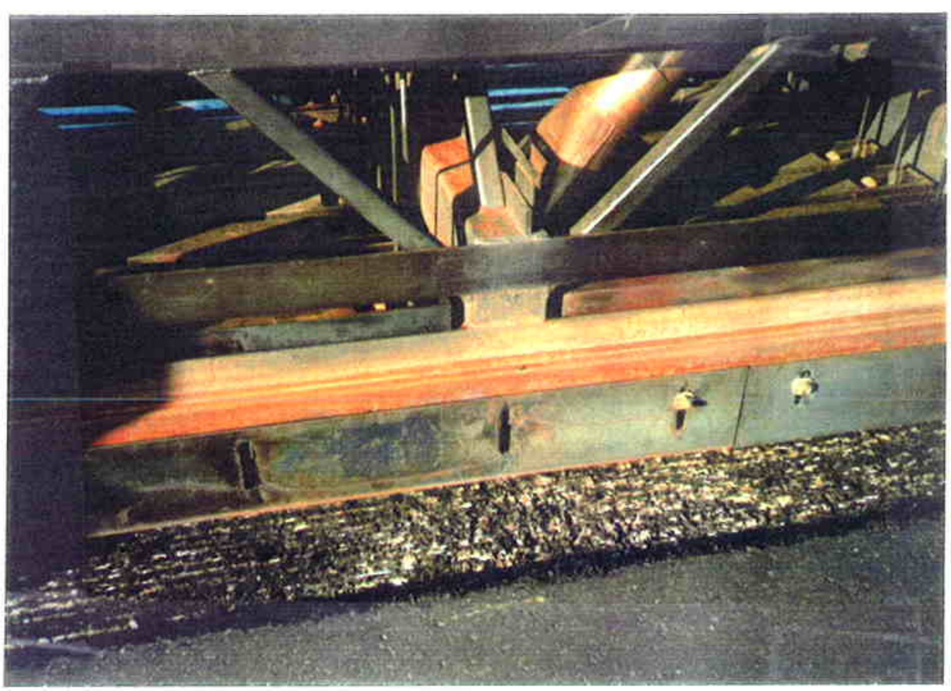


Figure 2.22 Close-up of heaters on unit 3.
(Photo courtesy of ARTEC.)

Figure 2.23 Close-up of pugmill at the rear of unit 3.
(Photo courtesy of ARTEC.)

Figure 2.24 View of recycled mixture windrow after passing through pugmill.

Figure 2.25 Windrow of recycled mixture entering pickup paver.
(Photo courtesy of ARTEC.)

Figure 2.26 Recycled mat just behind screed.
(Photo courtesy of ARTEC.)

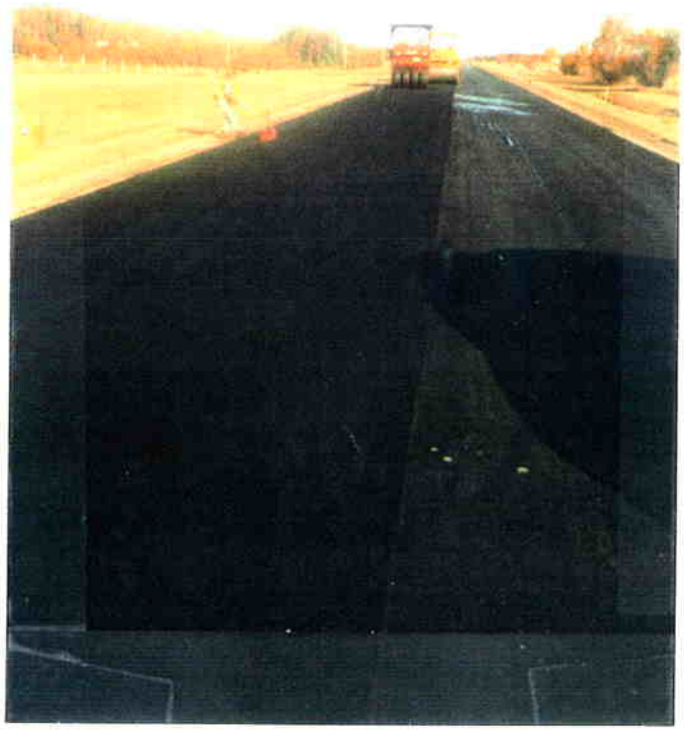


Figure 2.27 Compaction of HIR mat using conventional rollers.
(Photo, courtesy of ARTEC.)

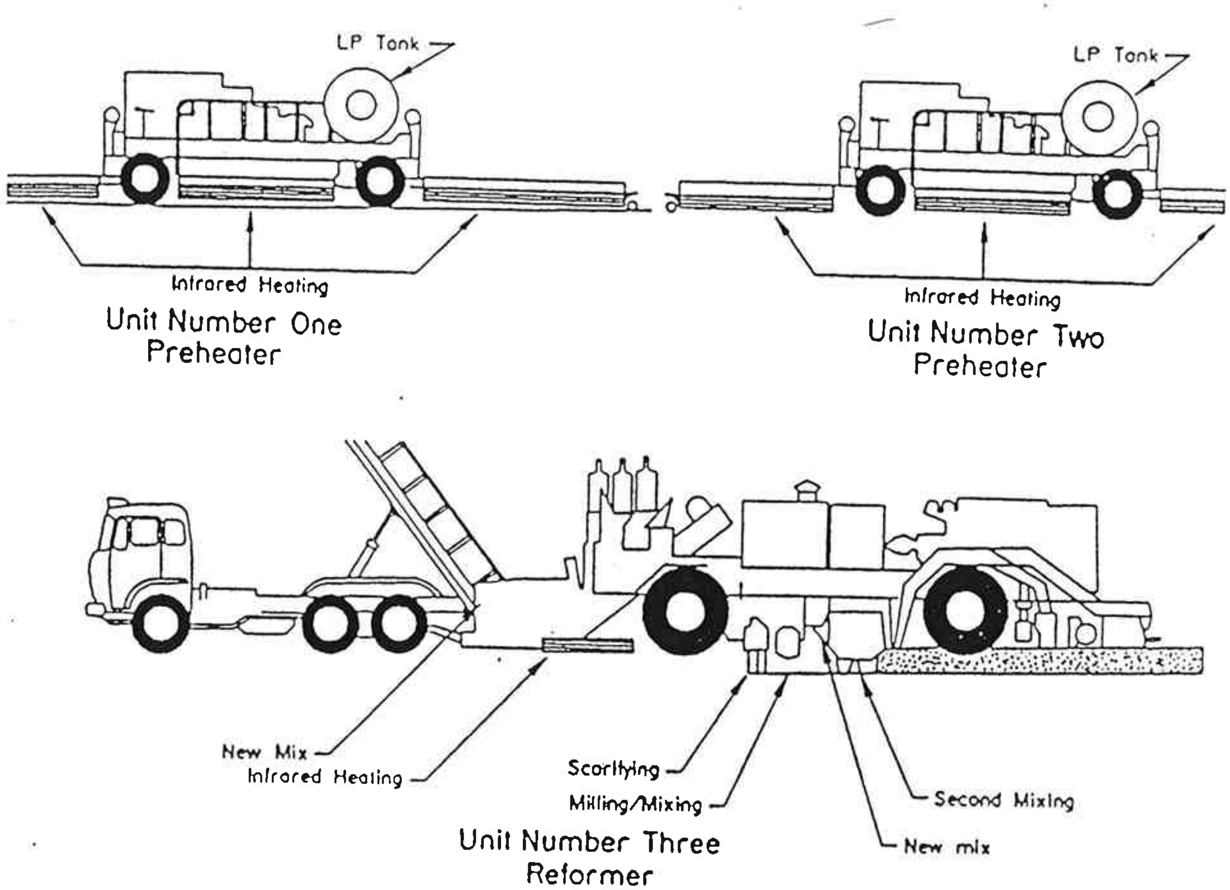


Figure 2.28 Schematic of Taisei HPR-5 recycling train (after Gavin & McMillan, 1993).

2.3.2 Other Equipment

HIR has been used with varying results by several Southeastern, Southern, and Midwestern states, mostly using equipment different from that cited previously (Doucet, 1991; Dowdy, 1987; Paul, 1986). The most extensively used equipment have been the Wirtgen Remixer 4500 and the Cutler Repaving.

2.3.2.1 Wirtgen Remixer 4500

The Wirtgen Remixer 4500 is illustrated in Figure 2.29. The Wirtgen equipment has two sets of infrared heaters, variable scarifiers following the heaters, a pugmill mixer, and a distribution auger (Wirtgen, 1992). Virgin mix can be added at the front of the train, typically between 30 and 55 pounds per square yard, and routed back to the pugmill. Like Taisei, this equipment has the ability to HIR and overlay in a single pass by mounting a second screed after the first. The Wirtgen equipment has the capability to mill to 3 inches. The working width can be 10 to 14 feet with speeds of 8 to 12 feet per minute.

2.3.2.2 Cutler Repaving

Cutler's recycling equipment consists of a forced air heating system, scarifiers, a liquid application system, a leveling blade, and mixing augers and screeds. The Cutler manufacturers claim that, like most recycling equipment, their machinery works over almost all types of existing asphalt pavements: (1) bituminous hot mix, (2) sheet asphalt, (3) seal coated surfaces, (4) slurry sealed surfaces, and (5) newly recycled and rejuvenated hot mix (Cutler, 1993). The milled material is mixed only with augers, and not a pugmill. The Cutler equipment can combine recycled and new mix pavement to between 1 1/2 and 3 1/2 inches in thickness. It is interesting to note that Cutler and Southwest Laboratories worked

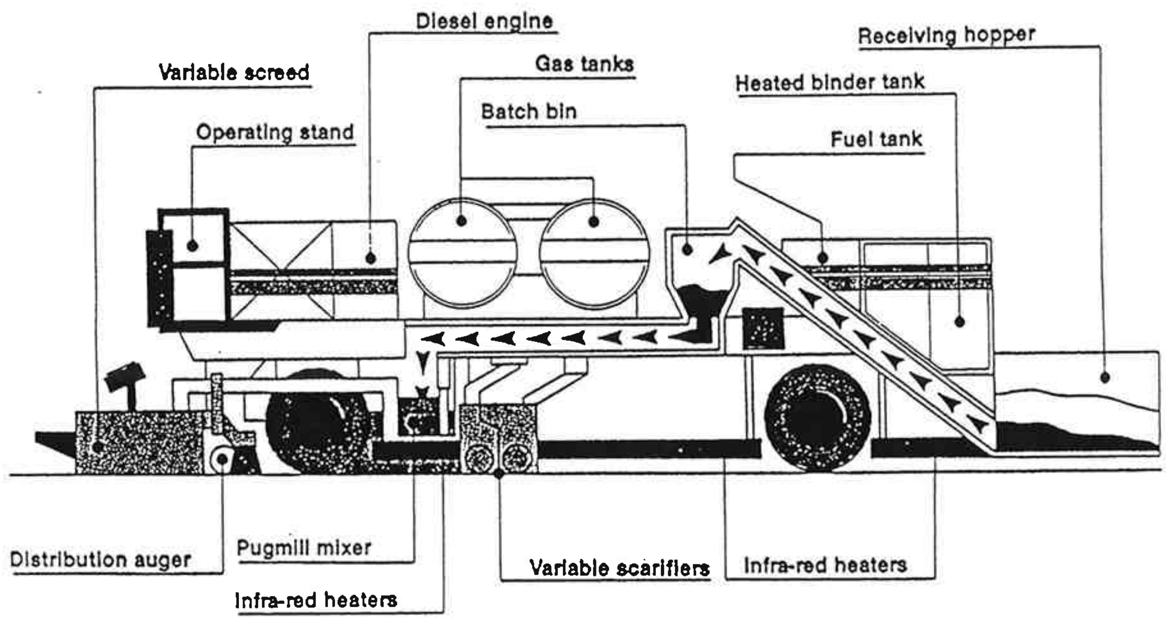


Figure 2.29 Wirtgen Remixer 4500 recycling train (Wirtgen Co. literature, 1989).

on a study that used crumb rubber with the Cutler HIR process (Southwest Laboratory 1992 report).

3.0 FIELD STUDY

3.1 Description of Field Study

The objective of the field study was to obtain as much information as possible from the hot in-place recycling (HIR) projects constructed in Oregon in 1992-93. Figure 3.1 shows the locations and Table 3.1 presents basic information on the six HIR projects. Information was collected and evaluated to determine which factors were most critical for project success. Particular attention was given to the Project Manager's narrative report for each project and ODOT memos on HIR (gathered in Appendix A). The information presented comes from all phases of the HIR process including:

- Preliminary data: Pre-construction core data, recovered asphalt properties, gradations, background information and mix design methods and results.
- Construction records: Information specific to the construction process, factors that affected the project's success, problems with equipment, weather, and the reclaimed asphalt pavement (RAP) being recycled.
- Post-construction information: Field cores and samples to compare with pre-construction cores, visual observations, and ride evaluation data when available.

Each of the six HIR projects had distinctive features and problems and varying degrees of success. They are presented in chronological order to show how the HIR process has developed in Oregon. It must be noted that most of the projects were conceived and executed independently on a regional/district level and hence, the sampling protocol, design

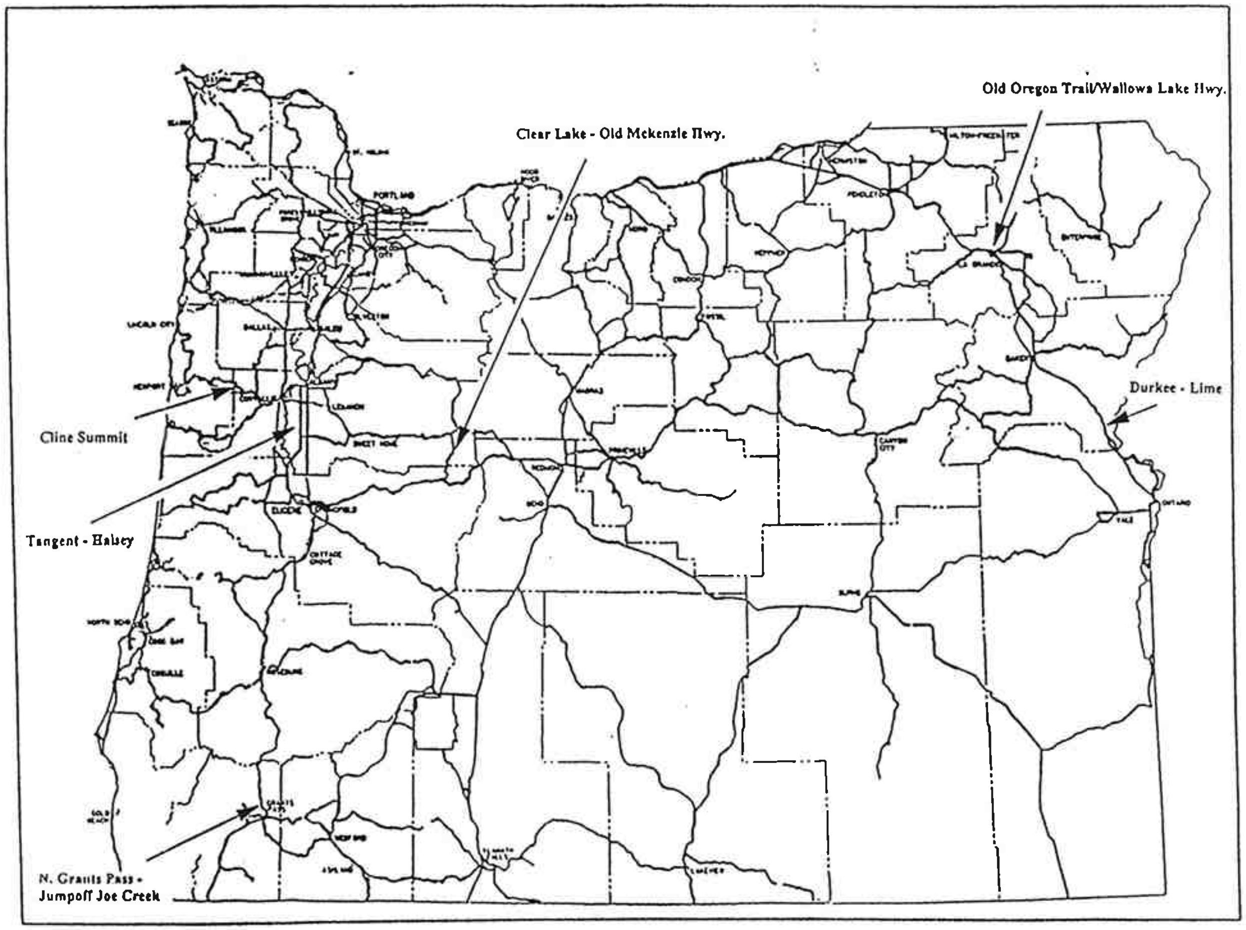


Figure 3.1 Location of ODOT HIR Projects.

Table 3.1 ODOT HIR Projects.

Location	Construction Dates	Length (Miles)	Area (SY)	Bid Quantity $/SY	Recycling Equipment
Old Oregon Trail Freeway/Wallowa Lake Hwy. (I-84)	May19-June 19,1992	6.6	76,790	2.02	Pyrotech
Clear Lake -Old Mckenzie Highway (Hwy 126)	June 1- July 27, 1992	16.8	252,735	1.97	Pyrotech
N. Grants Pass - Jumpoff Joe Creek (I-5)	July 7-26, 1992	8.9	236,380	2.20	Pyrotech
Tangent-Halsey (Hwy 99E)	Aug. 3 - Sept. 2, 1992	11.6	163,200	1.84	Pyrotech
Cline Summit (Hwy 20)	October 21-24, 1992	2.2	44,210	1.87	Artec
Durkee-Lime (I-84)	May 5-June 25,1993	15.0	205,420	2.78	Pyrotech-Artec*

* Recycling train used both Pyrotech and Artec equipment.

methods, etc. will vary from project to project. As each project is presented, the "lessons learned" from that particular project will be discussed. After all six projects have been discussed, the critical factors in HIR will be summarized for use in developing a protocol for selecting HIR candidate projects and mix design.

3.2 Project Descriptions

3.2.1 Old Oregon Trail-Wallowa Lake Highway

This project was made up of two units, one on the Old Oregon Trail Freeway, Interstate-84 (I-84) and the other on the Wallowa Lake Highway, State Highway 82 (Hwy. 82). On I-84, the work consisted of recycling the ten foot outside shoulders from mile point 265.5 to mile point 272.1 in both directions and the travel lanes in the Charles Reynolds rest area. The average daily traffic (ADT) on this section of I-84 was 6,800. The Wallowa Lake Highway project consisted of the travel lanes from mile point 0.16 to mile point 1.19 and mile point 2.66 to mile point 5.10. The ADT for these sections was 14,000 and 8,300 respectively. All of the Wallowa Lake Highway sections were badly rutted and had inadequate structural strength. The shoulders on I-84 were severely stripped (loss of asphalt) in several places. Figure 3.2 shows the stripping on the eastbound shoulder near mile point 266. Figure 3.3 presents a close-up of the stripped, "dry" pavement just ahead of the preheater unit.

The preliminary investigation for mix design consisted of taking cores at random locations on both sections of the project. The recovered asphalt/mixture properties for the Old Oregon Trail cores are presented in Table 3.2. The recovered asphalt/mixture properties for the Wallowa Lake Highway cores are shown in Tables 3.3-3.4. The average

Figure 3.2 Example of I-84 shoulder pavement prior to HIR.

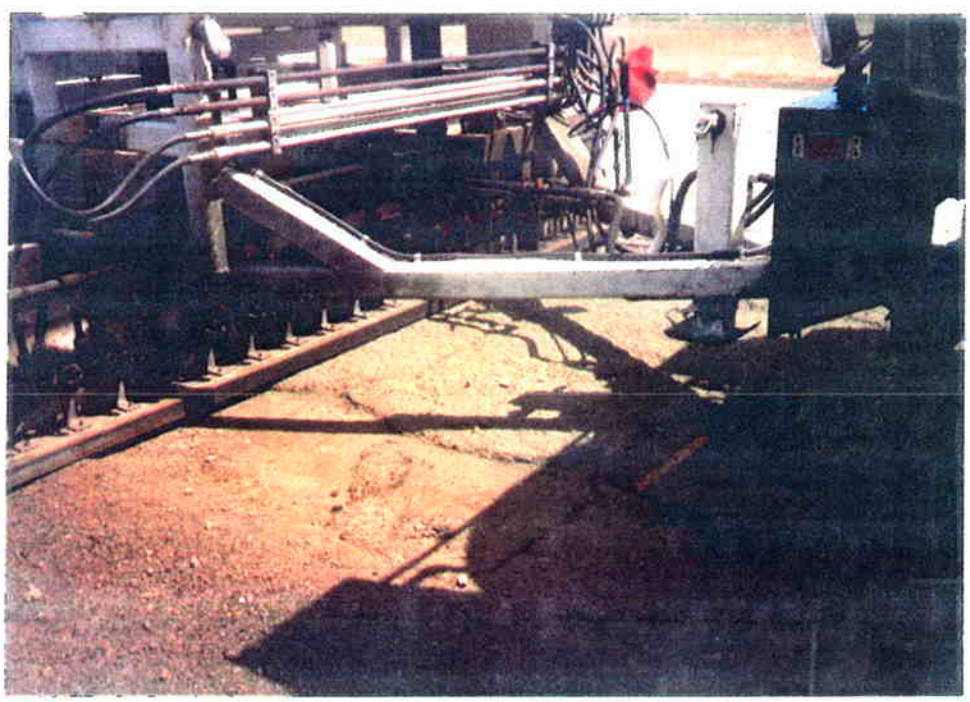


Figure 3.3 Close-up of I-84 shoulder pavement (in front of preheater unit).

Table 3.2 Recovered Pre-construction Asphalt/Mixture Properties for Old Oregon Trail (I-84) HIR Project.

Mile Point	Core Density (lb/cf)	Asphalt Content %	Air Voids %	Index of Retained Modulus %	Recovered Asphalt Properties: Absolute Viscosity (Poises)	Recovered Asphalt Properties: Kinematic Viscosity (cSt)	Recovered Asphalt Properties: Penetration @25C (dmm)
267.0 WB	135.2	----	10.6	----	----	----	----
270.6 WB	132.1	----	12.6	46	----	----	----
271.9 WB	132.9	----	----	30	785,000	5,100	----
268.1 WB	136.3	7.0	9.7	----	----	----	----
267.7 WB	135.3	----	11.8	----	----	----	----
269.5 WB	133.1	----	12.7	----	----	----	----
Average Value	134.2	7.0	11.5	38	785,000	5,100	----
266.6 EB	136.8	----	6.2	19	344,000	3,240	----
267.7 EB	137.7	----	9.0	----	77,000	2,010	----
265.6 EB	138.7	7.2	----	----	----	----	----
269.9 EB	138.5	----	7.6	----	206,000	2,500	----
271.3 EB	139.2	----	----	66	----	----	----
268.7 EB	137.2	7.9	7.8	58	793,000	4,160	----
Average Value	138.0	7.6	7.7	48	355,000	2,978	----

Comparison Values	New PBA-2	4,000	----	40
	Typical 20 Yr. Old Asphalt	100,000	----	25

Note: Comparison values taken from Miles, 1991 Memo.

Table 3.3 Recovered Pre-construction Asphalt/Mixture Properties for Wallowa Lake Highway.

Mile Point	Core Density (lb/cf)	Asphalt Content %	Air Voids %	Index of Retained Modulus %	Recovered Asphalt: Absolute Viscosity (Poises)	Recovered Asphalt: Kinematic Viscosity (cSt)	Recovered Asphalt: Penetration @25C (dmm)
3.6	138.6	7.0	----	----	81,600	1,640	11
1.5	137.3	6.1	12.5	94	15,800	822	27
2.5	137.3	6.9	11.6	100	21,400	914	18
2.66	135.4	5.7	14.9	----	89,800	2,050	19
Average Value	137.2	6.4	13.0	97	52,150	1,357	19
Stan. Dev.	1.1	0.5	1.4	3	33,733	511	6

Comparison Values		Absolute Viscosity (Poises)	Kinematic Viscosity (cSt)	Penetration @25C (dmm)
	New PBA-2	4,000	----	40
	Typical 20 Yr. Old Asphalt	100,000	----	25

Note: Comparison values taken from Miles, 1991 Memo.

Table 3.4 Pre-construction Aggregate Gradations for Wallowa Lake Highway.

Mile Point	Sieve Analysis - Percent Passing							
	3/4	1/2	3/8	1/4	#4	#10	#40	#200
1.5	100	99	91	73	61	35	16	9.4
2.5	100	99	95	90	66	38	16	9.6
2.66	100	91	80	66	56	32	22	12.3
Average Value	100	96	89	76	61	35	18	10.0

ODOT Typical B- and C-mixes. (Miles,1991)

B-mix	96	80	70	57	49	28	11	5
C-mix	100	98	86	62	51	29	12	6

absolute viscosity for both of the Old Oregon Trail Freeway shoulders was 441,000 poises, much higher than typical values for a 20-year old asphalt pavement (100,000 poises). Wallowa Lake Highway was not as severely aged with average absolute viscosity of 52,150 poises. As the preliminary core data show, both pavements had significant variability in recovered asphalt properties.

The mix design was based on ASTM D4887-89, which uses the extracted percent asphalt, recovered asphalt viscosity, desired viscosity (9,000 poises), and rejuvenating agent (RA) viscosity to estimate the add rate for the RA. Air voids and IRRM of pre-construction field cores were also determined. The intent was to use the core data-ASTM D4887-89 predictions as guidelines to estimate the initial add rate and make adjustments in the field as necessary. The estimated addition rate of RA to rejuvenate the very stiff I-84 shoulders was 2.3 to 3.7 percent by weight of RAP and 0.5 to 1.3 percent by weight of RAP for Wallowa Lake Highway.

Pre-construction testing using the index of retained resilient modulus (IRRM) suggested potential stripping problems on the I-84 Freeway shoulders. The five specimens tested were well below the minimum acceptable IRRM value of 70 percent, averaging 44 percent. The recommended mix design included the warning, "Index of Retained Resilient Modulus results indicate mix may be sensitive to stripping."

Construction began on May 19, 1992, and was completed on June 19, 1992. The following summarizes key information from the Project Manager's report. The contractor immediately pointed out that the design add rate was much too high. Work began on the I-84 shoulders with the add rate of RA being left to the contractor's experience to keep from over-asphalting the mix. For the work done on both projects, the contractor used 18.81

tons of RA-25 for 85,980 square yards, for an average add rate of 0.22 percent. The add rate was varied throughout both projects as deemed necessary by the contractor. Virgin material was added to help fill the existing ruts and achieve the desirable crown.

Two major HIR problems, stripping and delaminating layers in old overlays, were discovered during construction. On the I-84 shoulders, the asphalt was so badly stripped that often there wasn't enough left for the RA to be effective.

Two boxed samples, 4,000-5,000 grams, of HIR mix were sent to the ODOT materials laboratory for specimen fabrication and testing. The results from these tests; Hveem stability and index of retained strength (IRS), along with recovery information are presented in Table 3.5. Both samples performed better then pre-construction field cores in water sensitivity testing, almost meeting the design criteria of 75 percent. The stability and air voids are both below the minimum accepted values as shown in Table 3.5. The viscosity was slightly improved but was still quite high averaging 291,000 poises. Using average values of pre-HIR viscosity equal to 441,000 poises, asphalt content at 7.4 percent, and an RA addition rate of 0.22 percent by weight of RAP, the ASTM D4887-89 design nomograph predicts a rejuvenated viscosity of 270,000 poises, which compares reasonably to field performance. The low penetration value (11 dmm) implied strong susceptibility to thermal cracking.

The pavement was in such poor condition that HIR wasn't producing acceptable shoulders. HIR was halted well short of completion. The unfinished portion was cold planed and inlaid with a new mat of class "B" mix.

Table 3.5 **Asphalt/Mixture Properties for Boxed Samples of Old Oregon Trail (I-84) Shoulder HIR Mix. (First Compaction Values/Second Compaction Values)**

Time of Coring	Mile Point	Core Density (lb/cf)	Asphalt Content %	Air Voids %	Index of Retained Strength %	Hveem Stability	Recovered Asphalt Properties: Absolute Viscosity (Poises)	Recovered Asphalt Properties: Kinematic Viscosity (cSt)	Recovered Asphalt Properties: Penetration @25C (dmm)
During HIR	Not Specified	149.2/150.3	----	1.6/0.9	70	20/11	197,000	2,290	11
		147.4/152.1	----	1.1/0.7	67	31/17	385,000	2,860	11
	Average Value	148.3/151.2	----	1.4/0.8	68.5	26/14	291,000	2,575	11
Before Construction	Average Value	137.2	6.4	9.8	----	----	441,000	3,402	----

Minimum Acceptable Values	4.0-5.0/1.5	75	30

Note: Comparison values taken from ODOT Asphalt Mix Design Guidelines.

Layer delamination was a problem with both units of the project. During the recycling operation, these non-bonded sections would form a thin layer of stripped material, primarily uncoated fine aggregate, just below the milling depth. During recycling, this stripped material became mixed with the rejuvenated RAP, leaving the mix too lean, creating significant variations in the finished mat. On Wallowa Lake Highway, this problem was compounded by the presence of water in-between the delaminated layers which acted as a thermal buffer, absorbing much of the heat being applied to the RAP. In these sections, the temperature behind the paver would be 20 to 30 degrees cooler than normal and the ride of the finished pavement was affected.

Other problems encountered during construction were relatively minor but are worth noting. Frequent equipment failures from improperly maintained equipment delayed work approximately two weeks. Wind and rainy weather caused another week's delay.

Overall, the HIR portion of the project was considered not to be a success as the I-84 shoulders weren't completed and the Wallowa Lake Highway's poor ride wasn't improved by the work. Wallowa Lake Highway was scheduled for cold planing and rehabilitation in the Summer of 1994 after only two years in service.

Summary. In summary, only 3.5 of 6.6 miles of the Old Oregon Trail Freeway shoulders were completed due to quality problems. The asphalt in the RAP was so badly stripped that even with the addition of "fat" virgin mix, the recycled mixture wasn't holding together. Molded specimens from box samples taken from the recycling train showed inadequate air voids, index of retained strength, and Hveem stability. Water-filled delaminations on the Wallowa Lake Highway project kept recycling temperatures low with resulting poor ride quality. In concluding his narrative report, the Project Manager (see

Appendix A) still believed that the HIR process will be beneficial to ODOT if the problems mentioned above can be solved.

In retrospect, it can be seen that the low IRRM value from the preliminary investigation should have warned against including the I-84 shoulders in the project and that pavements with severe stripping should not be recycled with current HIR technology.

3.2.2 Clear Lake-Old McKenzie Highway

This project was located on the Old McKenzie Highway (Hwy. 126) from just north of the road to Clear Lake Lodge at mile point 3.6 to just south of the road to Belknap Springs at mile point 19.81. The ADT for 1992 was 2,300. The existing pavement showed extensive thermal cracking from the severe freeze-thaw conditions. Rutting was also a significant problem. Numerous maintenance actions over the years had left the pavement substantially blade patched.

To determine the mixture quantities, field cores in both lanes were taken from near each end of the project and in the center. The construction mix properties for pre-construction, box samples during HIR, and post-construction are presented in Tables 3.6-3.7.

The pre-construction recovered asphalt showed absolute viscosity ranging from a low of 9,860 poises in the southbound lane at mile point 2.6 to a high value of 50,500 poises in the northbound lane at mile point 17.7. The average pre-construction gradation is "finer" than a "C" mix. The box samples taken during construction show higher percent passing than the pre-construction cores for all sieve sizes of 1/2 inch and smaller. Whether this is due to break-down during HIR or due to pavement variability is not known.

Table 3.6 Recovered Asphalt Properties for Clear Lake-Old McKenzie Highway

Time of Coring	Core Properties				Recovered Asphalt			Remolded Properties		
	Mile Point	Core Density (lb/cf)	Asphalt Content %	Air Voids %	Absolute Viscosity (Poises)	Kinematic Viscosity (cSt)	Penetration @ 25C (dmm)	Air Voids	Hveem Stability	IMMR %
Before Construction	2.6 NB	135.3	5.4	11.6	29,400	1,030	13	0.7		
	2.6 SB	135.8	7.1	12.1	9,860	670	27	0.8		
	11.9 NB	147.8	5.6	6.3	10,500	655	26			129
	11.9 SB	145.5	5.7	7.8	15,500	736	22			111
	17.7 NB	147.5	5.7	6.0	50,500	1,270	22	1.1	13	
	17.7 SB	146.4	6.5	7.2	33,000	614	27	1.2	21	
Average Value	---	143.1	6.0	8.5	24,793	829	23	1.0	17	120
Stan. Dev.	---	5.9	0.7	3.6	15,894	263	12			
During Construction (Box Samples Recompacted in Laboratory)	18.92 NB	151.4	---	0.7	9,940	279	18			
	18.35 SB	15.38	---	2.2	17,400	752	23			
	12.20 NB	151.1	5.7	4.4	12,200	688	28			
	12.23 NB	153.6	6.4	1.9	9,810	576	32			
	12.25 NB	153.9	6.4	0.8	5,270	469	61			
	7.63 NB	152.9	3.9	1.0	9,180	564	28			
	10.42 NB	154.6	14.6	1.1	13,300	661	27			
	8.09 NB	152.8	6.4	3.7	49,700	1,320	16			
	5.24 (?)	154.3	6.2	1.1	9,740	625	31			
Average Value	---	153.2	7.1	1.9	15,171	659	29			
Stan. Dev.	---	1.2	3.4	1.3	14,134	263	13			
Post Construction Cores	11.9 NB	146.0	---	6.8	7,370	534	32			
	11.9 SB	146.5	---	6.9	11,000	645	27			
	17.7 NB	145.8	---	7.5	5,790	552	30			
	17.7 SB	142.1	---	9.9	7,230	551	32			
	18.35 SB	144.5	---	9.5	42,840	1,204	17			
	18.92 NB	139.9	---	10.6	24,180	917	19			
Average Value	---	144.1	---	6.8	16,420	734	26			
Stan. Dev.	---	2.6	---	3.6	14,608	272	2.6			
Comparison Values	New PBA-2				4,000	---	40			
	Typical 20 Yr. Old AC				100,000	---	25			

Note: Comparison values taken from Miles, 1991 Memo

Table 3.7 Aggregate Gradations for Clear Lake-Old McKenzie Highway.

Time of Coring	Mile Point	Sieve Analysis - Percent Passing							
		3/4	1/2	3/8	1/4	#4	#10	#40	#200
Before Construction	2.6 NB	100	100	96	77	65	40	19	8
	2.6 SB	100	99.7	96	85	76	56	28	13
	11.9 NB	100	96	88	74	66	47	23	11
	11.9 SB	100	97	87	75	65	46	22	10
	17.7 NB	100	96	88	74	65	46	23	11
	17.7 SB	100	95	83	67	58	41	19	9
Average Value	-----	100	97.3	89.7	75.3	65.8	46.0	22.3	10.3
During Construction (Box Samples	18.92 NB	----	----	----	----	----	----	----	----
	18.35 SB	----	----	----	----	----	----	----	----
	12.20 NB	100	98	92	79	----	49	25	11.5
	12.23 NB	100	97	92	81	----	52	25	12.1
	12.25 NB	100	98	92	81	----	52	27	13.0
	7.63 NB	100	99	93	81	----	52	27	12.3
	10.42 NB	100	99	94	81	----	49	24	11.2
	8.09 NB	100	98	91	79	----	50	25	11.8
	5.24 (?)	100	98	92	80	----	52	26	11.9
Average Value	----	100	98.1	92.3	80.3	----	50.9	25.6	12.0

ODOT Typical B- and C-mixes. (Miles,1991)

B-mix	96	80	70	57	49	28	11	5
C-mix	100	98	86	62	51	29	12	6

Remolded specimens were tested for air voids, Hveem stability, and IRRM. These values are included in Table 3.6. No stripping potential was indicated, but stabilities and air voids values did not meet ODOT design criteria for dense-graded hot mix, even without addition of RA.

To estimate the addition rate for the RA, the nomograph from ASTM D4887-89 was used with a target viscosity of 9,000 poises for both RA-5 and RA-25. For RA-5, the recommended addition rate would have been 0.5 percent in the southbound lane and 0.7 percent in the northbound lane. Because RA-25 was thought to be more tolerant of variations in asphalt properties, it was selected for use with laboratory recommendations of 0.8 percent in the southbound lane and 1.0 percent in the northbound lane.

Construction began June 1, 1992, at mile point 19.81 in the southbound lane. The Project Manager, in her narrative construction summary, noted that it soon became apparent that the initial add rate of Cyclogen M (RA-25) was excessive and "... *that the mix would go to zero voids and probably flush. The mix slumped in the windrow at this add rate.*" (See project manager's report, Appendix A.) The add rate for RA was lowered to 0.5 percent but adjustments for field conditions resulted in an average of 0.54 percent for the remainder of the project.

During construction, nine box samples taken at various locations throughout the section were recompacted and tested in the ODOT laboratory for Hveem stability. The results of these lab tests (see Table 3.6) predicted rutting problems for the HIR pavement. Stability numbers averaged 22, well below the design criteria value of 35 for medium traffic roads. The percent air voids averaged 1.9 percent, well below the recommended 4 percent. Only two of the nine tests were above the 3 percent minimum.

In construction, only minor problems were noted, the most significant pertaining to how the equipment performed on steep grades. On grades up to 10 percent, the equipment worked fine. Over 10 percent, the equipment bogged down, causing the pavement to ripple. By transporting the equipment up the grade and working downhill against traffic, the problem was solved.

The project was completed on July 28, 1992, in 57 days, of which 8 days were lost to equipment breakdown, 10 to rain or wet conditions, and one for an extra pass on Sahalie Falls access road. The contractor used 85.97 tons of RA-25 for 242,578 square yards, for an average add rate of 0.54 percent RA.

The Clear Lake-Old McKenzie Highway project demonstrated the rejuvenating abilities of HIR. Table 3.8 compares the preconstruction and post construction core properties at four locations and shows that the asphalt was considerably softened by HIR. The averaged results show that 1 percent air voids was gained, absolute viscosity decreased from 27,000 to 8,000 poises, and penetration increased from 24 to 30 dmm.

Table 3.9 compares the properties of lab specimens prepared from box samples taken during construction (after addition of RA) and the post construction cores taken 15 months after construction at two locations. The higher densities and lower air voids from the "after" cores suggest greater compactive effort in the laboratory than in the field. Measured viscosities are much higher for the post-construction cores than for the box samples taken at the time of construction. Measured penetration values do not agree with the viscosity readings. Some hardening would be expected in the 15 months after construction, but not the level suggested by the viscosity measurements.

Table 3.8 Comparison of Pavement Properties Before and After HIR for Clear Lake-Old McKenzie Highway.

Mile Point	Core Density (lbs/cf)				Air Voids (%)				Absolute Viscosity (Poises)				Kinematic Viscosity (cSt)				Penetration @ 25c (dmm)			
	Bef.	Aft.	Diff.	% Diff	Bef.	Aft.	Diff.	% Diff	Bef.	Aft.	Diff.	% Diff	Bef.	Aft.	Diff.	% Diff	Bef.	Aft.	Diff.	% Diff
11.9 NB	147.8	146.0	-1.8	-1%	6.3	6.8	0.5	8%	10500	7370	-3130	-30%	655	534	-121	-18%	26	32	6	23%
11.9 SB	145.5	146.5	1.0	1%	7.8	6.9	-0.9	-12%	15500	11000	-4500	-29%	736	645	-91	-12%	22	27	5	23%
17.7 NB	147.5	145.8	-1.7	-1%	6.0	7.5	1.5	25%	50500	5790	-44710	-89%	1270	552	-718	-57%	22	30	8	36%
17.7 SB	146.4	142.1	-4.3	-3%	7.2	9.9	2.7	38%	33000	7230	-25770	-78%	614	551	-63	-10%	27	32	5	19%
Average	146.8	145.1	-1.7	-1%	6.8	7.8	0.95	14%	27375	7848	-19528	-71%	819	571	-248	-24%	24	30	6	25%
Stan. Dev	0.9	1.8			0.7	1.3			15750	1922			264	44			2.3	2.0		

Table 3.9 Comparison of Properties of Laboratory Specimens prepared from Box Samples Taken During Construction with Properties of Cores Taken at the Same Locations 15 Months After Construction for Clear Lake-Old McKenzie Highway.

Mile Point	Core Density (lb/cf)				Air Voids (%)				Absolute Viscosity (Poises)				Kinematic Viscosity (cSt)				Penetration @25C (dmm)			
	Lab.	Aft.	Diff.	% Diff.	Lab.	Aft.	Diff.	% Diff.	During	Aft.	Diff.	% Diff.	During	Aft.	Diff.	% Diff.	During	Aft.	Diff.	% Diff.
18.35 SB	153.8	144.5	-9.3	-6.0	2.2	9.5	7.3	332	17,400	42,840	25,440	146	752	1,204	452	60	23	17	-6	-26
18.92 NB	151.4	139.9	-11.5	-7.6	0.7	10.6	9.9	1,414	9,940	24,180	14,240	143	279	917	638	229	18	19	1	6

Note: During HIR specimens were recompacted in the laboratory.

Table 3.10 Before and During HIR Aggregate Gradations for Clear Lake-Old McKenzie Highway.

Mile Point	Sieve Analysis - Percent Passing													
	3/4		1/2		3/8		1/4		#10		#40		#200	
	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.
11.9 NB-12.2 NB*	100	100	96	98	88	92	74	80	47	51	23	26	11	12

Note: 12.2 NB is the average of three box samples taken at Mile Point 12.20, 12.23, and 12.25 NB.

Figure 3.5 Good section on Clear Lake-Old McKenzie Hwy. two years after HIR. (Looking southward near mile point 17.7.)

Figure 3.6 Minor problem area, what appears to be a previous coring site. (Looking northward near mile point 17.7.)

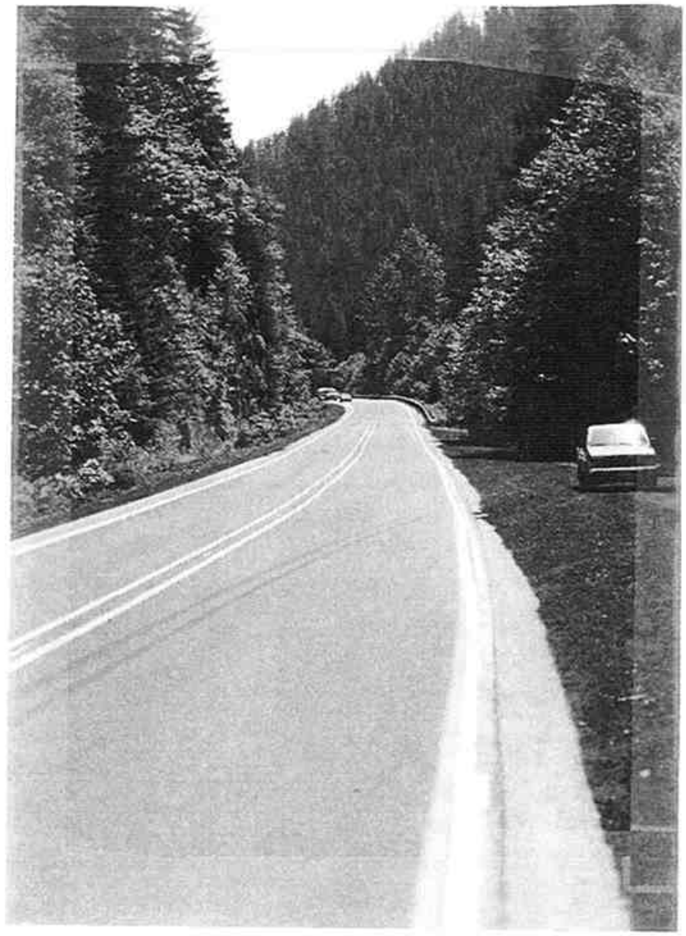


Figure 3.7 Section on Clear Lake Highway near mile point 15.3, looking good two years after HIR.

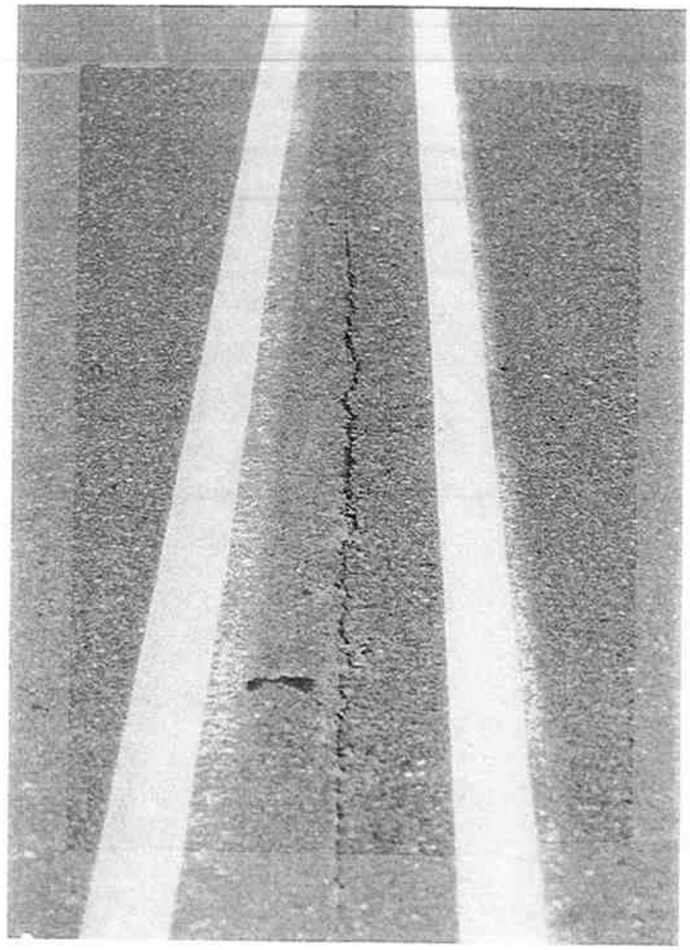


Figure 3.8 Section where centerline "seam" pulled apart near mile point 12.8.

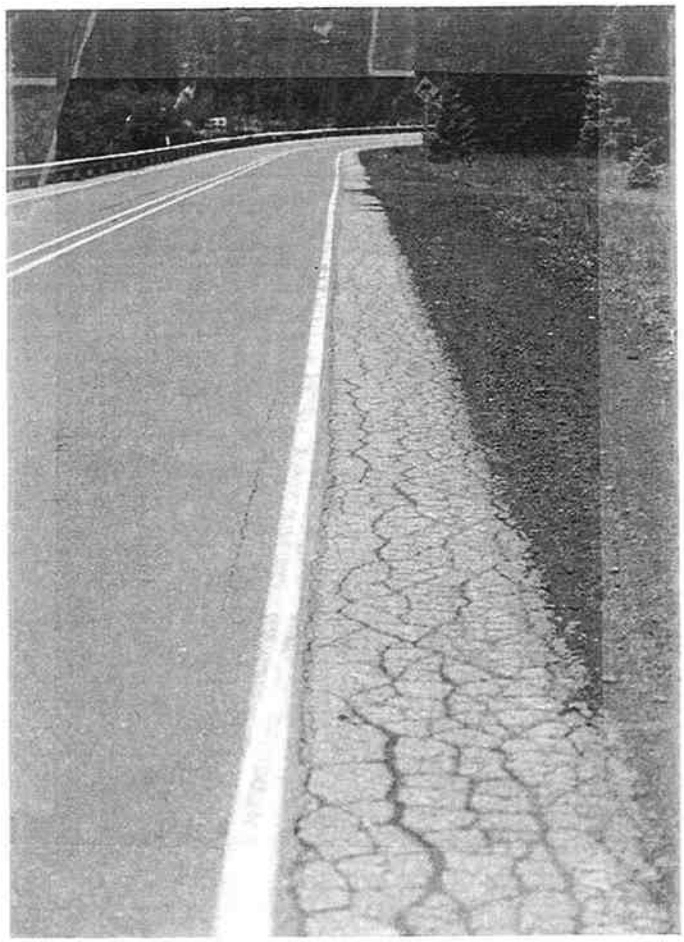


Figure 3.9 Longitudinal cracking near the fog line, along with extensive thermal cracking in the non-recycled shoulder near mile point 12.8.

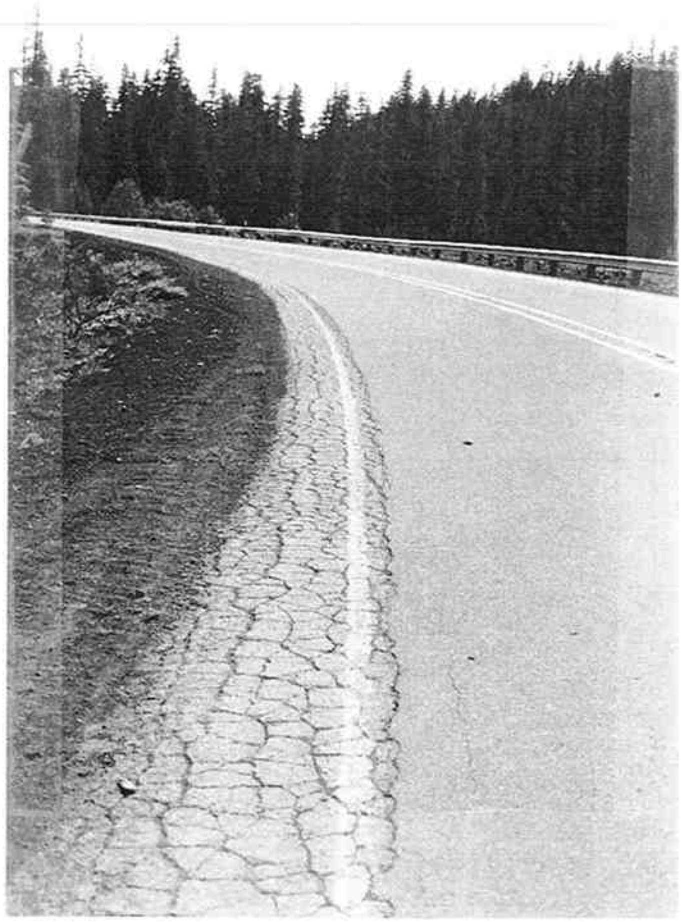


Figure 3.10 Section where the HIR recycling train "missed" the curve taken near mile point 11.5. The seam is just at the edge of the alligator cracking.

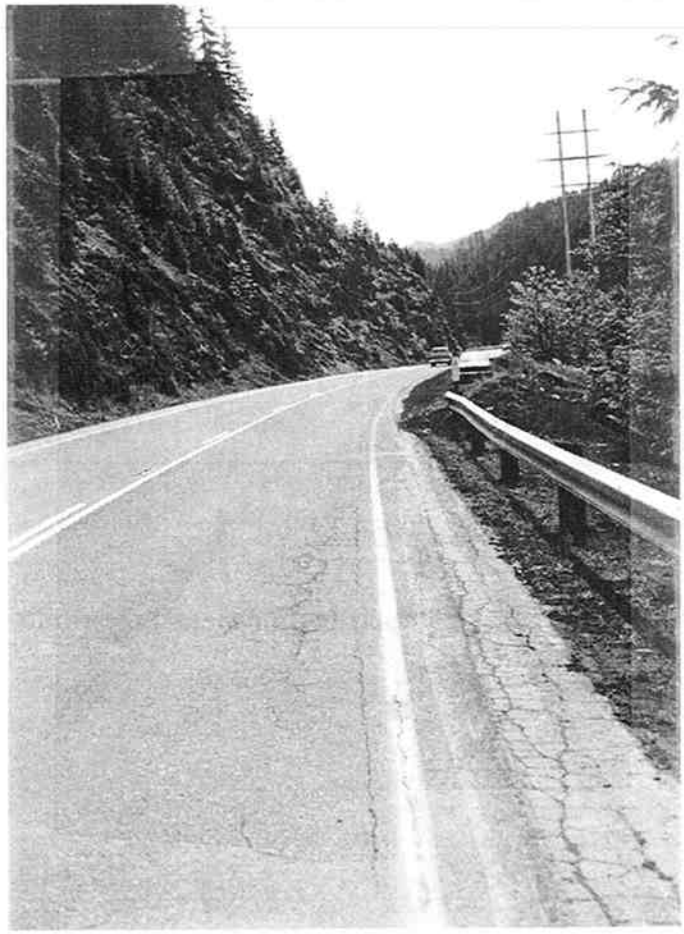


Figure 3.11 Section with reflective cracking breaking through the HIR pavement near mile point 11.1.

Figure 3.12 Patched section near mile point 11.0.

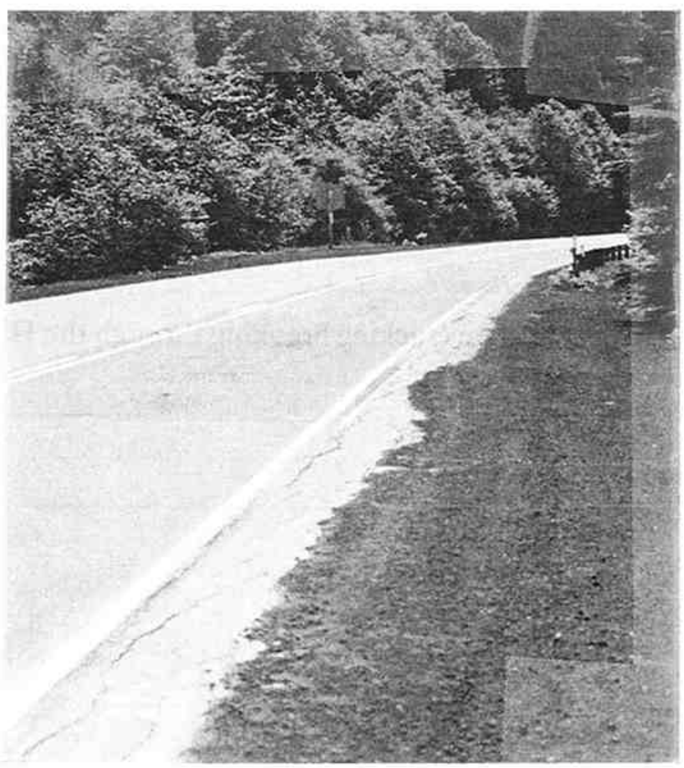


Figure 3.13 Patched section near mile point 10.3.

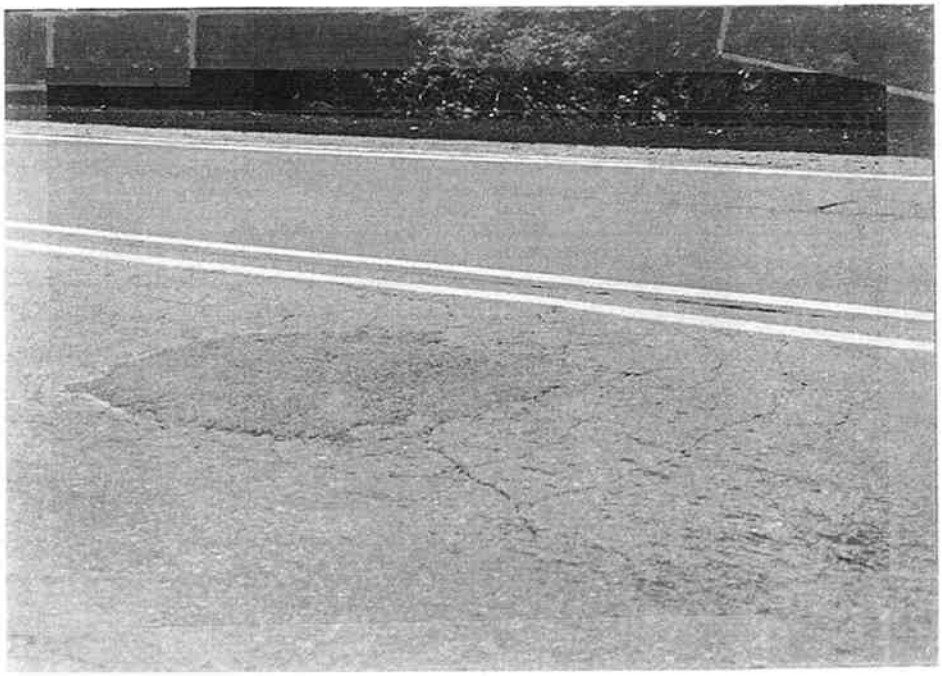


Figure 3.14 Section with major patch and cracking near mile point 8.7. Note reflective cracking in other lane.

Figure 3.15 Good section near mile point 7.4.

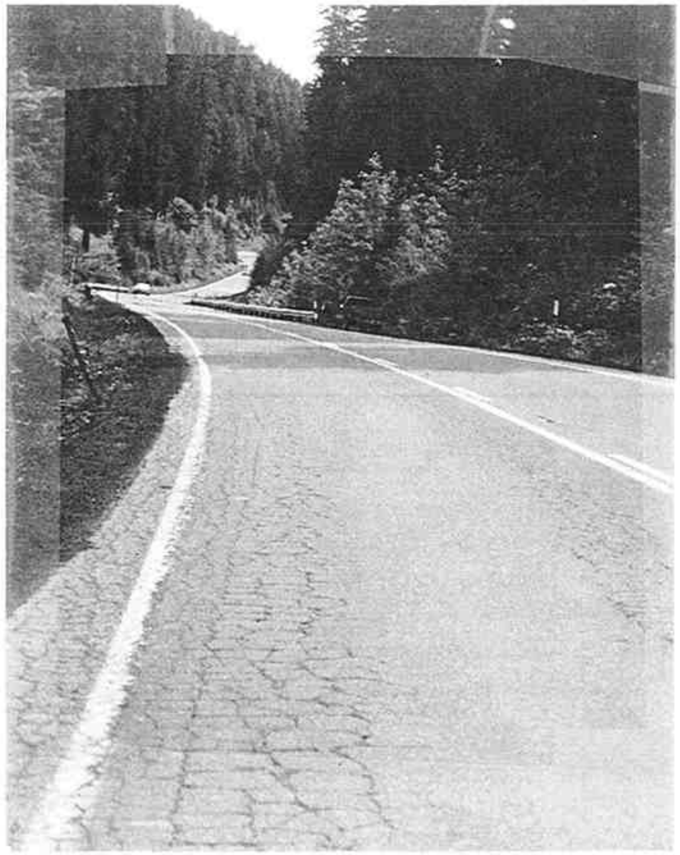


Figure 3.16 Section with extensive reflective cracking near mile point 5.1.

Figure 3.17 Close-up of section with heavy reflective cracking near mile point 5.1.

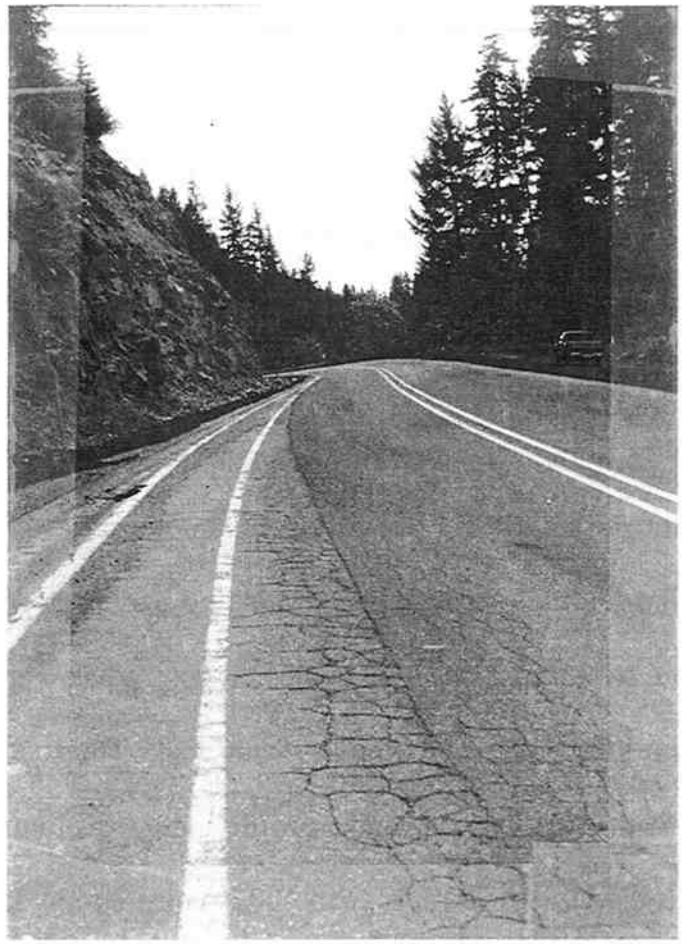


Figure 3.18 Section where cracking in pre-HIR pavement has reflected through near mile point 5.1.

reflective cracking has broken through the HIR pavement, also near mile point 5.1. Figure 3.19 shows a section where the patching is delaminating. Figure 3.20 shows a section where the HIR pavement has a very irregular edge seam near mile point 5.4. Figure 3.21 shows a section where the HIR recycling train missed part of the lane near mile point 5.4. Figure 3.22 shows a section approximately 100 feet long where it appears a chunk of asphalt was dragged by the paver. Figure 3.23 shows a patched section near the entrance to Coldwater Cove near mile point 4.5 at the northern end of the HIR project.

The Clear Lake-Old McKenzie Highway project demonstrated the ability of HIR to produce a quality riding surface as the completed mat resembled a very fine "C" mix. It looked slick enough that friction tests were scheduled for the completed project shortly after completion. The southbound lane was tested and had an average friction number of 61.6. After the initial winter season, it was retested with a new value of 66.4. Both values are excellent, comparing quite well with a new chip seal. The southbound lane was also tested for roughness with the South Dakota profilometer to obtain the average international roughness index (IRI). An IRI less than 100 is considered good. After HIR, Clear Lake-Old McKenzie Highway had an IRI of 91.4 which is quite good for a pavement rehabilitation.

<u>Summary</u>. This project was easily the most successful HIR project of the six undertaken in Oregon in spite of what would be expected from the testing of laboratory specimens prepared from box samples taken during construction. HIR rejuvenated the pavement and increased the air voids. After 24 months, the recycled pavement appears to be holding up quite well in spite of the pre-HIR pavement distress from rutting, alligator cracking, and the extensive blade patching. There are isolated sections where the alligator

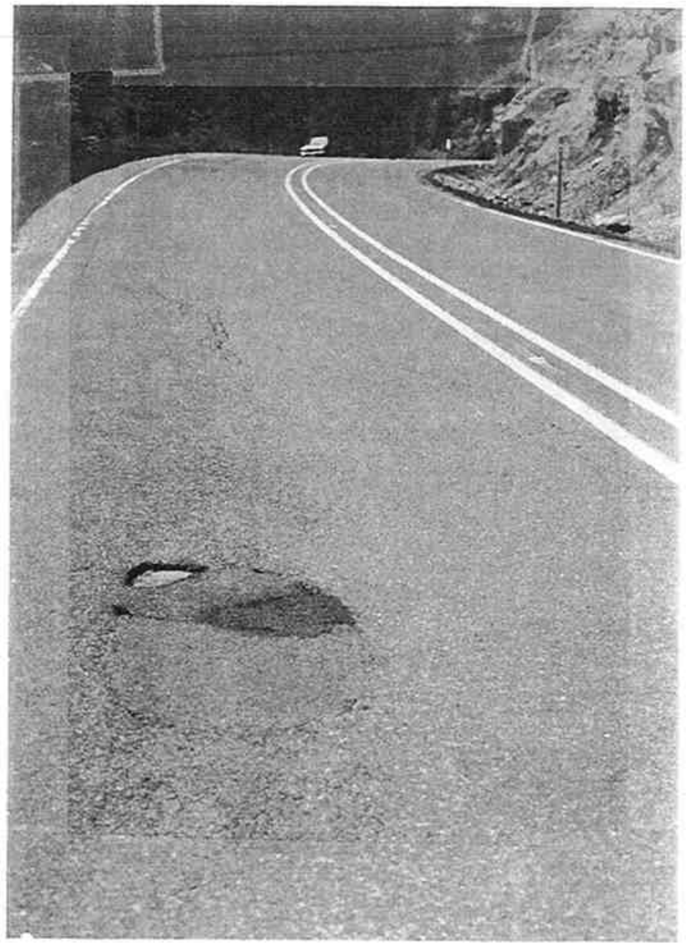


Figure 3.19 Patched section in HIR pavement between mile points 5.0 and 5.5.

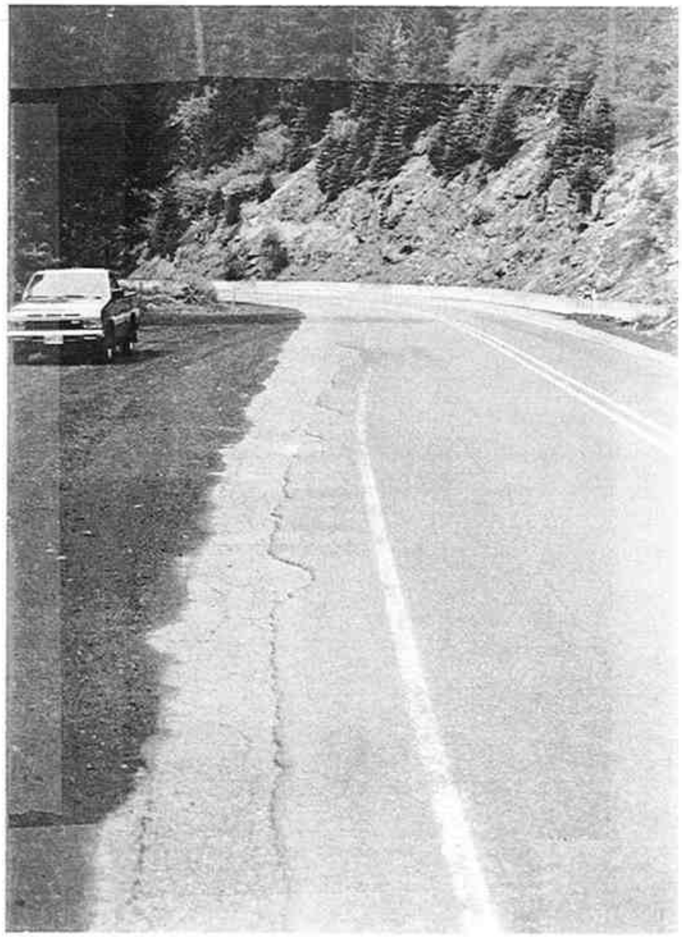


Figure 3.20 Section where HIR pavement has irregular edge seam near mile point 5.4.

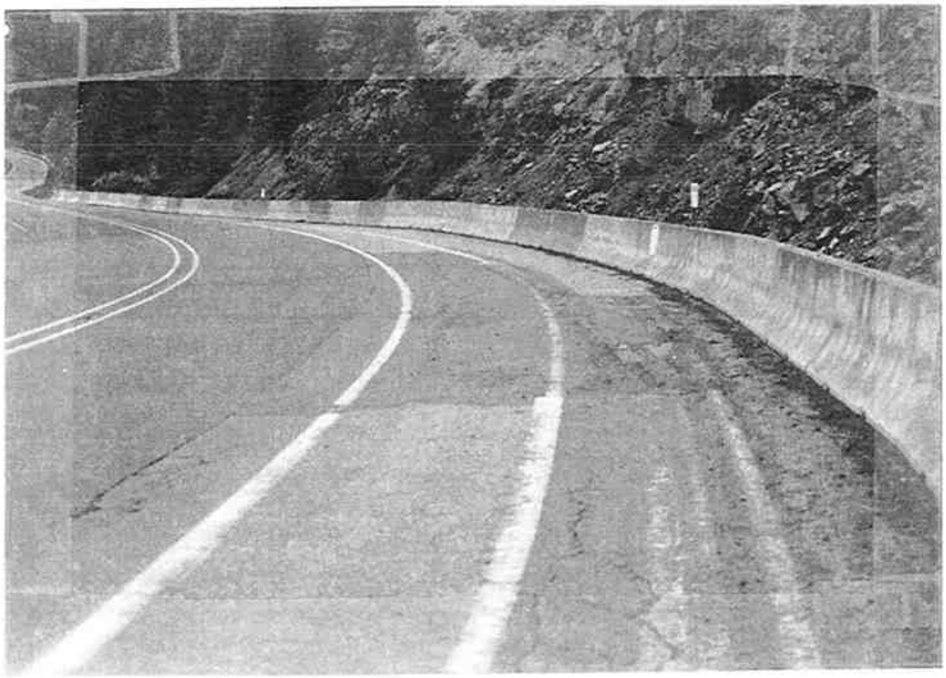


Figure 3.21 HIR edge seam well inside of fogline near mile point 5.4.

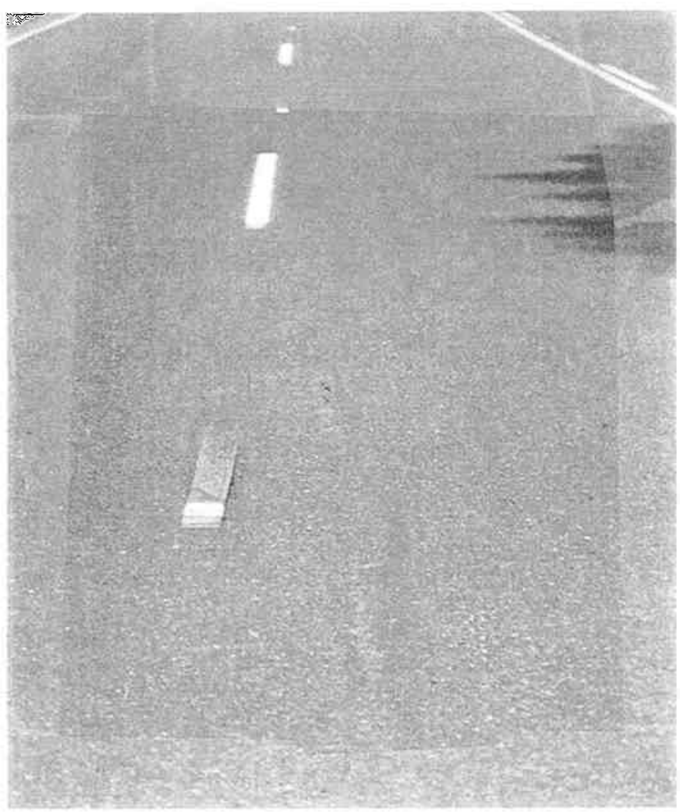


Figure 3.22 Section where asphalt chunk was dragged by paver near mile point 5.4.

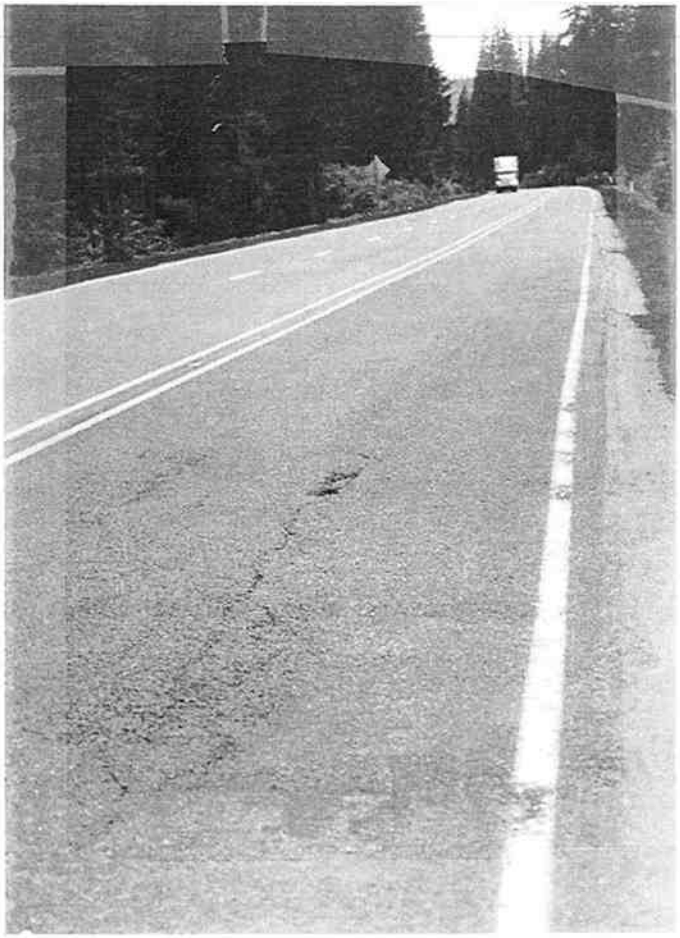


Figure 3.23. Patched HIR section near entrance to Coldwater Cove near mile point 4.5.

cracking has begun reflecting through the HIR pavement including a one half-mile long section near mile point 5.0. It is likely that this section experiences subgrade problems which make the existing structural section inadequate.

3.2.3 N. Grants Pass-Jumpoff Joe Creek

This project is the section of Interstate 5 located between N. Grants Pass at mile point 58.2 and Jumpoff Joe Creek at mile point 67.1. The 1992 ADT for the section was 17,000. This was the first project where HIR was to be performed on the existing pavement with the intent of overlaying it later with an open-graded wearing surface.

Preliminary investigation consisted of coring the section at four locations. The pre-construction recovered asphalt properties and aggregate gradations are shown in Tables 3.11-3.12. This data shows the existing pavement to be uniform in gradation, asphalt content, viscosity, and penetration. The recovered asphalt was much "softer" than would be expected for a 20 year old pavement. The mix design for this project again used the ASTM D4887-89 nomograph. The average value of absolute viscosity (14,350 poises) was used with the nomograph and the viscosity of RA-25 to predict an average add rate of 0.3 percent to achieve rejuvenation to 9,000 poises.

Construction began on July 7, 1992. Almost immediately, problems began to surface with the quality of the contractor's RA. The first test sample of RA failed the viscosity requirement. This led to sample coring the first two miles of work. Results from testing the cores were inconclusive. Throughout the project, there were problems with inadequate certification for the RA used. In addition to the RA-25, some out-of-specification RA-5 was used. The combined total amounts of certified RA-25 and RA-5 never equaled the quantity used on the project, leading to a price reduction of almost $28,000 on the project. The lack

Table 3.11 Recovered Pre-construction Asphalt Properties for N. Grants Pass-Jumpoff Joe Creek.

Mile Point	Asphalt Content %	Recovered Asphalt Properties		
		Absolute Viscosity	Kinematic Viscosity	Penetration @25C
61.5	6.3	15,400	1,030	32
64.6	5.9	16,600	924	29
64.6	6.0	11,800	883	34
62.4	5.9	13,600	882	31
Average Value	6.0	14,350	672	32

New PBA-2	4,000	----	40
Typical 20 Yr. Old Asphalt	100,000	----	25

Table 3.12 Extracted Pre-construction Aggregate Gradations for N. Grants Pass-Jumpoff Joe Creek.

Mile Point	Sieve Analysis - Percent Passing						
	3/4	1/2	3/8	1/4	#10	#40	#200
61.5	100	93.4	82.6	65.2	34.0	13.9	5.7
64.6	100	82.4	67.1	74.0	35.0	14.7	5.5
64.6	100	88.9	76.9	63.2	33.7	14.6	6.5
62.4	99.6	93.1	82.1	68.8	38.0	16.4	6.5
Average Value	99.9	89.5	77.2	67.8	35.2	14.9	6.1

ODOT Standard Specifications.

B-mix	92-100	75-91	----	50-70	21-41	6-24	2-7
C-mix	99-100	90-100	----	52-80	21-46	8-25	3-8

of control over quality and quantity of RA used on this project makes it difficult to analyze the rejuvenating effects of HIR.

Table 3.13 presents various mix properties of box samples taken during construction. Comparing Tables 3.11 and 3.13, it is quite apparent that HIR didn't rejuvenate the pavement. HIR aged the pavement severely, increasing the average absolute viscosity from 14,350 to 320,000 poises for both lanes and decreasing the average penetration at 25°C from 32 to 16 dmm. Specimens prepared from these box samples indicated inadequate air voids and 4 out of 8 stabilities below the required value of 35. These results may not be significant considering that at Clear Lake Highway, specimens compacted from box samples did not predict post-construction core values. Post-construction cores have not been taken on this project.

Other problems related to HIR were noted in the Project Manager's narrative report (see Appendix A). The scheduling of HIR paving operations at night presented an additional challenge to safe operation and for traffic control. The project was conducted during the fire season which raised great concern about the threat of a fire coming from the preheaters. The contractor was required by the Oregon Department of Forestry to have two fire trucks on the job site during HIR operations. Pollution control was also a problem. The contractor wasn't using state of the art pollution control equipment, and work had to be shut down twice to repair broken air emission controls. The HIR work was completed on July 26, 1992, 19 days after starting work.

Table 3.13 Recovered Mix Properties for N. Grants Pass-Jumpoff Joe Creek.

Time of Sampling	Mile Point	Unit Wt. (lb/cf)	Asphalt Content %	Air Voids %	Hveem Stability	Recovered Asphalt		
						Absolute Viscosity (Poises)	Kinematic Viscosity (cSt.)	Penetration at 25C (dmm)
During Construction (Box Samples Compacted in Laboratory)	60.6 NB	156.6	5.4	2.1	41	108,000	1,870	22
	61.1 NB	156.9	5.7	3.3	54	148,000	2,450	18
	62.1 NB	157.2	5.9	0.6	13	93,600	1,940	22
	62.7 NB	157.6	4.9	1.4	21	376,000	3,250	16
	63.9 NB	156.9	5.5	0.7	11	Too Thick	6,680	10
	64.3 NB	156.4	5.3	2.6	40	317,000	3,060	15
	65.9 NB	155.0	4.9	1.8	35	518,000	3,970	13
	66.5 NB	153.9	5.2	1.7	21	Too Thick	7,510	9
Average	NB Lane	156.3	5.4	1.8	30	260,100*	3,841	16
During Construction Core Samples	66.9 SB	----	----	----	----	70,900	1,640	22
	66.4 SB	----	----	----	----	311,000	2,560	14
	64.8 SB	----	----	----	----	564,000	2,270	10
	63.4 SB	----	----	----	----	183,000	4,030	18
	62.8 SB	----	----	----	----	161,000	2,670	16
	62.0 SB	----	----	----	----	990,000	4,130	12
Average	SB Lane	----	----	----	----	379,983	2,883	15

* Average NB lane absolute viscosity is based on 6 values.

Summary. The N. Grants Pass-Jumpoff Joe Creek project was the first HIR project where the recycled mat was overlaid with an open-graded wearing course. Comparing the pre- and post-HIR asphalt properties, recycling didn't rejuvenate the pavement, as it increased the average absolute viscosity from 14,350 to 320,000 poises for both lanes and decreased the average penetration from 32 to 16 dmm. This project also identified HIR concerns regarding fire danger and air pollution control, and highlighted the importance of contractor skill and equipment condition. This project, which included an open-graded HMA overlay, has not shown distress in the two years since construction.

3.2.4 Tangent-Halsey

This project is a section of the Albany-Junction City Highway located between Tangent and Halsey in Linn County. The 1988 ADT was between 2,300 and 3,700. Construction records show that the center 16 feet of the existing pavement structure was built prior to the 1930's and was widened 4 feet on either side in the mid-to-late 1930's. Other than being immediately covered with a 5/8 inch thick bituminous macadam wearing surface after being widened, there was no major construction on this section prior to HIR. Maintenance and construction over the years included adding shoulders, blade patching, and overlays. The existing section was quite weathered and had significant problems with longitudinal and transverse cracking, stripping, and flushing. Patching was extensive, covering more than 80 percent of the wearing surface.

To determine mix qualities, pre-construction sampling of the existing pavement included both grindings and cores. Recovered asphalt and gradation properties are shown in Tables 3.14-3.15. The pre-construction recovered asphalt properties were quite varied. Absolute viscosity averaged 40,000 poises, ranging between 4,000 and 80,000 poises. Also,

Table 3.14 Recovered Pre-construction Asphalt/Mixture Properties for Tangent-Halsey HIR Project.

Time of Sampling	Mile Point	Core Density (lb/cf)	Asphalt Content %	Remolded Specimens		Recovered Asphalt Properties		
				Air Voids %	Hveem Stability	Absolute Viscosity (Poises)	Kinematic Viscosity (cSt)	Penetration @25C (dmm)
Before HIR Millings	8.6 NB	----	5.7	----	----	10,600	498	21
	14.7 NB	----	4.0	----	----	80,000	1,960	4
	19.20 NB	----	5.4	----	----	67,600	1,170	9
	10.6 SB	----	5.9	----	----	10,900	543	19
	16.6 SB	----	5.4	----	----	60,100	1,210	8
Average Value	----	----	2.6	----	----	45,840	1,076	9
Before HIR Cores	9.6 SB	146.6/151.6	6.2	4.4/1.2	41/44	22,200	775	12
	11.6 SB	150.4/152.3	6.0	1.6/0.3	11/2	4,010	382	41
	14.7 SB	149.8/153.5	5.6	2.8/0.3	27/8	25,900	829	15
	16.6 SB	151.0/154.1	5.5	2.1/0.0	22/5	43,900	1,100	10
	19.2 SB	144.8/150.4	5.9	7.2/3.6	54/56	80,000	2,610	4
Average Value	----	148.5/152.4	5.8	3.6/0.5	31/23	35,202	1,139	16
During HIR (Box Samples)	18.88	151.7	5.6	2.8	36	70,100	1,290	10
	14.49	150.6	5.9	1.5	28	6,260	455	35
	13.95	149.8	4.9	5.1	36	102,000	1,490	9
	11.46	153.1	6.8	0.7	9	2,350	285	56
Average Value	----	113.4	5.8	2.5	25	45,178	880	25

Table 3.15 Aggregate Gradations for Tangent-Halsey HIR Project.

Time of Sampling	Mile Point	Sieve Analysis - Percent Passing							
		3/4	1/2	3/8	1/4	#4	#10	#40	#200
Before HIR Millings	8.6 NB	100	100	96	88	80	58	30	13.7
	14.7 NB	100	97	86	68	57	33	16	5.5
	19.20 NB	100	98	90	75	63	38	16	6.9
	10.6 SB	100	98	92	79	68	45	19	7.8
	16.6 SB	100	96	88	72	62	38	17	7.5
Average Value	----	100	78	90	76	66	42	20	5.5
Before HIR Cores	9.6 SB	100	97	86	63	----	31	14	6.4
	11.6 SB	100	96	87	68	----	37	16	7.4
	14.7 SB	100	93	80	62	----	33	15	6.5
	16.6 SB	100	92	79	62	----	32	14	6.1
	19.2 SB	100	95	84	69	----	32	13	5.2
Average Value	----	100	95	83	52	----	33	14	6.3
During HIR (Box Samples)	18.88	100	94	81	64	53	32	14	7.2
	14.49	100	94	80	62	51	32	14	6.4
	13.95	100	95	79	56	44	26	12	5.3
	11.46	100	97	89	67	57	37	15	6.8
Average Value	----	100	95	82	60	41	32	14	6.4

B-mix	92-100	75-91	----	50-70	----	21-41	6-24	2-7
C-mix	99-100	90-100	----	52-80	----	21-46	8-25	3-8

the average penetration was 14 dmm, ranging between 4 and 41 dmm. This variability suggests the extent of patching. Testing of specimens remolded from cores (no RA) showed widely varying Hveem stability and air voids. Three of five locations did not meet stability and air voids design criteria. RA-5 was selected and was estimated at 0.2 percent by weight of RAP (0.44 lb/yd^2) using the core data and ASTM D4887-89. Because the pavement surface was so heavily patched, the RA addition rate was expected to vary significantly. Also, it was anticipated that some virgin material might be required in thin areas of the pavement.

Construction began on August 3, 1992. and was completed on September 2, 1992. The contractor's equipment was old and poorly maintained. Because of problems with equipment breakdowns, weather, and the poor condition of the pavement being recycled, the project took 31 days to complete instead of the 12 estimated. The pavement had major stripping problems and much of the blade patching had delaminated. The stripped asphalt was partially burned by the heaters, leaving the recycled mix very dry and vulnerable to raveling. At first, this was corrected by patching raveled areas with new mix and later by adding between 9 and 27 percent virgin "C" mix to the windrow. When the project was completed, these areas were covered with a sand seal to protect the pavement from further raveling.

The delaminated blade patches posed a more difficult problem. The scarifier on the recycling equipment would scrape open pockets of loose rock which wouldn't bond with the recycled mixture. These sections also raveled out and required patching. To keep from scraping out these pockets of loose rock, the recycling depth was decreased to less than 2 inches. This was only partially successful because it was very difficult to predict the depth of delamination until it was exposed.

A final construction problem worth mentioning occurred whenever the lane width got below 12 feet. From the Project Manager's narrative (see Appendix A):

> *The heaters and milling heads of these machines are set at 12 feet. Because of the lane widths were less than 12, we had to reduce the scarifying path to eleven feet to accommodate the variable width of the roadway and to keep the meet line from occurring in the wheeltrack of the southbound lane. While the contractor could pull the outside teeth from the scarifier, the widths of the heater banks could not be reduced; therefore the northbound lane from fogline to edge of pavement was subjected to the same intense temperatures of the heater banks as the travel lane. This heat aged the asphalt in the pavement needed for bonding the recycled mix to the existing pavement, causing transverse cracks at the fogline seam. It also resulted in a certain width in the center to be recycled twice. Obviously, highways with lane widths less than 12 feet are not good candidates for this* [HIR] *process.*

Some of the problems encountered during the Tangent-Halsey HIR project are shown in Figures 3.24-3.29. Figures 3.24-3.25 contrast the pre- and post-HIR pavement, showing the poor condition of the existing pavement. In Figure 3.24, the three small patches mark where the pre-construction pavement was milled. This pre-construction milling "uncovered" the problem with the thinness of the widened section of the highway as the unbound base material was milled up along with the pavement. Figure 3.25 shows cracking and what appears to be flushing at another section of the road. Figure 3.26 shows the raised edge seam produced by the added virgin mix. The raveling produced by the delaminations is shown in Figures 3.27-3.28. After the project was completed the raveled areas were patched, then covered with a sand seal as shown in Figure 3.29. Figures 3.25 and 3.27 shows how far the recycling equipment extended over the center line which resulted in the HIR seam being in the wheel track in places.

Figure 3.24 Section contrasting pre- and post-HIR pavement. The patched areas mark where the pre-construction pavement was milled.

Figure 3.25 Section showing cracking and apparent flushing.

Figure 3.26 Section showing the raised edge seam produced by the added virgin mix.

Figure 3.27 Raveled section after HIR.

Figure 3.28 Close-up of raveled section.

Figure 3.29 Freshly sand sealed area with visible patched area.

Summary. Prior to HIR, the Tangent-Halsey pavement was the most distressed of the six ODOT projects, with extensive cracking, stripping, flushing, and patching. In retrospect, this pavement should not have been selected for HIR due to extreme variability and layer delaminations. The finished pavement didn't perform well and was overlaid after one year of service. While the project was less than successful, it did identify some of the limits of HIR and where it should not be used.

3.2.5 Cline Summit

This project was originally intended to be a two unit HIR project recycling a 24-foot panel of roadway surface to a depth of 2 inches. Unit A was on Pacific Highway West (Hwy. 1W), beginning just south of Kiger Island Road at mile point 86.23 and continuing to just north of the Bruce Road intersection at mile point 95.63. Unit B was on the Corvallis-Newport Highway (Hwy. 20) beginning at the west base of Cline Hill at mile point 29.20 and continuing to the east base of Cline Hill at mile point 31.40. Pre-construction field cores taken at twenty random locations throughout Unit A showed that significant stripping problems, alligator cracking, and delamination between the pavement layers were present. Because the same problems had plagued the Tangent-Halsey HIR project, it was decided to delete Unit A from the project.

Unit B had some of the same problems but was in better condition overall. Construction records showed that the 2.20-mile long section had been realigned and constructed in 1963 to provide a climbing lane for east bound traffic. Pavement width varied between 30.0 and 46.5 feet with three 12-foot travel lanes, two east bound and one west bound. The existing pavement structure was constructed with a 17-inch stone base, 2-4 inches of bituminous binder base, a 2 inch asphalt concrete base lift, and a 1.5-inch wearing surface. The ADT was 3,400. The pre- and post-construction data for this project are shown in Tables 3.16-3.17. RA-25 was selected with an estimated quantity of 0.2 percent by weight of RAP based upon the Project Manager's experience, as this was her third HIR project.

Construction began on October 21, 1992, using Artec multi-stage equipment. Despite being slowed by problems with moist pavement from the previous days rain, construction went smoothly. As work progressed, problems with the pavement layers delaminating approximately 2.5 to 3 inches below the surface developed and intensified. Chunks of RAP would break loose as the recycling equipment passed over it and clog the paver augers or were floating free in the completed mat. To correct this problem, the milling depth was increased to try to recycle the whole layer, but this didn't work.

Another problem was rutting, which had created a 1 to 2 inch crown in each lane. To use all of the milled RAP, either the new mat was "crowned" or the mat was paved on a plane surface with the edges thicker than usual. Other problems were with the new mat not bonding properly at the edges and some minor stripping. Because of the delamination and rutting/crown problems, recycling was halted after 4 days of construction. None of the west bound lane was done and recycling of the eastbound lane stopped 3,500 feet short of the west end of the project. Comparing before and post-HIR asphalt properties for the one common coring location as shown in Table 3.18 gave mixed results. Asphalt binder stiffness measurements are contradictory. Absolute viscosity decreased from 33,300 poises to 23,000 poises while at the same time penetration decreased from 27 dmm to 20 dmm. Table 3.19 compares the gradation before and after HIR at this location and indicates the possibility of some aggregate crushing during hot milling.

Table 3.16 Before, During, and Post-construction Asphalt Recovery Data for Cline Summit HIR Project.

Time of Sampling	Mile Point	Core Density (lb/cf)	Asphalt Content %	Air Voids %	Recovered Asphalt Properties		
					Absolute Viscosity (Poises)	Kinematic Viscosity (cSt)	Penetration @25C (dmm)
Before HIR	30.5 EB	135.2	5.5	2.5	33,300	682	27
During HIR	30.0 EB	----	6.2	----	32,100	1,240	17
	30.3 EB	----	5.6	----	116,000	2,230	10
	31.0 EB	----	5.8	----	64,000	1,450	13
	31.35 EB	----	6.5	----	4,350	318	85
Average	----	----	6.0	----	54,113	1,310	31
Stan. Dev.	----	----	0.3	----	41,499	681	31
Post HIR	30.5 EB	----	----	----	23,000	----	20

Table 3.17 Before, During, and Post-construction Aggregate Gradations for Cline Summit HIR Project.

Time of Sampling	Mile Point	Sieve Analysis - Percent Passing							
		3/4	1/2	3/8	1/4	#4	#10	#40	#200
Before HIR	30.5 EB	100	90	79	63	52	33	18	9
During HIR	30.0 EB	100	90	80	65	55	35	20	8
	30.3 EB	100	93	81	66	55	35	20	8
	31.0 EB	100	91	82	67	57	37	21	8
	31.35 EB	100	91	78	62	52	33	18	7
Average	----	100	91	80	65	55	35	20	8
Stan. Dev.	----	0	1	1	2	2	1	1	0
Post HIR	30.5 EB	100	94	85	72	62	41	22	9

ODOT Standard Specification

B-mix	92-100	75-91	----	50-70	----	21-41	6-24	2-7
C-mix	99-100	90-100	----	52-80	----	21-46	8-25	3-8

Table 3.18 Comparison of Before and After HIR Asphalt Properties for Cline Summit HIR Project.

Mile Point	Absolute Viscosity (Poises)				Kinematic Viscosity (cSt)				Penetration @ 25C (dmm)			
	Bef.	Aft.	Diff.	%Diff.	Bef.	Aft.	Diff.	%Diff.	Bef.	Aft.	Diff.	%Diff.
30.5 EB	33,300	23,000	-10,300	-31	682	----	----	----	27	20	-7	-26

Table 3.19 Before and During Construction Aggregate Gradations for Cline Summit HIR Project.

Mile Point	Sieve Analysis - Percent Passing															
	3/4		1/2		3/8		1/4		#4		#10		#40		#200	
	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.	Bef.	Dur.
30.5 EB	100	100	90	94	79	85	63	72	52	62	33	41	18	22	9	9

Figures 3.30-3.41 show the condition of the Cline Summit HIR project twenty-two months after completion. The photographs begin at the starting point of HIR and document the problem areas of the project. Figure 3.30 is a photograph (looking East) of the patched area at the beginning of the HIR project at milepost 31.4. Figure 3.31 shows raveling and patching at the end of the slow moving vehicle turnout lane near mile point 31.2. Figure 3.32 shows a section where the meet line in the two HIR lanes did not bond together well. Figure 3.33 shows a poor looking section in the slow moving vehicle turnout lane near mile point 30.9. Figure 3.34 shows a close-up of the poor section near mile point 30.9. Figure 3.35 shows a patched, very rough looking section followed by a very good section near mile point 30.8. Figure 3.36 is a close-up of a raveled section near mile point 30.6. Figure 3.37 shows a close-up of cracking near mile point 30.6. Figure 3.38 shows the "wandering" edge seam between HIR and non-HIR lanes near mile point 30.4. This photograph also shows raveling and cracking in this section. Figure 3.39 shows a good looking section near mile point 30.0. Figure 3.40 contrasts blade patching in the non-HIR lane with a good-looking HIR section. Figure 3.41 shows where the HIR work stopped.

Summary. While this project was less than successful, it "showcases" several problems that need to be addressed before HIR will reach its true potential. The importance of preliminary research and investigation cannot be over emphasized, even for a 2.2 mile long section. Stripping, alligator cracking, and layer delamination are serious problems for HIR and must be thoroughly evaluated before construction begins. After two winters the pavement looked rough, but the HIR section appeared in considerably better shape than the non-recycled sections, which required substantial blade patching. The entire section was

Figure 3.30 Photograph (looking East) of the patched area marking beginning of the HIR project near mile point 31.4.

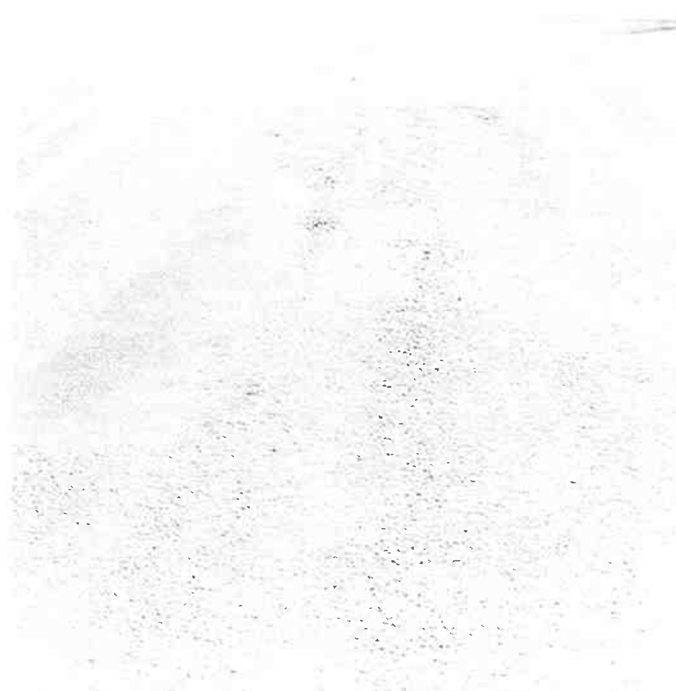


Figure 3.31 Raveled and patched area at the end of the slow moving vehicle turnout lane near mile point 31.2.

Figure 3.32 Section where the center seam did not bond well between the two HIR lanes.

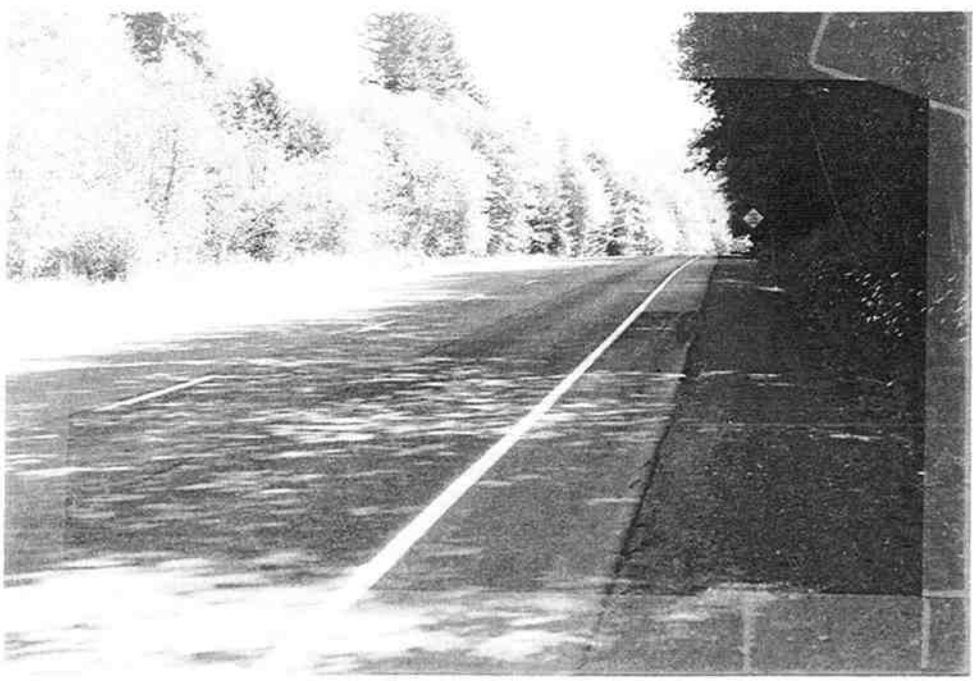


Figure 3.33 Poor looking section in the slow moving vehicle turnout lane near mile point 30.9.

Figure 3.34 Close-up of the poor section near mile point 30.9.

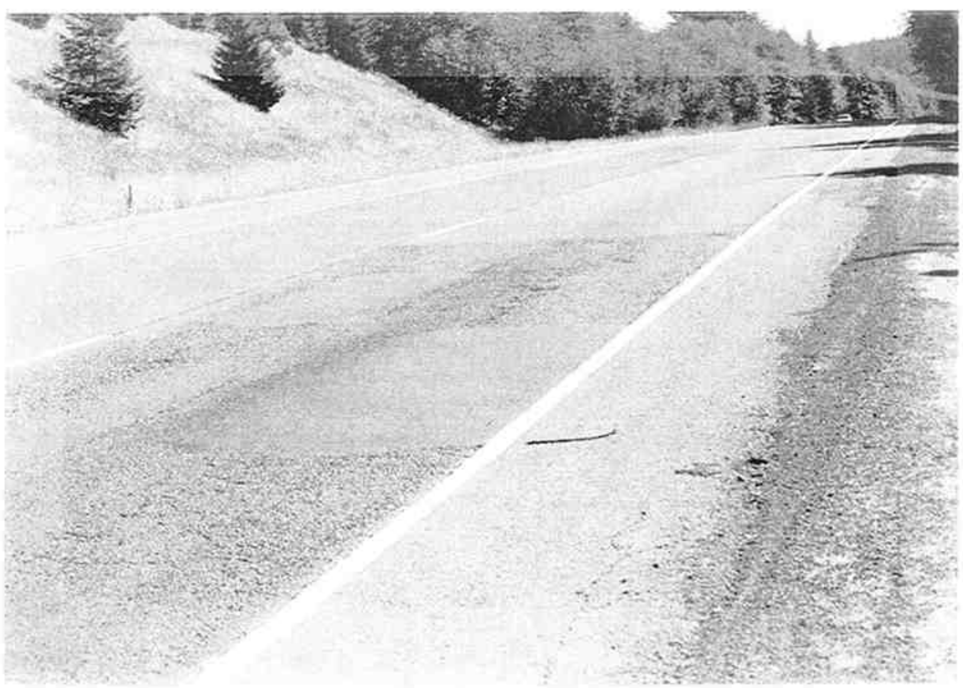


Figure 3.35 Patched, very rough looking section followed by a very good section near mile point 30.8.

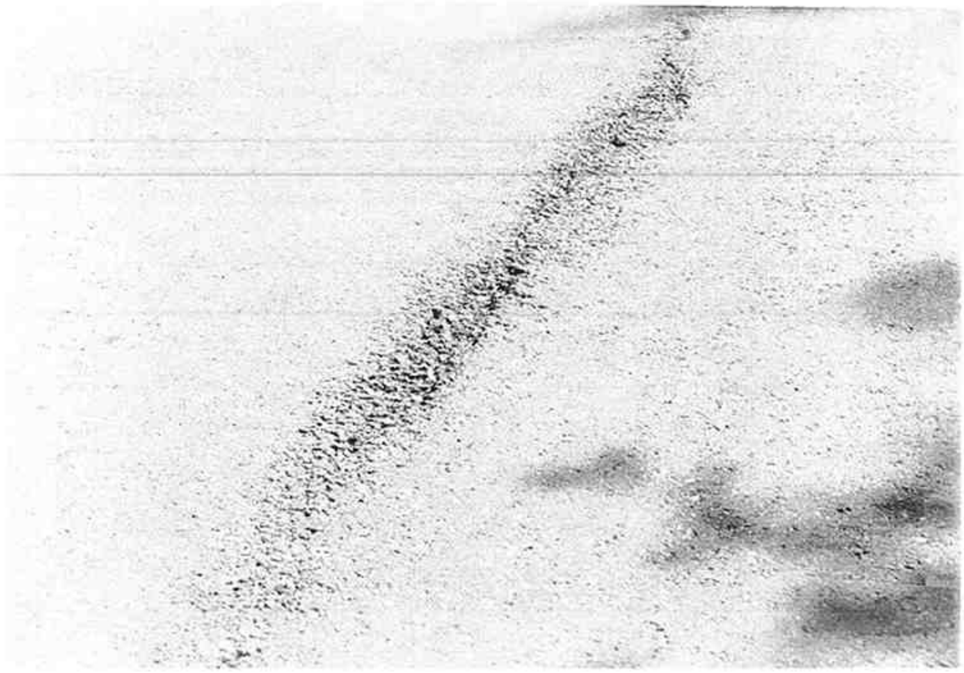


Figure 3.36 Close-up of a raveled section near mile point 30.6.

Figure 3.37 Close-up cracking near mile point 30.6.

Figure 3.38 Section with "wandering" edge seam between HIR and non-HIR lanes near mile point 30.4. This photograph also shows raveling and cracking in this section.

Figure 3.39 Good looking section near mile point 30.0.

Figure 3.40 Section with blade patching in the non-HIR lane and good looking HIR lanes.

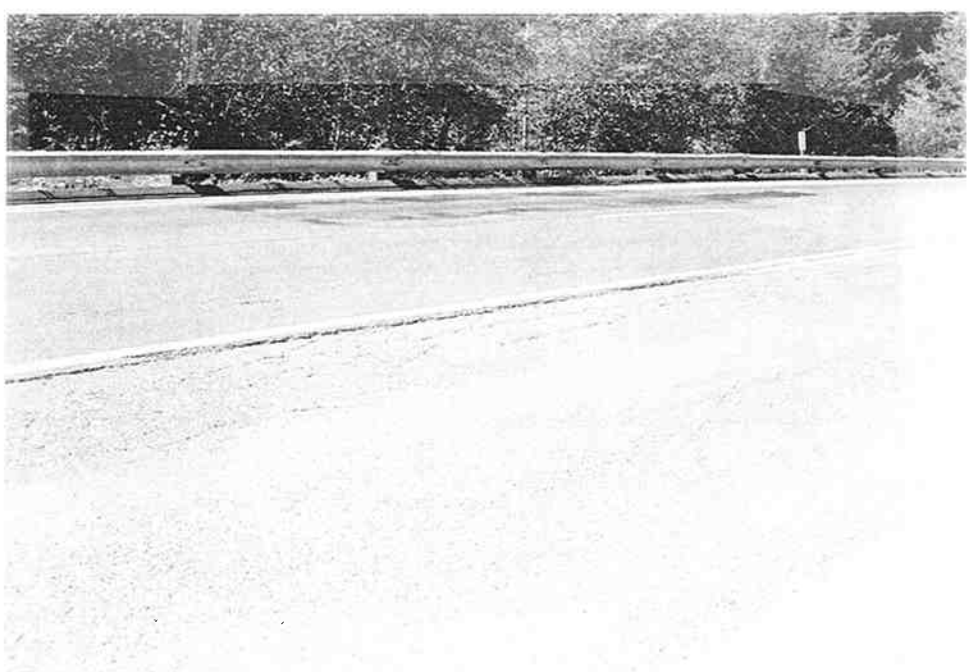


Figure 3.41 Section where the HIR was terminated.

overlayed in September, 1994 as part of the 16.73 mile long Pioneer Mountain Road-Coast Range Summit project.

3.2.6 Durkee-Lime

This project was located on the Old Oregon Trail (I-84) between the Durkee interchange, at mile point 327.15, and Lime at mile point 342.15. The passing lane in each direction was to be hot in-place recycled and overlaid with a 2-inch open-graded wearing course. The 1992 ADT for this section was 6,800.

Construction records showed that the 15-mile section had been built as three separate construction projects. Preliminary investigation consisted of coring the section at five locations in each direction. The recovered asphalt properties and aggregate gradations for both pre- and post-construction cores are presented in Tables 3.20-3.21. These cores, taken at three-mile intervals, confirmed that the existing pavement was comprised of three sections from different construction projects. There were significant changes in asphalt/aggregate composition between the sections. Specimens were remolded from core materials (no RA) and tested for air voids, Hveem stability, and IRRM. Stripping was not indicated to be a problem. The majority of values did not meet ODOT design guidelines for Hveem stability for dense-graded hot mix. The addition of 1% RA-25 was recommended for the majority of the project. No RA addition was recommended from about MP 328 to about MP 330 because of "very soft asphalt." During construction, pavement variability led to addition of RA based upon the contractor's experience.

Table 3.20 Recovered Asphalt/Mixture Properties for Durkee-Lime (I-84) HIR Project

Time of Coring	Core Properties					Recovered Asphalt			Remolded Properties			
	Mile Point	Core Density (lb/cf)	Asphalt Content %	Air Voids %	Modulus (ksi)	Absolute Viscosity (Poises)	Kinematic Viscosity (cSt)	Penetration @ 25C (dmm)	IRMR %	Modulus (ksi)	Air Voids %	Hveem Stability
Before Construction	328.5 EB	149.1	12.7	3.1		---	---	---	84	317.6		7
	331.5 EB	150.2	4.7	---		Too thick	7,100	6	86	864.5		6
	334.5 EB	150.0	4.7	6.8		900,000+	4,150	12	75	849.7		
	337.5 EB	139.1	5.0	---	---	127,000	2,120	11	---	---		
	340.5 EB	138.6	5.5	5.4		93,400	1,900	11	125	640.0		
	340.5 WB	139.8	5.0	5.8		55,600	1,490	14	123	504.6	1.9	28
	339.5 WB	141.0	6.0	4.1		67,540	1,820	11	---	985.0		
	337.5 WB	142.7	6.5	1.9		23,200	1,070	18	120	242.7	0.7	17
	334.5 WB	156.0	5.5	3.7		32,100	1,340	20	132	324.9	4.2	56
	331.5 WB	154.4	5.6	5.0		103,200	2,070	23	82	567.5	2.3	20
	328.5 WB	148.3	5.2	5.3		4,990	451	38	116	442.5		
Post Construction Cores	328.5 EB	150.4	6.2	2.3*	---	6,900	551	34				
	331.5 EB	148.5	4.5	10.8	---	318,000	3,800	11				
	334.5 EB	149.4	4.1	8.5	---	1,000,000+	7,010	10				
	337.5 EB	134.2	6.2	8.3	---	78,100	1,990	12				
	340.5 EB	136.7	4.9	7.6	---	37,500	3,600	7				
	340.5 WB	141.6	5.1	4.9	---	94,800	1,975	11				
	339.5 WB	144.7	---	---	588.0	10,300	815	27				
	337.5 WB	142.3	5.7	3.3	---	34,500	1,400	19				
	334.5 WB	149.8	4.8	7.7	---	319,000	6,450	11				
	331.5 WB	146.6	---	6.4	---	172,000	2,340	15				
	328.5 WB	139.2	5.5	8.9	---	56,600	1,177	10				
Comparison Values			New PBA-2			4,000	---	40				
			Typical 20 Yr. Old AC			100,000	---	25				

Note: Comparison values taken from Miles, 1991 Memo.
*Low air voids questionable - suspicious Rice gravity.

Table 3.21 Aggregate Gradations for Durkee-Lime HIR Project.

Time of Coring	Mile Point	Sieve Analysis - Percent Passing							
		3/4	1/2	3/8	1/4	#4	#10	#40	#200
Before Construction	328.5 EB	100	94	87	68	56	33	15	7.1
	331.5 EB	99	89	78	61	51	31	13	6.0
	334.5 EB	99	93	87	75	64	38	15	5.9
	337.5 EB	98	91	74	57	48	28	12	4.0
	340.5 EB	99	92	85	70	58	34	14	6.3
	340.5 WB	100	93	83	69	58	37	14	5.9
	339.5 WB	99	92	83	71	61	36	14	6.6
	337.5 WB	99	90	80	64	53	32	12	6.0
	334.5 WB	98	86	75	60	50	31	14	7.1
	331.5 WB	100	91	83	71	62	37	16	7.0
	328.5 WB	100	94	86	69	57	33	15	6.8
Post Construction	328.5 EB	100	99	94	76	64	40	20	11.2
	331.5 EB	98	84	69	53	45	29	13	6.0
	334.5 EB	98	84	74	60	51	31	14	5.1
	337.5 EB	99	95	88	74	65	40	19	10.4
	340.5 EB	99	86	71	56	47	29	13	6.9
	340.5 WB	99	93	82	66	57	37	17	7.1
	339.5 WB	----	----	----	----	----	----	----	----
	337.5 WB	99	90	78	62	52	33	14	7.4
	334.5 WB	98	86	74	60	51	32	15	6.5
	331.5 WB*	----	----	----	----	----	----	----	----
	328.5 WB	100	95	88	66	54	33	16	8.4

* Insufficient material for extraction

ODOT Typical B- and C-mixes. (Miles,1991)

B-mix	96	80	70	57	49	28	11	5
C-mix	100	98	86	62	51	29	12	6

Construction began on May 5, 1993, at mile point 327.15 in the eastbound passing lane. The unique recycling train used for this project, incorporating both Pyrotech and Artec equipment is shown in Figures 3.42-3.43. The recycling train consisted of a preheater, #1 heater-grinder unit, #2 heater-grinder unit, post-heater unit, and pickup-paver unit.

Some of problems that were encountered during HIR were the result of the contractor's equipment not being properly maintained at the start of HIR operations. Specific problems included inconsistent grinding depth, frequent mechanical breakdowns, and improper adjustment of screed. Another source of problems was the variation in the existing pavement mat. Stripping problems and moisture in the pavement mat slowed down HIR operations by lowering mix temperature. The worst section was the pavement between mile point 327 and 335, which had not been rehabilitated for 22 years. This section was cracked and badly stripped in the underlying layer, lacking sufficient asphalt to be rejuvenated. HIR construction was completed on June 25, 1993.

Tables 3.22 and 3.23 compare the pre- and post-construction properties at what were intended to be 11 common coring locations. After HIR, decreases in asphalt content and decreases in "percent passing" mean that either coring locations were not the same or that pavement properties are highly variable. Viscosity and penetration data present a mixed picture, indicating that sometimes asphalt was hardened by HIR and sometimes it was softened.

Summary. The Durkee-Lime project was relatively uneventful once the initial problems with equipment were overcome. HIR had mixed rejuvenating effects. In some places it appeared to soften the asphalt binder. In others it appeared to stiffen it. Some

Figure 3.42 Unique Pyrotech-Artec recycling train used on Durkee-Lime HIR project.

Figure 3.43 Close-up of Pyrotech-Artec recycling train used on Durkee-Lime HIR project.

Table 3.22 Comparison of pavement properties before and after HIR for Durkee-Lime (I-84) project.

Mile Point	Air Voids (%)				Asphalt Content (%)				Absolute Viscosity (Poises)				Kinematic Viscosity (cSt)				Penetration @ 25c (dmm)			
	Bef.	Aft.	Diff.	% Dif	Bef.	Aft.	Diff.	% Dif	Bef.	Aft.	Diff.	% Dif	Bef.	Aft.	Diff.	% Dif	Bef.	Aft.	Diff	% Dif
328.5 EB	3.1	2.3	-0.8	-26%	12.7	6.2	-6.5	-51%		6900				551				34		
331.5 EB		10.8			4.7	4.5	-0.2	-4%		318000			7100	3800	-3300	-46%	6	11	5	83%
334.5 EB	6.8	8.5	1.7	25%	4.7	4.1	-0.6	-13%	900000	1000000	100000	11%	4150	7010	2860	69%	12	10	-2	-17%
337.5 EB		8.3			5.0	6.2	1.2	24%	127000	78100	-48900	-39%	2120	1990	-130	-6%	11	12	1	9%
340.5 EB	5.4	7.6	2.2	41%	5.5	4.9	-0.6	-11%	93400	37500	-55900	-60%	1900	3600	1700	89%	11	7	-4	-36%
EB Average	5.1	7.5			6.5	5.2			373467	288100			3818	3390			10	15		
EB Stan. Dev	1.5	2.8			3.1	0.9			372568	372470			2088	2160			2.3	9.7		
EB Comp. Avg	5.1	6.1	1.0	20%	6.5	5.2	-1.3	-21%	373467	371867	-1600	-0%	3818	4100	283	7%	10	10	0	0%
340.5 WB	5.8	4.9	-0.9	-16%	5.0	5.1	0.1	2%	55600	94800	39200	71%	1490	1975	485	33%	14	11	-3	-21%
339.5 WB	3.9	1.5	-2.4	-62%	6.0				67540	10300	-57240	-85%	1820	815	-1005	-55%	11	27	16	145%
337.5 WB	1.9	3.3	1.4	74%	6.5	5.7	-0.8	-12%	23200	34500	11300	49%	1070	1400	330	31%	18	19	1	6%
334.5 WB	3.7	7.7	4.0	108%	5.5	4.8	-0.7	-13%	32100	319000	286900	894%	1340	6450	5110	381%	20	11	-9	-45%
331.5 WB	5.0	6.4	1.4	28%	5.6				103200	172000	68800	67%	2070	2340	270	13%	23	15	-8	-35%
328.5 WB	5.3	8.9	3.6	68%	5.2	5.5	0.3	6%	4990	56600	51610	1034%	451	1177	726	161%	38	10	-28	-74%
WB Average	4.3	5.5			5.6	5.3			47772	114533			1374	2360			21	16		
WB Stan. Dev	1.3	2.5			0.5	0.3			32156	104980			523	1897			8.7	6.0		
WB Comp. Avg	4.3	5.5	1.2	28%	5.6	5.3	-0.4	-6%	47772	114533	66762	140%	1374	2360	986	72%	21	16	-5	-25%

	Absolute Viscosity	Kinematic Viscosity	Penetration
New PBA-2	4000		40
Typical 20-yr. Old Asphalt	100000		25

NOTE: Comp. Avg. is the Comparable Average based on only the locations where paired before and after values exist.

Table 3.23 Comparison of Before and After Aggregate Gradations for Durkee-Lime (I-84) HIR Project.

Mile Point	Sieve Analysis - Percent Passing																							
	3/4			1/2			3/8			1/4			#4			#10			#40			#200		
	Bef.	After	Change	Bef.	After	Change	Bef.	After	Change	Bef.	After	Change	Bef.	After	Change	Bef.	After	Change	Bef.	After	Change	Bef.	After	Change
328.5 EB	100	100	0	94	99	5	87	94	7	68	76	8	56	64	8	33	40	7	15	20	5	7.1	11.2	4.1
331.5 EB	99	98	-1	89	84	-5	78	69	-9	61	53	-8	51	45	-6	31	29	-2	13	13	0	6.0	6.0	0.0
334.5 EB	99	98	-1	93	84	-9	87	74	-13	75	60	-15	64	51	-13	38	31	-7	15	14	-1	5.9	5.1	-0.8
337.5 EB	98	99	1	91	95	4	74	88	14	57	74	17	48	65	17	28	40	12	12	19	7	4.0	10.4	6.4
340.5 EB	99	99	0	92	86	-6	85	71	-14	70	56	-14	58	47	-11	34	29	-5	14	13	-1	6.3	6.9	0.6
EB Average	99	79	0.2	92	90	2.2	82	79	3.0	66	64	2.4	55	54	1.0	33	34	-1.0	14	16	-2.4	5.9	7.9	-2.1
EB Stan. Dev.	1	1	0.8	2	7	6.3	6	11	12.7	7	11	14.2	6	9	13.0	4	6	8.2	1	3	3.4	1.1	2.7	3.1
340.5 WB	100	99	99	93	93	0	83	82	-1	69	66	-3	58	57	-1	37	37	0	14	17	3	5.9	7.1	1.2
339.5 WB	99	----	****	92	----	****	83	----	****	71	----	****	61	----	****	36	----	****	14	----	****	6.6	----	****
337.5 WB	99	99	0	90	90	0	80	78	-2	64	62	-2	53	52	-1	32	33	1	12	14	2	6.0	7.4	1.4
334.5 WB	98	98	0	86	86	0	75	74	-1	60	60	0	50	51	1	31	32	1	14	15	1	7.1	6.5	-0.6
331.5 WB	100	----	----	91	----	----	83	----	----	71	----	----	62	----	----	37	----	----	16	----	----	7.0	----	----
328.5 WB	100	100	0	94	95	1	86	88	2	69	66	-3	57	54	-3	33	33	0	15	16	1	6.8	8.4	1.6
WB Average	99	99	0.3	91	91	-0.3	81	81	0.5	67	64	2.0	57	54	1.3	34	34	-0.5	14	16	-1.8	6.7	7.4	-0.9
WB Stan. Dev.	1	1	0.5	3	4	0.4	4	6	1.4	4	3	1.5	5	3	1.2	3	2	0.5	1	1	1.2	0.5	0.8	0.9

ODOT Typical B- and C-mixes. (Miles,1991)

B-mix	96	80	70	57	49	28	11	5
C-mix	100	98	86	62	51	29	12	6

* Insufficient material for extraction

recovered specimens had both decreased absolute viscosity and decreased penetration. The overlaid HIR pavement has not experienced problems in one year of service.

3.3 Summary of Findings

Table 3.24 summarizes the essential features of the six Oregon HIR projects constructed during 1992-93. The data suggest that mix design approaches were unsatisfactory, that preliminary engineering was inadequate, and that three of the four wearing course HIR projects did not perform well and required conventional rehabilitation.

Significant findings of the field study included:

- Project selection is the most critical step in the HIR process. A candidate project needs to be evaluated for all major pavement distresses, e.g., stripping, layer delamination, alligator cracking, etc. Pavements with extensive stripping, layer delaminations, or patching, are not good HIR candidates.
- Candidate Projects must be adequately characterized. This means knowing the composition of the existing pavement, which requires coring and testing. These cores must reflect all changes in pavement properties and should be taken at frequent and regular intervals.
- HIR requires a mix design process similar to the existing methods for conventional dense-graded mixes. Early HIR project mix designs were based primarily on the ASTM D4887-89 nomograph, with the objective of rejuvenating the asphalt binder. Testing for air voids and stability was minimal and was only for remolded specimens without RA

Table 3.24 Summary Discussion of 1992-93 ODOT HIR Projects.

Project:	Preliminary Mix Design Approach	Design Add Rate of RA (% By Wt. of RAP)	Add Rate of RA Used In the Field (% By Wt. of RAP)	Addition of Virgin Mix Required?	Problems Encountered	Outcomes Predicted	HIR Lessons Learned
Old Oregon Trail	ASTM D4887-89 Target viscosity	3.7 WB RA-25 2.3 EB RA-25	0.24 to 0.35 RA-25 Averaged 0.31	Yes - 488.80 Tons	Severely Stripped Pavement	Testing Showed Long Term Fatigue Cracking Problems	Importance of Preliminary Engineering/Testing
Wallowa Lake Hwy	ASTM D4887-89 Target viscosity	0.5-1.3 RA-25	0.16 to 0.19 RA-25 Averaged 0.18	Yes - 547.05 Tons	Delaminations Between Layers	Rough Ride - Rehabilitated Summer 1994	Importance of Project Selection/Investigation
Clear Lake - Old McKenzie Hwy	ASTM D4887-89 Target viscosity	0.7 to 1.0 RA-25	0.3 to 0.7 RA-25 Averaged 0.54	No	Thermal Cracking	Two Years later - Some Reflective Cracking	HIR Can Work
N. Grants Pass - Jumpoff Joe Creek *	ASTM D4887-89 Target viscosity	0.3 RA-25	Averaged 0.2 % RA Both RA-5 & RA-25	No	Quality/Quantity of RA	Effects of Severely Aged Base Course ???	Importance of Contractor Skill and Experience
Tangent-Halsey	ASTM D4887-89 Target viscosity	0.2 RA-5	0.1 to 0.5 RA-5 Averaged 0.31	Yes - 407.04 Tons	Extensive Patching - Delaminations	Unsuccessful Project - Overlayed After One Year	Importance of Project Selection/Investigation
Cline Summit	Project Manager & Contractor Experience	0.2 RA-25	0.3 to 0.7 RA-25 Averaged 0.45	No	Delaminations, Rutting, Alligator Cracking	Project terminated early - Overlay Scheduled Fall 1994	Importance of Project Selection/Investigation
Durkee-Lime *	ASTM D4887-89 Target viscosity	1.0% RA-25 (Majority) and 0.0%	0.03 to 0.91 RA-25** Averaged 0.19**	No	Variations in RAP, Stripping, Raveling	One Year Later - Performing Well	Using HIR as base course prior to overlay can work

Notes: * Denotes projects where HIR pavement was intended for base course for subsequent F-mix overlay.
** Discrepancy on this project between total quantities used by contractor and spreads recorded in the daily construction reports.

Values for RA used in field taken from construction daily reports except for Clear Lake - Old McKenzie Hwy., Tangent - Halsey, and Cline Summit which were taken from hot in-place recycling presentation at the ODOT Project Manager's Meeting, March 29-31, 1993.

addition. This design approach didn't account for loss of stability and air voids from the addition of RA. During field coring, enough material must be obtained to adequately test stability, water sensitivity, and loss of air voids.

- Aging is a critical parameter that needs to be closely examined before doing HIR. Experience indicates that even with the most active RA (RA-5), the amount of RA required to rejuvenate the asphalt binder in a severely aged RAP to "like newly-constructed" is likely to produce air void and stability problems in the field. When the decision is made to reduce the level of RA addition, rejuvenation will be less than desired. If a pavement has an absolute viscosity well above that of the typical 20-year-old Oregon pavement, 100,000-200,000 poises (Miles, 1991), the potential for thermal or fatigue cracking will remain high, even after HIR.

- Other Concerns. One-hundred percent smoke-free HIR presents a challenge, even with state-of-the-art afterburners. This is particularly a concern for projects near urban or populated areas. The intense heat of the recycling train makes fire a potential danger in arid climates. In dry areas, HIR may require more firefighting equipment than would normally be on the job site. The contractor's skill and equipment are always important factors in project success. This is even more important for an emerging technology such as HIR.

4.0 SELECTION PROCESS FOR HIR PROJECTS

4.1 Introduction

The objective of hot in-place recycling (HIR) of asphalt pavements is to rehabilitate the existing distressed wearing surface in an efficient and cost effective manner. The Oregon Department of Transportation (ODOT) experience with HIR suggests that there are limits to how distressed a candidate pavement can be and still be successfully recycled. The field study discussed in Chapter 3 showed that extensive aging, stripping, delamination, and rutting present problems for HIR. None of the projects produced a recycled mixture comparable to a new hot-mix. Only one of the four wearing course projects, Clear Lake-Old McKenzie Highway, showed demonstrative rejuvenation in comparing pre- and post-HIR asphalt properties. Thus, the first and most critical step in the HIR process is the evaluation of candidate pavements to ensure that only projects with a high probability of success will be chosen.

In essence, evaluating candidate HIR projects is a four step process as follows:

1) Identify potential rehabilitation projects,
2) Conduct a preliminary investigation of the candidate project,
3) Conduct a field evaluation of the existing pavement, and
4) Use preliminary field coring to make final decisions.

The goal of the following sections is to refine the ODOT selection process for HIR projects. Building from the current literature and the six 1992-93 Oregon HIR projects, the project selection process put forth in Section 4.3 was developed.

4.2 Review of HIR Selection Processes

4.2.1 ODOT HIR Experience

The mixed results of the six ODOT HIR projects discussed in Chapter 3 suggests how vital the project selection and evaluation process is to ensuring HIR success. Each of the projects had unique concerns that often were not recognized until problems developed, often in the middle of HIR construction. Two projects, Cline Summit and the Old Oregon Trail Freeway shoulders, had to be stopped prior to completion. Two others, Tangent-Halsey and Wallowa Lake Highway, were unsatisfactory and were overlayed after only one and two years of service, respectively. In all four cases, a detailed preliminary investigation should have found the problems and HIR should probably have not been attempted. It is noteworthy that one proposed HIR project on Highway 99W was canceled after randomly sampled field cores showed significant layer delamination.

These types of problems led to the formulation of a recommended ODOT HIR project selection process, put forth in the memo shown in Figure 4.1. This memo summarizes the lessons learned from the 1992 HIR projects and stresses the need for preliminary investigation and evaluation. This memo and the attached proposed sampling and testing protocol (in Appendix A) for HIR pavements formed the basis for the proposed selection procedures presented in Section 4.3.

4.2.2 Literature Review

The National Cooperative Highway Research Project (NCHRP) "Guidelines for Recycling Pavement Materials" (Epps, et al., 1980) suggested the extensive evaluation process shown in Figure 4.2. This 5-year long research project focused on all forms of

STATE OF OREGON INTEROFFICE MEMO
DEPARTMENT OF TRANSPORTATION - OFFICE OF OPERATIONS 378-6528

FILE: CON

DATE: December 28, 1992

TO: Region Construction Engineers
District Managers

FROM: Wayne F. Cobine
Manager, Office of Operations

SUBJECT: Hot-In-Place Recycle (HIR) Projects
Recommended Selection Process

The 1992 construction season included several HIR projects. Some were successful, some were not, but we learned something from all of them. The continued successful use of this technology requires that we learn (as opposed to run) from our mistakes.

Based on our experience with HIR to date, we have the following conclusions and recommendations.

<u>Conclusions</u>

- Preliminary engineering to evaluate the suitability of a site for HIR and to develop the mix design was inadequate on all jobs in 1992.
- Heavily patched pavements with internal stripping and/or delamination in the top 3-4 inches are not good candidates for HIR. These pavements typically hold moisture and therefore require excessive heating, resulting in a brittle mix, low in asphalt which is very susceptible to raveling.
- Polution control is poor to marginal and the DEQ will not be as lenient in '93 as they were in '92 when examining this process.
- Adding material in one direction only results in a poor match at the meet line and affect drainage characteristics.
- Most of the projects hardened the asphalt.
- Sections of fairly uniform older pavement recycled well, with excellent bond between the recycled layers and the underlying asphalt concrete.

Region Construction Engineers
District Managers

<u>Recommendations</u>

- Perform the recommended minimum investigation prior to selecting a job for HIR or don't do HIR. Get help in examining job sites from Pavement Design and/or Operations and Materials. They are both very willing to help and will help you maximize the potential for success.
- Do enough coring on the job to assure that you do not have significant amounts of stripping and/or delamination in the top 3-4 inches of the mat. Log and photograph all of the cores and supply them to Materials for evaluation.
- Select sites in low population, rural areas where the potential smoke and polution problems will have minimum impact.
- Include a light fog or sand seal in the contract for jobs planned as a wearing surface. This will seal the surface and help minimize raveling.
- If it is your desire to add crown, then figure and include a bid item for added new mix. You will obviously need to add the mix in both lanes.
- Follow the <u>attached</u> sampling and testing protocol.
- Try to select jobs that performed well but are now wearing out due to age and traffic, these "good old" pavements make the best candidates. Remember the GIGo principle (garbage in-garbage out) applies directly to HIR.

IJH:dp
regidist.ijh

Attachment

cc: Tom Lulay
Jim Huddleston
Tony George

Figure 4.1 ODOT HIR project recommended selection process (Cobine memo, 1992).

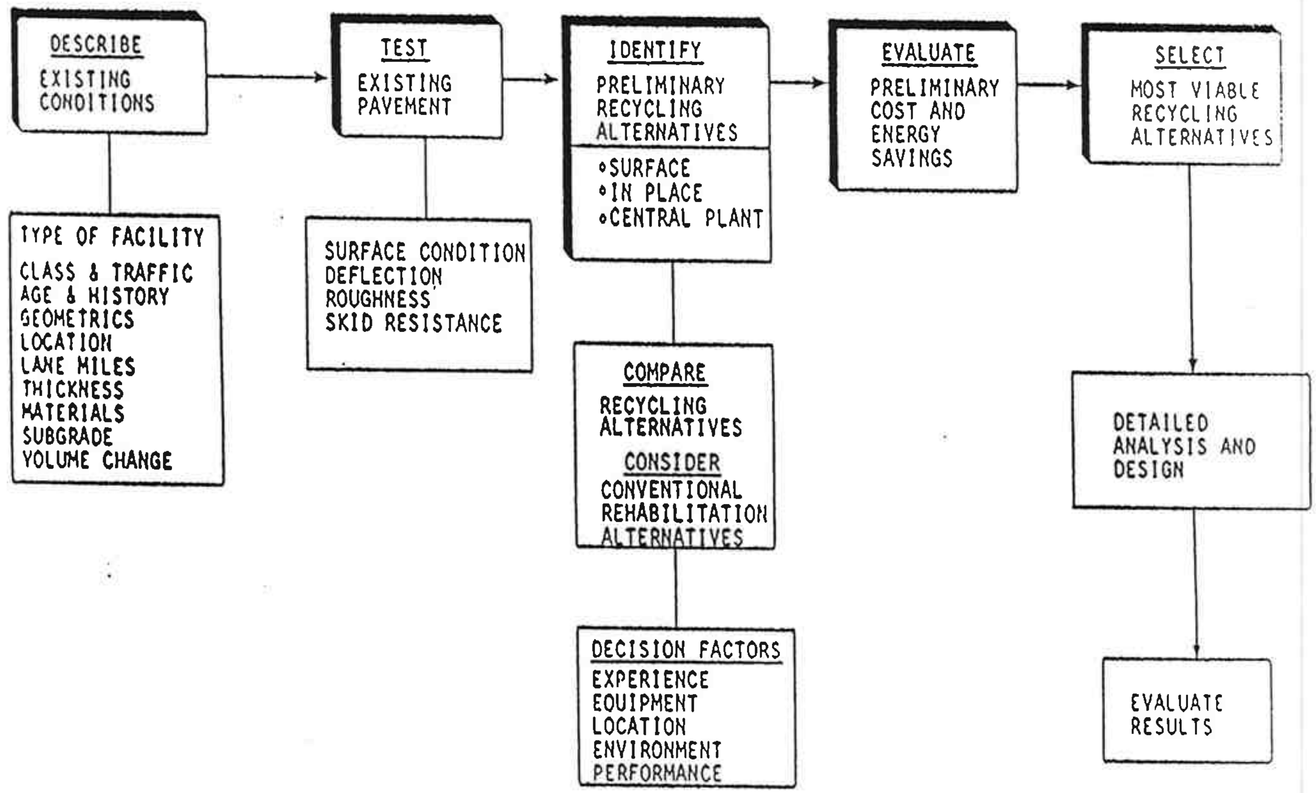


Figure 4.2 Example of preliminary pavement evaluation (Epps, et al., 1980).

recycling, not just HIR, so in Figure 4.2 a variety of recycling alternatives are shown. The preliminary evaluation considers construction and maintenance records, and includes a pavement condition survey prior to taking field cores. This preliminary evaluation would possibly detect unsuitable projects (e.g., extensive patching or stripping) and would be cost effective for HIR design and construction.

At the 1991 Hot In-place Asphalt Recycling Conference in British Columbia, Bishop (Bishop, 1991) presented and discussed the following characteristics and factors to be used in considering HIR:

1) Seal coated surfaces present problems. They lower production, raise costs, create air pollution, and give mixed results for final surface quality.
2) Pavement thickness should be at least 75 mm (3 inches) deep. The remaining pavement below the specified recycling depth may break loose and be mixed with the recycled pavement. Pavements that are 150 mm (6 inches) deep or more with severe thermal cracking require special considerations also.
3) The pavement should have enough remaining structural life as HIR will only slightly improve structural capacity.
4) Patched and rough pavements can be treated provided the pavement is structurally sound.
5) Pavements with rutting problems require special techniques if HIR is to effectively rehabilitate them. Further analysis is needed to determine if the problem is a poor mix design or poor aggregate.

6) Environmental and noise pollution concerns make using HIR in residential neighborhoods or city streets a less viable option.

The heat reforming process presented by Emery and Terao (Emery and Terao, 1992) emphasized the importance of conducting a preliminary pavement evaluation before HIR. Their discussion focuses on utilizing Taisei equipment which has the capability to immediately overlay the HIR mat. Table 4.1 shows their suggested preliminary pavement evaluation process for determining the adequacy of the existing structure. If a candidate pavement passes this preliminary evaluation and HIR is selected, the detailed pavement evaluation shown in Table 4.2 is conducted to investigate whether the HIR mat should be overlaid with virgin mix.

4.3 HIR Project Selection Process

4.3.1 Identification of Potential Rehabilitation Projects

HIR is just one of the many possible options available for rehabilitating a distressed pavement. Because it appears to have a 25-35 percent cost advantage over conventional methods (Button, et al., 1994) and may be used in weather conditions where cold in-place recycling could not be used, it should be considered seriously as a rehabilitation option.

Ideally, the HIR selection process would be conducted as part of a larger pavement management and rehabilitation strategy, similar to the NCHRP procedure shown in Figure 4.3. Assuming recycling is the preferred alternative, the preliminary evaluation procedure shown in Figure 4.2 suggests a general approach that would help identify potential HIR projects. To determine if HIR is viable, the evaluation procedures shown in Figure 4.4 should be followed. Each of the steps is discussed at length in the following sections.

Table 4.1 Example of Preliminary Pavement Evaluation (Emery and Terao, 1992).

ITEM	DETAILS	REASON
1. Inventory Information	• class of pavement • pavement structure(a)	• work schedule • applicability of Heat Reforming Process
	• pavement history	• supplements detailed valuation
	• traffic volume	• work schedule
2. Pavement Structure	• structural defects (types and extent)(a) • non-structural defects (types and extent) • localized structural defects	• applicability of heat reforming process • selection of heat Reforming Process Option • need for preliminary localized repairs
3. Prior Treatments (See Inventory Also)	• any special treatments or materials (surface treatment, rubberized asphalt, road markings, fabrics, epoxy, patching, etc.)	• need for removal (cold milling for instance), if possible, before Heat Reforming Process
4. Geometry and Profile	• width, alignment and gradient(a) • surface profile (extensive rutting and wear)(b)	• applicability of Heat Reforming Process • need for preliminary treatment (cold milling for instance) if possible, before Heat Reforming Process
5. Miscellaneous	• manholes, catch-basins, utility covers, etc.	• work schedule, protection and potential flammable gas counter-measures
	• adjacent (close) plants, trees, flammables, etc.	• work schedule and protective action as necessary

Notes: a. In general, a pavement with structural defects (i.e. lack of structural capacity and/or inadequate base, beyond localized defects that can be readily repaired) will not be a suitable candidate for the Heat Reforming Process. Pavements with non-structural surface defects (rutting, wearing, cracking, aging, poor frictional characteristics, etc.) are suitable candidates for the Heat Reforming Process.

b. Pavement width, alignment and/or gradient improvement requirements, or excessive rutting and wear (greater than about 50 mm), may preclude the Heat Reforming Process.

Table 4.2 Example of Detailed Pavement Evaluation (Emery and Terao, 1992).

ITEM	DETAILS	TYPE OF SURFACE DEFECT(a)			
		WEAR	RUTTING	CRACKING	FRICTION
1. Surface Condition	• cracks (types and extent)	N	N	M	N
	transverse profile	M	M	N	R
	• longitudinal profile	R	R	N	N
2. Existing Asphalt Concrete(b) (Usually surface course, but must be at least to proposed scarification depth.)	• thickness	M	M	M	M
	• asphalt cement content (for scarification depth)	M	M	M	M
	• gradation (for scarification depth)	M	M	M	M
	• density	M	M	M	M
	• air voids	M	M	M	M
	• penetration/viscosity of recovered asphalt cement (for scarification depth)	M	R	M	N

M - Mandatory R - Recommended N - Not Necessary

Notes: a. Information to be representative of the pavement section involved, with special areas (spray patching for instance) and localized structural distress areas noted.

b. Typically based on a coring program. Cores to be representative of pavement section involved, with additional cores taken as necessary for special areas.

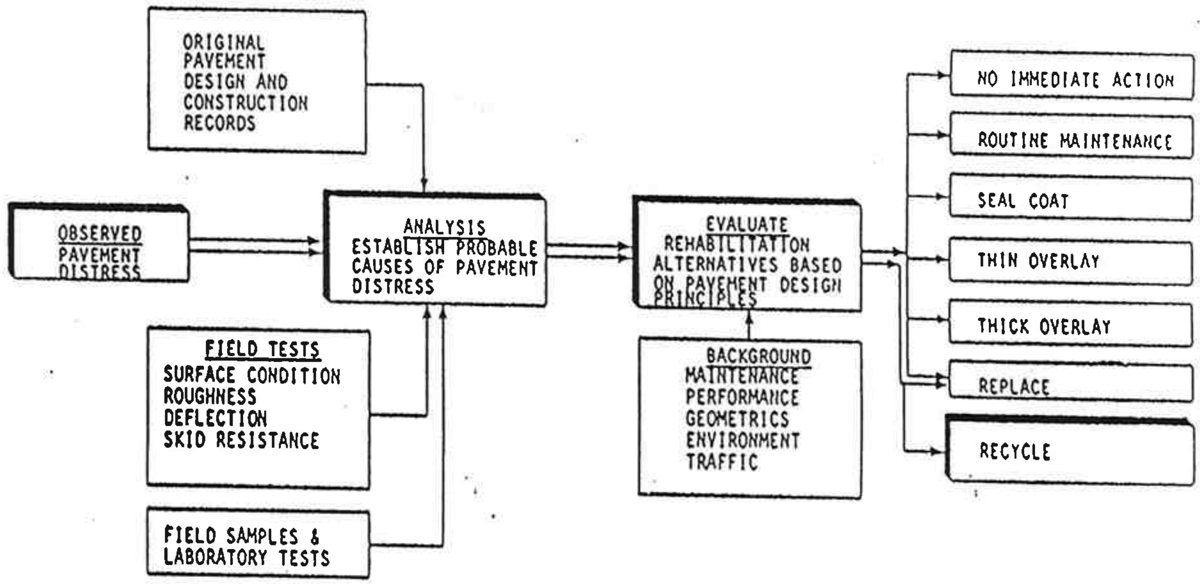


Figure 4.3 NCHRP pavement rehabilitation alternatives flowchart (Epps, et al., 1980).

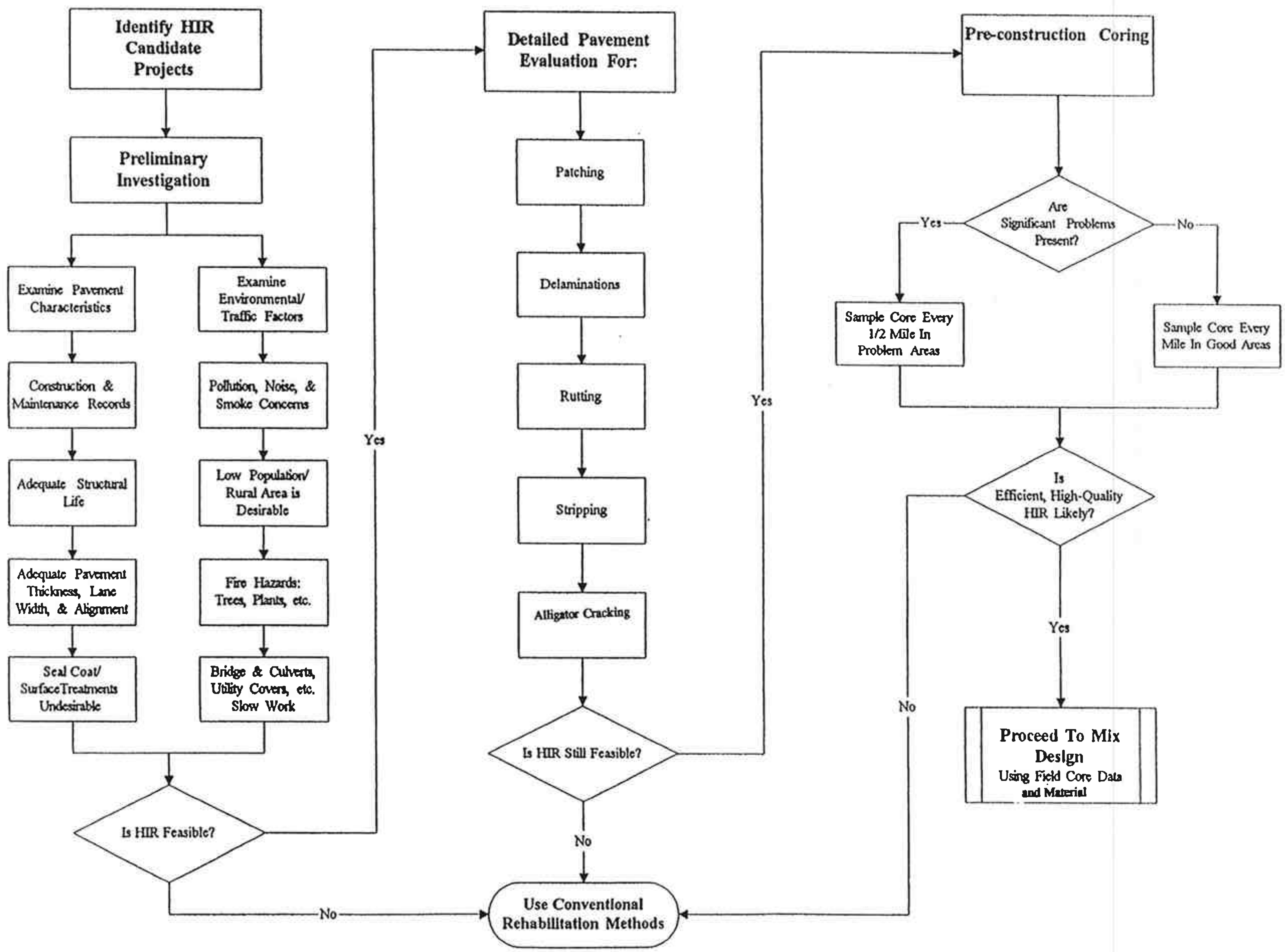


Figure 4.4 Proposed HIR project selection process.

4.3.2 Preliminary Investigation

The preliminary pavement investigation should include the following:

1. An examination of the pavement's characteristics. The existing pavement structure needs to be thoroughly investigated and understood early in the HIR process. This involves reviewing the design, the construction records, and the latest ride and condition information available for the candidate pavement. This information may uncover problems that suggest adding virgin mix, overlaying the HIR mat, or not using HIR at all. It will also be very useful in deciding the location and frequency for field core sampling. Things to look for include:
   - a) roadway geometry - 12 foot-lanes, adequate corners for recycling train.
   - b) skid numbers - may indicate an over-asphalted mix in existing pavement.
   - c) pavement distress - existing patching, rutting, cracking, or delamination problems.
   - d) layer or lift thickness of pavement as built. 2-1/2 to 3-inch lifts may have delaminations that will break loose during construction.
   - e) any problems in the pavement's life history.
2. Examination of non-pavement characteristics such as the proposed construction environment, season, and traffic flow. This may appear

a secondary issue, but air pollution, noise, rain, wind, etc., are also significant concerns for HIR. Low population and rural areas are preferred locations for HIR. Other concerns are potential fire hazards such as overhanging trees, brush, etc., especially during the fire season.

4.3.3 Detailed Pavement Evaluation

If the preliminary investigation does not preclude the possibility of HIR, the pavement needs to be inspected to correlate the findings of the preliminary investigation with the actual pavement condition in the field. This step is quantifying the type and extent of potential HIR problem areas. The pavement needs to be evaluated for:

1. Patching. Extensive patching is a problem because the patch usually has quite different properties than the original pavement surface. Typically, this implies a different asphalt content and stiffness forcing changes in the design add rate of rejuvenating agent (RA). If patching covers greater than 50 to 60 percent of the pavement, this may create problems in characterizing the pavement effectively and economically. Pavements with extensive blade patching should be approached with caution as they are prone to delaminations and in ODOT's experience, frequently water-filled delaminations, with the problems discussed below.
2. Delaminations. Delamination between layers 2-3 inches below the surface usually create serious difficulties for the HIR process. It leaves an unstable base to pave on and chunks of pavement get picked up and stuck in the augers or passed through to the finished mat. Often

the material near the delamination is stripped, changing the RAP properties significantly. If water gets between the layers, it acts as a thermal "sink", absorbing much of the applied heat, lowering mixing temperatures and slowing forward progress to the point that HIR does not work effectively.

3. Stripping. Stripping is another area that is problematic for HIR. RA does not serve as an aggregate binder; it acts to rejuvenate the asphalt in the RAP. The stripped material does not have enough asphalt for the RA to rejuvenate effectively. In three of the six Oregon HIR projects, stripping and delamination were found together. If stripping is found, HIR is strongly discouraged.

4. Rutting. Rutting is a problem because of uneven heat penetration and because all of the material used in HIR comes from the existing pavement. Filling the ruts takes material that would ordinarily go into the lane crown, and may create ride problems. This problem was encountered on the Cline Summit project. Rutted pavements will require the addition of carefully designed new coated aggregate to eliminate instability problems. In British Columbia, if rutting is less than the HIR milling depth (2 inches) HIR is frequently used as a leveling course prior to conventional overlay (Symons, 1994).

5. Alligator Cracking. Extensive (deep) alligator cracking is a problem for HIR because the cracking is often indicative of an inadequate structural section or subgrade problems. Until the underlying problem

is solved or a pavement of adequate section is constructed, HIR will only provide a temporary cosmetic improvement. Combination of HIR with a structural overlay could provide a viable rehabilitation option.

If any of these problems are extensive enough that HIR would not be a continuous, smooth running operation, other rehabilitation techniques should be used. If the problems are isolated or minor, HIR may still be a viable alternative.

Ideally, much of the above evaluation could be done at driving speed, but at present there are no guaranteed methods for efficiently determining whether or not delamination is a problem. The falling weight deflectometer might give an adequate indication of the extent of delamination. Ground penetrating radar equipment manufacturers claim their equipment can do this at present; if so, it would be perfect for this. Currently, coring at random locations is the most reliable method of finding delaminations.

4.3.4 Pre-construction Core Sampling

If the proposed HIR project has passed the screening procedure described above, there is a good chance that HIR will be the chosen rehabilitation technique. Core sampling at "representative" locations is still necessary, to make sure there are no hidden layer delaminations or stripping problems. Representative locations would cover all visible changes in the existing pavement. As discussed in Section 3.2.5, coring at random locations along Pacific Highway West (Hwy. 1W) uncovered a serious delamination problem that led to Unit A of the project being deleted.

If HIR is chosen as the rehabilitation option, core material (RAP) will be needed for the mix design testing. Because both selection and mix design (to be discussed in Chapter 5) require coring at representative locations, it is more efficient to obtain all required corings in one operation. Current ODOT coring recommendations are, in the absence of major changes in pavement, one set of four 6-inch cores per lane mile, with one additional core taken between each set of four to further evaluate stripping and delamination (Cobine memo, 1992). A change to five cores (three 8-inch and two 4-inch) is recommended for the following reasons:

1. The mix design process to be proposed in Chapter 5 requires approximately 6,000 grams of RAP material in addition to the material required for Abson recovery. Three 8-inch cores provide the necessary quantity of material. If 8-inch cores are not practical, equivalent material should be obtained with smaller cores. Additionally, two 4-inch cores are required to obtain in situ air voids, modulus, and Hveem stability.

2. Taking three 8-inch cores and two 4-inch cores in place of the four 6-inch cores and taking one 4-inch between each set of five would take little additional time and effort over the ODOT recommended frequency, and would give more representative sample sizes for the necessary tests.

If the field cores show problems, the viability of HIR as the rehabilitation method will need to be re-evaluated. If the detailed preliminary investigation and pavement evaluation presented above is followed, the ODOT recommendations should work well and HIR should be successful. If there are no problems detected with the cores, proceed to the proposed mix design procedures discussed in Chapter 5.0.

5.0 MIX DESIGN PROCEDURES

5.1 Introduction

The "ideal" hot in-place recycling (HIR) mix design would fully rejuvenate the binder while maintaining acceptable air voids without creating stability problems. Optimizing this trade-off is difficult because, presumably, the pavement was constructed near optimum asphalt content, and any addition of rejuvenating agent (RA) will tend to create an over-asphalted mix. The "harder" the existing asphalt, the greater the required addition of RA and the more likely that instability may be a problem. If the existing pavement varies from place to place throughout the section, the number of mix designs becomes impractical and must be compromised by necessity. Difficulty increases when the addition of new aggregate, asphalt, or virgin mix are considered.

Almost all mix design methods used for HIR follow the same procedures:

1) Obtain representative values for asphalt content, gradation, air voids, density, asphalt penetration, and asphalt viscosity for the existing pavement (through field coring, extraction, and Abson recovery).
2) Estimate RA required to rejuvenate pavement to desired viscosity, using American Society for Testing and Materials (ASTM) D4887-89 or similar methods. British Columbia's Transportation agency skips this step and uses 0.5 percent Cyclogen L (RA-5) [Sam, 1994].
3) Fabricate test specimens using cored material and target RA add rate from step 2. Test specimens for air voids, stability, water sensitivity, modulus, etc., similar to conventional mix design.

4) Based on results of step 3, adjust RA add rate or, if stability and acceptable air voids can not be achieved, design for addition of up to 30% admixture (coated aggregate or lean hot mix).

The goal of the following sections is to refine the Oregon Department of Transportation (ODOT) mix design procedures for HIR. Building from the current literature, the six 1992-3 Oregon HIR projects, and from laboratory testing, the mix design process put forth in Section 5.5 was synthesized.

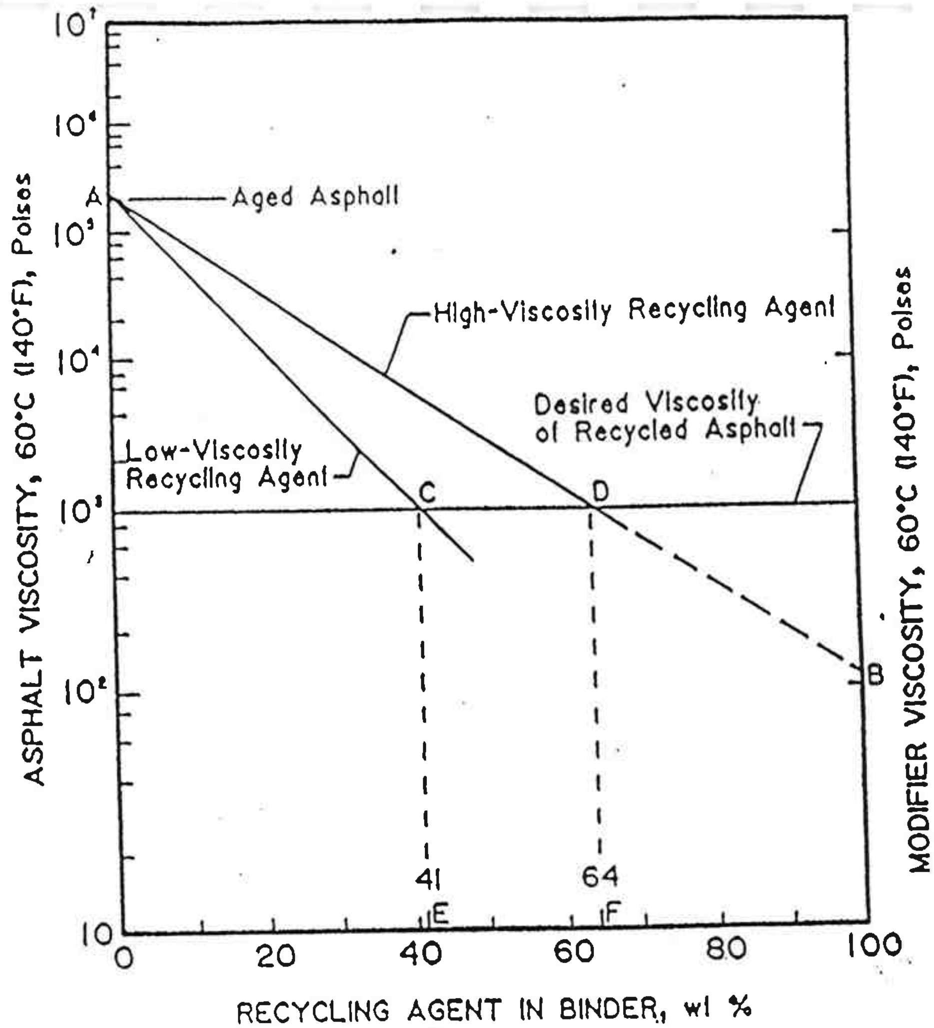
5.2 Literature Review

Over the past 15-20 years, as interest in HIR has steadily increased, there have been several noteworthy approaches to developing a mix design methodology. The following mix design methods are worth a brief discussion because they were either used for one of the six ODOT projects or they helped to formulate the final "refined" HIR mix design.

5.2.1 ASTM D4887-89 Mix Procedure

One method for HIR mix design utilizes ASTM D4887-89 to target viscosity for the recycled mix. This procedure is based on the viscosity nomograph shown in Figure 5.1 and "reasonably" predicts the quantity of RA to add to the aged binder to get the desired rejuvenation. To use the nomographs, the asphalt content of the RAP must be known, and the recovered asphalt's viscosity must be known. Figure 5.1 describes how the nomograph is used.

For the early ODOT HIR projects, this nomograph was used to predict the addition rate of the RA based upon the viscosity recovered from the field cores and a desired viscosity of 9,000 poises. The nomograph recommended RA addition rates were judged to



NOTE 1—*How to Use the Chart:*

(1) Plot reclaimed asphalt viscosity (140°F) on left ordinate (A).
(2) Plot recycling agent viscosity (140°F) on right ordinate (B).
(3) Connect points A and B with a straight line.
(4) Draw a horizontal line through the target (blend) viscosity intersecting the component viscosity line (AB).
(5) Repeat steps 2 through 4 to form line A C for another candidate recycling agent or paving-grade asphalt.
(6) The projections of points C and D yield estimates of percent recycling agent or paving-grade asphalt required to meet the target blend viscosity.
(7) The estimate in step 6 can be scaled back and forth to establish the exact blend that will produce the desired viscosity or other target property within the limits of the test material.

NOTE 2—Calculations using ordinate viscosity (η) values (scales A and B) can be simplified by using loglog (100 × η_A or η_B (Poises)) such that ordinates and abscisca axes become linear.

Figure 5.1 ASTM D4887-89 viscosity nomograph.

be too high when construction began. Consequently, these rates were drastically reduced to prevent stability problems. On some projects, the nomograph predicted RA addition rate was so high that the rejuvenated mix slumped in the windrow. This led to the practice of letting the contractor add lesser amounts of rejuvenator based on his experience. The implication is that these projects should have required the addition of coated virgin aggregate.

5.2.2 Witco Design Procedure

This procedure is similar to the ASTM D4887-89 procedure in that it uses nomographs to estimate the RA addition rate to achieve a desired rejuvenation. It utilizes two nomographs, the viscosity and penetration nomographs shown in Figures 5.2-5.3. To use the nomographs, the asphalt content of the RAP must be known, and the recovered asphalt's viscosity and penetration must be known.

The viscosity nomograph is identical to the ASTM D4887-89 nomograph above, except that the viscosities of the Witco rejuvenators are marked on the nomograph. The ASTM procedure shown in Figure 5.1 is followed.

To use the penetration nomograph, the asphalt content and the penetration of the recovered asphalt must be plotted as a point on the nomograph. A straight line is drawn connecting this point and the RA point on the nomographs. A vertical line is drawn up from the total percent of the blend of rejuvenating agent and asphalt cement in the recycled mix. The two lines intersect at the approximate predicted penetration of the recycled asphalt.

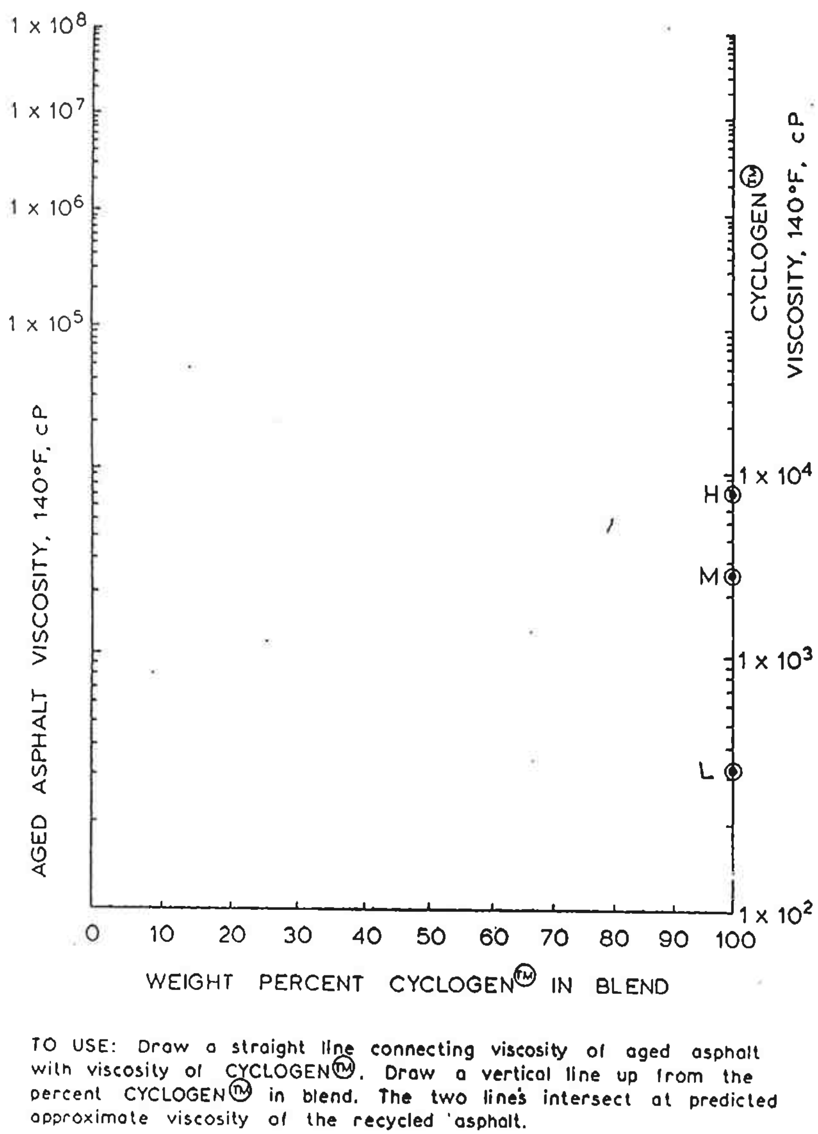


Figure 5.2 Witco viscosity nomograph (courtesy of Witco Corporation).

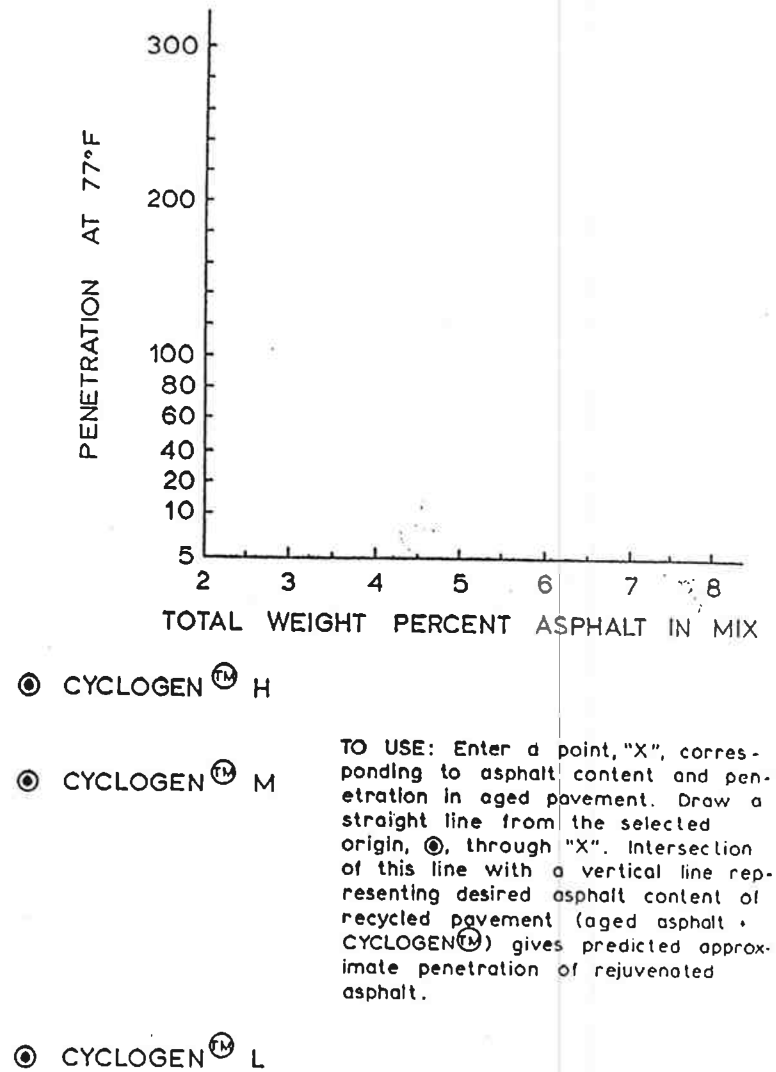


Figure 5.3 Witco penetration nomograph (courtesy of Witco Corporation).

The nomographs were developed through testing of aged and unaged samples of several rejuvenating agents mixed with pavement of different ages [Davidson, et al., 1977]. The Witco design procedure guidelines consist of the following steps:

1) Separation of a representative sample of the pavement to be recycled into its two components, aggregate and extracted asphalt,
2) Dividing the aggregate by sieve sizes,
3) Determining the consistency of the extracted asphalt,
4) Calculating the amount of asphalt required to satisfy the demand of the aggregate, based on the following equation:

$$P = \frac{(4R + 7S + 12F)}{100} \times 1.1$$

Where P = wt. percent asphalt in mix,

R = wt. percent retained on #8 sieve,

S = wt. percent passing #8 and retained on #200 sieve,

F = wt. percent passing #200 sieve.

5) Calculating the amount of recycling agent to be used, and
6) Assuring that the amount of reclaiming agent does not take the new mix outside the consistency range of paving grade asphalt.

5.2.3 National Cooperative Highway Research Program (NCHRP) Design Procedure

The NCHRP design procedure, put forth in the early 1980's, presents a general yet comprehensive approach towards recycling asphalt pavements. It focuses on central in-plant recycling, not HIR, but considers several mix design properties, in addition to penetration and viscosity, during the mix design process. Stability, water-susceptibility, air void content, and resilient modulus are all examined and considered. Figure 5.4 shows the recommended mix design procedure. The paper presents an example problem outlining the mix design procedure (Epps, et al., 1982).

5.2.4 Terra Engineering, Ltd. Design Procedure

Ken Fyvie of Terra Engineering (Fyvie, 1991) outlined a detailed HIR mix design procedure at The 1991 Summer Conference on Hot-In-Place Recycling. The procedure is summarized below:

1) Obtain core samples - preferably 150 or 200 mm (6 or 8 in) diameter. Suggested sample frequency: one core per 1000 m^2 recommended minimum; 8 cores per material type, sub-lot or site. Cores should be drilled to the full depth of pavement, then trimmed to planned depth for HIR.

2) Determine core density and in situ air voids, only testing to depth planned for treatment. The RAP can be divided into large sub-sections of different material types with some allowances for testing limitations and material variability. The sub-sections need to have enough material to obtain three binder/aggregate assessments per lot and still have material for specimen fabrication.

3) Compare individual and overall aggregate gradations, air voids, asphalt content, filler content, and pavement thickness (should be at least 35 mm thicker than planned treatment depth) to desired mix requirements. Perform Abson recoveries (suggested minimum, three per lot) and compare to target values.

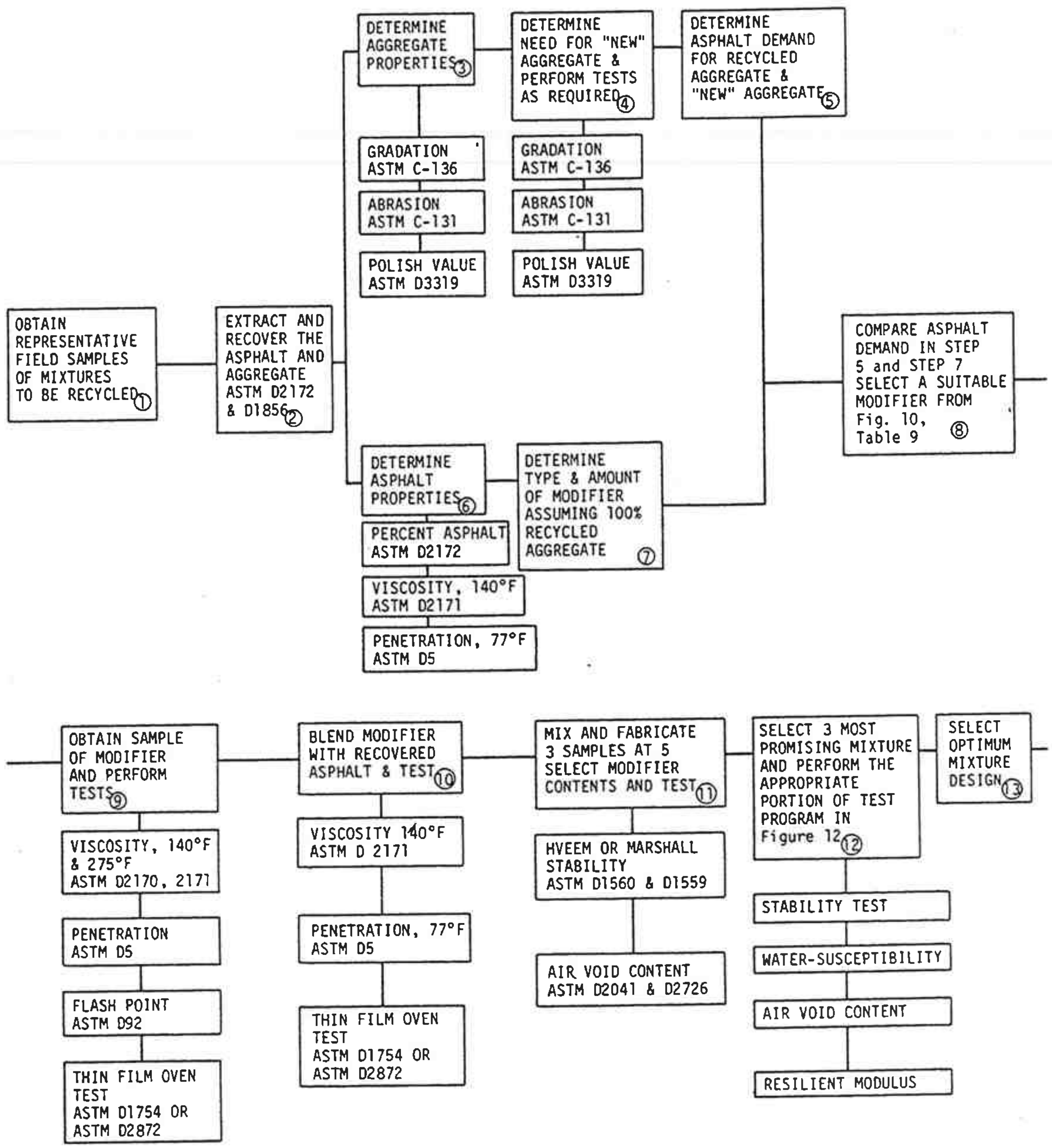


Figure 5.4 NCHRP mix design procedure (Epps, et al., 1980)

4) Determine target penetration and whether virgin mix will be needed to improve gradation, increase air voids, or stability.

5) Select tentative virgin mix and rate of addition expected.

6) Perform trial mixes adding supplemental materials to determine and measure mix properties using RAP from core materials. Insure air voids in recycled mix will not be too low - allow some margin for variation of in situ aggregate gradation and asphalt content.

7) Determine final mixture properties and components. Recover asphalt binder from project design mix for viscosity and penetration before startup and compare with target values. Specify a range of addition rates in tendered quantities to allow for changes in addition of recycling agent and/or virgin mix.

5.2.5 Alberta Transportation & Utilities (AT&U) Design Procedure

AT&U developed an HIR mix design procedure based on experience gained from four projects in 1989-93. The process is as follows [Gavin and McMillan, 1993]:

1) Review the existing pavement's as-built construction records.

2) Characterize the existing pavement through sampling and extraction using field cores. At least three 150 mm (6 inch) cores should be taken per kilometer (0.62 miles) for forming Marshall specimens.

   a) One of the three cores is used for determining in-place pavement density, asphalt content, and gradation. Rheological testing is performed using the Abson recovered asphalt to determine penetration and viscosity. This is then used to determine the quantity of rejuvenator needed to restore the asphalt's rheological properties.

b) The other two cores are used to form Marshall specimens and tested for Marshall density, air voids, stability, and flow. Rejuvenator and additional aggregate are added as necessary to meet Marshall design criteria. AT&U uses the same Marshall design criteria as for conventional asphalt mixes.

AT&U notes that obtaining the 3-5 percent air voids is usually the critical factor, and that often the mix must be modified by adding virgin aggregate to open up the aggregate gradation.

5.2.6 Idaho Transportation Department (ITD) Design Procedures

Idaho takes a different approach toward HIR mix design, focusing on the stability of the recycled mix rather than "softening" the RAP. They remix the cored material and use conventional Hveem design criteria to evaluate the mix for air voids in addition to stability. To lower the asphalt content of the mixture, coated aggregate is mixed with the RAP, usually with only 1.5 to 2 percent asphalt added. If the pavement needs additional asphalt, various grades of asphalts down to AC-3 will be tried before using RA. ITD uses RA only if conventional asphalts prove ineffective as it is considered too sensitive to fluctuations in metering and mixing. ITD prefers to use HIR on seal coated pavements because the chip seal asphalts respond well to the addition of pre-coated crushed virgin aggregate. On pavements without a seal coat more asphalt is added to the virgin mix [Mort, 1991]. As might be expected from the lack of use of a rejuvenating agent, transverse cracking has been a problem on some of the roads which they have recycled [Smith, 1994; Stanley, 1994].

5.3 ODOT HIR Mix Design Review

For the six 1992-93 Oregon HIR projects, most of the mix designs centered around target viscosity using ASTM D4887-89, the process discussed in Section 5.2.1 above. Mix design procedures and performance information for each of the six ODOT HIR projects are presented in Table 5.1 and discussed below.

5.3.1 Old Oregon Trail Freeway (I-84) Shoulders/Wallowa Lake Highway

On the first ODOT HIR project, the I-84 shoulders, the mix design was based upon ASTM D4887-89 and a target viscosity of 9,000 poises. It called for addition of RA-25 at the rates 2.3 and 3.7 percent. IRRM was determined (remolded specimens without RA) and it was noted that IRRM results "indicate mix may be sensitive to stripping." When construction began, the contractor pointed out that the design add rate was much too high, and the RA was added by the contractor based upon his experience. The average addition rate for the project was approximately 0.31 percent. Construction problems (discussed in Section 3.2.1) led to testing the rejuvenated mixture for stability and water sensitivity. During construction, 488.80 tons of commercial "B" mix was added to the recycled mixture to overcome the extensive stripping problems, with asphalt content ranging up to 7 percent. The project was stopped prior to completion because the laboratory testing revealed potential problems with stability, water sensitivity, and fatigue cracking. The existing pavement was severely stripped to the extent that there was not enough asphalt to be rejuvenated.

The mix design for the Wallowa Lake Highway was similarly based upon ASTM D4887-89, and called for addition of 0.5, 0.8, and 1.3 percent RA-25 to the RAP. IRRM

Table 5.1 Summary of Mix Design Procedures Used in 1992-93 ODOT HIR Projects.

Project:	Preliminary Mix Design Approach	Pre-Construction Absom Recovery (Average)	Preliminary Mix Design Testing (Average)	Design Add Rate of RA (% By Wt. of RAP)	Add Rate of RA Used In the Field (% By Wt. of RAP)	Testing During Construction (Laboratory Compacted) (Average)	Post-Construction Absom Recovery (Average)	Problems Encountered	HIR Mix Design Lessons Learned
Old Oregon Trail	ASTM D4887-89 Target viscosity	Pen. - Not Done Vis. - 441,000 Poises	IRRM - Failed Air Voids - 9.8%	3.7 WB RA-25 2.3 EB RA-25	0.24 to 0.35 RA-25 Averaged 0.31	IRS - Failed Hveem - Failed	Pen. - 11 Vis. - 291,000 Poises	Severely Stripped Pavement	Importance of Project Selection/Investigation
Wallowa Lake Hwy	ASTM D4887-89 Target viscosity	Pen. - 19 dmm Vis. - 52,150 Poises	IRRM - Adequate Air Voids - 13%	0.5-1.3 RA-25	0.16 to 0.19 RA-25 Averaged 0.18	No Tests Performed	No Tests Performed	Delaminations Between Layers	Importance of Project Selection/Investigation
Clear Lake - Old McKenzie Hwy	ASTM D4887-89 Target viscosity	Pen. - 23 Vis. - 24,793 Poises	Air Voids - 8.5% IRRM - Adequate Low Stability Low Air Voids	0.7 to 1.0 RA-25	0.3 to 0.7 RA-25 Averaged 0.54	Hveem - Failed Air Voids - 1.9%	Pen. - 26 Vis. - 16,402 Poises	(Thermal Cracking) No Major Problems	HIR Can Work
N. Grants Pass - Jumpoff Joe Creek *	ASTM D4887-89 Target viscosity	Pen. - 32 Vis. - 14,350 Poises	—	0.3 RA-25	Averaged 0.2 % RA Both RA-5 & RA-25	Hveem - Passed Air Voids - 1.8%	Pen. - 15 Vis. - 379,983 Poises	Quality/Quantity of RA Recycled Mix Severely Aged	Importance of Contractor Skill and Experience
Tangent-Halsey	Project Manager & Contractor Experience	Pen. - 16 Vis. - 35,202 Poises	Low Stabilities and Air Voids in the Majority of Tests	0.2 RA-5	0.1 to 0.5 RA-5 Averaged 0.31	Hveem - Passed Air Voids - 3.6%	Pen. - 28 Vis. - 45,178 Poises	Extensive Patching - Delaminations	Importance of Project Selection/Investigation
Cline Summit	Project Manager & Contractor Experience	Pen. - 27 Vis. - 33,000 Poises	Air Voids - 2.5%	0.2 RA-25	0.3 to 0.7 RA-25 Averaged 0.45	No Tests Performed	Pen. - 20 Vis. - 23,000 Poises	Delaminations, Rutting, Alligator Cracking	Importance of Project Selection/Investigation
Durkee-Lime *	Project Manager & Contractor Experience	Pen. - 17 Vis. - 197,640 Poises	IRRM - Adequate Air Voids - 4.6% Low Remolded Air Voids and Stabilities	1.0% RA-25 (Majority) and 0.0%	0.03 to 0.91 RA-25** Averaged 0.19**	No Tests Performed	Pen. - 14 Vis. -199,805 Poises	Variations in RAP, Stripping, Raveling	Using HIR as base course prior to overlay can work

Notes * Denotes projects where HIR pavement was intended for base course for subsequent F-mix overlay.
** Discrepancy on this project between total quantities used by contractor and spreads recorded in the daily construction reports.

Abbreviations: IRRM = Index of Retained Resilient Modulus
IRS = Index of Retained Strength

Values for RA used in field taken from construction daily reports except for Clear Lake - Old McKenzie Hwy., Tangent - Halsey, and Cline Summit which were taken from hot in-place recycling presentation at the ODOT Project Manager's Meeting, March 29-31, 1993.

testing did not show stripping potential. In the field, the RA addition rate was again left to the contractor's judgment. For the project, the addition rate for RA started at 0.18 percent, and dropped to 0.07 percent, on the last few miles. The average addition rate was 0.16 percent by weight of RAP.

5.3.2 Clear Lake-Old McKenzie Highway

For the Clear Lake-Old McKenzie Highway project, the mix design was again based on ASTM D4887-89, using the recovered viscosity of field cores and a desired recycled viscosity of 9,000 poises. Laboratory predictions for the addition rate of RA-25 ranged from 0.7 to 1.0 percent of the RAP weight. Limited testing of remolded cores (without RA) showed low stabilities and air voids, with no indication of a stripping problem. Field construction began at 0.7 percent RA-25, and it soon became apparent that the mix would go to zero voids and probably would flush, as it slumped in the windrow. Again, the addition rate was left to the contractor's judgment, and ranged from 0.3 to 0.7 percent, averaging 0.54 percent. This was the only project that showed rejuvenation at every site sampled before and after HIR.

5.3.3 N. Grants Pass-Jumpoff Joe Creek (I-5)

Mix design for this HIR project again used the ASTM D4887-89 viscosity nomograph. The pavement had fairly uniform asphalt properties, and the recommended RA addition rate was 0.30 percent RA-25. Problems with the contractor supplied RA led to the taking of core samples throughout the first two miles of the project. The recovered properties were inconclusive as to the quality of the RA, but they showed that the HIR project greatly "aged" the asphalt. The post construction absolute viscosities ranged from 43,000 poises to approximately 1 million poises with several specimens too viscous to be tested, compared to an average pre-construction viscosity of 14,350 poises. The finished HIR mat was overlaid with a two-inch thick open-graded wearing surface. After two years in service, no serious problems have been detected. The average RA addition rate for the project was 0.20 percent by weight of RAP.

5.3.4 Tangent-Halsey (Hwy. 99E)

The recovered asphalt properties from the preliminary grindings and core sampling showed the existing pavement to be quite variable (see Table 3.14). Portions of the pavement were 60 years old and over eighty percent had been patched. Hveem stability and air voids for specimens remolded (without RA) from pre-construction core material varied widely, with the majority of specimens not meeting ODOT dense-graded hot-mix criteria. Using the experience gained from the Clear Lake-Old McKenzie Highway HIR project, the RA addition rate was estimated at 0.2 percent RA-5 by weight of RAP. During construction, the addition rate varied from 0.1 to 0.5 percent, averaging 0.31 percent. Along one 3.6 mile long section with severe raveling, commercial C-mix was added at a variable 9-27 percent rate to the rejuvenated mixture. The pavement was overlaid the following year to correct ride problems.

5.3.5 Cline Summit

For the Cline Summit HIR project, the preliminary coring used to estimate asphalt properties consisted of one coring location in each lane, in the middle of the project. From the recovered asphalt properties, the addition rate was estimated at 0.2 percent RA-25 by weight of RAP. In the field, the addition rate varied from 0.3 to 0.7 percent. After two winters the pavement looked rough, but the HIR section appeared in considerably better shape than the non-recycled sections, which required substantial blade patching. The entire section was overlayed in September, 1994 as part of the 16.73 mile long Pioneer Mountain Road-Coast Range Summit project.

5.3.6 Durkee-Lime (I-84)

The preliminary mix design used for the Durkee-Lime HIR project was based on data obtained from field cores and from Hveem stability, air voids, and IRRM data obtained from remolded specimens. The addition of 1.0% RA-25 was recommended for the project, with the exception of an approximate 1.5-mile section where no RA was recommended due to a very soft asphalt in the existing pavement. When construction began, the RA meters were not functioning, and RA was added by the contractor's judgment. After a few days construction, the meters were fixed and the RA addition rate was monitored. Upon completion of the project, it was observed that the daily construction reports total RA spread (54.56 tons) was considerably different from the total quantity (40.62 tons) billed by the contractor. This makes the daily amounts questionable, so the average value was taken as 40.62 tons divided by 192,190 square yards or 0.19 percent RA-25 by weight of RAP. This project, like the N. Grants Pass-Jumpoff Joe Creek HIR project, was intended for immediate overlay upon completion. Comparing pre- and post-construction cores from the same locations, the results are varied in that in some places the RAP was rejuvenated by HIR, while in others it was aged. One year after construction no problems have been observed.

5.4 Laboratory Testing Program

5.4.1 Description of Laboratory Study

The objectives of the laboratory study were as follows:

- To identify the most critical HIR design inputs.
- To refine the mix design process, when possible distinguishing between HIR to be used as a base or surface course.
- To determine the probable range of quality of HIR mixes.

To accomplish these goals, a detailed laboratory testing program was developed modeled upon ODOT's dense-graded mix design process. The flowchart for HIR testing is shown in Figure 5.5. The following tests were used to evaluate mixture performance;

- Index of Retained Strength (IRS) following AASHTO T 165,
- Index of Retained Resilient Modulus (IRRM) following AASHTO T 283,
- Hveem Stability (first and second) following modified AASHTO T 246 procedures, and
- Fatigue testing in the diametral mode.

Each test cycle (see Figure 5.5) tested one combination of rejuvenating agent and RAP/coated aggregate and consisted of fourteen 1,200 and six 1,800 gram specimens as follows:

- The six 1,800 gram specimens were used to characterize the index of retained strength.
- Three of the 1,200 gram specimens at 0.2, 0.8, and 1.4 percent RA content by aggregate weight were tested for IRRM.

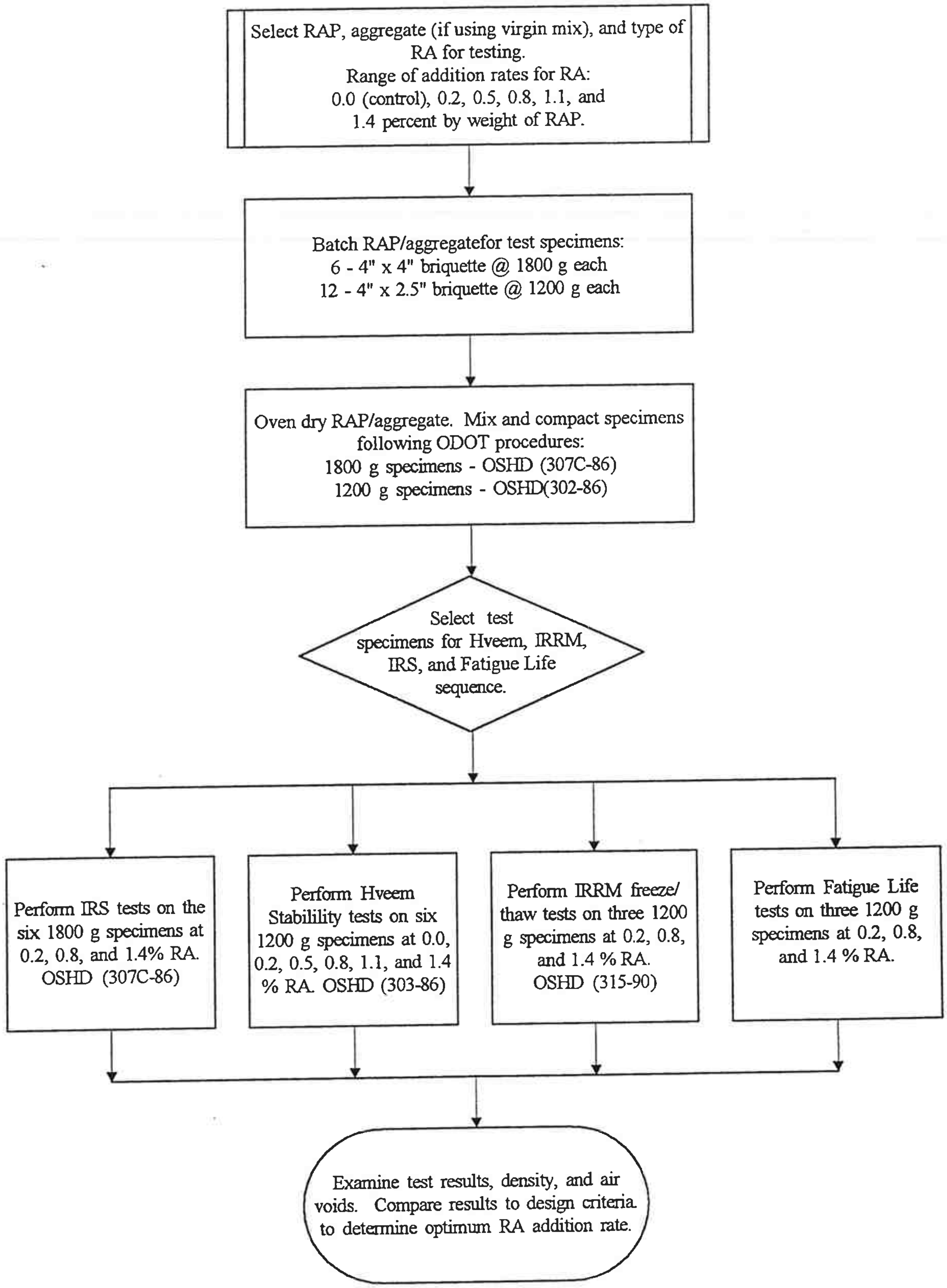


Figure 5.5 Flowchart for each laboratory test cycle.

- Six of the 1,200 gram specimens at 0.0 (control), 0.2, 0.5, 0.8, 1.1, and 1.4 percent were tested for stability using the Hveem stabilometer.
- Three of the 1,200 gram specimens at 0.2, 0.8, and 1.4 percent RA content by aggregate weight were tested for diametral fatigue life.

The wide range of RA addition rates (0 to 1.4 percent of RAP weight) exceeds the typical values (0.2 to 0.8 percent of RAP weight) used in the field. The average RA addition rate for the six ODOT projects was 0.35 percent and ranged from 0.03 to 0.91 percent. The expanded range used in laboratory testing was selected to examine how mix properties depend on the rejuvenating agent, and to see how much RA could be added without creating stability problems.

To accomplish the objectives of the laboratory study, representative RAP, rejuvenating agents, asphalt cements, and aggregates were used for testing and combined in commonly used mixtures. Mix combinations are presented in Table 5.2. As shown in the table, mixes utilized a wide range of RA additions; 0.0 (control), 0.2, 0.5, 0.8, 1.1, and 1.4 percent.

The materials used to fabricate the laboratory specimens were as follows:

1) RAP

   a) Cold millings from the 1993 mill and inlay project on I-5 near Halsey, Oregon.

   b) Material taken from six inch field cores taken at mile point 339.5 in the westbound lane of I-84 immediately prior to recycling on the Durkee-Lime HIR project.

2) RA-5 and RA-25 recycling agents supplied by Witco Corporation.

Table 5.2 Laboratory Tests Performed Categorized by RAP and Rejuvenating Agent/Asphalt.

Tests	Hveem Stability		Index of Retained Modulus		Fatigue Life		Index of Retained Strength	
RAP	Halsey	Durkee - Lime	Halsey	Durkee - Lime	Halsey	Durkee - Lime	Halsey	Durkee - Lime
RA-5	X	X	X	X	X		X	
RA-25	X	X	X	X	X	X	X	
AC-3	X		X		X		X	
PBA-2	X		X		X		X	
10% Virgin Mix/RA-5	X		X				X	
10% Virgin Mix/RA-25	X		X				X	
30% Virgin Mix/RA-5	X		X				X	
30% Virgin Mix/RA-25	X		X				X	

3) PBA-2 and AC-3 asphalt cement supplied by McCall Oil & Chemical Corporation.

4) Aggregate from Morse Bros. Corvallis stockpiles, that was lightly coated with 2-3 percent PBA-2 and used as virgin mix in the laboratory.

Ideally, all RAP used in the laboratory would come from "trimmed" field cores, as cold milled RAP may not be representative due to the aggregate fracturing that occurs. However, the size of the laboratory study coupled with the prohibitive cost of field coring necessitated use of cold milled RAP as test material. Two test cycles were performed using field cored material from the Durkee-Lime project.

5.4.2 Materials

It was desirable to use consistent and uniform RAP material which would allow comparison of the test results for the various rejuvenating agents. For the majority of laboratory testing, RAP taken from cold millings from an I-5 mill and inlay project near Halsey, Oregon, was used. Since this material was taken from a stockpile, it was broken into 5 gallon lots, then mixed, quartered, and split into approximately 1,200 gram fractions for subsequent testing. When recovered absolute viscosity showed high variation in values for the first two samples, two additional samples of this RAP were recovered and extracted.

The recovered RAP gradations of the Halsey RAP and the Durkee-Lime RAP (discussed below) used in the laboratory study are shown in Table 5.3, and the recovered asphalt properties are shown in Table 5.4. Table 5.4 shows reasonable variability in gradation, asphalt content, and penetration. Variability in recovered absolute viscosity for the Halsey RAP was high. When the high variability of RAP viscosity was revealed,

Table 5.3 Gradations and Asphalt Content for Halsey and Durkee-Lime RAP Used in Laboratory Tests.

Gradation % Passing	Halsey			Durkee-Lime
	1	2	Avg.	
1"	100	100	100	100
3/4"	99	100	100	99
1/2"	90	91	91	92
3/8"	79	78	79	83
1/4"	66	64	65	71
#4	56	54	55	61
#10	33	30	32	36
#40	14	13	14	14
#200	6.3	6.2	6.3	6.6
Asphalt Content, %	5.1	4.9	5.0	6.0

Table 5.4 Modified Abson Recovery for Halsey and Durkee-Lime RAP Used in Laboratory Tests.

RAP Source	Halsey						Durkee-Lime
	1	2	3	4	Avg.	Stan. Dev.	
Viscosity, Absolute	358,000	223,000	83,100	130,000	198,525	121,175	67,540
Penetration of Res. at 77°F	11	10	15	12	12	2	11

significant laboratory testing had already taken place, so the decision was made to proceed with testing using the Halsey RAP.

A smaller laboratory investigation was undertaken utilizing RAP from the Durkee-Lime project. Thirty 6-inch cores were taken near mile point 339.5 in the westbound lane. These cores were trimmed so that only the top 2 inches were used and to remove the cut aggregate faces.

The material properties of the two rejuvenating agents, RA-5 and RA-25, and the two asphalts, PBA-2 and AC-3, are shown in Tables 5.5-5.6.

For the test sequence involving the addition of virgin mix to HIR RAP, the goal was to reach a gradation near the ideal "B" mix gradation. The intent was to keep the approach simple, using a single stockpile (3/4 inch-1/4 inch) to meet the desired gradation. This was not feasible with the existing stockpile, so all four stockpiles were used, manipulating and combining percentages from each, to get the desired gradation. The percentage of asphalt used to coat the aggregate was done visually, based on ODOT estimates. For the RAP with 10 percent virgin mix, 2 percent PBA-2 appeared to satisfactorily coat the aggregate. The RAP with 30 percent virgin mix required 3 percent PBA-2. The projected gradations for the laboratory mixes with addition of virgin materials are shown in Tables 5.7-5.8.

5.4.3 Mix Procedures

As mentioned in Section 5.1, there are no well established detailed mix procedures for HIR mixtures. This is noteworthy because, as previously discussed, most HIR mix designs focus on binder penetration and viscosity, which are significantly affected by laboratory heating. In formulating the mix procedures used for the laboratory study, it was

Table 5.5 Physical Properties of Rejuvenating Agents Used in HIR Study.

Property	RA-5	RA-25
Viscosity @60C (poises)	2-5	10-40
Flash Point COC, deg. C	>204	>232
Volatility 1BP, C 2% v, C 5% v, C	 149 min. 191 min. 210 min.	 163 min. 204 min. 221 min.
RTF-C Weight Change, %w	4.0 max.	2.0 max.
Compatibility PC/S	0.5 min.	0.5 min.
Saturates, %w	28 max.	28 max.
Asphaltenes, %w	1.5 max.	7.0 max.
Chemical Comp. (PC+A1)/(S+A2)	0.4-0.8	0.6-1.0
RTF-C Ratio	2.5 max.	2.5 max.
Specific Gravity	0.98-1.02	0.98-1.02

Table 5.6 Physical Properties of Asphalt Cements Used in HIR Study.

Property	AC-3	McCall PBA-2
Viscosity @ 60C (poises)	200-400	min 1100
Viscosity,135C cS-min.	80	----
Penetration, 25C 100g, 5sec	180	----
Flash Point, COC, deg. C	>177	>232
RTFO-T		
Viscosity,60C poises	1,000	2,500-6,000
Viscosity,135C cS-min.	----	min 275
Ductility	100	min 75

Table 5.7 Projected Gradations for Halsey RAP with Addition of 10% Virgin Mix.

	Pile #1	Pile #2	Pile #3	Pile #4	Pile #5	Combined Gradation Halsey RAP With 10% Virgin Mix		Typical "B"-Mix Gradation
% by RAP weight	10.0	0.0	0.0	0.0	90.0			
Sieve	3/4-1/4	1/2-1/4	1/4-#10	#10-0	RAP	Sieve	% Passing	% Passing
1	100.0	100.0	100.0	100.0	100.0	1	100.0	100
3/4	76.0	100.0	100.0	100.0	99.0	3/4	96.9	96
1/2	3.8	94.0	100.0	100.0	90.0	1/2	82.8	80
3/8	1.9	49.0	100.0	100.0	79.0	3/8	70.4	70
1/4	0.7	3.6	83.0	100.0	66.0	1/4	55.8	57
#4	0.7	1.2	52.4	100.0	56.0	#4	47.0	49
#10	0.6	1.0	8.8	80.0	33.0	#10	27.7	28
#40	0.5	0.9	2.7	26.3	14.0	#40	11.4	11
#200	0.3	0.5	1.7	6.9	6.3	#200	4.9	5

Table 5.8 Projected Gradations for Halsey RAP with Addition of 30% Virgin Mix.

	Pile #1	Pile #2	Pile #3	Pile #4	Pile #5	Combined Gradation Halsey RAP With 30% Virgin Mix		Typical "B"-Mix Gradation
% by RAP weight	10.0	10.0	5.0	5.0	70.0			
Sieve	3/4-1/4	1/2-1/4	1/4-#10	#10-0	RAP	Sieve	% Passing	% Passing
1	100.0	100.0	100.0	100.0	100.0	1	100.0	100
3/4	76.0	100.0	100.0	100.0	99.0	3/4	96.7	96
1/2	3.8	94.0	100.0	100.0	90.0	1/2	81.4	80
3/8	1.9	49.0	100.0	100.0	79.0	3/8	71.3	70
1/4	0.7	3.6	83.0	100.0	66.0	1/4	59.5	57
#4	0.7	1.2	52.4	100.0	56.0	#4	50.5	49
#10	0.6	1.0	8.8	80.0	33.0	#10	29.8	28
#40	0.5	0.9	2.7	26.3	14.0	#40	12.7	11
#200	0.3	0.5	1.7	6.9	6.3	#200	5.7	5

decided to use established dense-graded mix procedures, modified slightly for use with RAP as opposed to virgin aggregate.

The modifications, taken from "Guideline for Hot Mix Recycling In Georgia" (Kandhal, et al., 1989) which focused on in-plant recycling, were used only for the 1,200 gram specimens. The Georgia mix design procedure is shown in Figure 5.6. Essentially, the 1,200 gram specimens were fabricated using AASHTO T247, with the following procedural changes:

1) Heat the RAP to 116°C (240°F) for approximately 2 hours prior to mixing. Keep the RAP covered while heating. If adding virgin mix, heat new aggregate overnight at 163°C (325°F).
2) Heat rejuvenating agent (and asphalt) RAP to 140°C (285°F). Add prescribed amount of rejuvenating agent to RAP and mix for 3 minutes. Add asphalt to coat aggregate, mixing for 2 minutes. Combine both mixtures and mix an additional 2 minutes. After mixing, place covered mix in oven for 30 to 60 minutes at 149°C (300°F).
3) Mold samples using the standard Hveem procedure, then compact.
4) After compaction, cure for 4 hours at 60°C (140°F) to reduce variability.

Detailed laboratory mix procedures for 1,200 gram specimens are listed in Appendix B.

For the 1,800 gram (IRS) test specimens, AASHTO T 167 mix procedures were used in preparing test mixtures. Unfortunately, this resulted in heating the RAP to 325°F for a minimum of 15 hours. This method should not be used for RAP, because the prolonged exposure to the higher temperatures severely ages the asphalt binder and is not

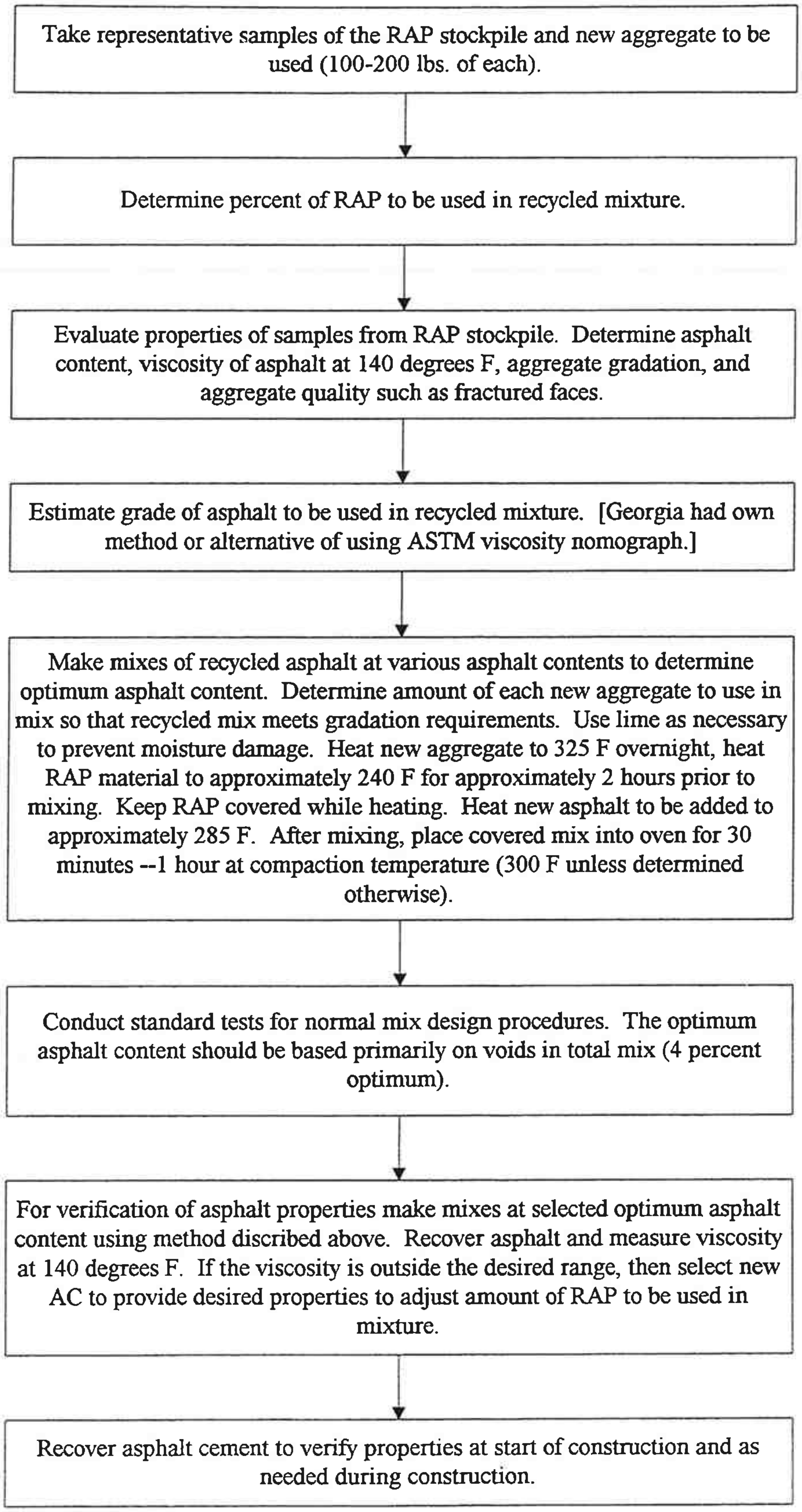


Figure 5.6 Georgia mix design procedures (adapted from Kandhal, et al., 1989).

representative of actual construction conditions. Because of this error, compressive strength and IRS values from this test data would be misleading and are not included in this report.

5.4.4 Test Results and Discussion

One objective of the laboratory testing program, determination of the probable range of quality of HIR mixes, is discussed in this section. The mix design refinement and critical design input objectives are addressed in the next section.

Test results for the laboratory testing program were obtained in the following areas:

- Binder properties from RAP-RA mixes.
    1. Predicted vs recovered absolute viscosity.
    2. Predicted vs recovered penetration.
- Mix properties from RAP-RA mixes and RAP-RA-Virgin mix mixtures.
    1. Air voids and unit weight.
    2. First and second Hveem stability.
    3. Index of retained resilient modulus (IRRM).
    4. Index of retained strength (IRS).
    5. Fatigue testing in the diametral mode.

These mix properties were determined by the same test procedures as are used for testing of dense-graded hot mix.

Complete test results are presented in Appendix C. Selected results are discussed below. Tables 5.9 and 5.10 summarize testing of recovered binder from RAP-RA mixes. Mix test results are presented in Tables 5.11-5.14 and shown graphically in Figures 5.7-5.18.

Table 5.9 Comparison of Recovered and Nomograph Predicted Viscosity Properties of Recovered Laboratory Specimens.

RA Added (%)	RA-5						
	Measured Viscosity (Poises)	Assumed RAP Viscosity					
		100,000 (Poises)	Difference (%)	200,000 (Poises)	Difference (%)	300,000 (Poises)	Difference (%)
0.2	71,600	56,000	-22	110,000	54	170,000	137
0.8	51,500	15,000	-71	23,000	-55	33,000	-36
1.4	164,000	4,500	-97	7,500	-95	9,200	-94

RA Added (%)	RA-25						
	Measured Viscosity (Poises)	Assumed RAP Viscosity					
		100,000 (Poises)	Difference (%)	200,000 (Poises)	Difference (%)	300,000 (Poises)	Difference (%)
0.2	471,000	69,000	-85	140,000	-70	200,000	-58
0.8	254,000	25,000	-90	40,000	-84	59,000	-77
1.4	7,300	11,000	51	17,000	133	22,000	201

Table 5.10 Comparison of Recovered and Nomograph Predicted Penetration Properties of Recovered Laboratory Specimens.

RA Added (%)	RA-5						
	Measured Penetration (dmm)	Assumed RAP Penetration					
		10 (dmm)	Difference (%)	12 (dmm)	Difference (%)	14 (dmm)	Difference (%)
0.2	11	14	27	16	45	20	82
0.8	18	40	122	44	144	56	211
1.4	27	77	185	80	196	91	237
RA Added (%)	RA-25						
	Measured Penetration (dmm)	Assumed RAP Penetration					
		10 (dmm)	Difference (%)	12 (dmm)	Difference (%)	14 (dmm)	Difference (%)
0.2	8	12	50	13	63	18	125
0.8	16	20	25	22	38	36	125
1.4	17	39	129	41	141	52	206

Table 5.11 Asphalt/Mixture Properties for RA-5 Specimens.

Laboratory Cycle:		Halsey RAP				Halsey RAP w/10% Coated Agg.				Halsey RAP w/30% Coated Agg.			
RA Content (%)		0.0	0.2	0.8	1.4	0.0	0.2	0.8	1.4	0.0	0.2	0.8	1.4
Asphalt Properties	Penetration (dmm)	12	11	18	27	---	---	---	---	---	---	---	---
	Kin. Viscosity (cSt)	2,038	3,397	1,520	1,560	---	---	---	---	---	---	---	---
	Abs. Viscosity (poises)	198,525	71,600	51,500	164,000	---	---	---	---	---	---	---	---
Mixture Properties	Air Voids (%)	5.8	3.9	3.8	1.4	2.3	4.2	2.5	2.3	6.0	6.4	4.7	2.5
	Modulus (ksi)	1,031	954	566	362	---	1,305.5	693	298	---	933	812.5	609.5
	Fatigue Life (repetitions	98,405	117,551	172,986	239,232	---	---	---	---	---	---	---	---
	Hveem Stability	49/49	44/29	46/49	41/30	39/35	36/64	35/42	30/44	50/56	44/53	40/48	25/33
	Comp. Strength (psi)	---	1,496	1,440	1,182	---	859	844	1,027	---	680	861	653
	IRS (%)	---	69	83	89	---	126	141	104	---	88	58	94
	IRMr (%)	---	100	115	137	---	93	96	94	---	84	78	111

Table 5.12 Asphalt/Mixture Properties for RA-25 Specimens.

Laboratory Cycle:		Halsey RAP				Halsey RAP w/10% Coated Agg.				Halsey RAP w/30% Coated Agg.			
RA Content (%)		0.0	0.2	0.8	1.4	0.0	0.2	0.8	1.4	0.0	0.2	0.8	1.4
Asphalt Properties	Penetration (dmm)	12	8	16	17	---	---	---	---	---	---	---	---
	Kin. Viscosity (cSt)	2,038	4,190	1,660	1,410	---	---	---	---	---	---	---	---
	Abs. Viscosity (poises)	198,525	471,000	254,000	7,300	---	---	---	---	---	---	---	---
Mixture Properties	Air Voids (%)	5.2	4.6	2.8	2.5	2.3	4.9	2.2	1.7	5.0	5.4	5.5	2.8
	Modulus (ksi)	1,031	1,175	841.5	510.5	---	1,023	1,127	724	---	933	812.5	609.5
	Fatigue Life (repetitions	98,405	---	234,260+	186,675	---	---	---	---	---	---	---	---
	Hveem Stability	38/52	35/46	28/28	12/7	46/56	50/59	37/22	22/14	50/58	30/49	33/36	34/33
	Comp. Strength (psi)	---	1,623	1,536	1,003	---	987	1,122	899	---	875	715	804
	IRS (%)	---	54	64	115	---	85	72	114	---	52	75	70
	IRMr (%)	---	129	121	147	---	105	111	116	---	124	126	158

Table 5.13 Asphalt/Mixture Properties for Asphalt/Halsey RAP Specimens.

Laboratory Cycle:		PBA-2				AC-3			
RA Content (%)		0.0	0.2	0.8	1.4	0.0	0.2	0.8	1.4
Asphalt Properties	Penetration (dmm)	12	----	21	----	12	----	10	----
	Kin. Viscosity (cSt)	2,038	----	1,890	----	2,038	----	3,780	----
	Abs. Viscosity (poises)	198,525	----	45,700	----	198,525	----	193,000	----
Mixture Properties	Air Voids (%)	5.8	3.3	2.5	1.7	3.3	3.7	2.7	0.8
	Modulus (ksi)	1,031	1,437	1,078	1,381	1,031	1,051	1,104	1,009
	Fatigue Life (repetitions)	98,405	108,452	200,362	312,382	98,405	186,675	300,000+	300,000+
	Hveem Stability	68/67	64/37	67/45	33/7	51/48	57/69	49/45	43/7
	IRMr (%)	----	108	114	89	----	105	111	116

Table 5.14 Asphalt/Mixture Properties for Durkee-Lime Specimens.

Laboratory Cycle:		Field		Durkee-Lime RAP/RA-5			Durkee-Lime RAP/RA-25		
RA Content (%)		Pre	Post	0.2	0.8	1.4	0.2	0.8	1.4
Asphalt Properties	Penetration (dmm)	11	27	----	----	----	----	----	----
	Kin. Viscosity (cSt)	1,820	815	----	----	----	----	----	----
	Abs. Viscosity (poises)	67,540	10,300	----	----	----	----	----	----
Mixture Properties	Air Voids (%)	3.9	1.5	1.6	0.8	1.2	1.6	1.0	1.6
	Modulus (ksi)	985	588	1,162.5	643	407.5	1,296.5	890	418
	Fatigue Life (repetitions)	220,000+	340,000+	----	----	----	300,000+	300,000+	300,000+
	Hveem Stability	----	----	35/21	14/4	12/8	35/12	14/4	34/17
	IRMr (%)	----	----	99	101	78	92	107	86

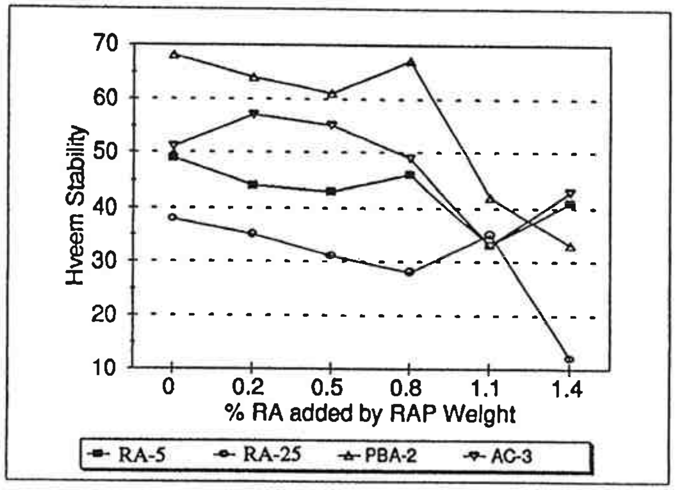


Figure 5.7 First Hveem stability numbers for 100% Halsey RAP mixes.

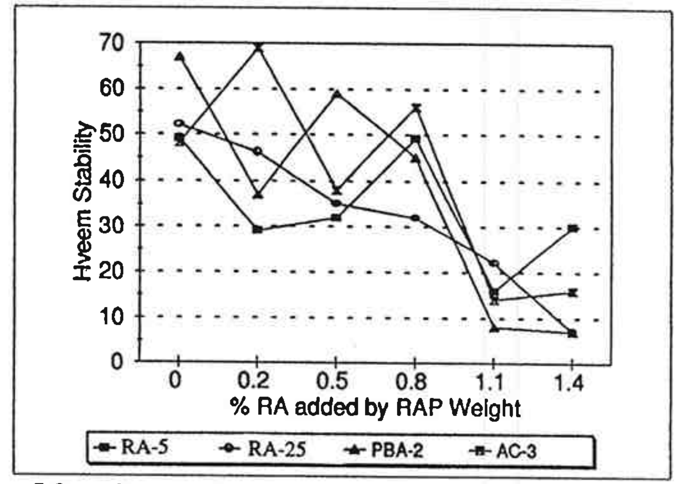


Figure 5.8 Second Hveem stability numbers for 100% Halsey RAP mixes.

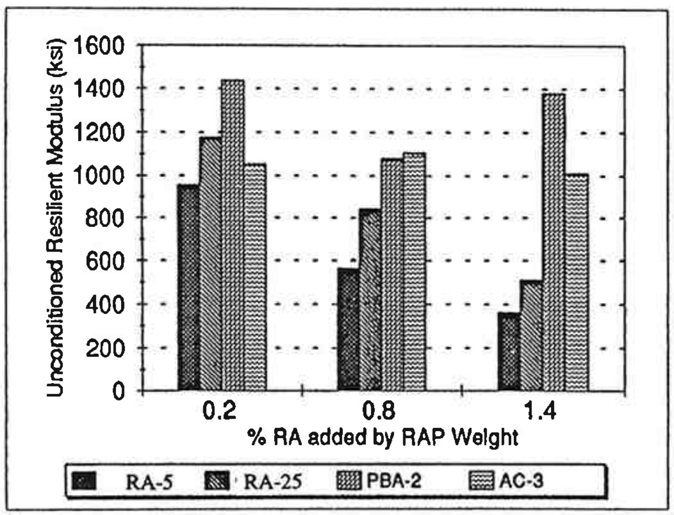


Figure 5.9 Diametral modulus results for 100% Halsey RAP mixes.

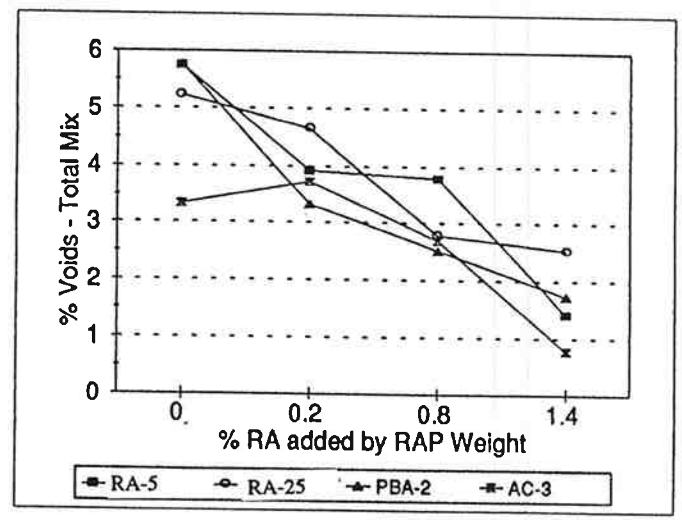


Figure 5.10 Percent air voids for 100% Halsey RAP mixes.

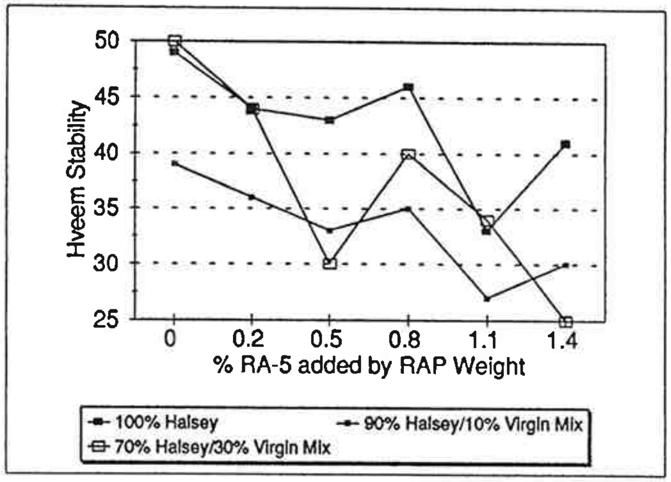


Figure 5.11 First Hveem stability numbers for RA-5 mixes.

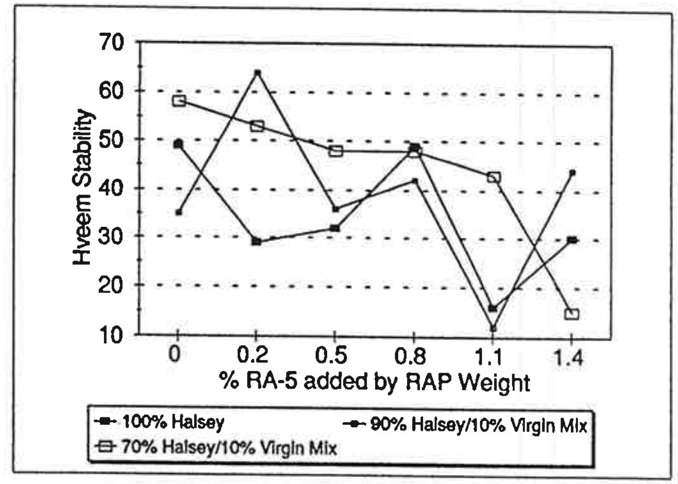


Figure 5.12 Second Hveem stability numbers for RA-5 mixes.

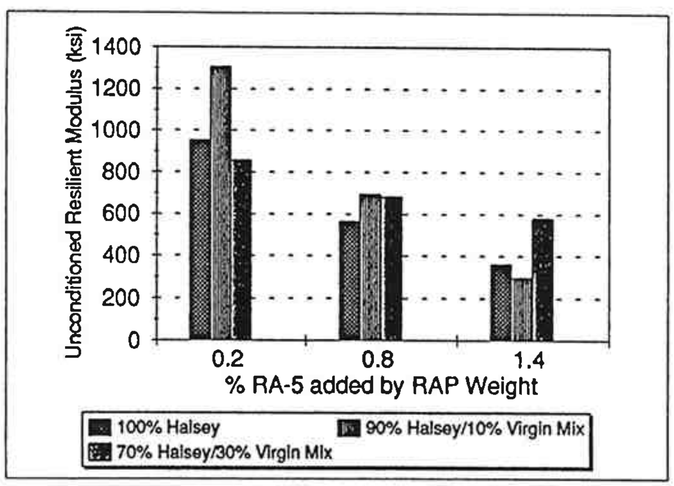


Figure 5.13 Diametral modulus results for RA-5 mixes.

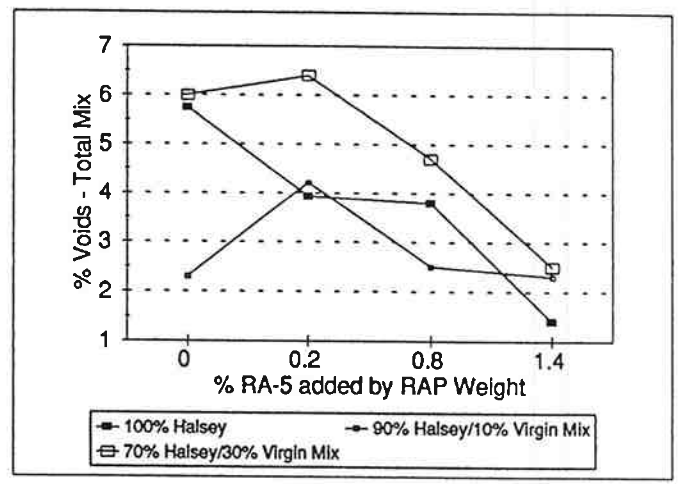


Figure 5.14 Percent air voids for RA-5 mixes.

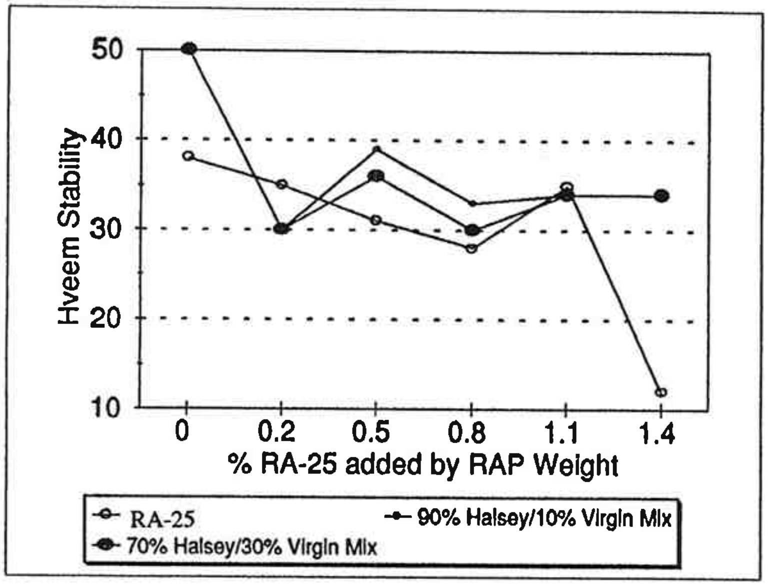


Figure 5.15 First Hveem Stability Numbers For RA-25 Mixes

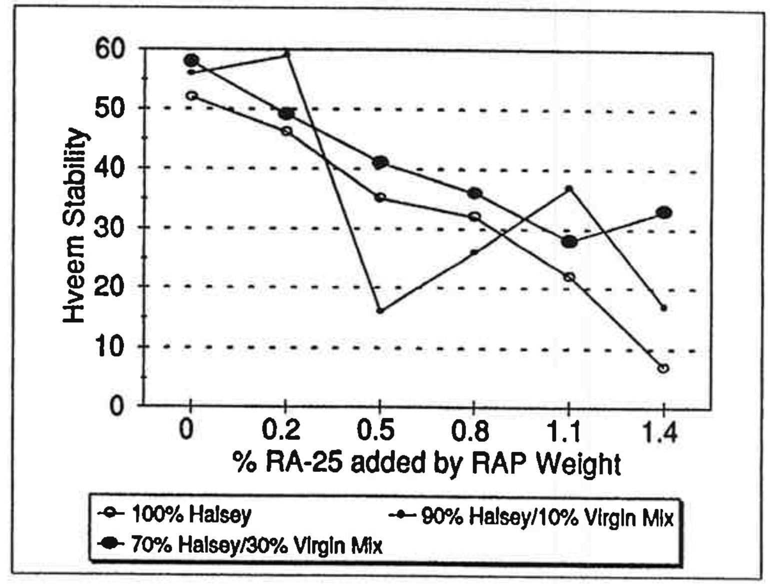


Figure 5.16 Second Hveem Stability Numbers For RA-25 Mixes

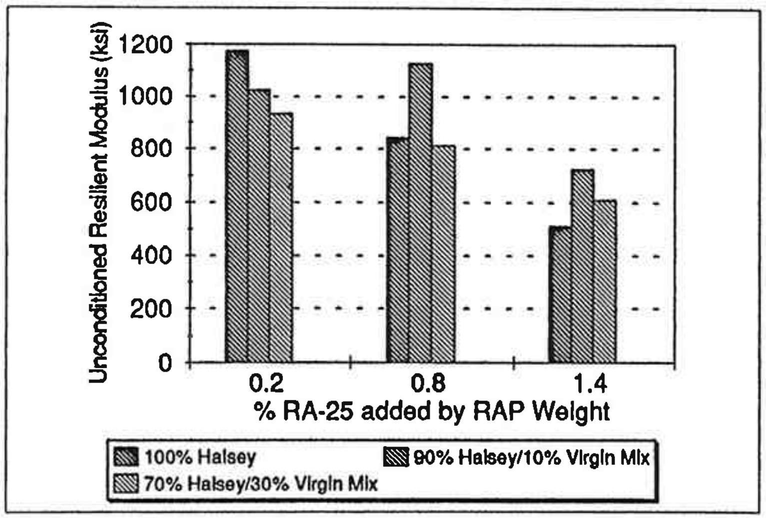


Figure 5.17 Diametral Modulus For RA-25 Mixes

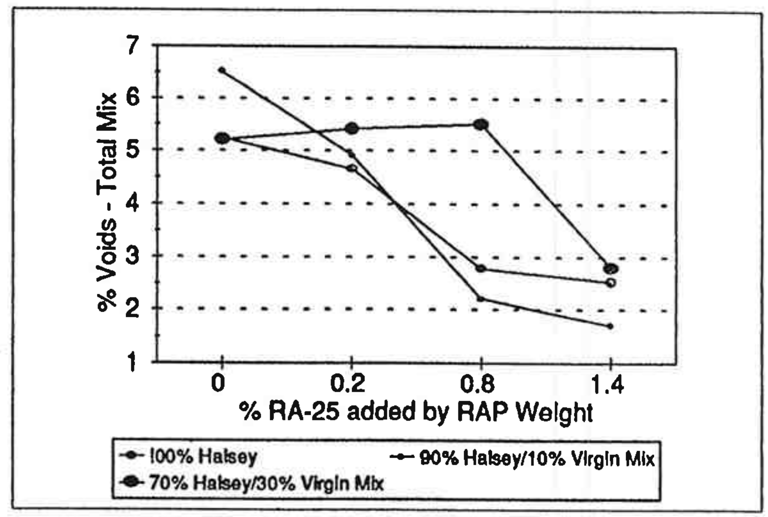


Figure 5.18 Percent Air Voids For RA-25 Mixes

Predicted vs recovered absolute viscosity. The majority of laboratory testing used the Halsey RAP. As was noted in Table 5.4, the viscosity of this RAP as determined by Abson recovery was highly variable, even though great care was taken to assure uniformity in RAP samples. The four absolute viscosity determinations ranged from 83,000 to 358,000 poises, with a mean of 198,500 and a standard deviation of 122,000 poises. With such highly vairable viscosities, comparison of recovered viscosities after the addition of RA to viscosities predicted by nomographs is extremely difficult, if not impossible. Nonetheless, since most mix design procedures involve the use of such a nomograph, a comparison was attempted.

To check the nomographs, asphalt was recovered from eight sets of two of the 1,200 gram laboratory specimens after testing. Table 5.9 shows the recovered properties, along with the nomograph predictions for 100,000 poise, 200,000 poise, and 300,000 poises, the approximate values of mean minus one standard deviation, mean, and mean plus one standard deviation for the Halsey RAP.

Increasing amounts of RA addition would be expected to result in lower recovered viscosities. Addition of RA-5 would be expected to result in lower viscosities than addition of comparable amounts of RA-25. The recovered viscosities do not meet these expectations.

- The 1.4% RA-5 had a much higher viscosity than either the 0.2% or the 0.8% specimens.
- The 1.4% RA-5 specimens had a much higher viscosity than the 1.4% RA-25 specimens.

- The 0.2% RA-25 specimens' recovered viscosity is more than 2 standard deviations higher than the mean value of the RAP without addition of RA.
- The 0.8% RA-25 specimens' recovered viscosity would be predicted only if the original RAP value were 800,000 poises, a value about 5 standard deviations above the mean of the 4 samples taken.

Possible explanations for these unexpected values include:

- high variability of RAP viscosity,
- difficulty in measuring viscosities > 100,000 poises, and
- highly aged asphalts may not respond to RA's; the asphalt may be aged to a point where it is beyond rejuvenation.

Predicted vs recovered penetration. The recovered penetration values (see Table 5.10) are more credible than the viscosity values. The variability of recovered penetration values for the Halsey RAP was much less than for recovered viscosities. For both RA-5 and RA-25, recovered penetration increased with increasing amounts of RA. At all 3 addition rates, recovered penetration for RA-5 are greater than for RA-25. In all cases, however, the nomograph overestimated the increases in penetration actually measured. It should also be noted that in both cases of addition of only 0.2% RA, the penetration was decreased. Apparently at this low level of RA addition, the hardening effects of heating during mixing prevailed over the softening effect of the small addition of RA.

For the severely aged Halsey RAP used in this laboratory study,

- recovered viscosity values were much more variable than recovered penetration values, both before and after addition of RA,

- prediction by penetration nomograph was better than prediction by viscosity nomograph, and
- measured increases in penetration were less than predicted.

Air Voids. As expected, air voids generally declined with increasing RA addition. With one exception (0.2% AC-3), Halsey RAP and mixes with RA-5, RA-25, PBA-2, and AC-3 showed decreases in air voids for every increment of addition of RA or liquid asphalt. Although the mixes of Durkee-Lime RAP with RA-5 and RA-25 did not follow the pattern as well, it must be expected that addition of RA or low viscosity asphalt will result in lower air voids.

The air voids data, shown graphically in Figures 5.10, 5.14, and 5.18, suggest that for the severely aged Halsey RAP, the loss of air voids became unacceptable as RA or low viscosity asphalt addition approached 1.0% by weight of RAP. Addition of some type of admixture, lean asphalt-coated aggregate or virgin hot mix, is the recommended procedure when air voids resulting from addition of RA or liquid asphalt are too low. Tables 5.11 and 5.12 or Figures 5.14 and 5.18 indicate that for the Halsey RAP, 10% addition of admixture had little effect, but 30% addition showed clear improvement in air voids. Even with admixture, 1.0% still appears to be an upper limit on RA addition for the Halsey RAP.

Hveem Stability. Variability was high, but as expected, the trend was clearly decreasing stability with increasing addition of RA or low viscosity asphalt. See Figures 5.7-5.8, 5.11-5.12, and 5.15-5.16 and Tables 5.11-5.14.

Resilent Modulus and Index of Retained Resilient Modulus (IRRM). Resilient modulus was tested before and after freeze-thaw conditioning. ODOT uses the IRRM to determine susceptibility to stripping. Values less than 70% indicate potential stripping.

None of the mixes with Halsey or Durkee-Lime RAP indicate stripping potential (Tables 5.11-5.14).

The modulus values indicate that RA's were more effective in reducing the stiffness of the RAP than were the low-viscosity asphalts. This is shown graphically in Figures 5.9, 5.13, and 5.17. Increased addition of soft asphalt did not significantly reduce the modulus values. Addition of RA did.

Index of Retained Strength (IRS). IRS testing procedures exposed the RAP to high heat far longer than would ever happen during HIR construction activity. Consequently, the test results are considered invalid and are omitted from the report.

Fatigue Life in the Diametral Mode. Time and budget restraints permitted only minimal exploration of the effect of RA addition on fatigue life. Mixes were tested with additions of RA-5, RA-25, PBA-2, and AC-3 at the 0.2 (except RA-25), 0.8, and 1.4% levels. In all cases except addition of 1.4% RA-25, fatigue life increased with increases in RA or liquid asphalt addition (see Tables 5.11-5.14 and Appendix Figure C.22). The decrease in fatigue life with 1.4% RA-25 is believed to be due to experimental error.

Comparison of Durkee-Lime Field Results With Durkee-Lime RAP-RA Laboratory Mix Test Results. The Durkee-Lime RAP used in the laboratory test program was obtained from cores taken at MP 339.5 WB just prior to HIR construction. Table 5.14 shows a comparison of test values at this location from pre-construction cores, from remolded specimens with RA-5 or RA-25 addition, and from post-construction coring. The three mix properties where field data and lab test data may be directly compared are air voids, modulus, and diametral fatigue.

Field and air voids data are consistent, with the exception of the illogical increase in air voids in the lab when going from 0.8% RA to 1.4% RA. Whether in the field or in the lab, recycled specimens showed air voids reduced to unacceptably low levels.

Addition of RA through HIR resulted in reduced modulus in the field, and increasing addition of RA resulted in decreasing modulus in the lab. The higher moduli for specimens with 0.2% RA in the lab remains unexplained.

HIR Test Properties vs ODOT Dense-Graded Design Criteria. Tables 5.15-5.17 present the data from the standpoint of which HIR test mixes met the conventional dense-graded mix standards which are shown in Table 5.18. The data suggest that air voids are a very critical parameter in HIR, as very few of the 100 percent RAP specimens met the design standards for air voids after second compaction. Adding 30% virgin mix increased the air voids in the RAP enough to frequently meet the design standards.

Table 5.17 data indicate that none of the trial mixes with Durkee-Lime RAP meet ODOT dense-graded mix criteria. This RAP was taken from one location on the Durkee-Lime project prior to HIR. A comparison of data from pre-construction cores and post-construction cores was presented in Table 3.22. Table 3.22 shows that results were highly variable, but generally post construction air voids were acceptable -- slightly higher on average than pre-construction air voids. However, the one post-construction core taken at the exact location where RAP for the laboratory testing program was taken shows only 1.5% air voids, by far the lowest of the 11 post-construction values and similar to lab test results.

5.5 Mix Design Procedure

Analysis of information from the literature, field study, and laboratory study led to the following assumptions upon which the proposed mix design process is based:

Table 5.15 Summary of Laboratory Results for Halsey RAP.

Mixture	RAP Source	Virgin Mix (%)	RA Content (%)	IRMR (%)	IRS (%)	1st Hveem Stability	2nd Hveem Stability	1st Compaction Air Voids (%)	2nd Compaction Air Voids (%)	Standard Traffic Acceptable Design Wearing Surface	Standard Traffic Acceptable Design Base Course
(RA-5)	Halsey	0	0.0	87	----	49	49	5.7	3.5	Yes	Yes
			0.2	100	69	44	29	3.9	0.7	No	No
			0.5	----	----	43	32	3.7	0.9	No	No
			0.8	115	83	46	49	3.8	1.7	Yes	Yes
			1.1	----	----	33	18	0.6	0.0	No	No
			1.4	137	89	41	30	1.4	1.1	No	No
	Halsey	10	0.0	----	----	39	35	2.3	0.3	No	No
			0.2	93	126	36	64	4.2	1.7	Yes	Yes
			0.5	----	----	33	36	3.1	0.3	No	No
			0.8	96	142	35	42	2.5	0.5	No	No
			1.1	----	----	27	12	1.4	0.0	No	No
			1.4	94	104	30	44	2.3	1.4	Yes	Yes
	Halsey	30	0.0	----	----	50	58	6.0	3.2	Yes	Yes
			0.2	84	88	44	53	6.4	2.8	Yes	Yes
			0.5	----	----	30	48	7.1	3.9	Yes	Yes
			0.8	78	58	40	48	4.7	2.3	Yes	Yes
			1.1	----	----	34	43	5.0	2.2	Yes	Yes
			1.4	111	94	25	15	2.5	0.0	No	No
(RA-25)	Halsey	0	0.0	----	----	38	52	5.2	1.1	No	Yes
			0.2	129	54	35	46	4.6	0.4	No	No
			0.5	----	----	31	35	2.3	1.2	No	Yes
			0.8	121	64	28	32	2.8	0.9	No	No
			1.1	----	----	35	22	5.9	0.1	No	No
			1.4	147	115	12	7	2.5	0.2	No	No
	Halsey	10	0.0	----	----	50	56	6.5	3.0	Yes	Yes
			0.2	105	85	30	59	4.9	3.3	No	Yes
			0.5	----	----	39	16	0.9	0.2	No	No
			0.8	117	72	33	26	2.2	0.1	No	No
			1.1	----	----	34	37	4.2	1.2	No	Yes
			1.4	114	114	34	17	1.7	0.1	No	No
	Halsey	30	0.0	----	----	50	58	5.2	3.2	Yes	Yes
			0.2	126	52	30	49	5.4	2.7	No	Yes
			0.5	----	----	36	41	4.4	3.8	Yes	Yes
			0.8	124	75	30	36	5.5	3.8	No	Yes
			1.1	----	----	34	28	3.4	0.6	No	No
			1.4	158	70	34	33	2.8	0.9	No	No

Table 5.16 Summary of Laboratory Results for Halsey RAP with PBA-2 and AC-3.

Mixture	RAP Source	RA Content (%)	IRMR (%)	IRS (%)	1st Hveem Stability	2nd Hveem Stability	1st Compaction Air Voids (%)	2nd Compaction Air Voids (%)	Standard Traffic Acceptable Design Wearing Surface	Base Course
PBA-2	Halsey	0.0	----	----	68	62	5.8	3.3	Yes	Yes
		0.2	108	91	64	32	3.3	0.1	No	No
		0.5	----	----	60	55	3.9	0.8	No	No
		0.8	114	89	67	38	2.5	0.1	No	No
		1.1	----	----	42	7	N.A	N.A.	No	No
		1.4	89	106	25	6	1.7	0.0	No	No
AC-3	Halsey	0.0	----	----	51	47	3.3	0.6	No	No
		0.2	105	58	57	69	3.7	1.1	No	No
		0.5	----	----	55	38	2.2	0.2	No	No
		0.8	111	74	49	56	2.7	1.2	No	No
		1.1	----	----	32	14	1.5	0.0	No	No
		1.4	116	100	43	16	0.8	0.0	No	No

Table 5.17 Summary of Laboratory Results for Durkee - Lime RAP.

Mixture	RAP Source	RA Content (%)	IRMR (%)	IRS (%)	1st Hveem Stability	2nd Hveem Stability	1st Compaction Air Voids (%)	2nd Compaction Air Voids (%)	Standard Traffic Acceptable Design Wearing Surface	Base Course
(RA 5)	Durkee-Lime	0.0	----	----	50	24	2.6	0.7	No	No
		0.2	99	----	35	12	1.6	0.5	No	No
		0.5	----	----	26	10	1.3	0.4	No	No
		0.8	101	----	14	4	0.8	0.5	No	No
		1.1	----	----	8	9	1.7	1.2	No	No
		1.4	78	----	34	17	1.2	0.6	No	No
RA-25	Durkee-Lime	0.0	----	----	45	35	2.3	0.2	No	No
		0.2	92	----	26	17	1.6	0.3	No	No
		0.5	----	----	21	7	1.0	0.2	No	No
		0.8	107	----	12	8	1.0	0.7	No	No
		1.1	----	----	17	9	1.1	0.6	No	No
		1.4	86	----	12	8	1.6	0.7	No	No

Table 5.18 Dense-Graded Hot Mix Design Criteria at the Recommended Asphalt Content (ODOT Asphalt Mix Design Guidelines, 1993)

Criteria	Heavy		Standard		Light	
	Wearing	Base	Wearing	Base	Wearing	Base
Asphalt Film Thickness	Sufficient to Sufficient-thick		Sufficient to Sufficient-thick		Sufficient to Sufficient-thick	
Design Air Voids (DAV) First compaction Second compaction (min.)	5.5-6.5% 2.5%	4.5-5.5% 2.0%	5.0-6.0% 2.0%	4.0-5.0% 1.5%	4.0-5.0% 1.5%	3.0-4.0% 1.0%
Stability, minimum First compaction Second compaction	37 37	35 35	35 35	30 30	30 30	25 25
IRS @ DAC; minimum	75	75	75	75	75	75
IRMR@ DAC; minimum	70	70	70	70	70	70
P200/AC ratio	0.6-1.2	0.6-1.2	0.6-1.2	0.6-1.2	0.6-1.2	0.6-1.2
VMA minimum "A-mix" "B-mix" "C-mix"	13% 14% 15%	13% 14% 15%	13% 14% 15%	13% 14% 15%	13% 14% 15%	13% 14% 15%

Notes: DAC is design asphalt content.

1. Don't use HIR when the RAP shows stripping potential (IRRM < 70%) or a history of stripping.

2. Use IRRM, stability (Marshall or Hveem), and air voids as key mixture tests. Use same criteria as for dense-graded hot mix.

3. Use absolute viscosity (60°C) and penetration (25°C) as key binder tests.

4. If HIR is to serve as a wearing course, restoration to "like newly constructed" absolute viscosity (RTFO) is required.

   a) Use the most active RA ==> RA-5.

   b) If absolute viscosity of RAP is > 200,000 poises, viscosity nomographs indicate that addition of more than 1.0% RA is likely to be needed to adequately soften the asphalt. Additions of RA greater than 1% are likely to produce unacceptable stabilities and air voids.

      i) If stability and air voids are not achieved at required RA add rate, admix is required.

      ii) Addition of > 30% admix is not feasible. If addition of 20-30% admix does not produce acceptable rejuvenation, air voids, and stability, reject as a wearing course. If design criteria for dense-graded base course are met, consider HIR for base course.

5. HIR as base course. Consider RAP's which failed to meet wearing course criteria as shown above. In addition, RAP's with absolute

viscosity >200,000 poises, although not likely to work as wearing course because of the conflict of rejuvenation with stability and air voids, may be suitable for base course HIR. If HIR design is required for these severely aged RAP's, the practical objective is to avoid further hardening, and take whatever rejuvenation results from the limited addition of RA. Experience indicates that RA add rate will be 0.3 to 1.0% (RA-5 or RA-25). As noted earlier, British Columbia simply starts with 0.5% RA-5. Prepare trial mix using 0.5% add rate and test for IRRM, stability, and air voids. Reject if IRRM is less than 70%. If stability and air voids do not meet design criteria for base course, adjust RA add rate downward.

6. Whether HIR is intended for base course or wearing course, the critical design inputs are the same. They are
   a) % asphalt in the RAP,
   b) penetration (25°C) of recovered asphalt,
   c) absolute viscosity (60°C) of recovered asphalt,
   d) RAP gradation, and
   e) additional core material (RAP) for trial mix preparation.

The mix design procedure proposed in this section is based on the above assumptions. It further assumes that the HIR selection process shown in Figure 4.4 has been conducted and that the pavement meets the suggested requirements. The mix design procedure is graphically illustrated in the flowchart of Figure 5.19 and is discussed below.

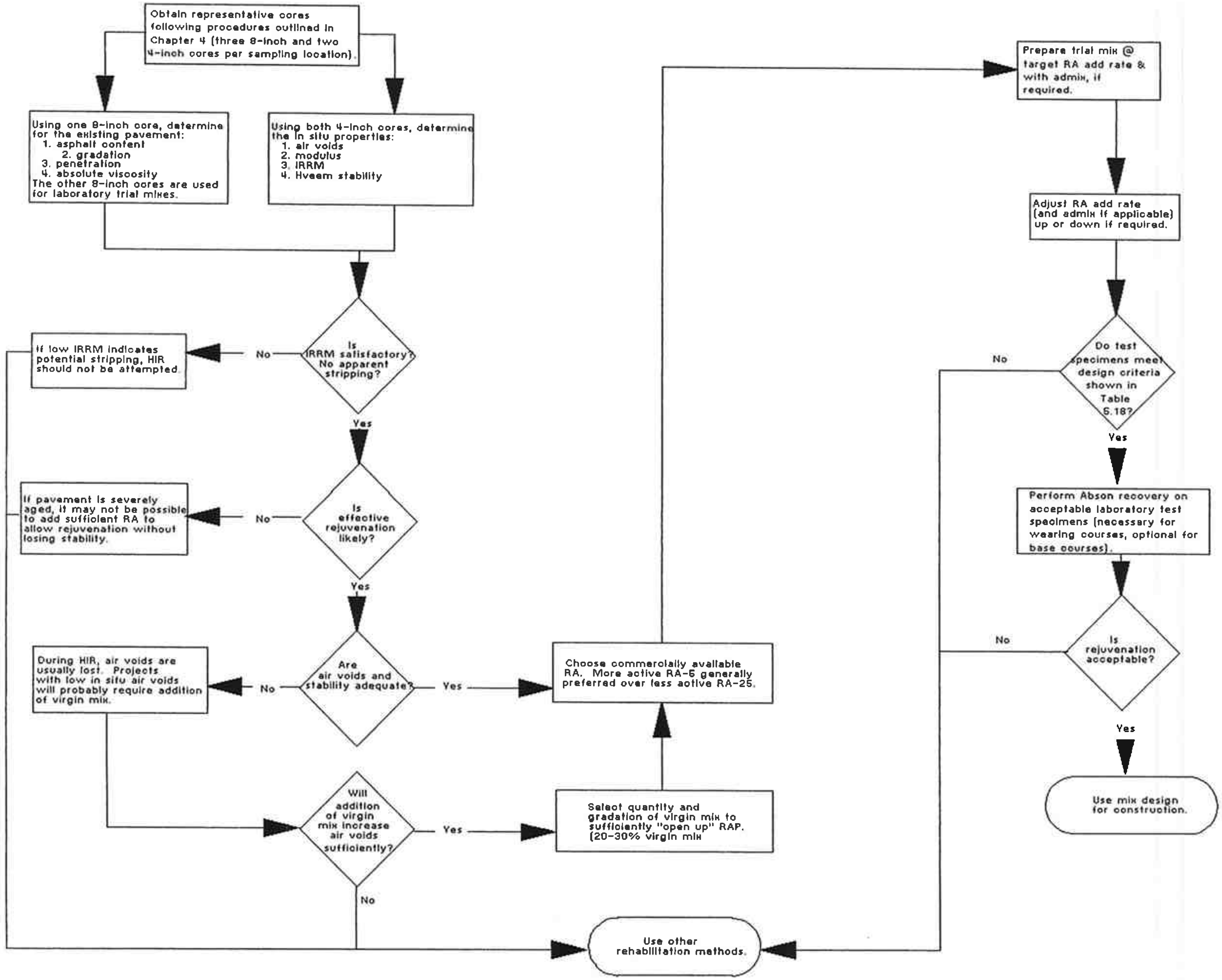


Figure 5.19 Suggested mix design procedures.

This mix design assumes that five cores (three 8 inch and two 4 inch) are taken wherever the pavement changes characteristics, or at a minimum of every mile. One 8-inch core is used to determine the asphalt content, gradation, penetration, and viscosity of the RAP. The design nomographs used to estimate the rejuvenation potential require the asphalt content, penetration, and viscosity. The gradation must be known if addition of admix becomes necessary. The 4-inch cores are used to determine the in situ air voids, modulus, Hveem stability, and water sensitivity. Once this information is gathered, the direction that HIR will take can be determined. The remaining two 8-inch cores are to be used as RAP for trial mixes.

Stripping and stripping potential should be evaluated (IRRM). The authors believe that RAP with stripping potential presents an unfair challenge to a developing technology such as HIR. In the future, use of lime or other anti-strip agents with HIR may be possible. For the present, the authors would reject HIR as an alternative if evidence of stripping is present.

If stripping is not indicated to be a problem, the probable degree of rejuvenation is evaluated. The RAP properties are evaluated to determine if HIR holds promise. Is acceptable rejuvenation possible? Experience indicates that RAP's with absolute viscosity higher than 200,000 poise are difficult to rejuvenate to a "like newly constructed" viscosity. Harder asphalts require more rejuvenating agent which has a tendency to produce unacceptably low air voids and low stabilities. If the highway agency is willing to accept less-than-new rejuvenation for a base course, it may be possible to use harder asphalts.

If data from testing the cores of in situ material indicate that low air voids are likely with addition of RA, the next step is to see if adding virgin mix or lightly coated aggregate will correct the problem. The probable range of addition is 20-30%. Any addition of admixture will have the effect of reducing any cost advantage of HIR over mill and inlay or conventional overlay. Elevation differential with adjoining non-recycled pavement will also be introduced. Admixture design should utilize the known gradation of the existing RAP to produce a stable gradation in the final mix. Aggregate will need to be at least minimally coated. Designed admix should be readily available commercially.

Trial mixes should be prepared. The two 8-inch cores not used to characterize the RAP (top two inches only) will provide enough material for five 1,200 gram specimens. It is recommended that a specimen be prepared at the target add rate and tested for air voids and stability. The target add rate is based on the viscosity nomograph or, if rejuvenation is not a concern simply choose 0.5%. Based on these results add rate may be adjusted up or down and additional specimens prepared. Mixes requiring admix may require adjustment of percent admix prior to additional trial mix preparation. Acceptable test results would parallel those values currently used for conventional asphalt pavement mix designs as shown in Table 5.18.

If the HIR pavement is to serve as a wearing course, one additional step is recommended. This is the recovery of asphalt from test specimens and determination of penetration and viscosity for comparison to rejuvenation targets.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions result from this exploratory study of hot in-place recycling (HIR):

1. HIR is a developing technology which shows promise for properly selected projects.
2. One of ODOT's four wearing course HIR projects (Clear Lake-Old McKenzie Highway) illustrated that if a suitable HIR candidate is chosen and a competent recycling contractor with state-of-the-art equipment is utilized, the HIR process can produce acceptable pavements.
3. Three of ODOT's four wearing course HIR projects showed that pavements with stripping, delaminations, or free water present in the pavement are not good HIR candidates.
4. None of the six ODOT projects experienced binder rejuvenation to like newly-constructed condition. Hardening occurred in some cases. During construction, concerns about stability resulted in RA additions generally lower than recommended for rejuvenation. The project where binder hardening was severe experienced out-of-spec RA and probable overheating.
5. Preliminary screening of candidate projects is the most crucial step in the HIR process. This evaluation includes:

   a) reviewing the pavement's construction and maintenance records,
   b) visual evaluation of pavement condition,
   c) field coring the pavement.

   Following the project selection guidelines presented in Chapter 4 of this report should greatly reduce the risk of unsuccessful HIR projects.

6. Air pollution, climate, and potential fire hazards are secondary concerns which must be considered in evaluating the suitability of HIR as a rehabilitation option.

7. Critical inputs for HIR design come from testing RAP properties and from testing remolded specimens with RA added. These test properties are presented below:
   a) For RAP, properties are
      i) % asphalt,
      ii) penetration (25°C) of recovered asphalt,
      iii) absolute viscosity (60°C) of recovered asphalt, and
      iv) RAP gradation.
   b) For remolded specimens with RA added, properties are
      i) % air,
      ii) stability (Hveem or Marshall), and
      iii) IRRM (or other stripping indicator).

8. Laboratory testing showed that increasing amounts of rejuvenating agents (RA) in HIR recycled dense-graded mixes

a) reduce asphalt viscosity,

b) soften penetration,

c) decrease modulus, and

d) increase fatigue life.

9. Laboratory testing also showed that mixes with higher RA additions resulted in

   a) decreased stability and

   b) reduced air voids.

10. Increasing additions of RA clearly reduced modulus. This was not true for addition of low-viscosity asphalts, where modulus remained high.

11. The mix design procedures presented in this report are based on very limited field and laboratory study. However, because of the similarity in laboratory behavior of HIR and conventional dense-graded hot mixes, these procedures should be adequate for the current state-of-the-art technology.

12. The field study showed only isolated instances where the RA addition rate was higher than 0.9 percent. Normally the range was 0.2 to 0.5 percent. The field study also showed that projects using small amounts (e.g., 0.2 percent or less) of RA usually did not rejuvenate the asphalt in the pavement and often the pavements were "aged" by HIR.

13. ODOT HIR projects experienced smoke emissions that would not be permissible at stationary hot-mix plants.

14. Addition of admixture (virgin mix or lightly coated aggregate) to HIR can improve stability and air void characteristics, but reduces HIR's economic competiveness with overlays or mill and inlay.

15. ODOT should consider HIR as an alternative for wearing course rehabilitation when

    a) traffic is classified "light duty,"
    b) stripping is not indicated,
    c) absolute viscosity of RAP is less than 200,000,
    d) patching is minimal,
    e) RAP is reasonably uniform,
    f) location is predominantly rural, and
    g) HIR has a cost advantage.

16. ODOT should consider HIR as an alternative for base course rehabilitation when

    a) stripping is not indicated,
    b) patching is not extensive,
    c) location is predominantly rural, and
    d) HIR has a cost advantage.

17. Extensive patching of pavements greatly increases the difficulty of any recycling activity, including HIR. If in-place recycling technology is to realize its full potential, pavement recycling should be scheduled before maintenance managers are forced to patch extensively.

18. Long-term performance of HIR pavements should be studied.

19. Refinement of procedures for determining optimum amount of admixture, amount and type of binder in the admixture, admixture gradation, and practical limits of availability would be useful.

20. Funding for research projects involving evolving technologies such as HIR should be authorized well ahead of scheduled construction to allow careful planning of data collection before, during, and after construction.

6.2 Recommendations

1. ODOT should continue to consider HIR as a rehabilitation option for asphalt pavements on carefully selected projects.

2. HIR for stripped pavements or for RAP which shows stripping potential is not recommended at the current stage of development of HIR technology.

3. If RAP binder absolute viscosity is greater than 200,000 poises, HIR to serve as a wearing course without addition of coated aggregate or virgin hot mix is not recommended. This is because it is likely that stability and air voids will be lost with the high percentage of RA addition required to rejuvenate the binder.

4. ODOT should consider implementation of the HIR selection procedure shown in Figure 4.4 and discussed in Section 4.3. This includes a change in core sampling from the current recommendation

of four 6-inch cores per lane-mile to three 8-inch and two 4-inch cores per lane-mile.

5. ODOT should consider implementation of the HIR mix design procedure shown in Figure 5.19 and discussed in Section 5.5.

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