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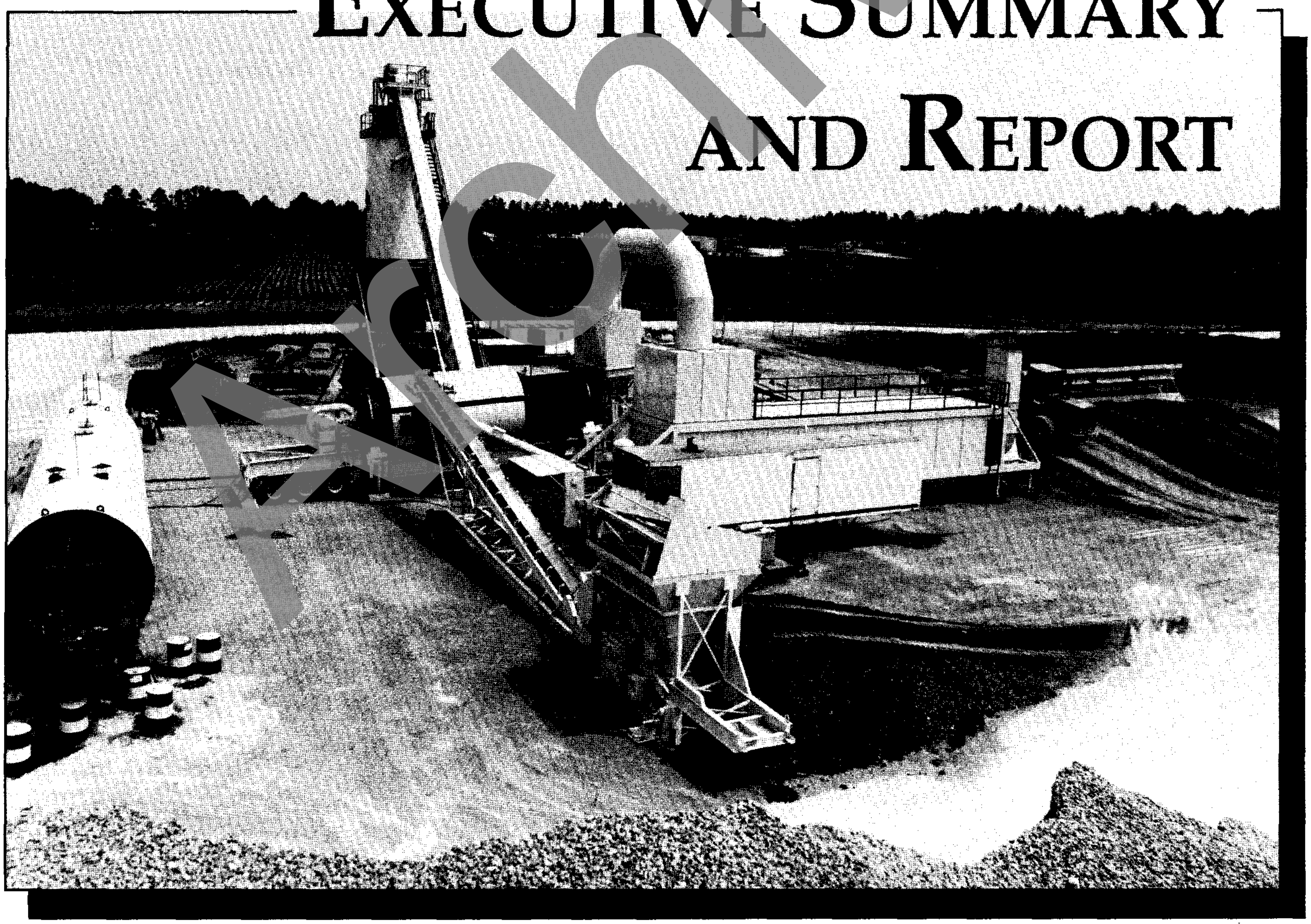
Pavement Recycling Executive Summary and Report



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16. Abstract

There is a considerable emphasis on waste management at national, State, and local levels. Government at various levels has passed or is considering legislation or ordinances that mandate the recycling of waste materials or by-products. Reusing or recycling old, deteriorated pavement structure in the rehabilitation or reconstruction of a new structural section is nothing new. Forms of asphalt pavement recycling date back as far as 1915. However, asphalt pavement recycling in its present form first took place in the mid-1979s, when interest in asphalt pavement recycling was sparked by inflation of construction prices and by the oil embargo. In response to these economic pressures, the FHWA initiated Demonstration Project 39, Recycling Asphalt Pavements, in June 1976. The project showed that asphalt pavement recycling was a technically viable rehabilitation technique, and it was estimated that the use of reclaimed asphalt pavement would amount to approximately 15 percent of the total hot-mix asphalt production by the mid-1980's. It was expected that most of the asphalt pavement removed would be reused in new pavement construction or overlays.

This publication reports on a project initiated in mid-1992 to assess the state-of-the-practice of recycled hot mix asphalt production. The scope of this project included site visits to 17 State highway agencies, with at least two state highway agencies in each FHWA region. Field contacts included discussions with design, research, and construction individuals from States, contractors, and industry. This report summarizes the state-of -the practice for the use, materials mix design, structural design, construction, and performance of recycled hot mix asphalts.

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EXECUTIVE SUMMARY

Currently, there is considerable emphasis on waste management at National, State, and local levels. Government at various levels has passed or is considering legislation or ordinances that mandate the recycling of waste materials or by-products. Reusing or recycling old, deteriorated pavement structure in the rehabilitation or reconstruction of a new structural section is nothing new. Forms of asphalt pavement recycling date back as far as 1915. However, asphalt pavement recycling in its present form first took place in the mid-1970s, when interest in asphalt pavement recycling was sparked by inflation of construction prices and by OPEC's oil embargo. In response to these economic pressures, the Federal Highway Administration (FHWA) initiated Demonstration Project 39 (DP 39) *Recycling Asphalt Pavements* in June 1976. The project showed that asphalt pavement recycling was a technically viable rehabilitation technique, and it was estimated that the use of reclaimed asphalt pavement (RAP) would amount to approximately 15 percent of the total hot-mix asphalt (HMA) production by the mid-1980s. It was expected that most of the asphalt pavement removed would be reused in new pavement construction or overlays.

What is the status of recycling asphalt pavements today? Is the use of RAP in HMA production widely accepted? The FHWA initiated a project in mid-1992 to assess the current state-of-practice of recycled HMA production. The scope of this project included site visits to 17 State highway agencies (SHAs), with at least 2 SHAs in each FHWA region. Field contacts included discussions with design, research, and construction individuals from SHAs, contractors, and industry. This report summarizes the state-of-the-practice for the use, materials mix design, structural design, construction, and performance of recycled HMA pavement.

CONCLUSIONS

1. Disposal of excess pavement materials in landfills does not appear to be a nationwide problem.

2. It is estimated that 33 percent of all asphalt pavement removed is recycled into HMA production.

3. The use of RAP in HMA production is not uniformly accepted throughout the United States.

4. Limitations placed in standard specifications, supplemental specifications, and special provisions are major obstacles to increased use of RAP.

5. Those SHAs that perform an evaluation of the RAP and report its composition in plans, specifications, and estimates generally permit greater percentages of RAP in all HMA mixtures.

6. Another obstacle to increased RAP use is that many engineers believe that recycled HMA is inferior to conventional HMA.

7. Long-term pavement performance (17 years) and detailed evaluations show that recycled HMA that is designed and controlled during production will perform comparably to conventional HMA and can improve materials properties of the existing pavement layer.

8. Similar to poor performing conventional HMA, poor recycled HMA performance can be related to poor mixture design procedures or use of control and acceptance procedures that do little to ensure the quality of the recycled HMA.

9. The recycled HMA mixture design procedure outlined in the Asphalt Institute's Manual Series No. 2 and No. 20 is a technically viable method for establishing ingredient proportions of a recycled mixture.

10. Recycled HMA, which is designed and produced in a quality assurance program that verifies mixture design assumptions to reasonable limits, can be expected to perform comparably to conventional HMA.

RECOMMENDATIONS

The following recommendations are provided to increase RAP usage and ensure HMA quality.

1. Sampling and testing of the pavement to be removed should be performed. Enough random samples should be taken to give an indication of variability of material properties. Test results and variability should be provided on plans, specifications, and estimates to provide contractors the best information. Producers in a few States use such information to determine preliminary RAP content to bid HMA prices. Reporting such composition and variability will also remove fear of the unknown and may encourage greater use.

2. States should consider revising their specifications so a given mix's RAP content is based on a thorough mixture design process, instead of arbitrary RAP limits.

3. Consideration should be given to permit up to 15 percent RAP in all mixtures without changing to a softer grade asphalt cement. This will minimize the amount of recovery and testing performed. This recommendation is in line with the Asphalt Institutes' Manual Series No. 2 and No. 20 and is also provided in research performed by Kandhal, Rao, and Young (*Performance of Recycled Mixtures in State of Georgia, January 1994*). The laboratory mixture design should be established using the RAP as an ingredient.

4. With RAP contents greater than 15 percent, the selection of the new type of asphalt cement or recycling agent added to recycled HMA should be based on the viscosity blending chart or equivalent procedure or formula. Currently some states' arbitrary selection of new asphalt cement to add to recycled HMA containing high RAP contents. Some state materials engineers have shown that this has been a problem leading to greater frequency of transverse cracking or premature fatigue cracking.

5. Production sampling and testing programs need to verify all mixture design assumptions including the asphalt cement blend properties. Extractions and recoveries should be added to a QA program to ensure optimum performance of recycled HMA. It is recommended that such sampling and testing is added by producer sampling and testing in a QC program or by SHA sampling and testing for acceptance or verification. Test results should be used to adjust plant production. Production tolerances should be established by each agency for its environment.

6. Additional training should be provided to increase the awareness of proper mixture design and analysis, producer equipment and handling procedures, performance evaluations, and quality control plans.

7. Follow-up production, construction, and performance evaluations of the Long-Term Pavement Performance Specific Pavement Study-5 and supplemental test sections should be provided to the highway community.

8. Research needs include the use of RAP with modified asphalt cements and use of RAP in the Strategic Highway Research Program's binder specifications and SuperPave™ mixture design and analysis system.

CHAPTER 1. INTRODUCTION

Currently, there is considerable emphasis on waste management at National, State, and local levels. Legislation or ordinances that mandate the recycling of waste materials or by-products are under consideration or have passed at various government levels.

The highway community has been practicing forms of first-priority recycling since the early days of road building. The best example of first-priority recycling performed by the highway community is the reuse of deteriorated pavement structures in the rehabilitation or reconstruction of new structural sections. Asphalt pavement recycling dates back as far as 1915.[1] However, recycling asphalt pavements in its present form evolved around the mid-1970s. The interest in asphalt pavement recycling during this time frame was sparked by inflation of construction prices and by OPEC's oil embargo. In response to these economic pressures, the FHWA initiated DP 39 *Recycling Asphalt Pavements* in June 1976. DP 39 provided partial funding for the construction and evaluation of approximately 50 demonstration installations concerning hot, cold, and surface recycling.

DP 39 and numerous other SHA studies showed that asphalt recycling is a technically viable rehabilitation technique. These efforts resulted in the development of materials mix design and construction guidelines for implementing an asphalt recycling project. Based on work accomplished under DP 39 and other projects, it was estimated that the use of RAP would amount to approximately 15 percent of the total HMA production by the mid-1980s. This work also was the foundation for the program guidance provided by the FHWA in Notice N 5080.13, issued October 6, 1981. This notice encourages the conservation of all nonrenewable resources and the reuse of highway products, such as RAP, that are cost-effective and do not reduce the quality of the pavement structure.

The notice provides the following recommendations to encourage the use of old pavement material:

- Consider recycling as one of the options at the design stage of all rehabilitation projects;
- Allow contractors to use RAP in the production of HMA;
- Allow contractors to determine the source and amount of RAP, as long as the recycled mix meets specifications for conventional HMA; and,
- Allow contractors to retain ownership of excess RAP.

What is the status of using RAP today? A literature search was conducted to determine the amount of recycling performed by HMA producers. Results of this literature search are described as follows.

The National Asphalt Pavement Association (NAPA) conducted a survey of HMA producers in 1986 that addressed trends in HMA production, including recycling. The results of the survey can be found in reference 2. Table 1 summarizes production data for HMA and recycled HMA for 1986.

Table 1.[2] HMA and recycled HMA production for 1986.

REGION	PRODUCTION (million t)	PRODUCERS THAT RECYCLE	RECYCLED HMA TO TOTAL PRODUCTION	AVERAGE RAP CONTENT IN RECYCLED HMA
NORTHEAST	71	42%	28%	16%
MIDWEST	100	65%	40%	26%
SOUTH	140	39%	26%	18%
WEST	98	35%	35%	21%
U.S.	409	49%	23%	22%

In 1986, 49 percent of HMA-producing companies in the U.S. produced recycled HMA. Twenty-three percent of HMA production contained some content of RAP during that year. The average RAP content in those mixes was 22 percent. Therefore, multiplying 23 percent by 22 percent provides the estimate that the RAP portion of all materials used in HMA production during that year was 5 percent. This amount is less than the amount estimated by DP 39.

Another reference claimed that 90.5 million metric tons (t) of asphalt pavement is removed annually in the U.S.[3] This reference also claimed that the majority of the material is wasted in landfills. Collins and Ciesielski have recently estimated that SHAs remove approximately 45 million t of asphalt pavement annually.[4] Research performed for the Environmental Protection Agency (EPA) and the FHWA found that more than 80 percent of the asphalt pavement removed is reused in highway applications and less than 20 percent is discarded.[5][6] Clearly, all available literature on the generation and use of RAP is not in agreement.

Although DP 39 demonstrated that asphalt pavement recycling was a technically viable technique, very few performance evaluations of those projects are available. No formal national follow up of this technology area has been conducted since DP 39; therefore, the FHWA has initiated a review of recycled HMA and the use of RAP under Technology Assessment Project 92-76 (TA 92-76).

SCOPE

The review included visits to at least two SHAs in each FHWA region. The States were selected in cooperation with the FHWA regional materials engineer to obtain a cross section of those States that regularly use RAP in recycled HMA and those that limit or do not permit the use of RAP in recycled HMA. A team consisting of representatives of the Pavement Division (HNG-40), Technology Management Division (HTA-10), and the appropriate regional pavement and materials engineer performed field visits. The SHAs that were visited during this project include:

- Arizona DOT
- Colorado DOT
- Florida DOT
- Kansas DOT
- Massachusetts Department of Public Works (DPW)
- Minnesota DOT
- Mississippi DOT
- Nevada DOT
- New Jersey DOT
- New Mexico State Highway and Transportation Department (SHTD)
- Pennsylvania DOT
- Texas DOT
- Virginia DOT
- Washington State DOT
- Wisconsin DOT
- Wyoming DOT

Field contacts included discussions with design, research, and construction individuals from SHAs, contractors, and industry. Construction site reviews gathered information regarding extent and location of use (asphalt surface course, asphalt base course, aggregate base course, or embankment), materials mix design, structural design, construction practices, disposal practices, and performance histories, if any.

This report summarizes the state-of-the-practice for the use, materials mix design, construction, and performance of recycled HMA pavement in the selected States.

CHAPTER 2. EXTENT OF USE

One objective of this review was to determine the amount of pavement removed and the amount of pavement reused in HMA production throughout the U.S. To accomplish the objective, a search of available literature was conducted. In addition, participating SHAs were asked to provide readily available data on the use of recycled HMA. Sources of information included annual summaries of bid quantities and prices; data from materials produced under approved job mix formulas; quality control and quality assurance data; and other published reports. The intent was to obtain data without exhaustive hours of labor. Such a review of data for individual projects was beyond the funding levels of this project.

Percent of HMA Production Containing RAP

Figure 1 was developed from data collected during field visits and from reference 4. It summarizes the amount of HMA production containing RAP.

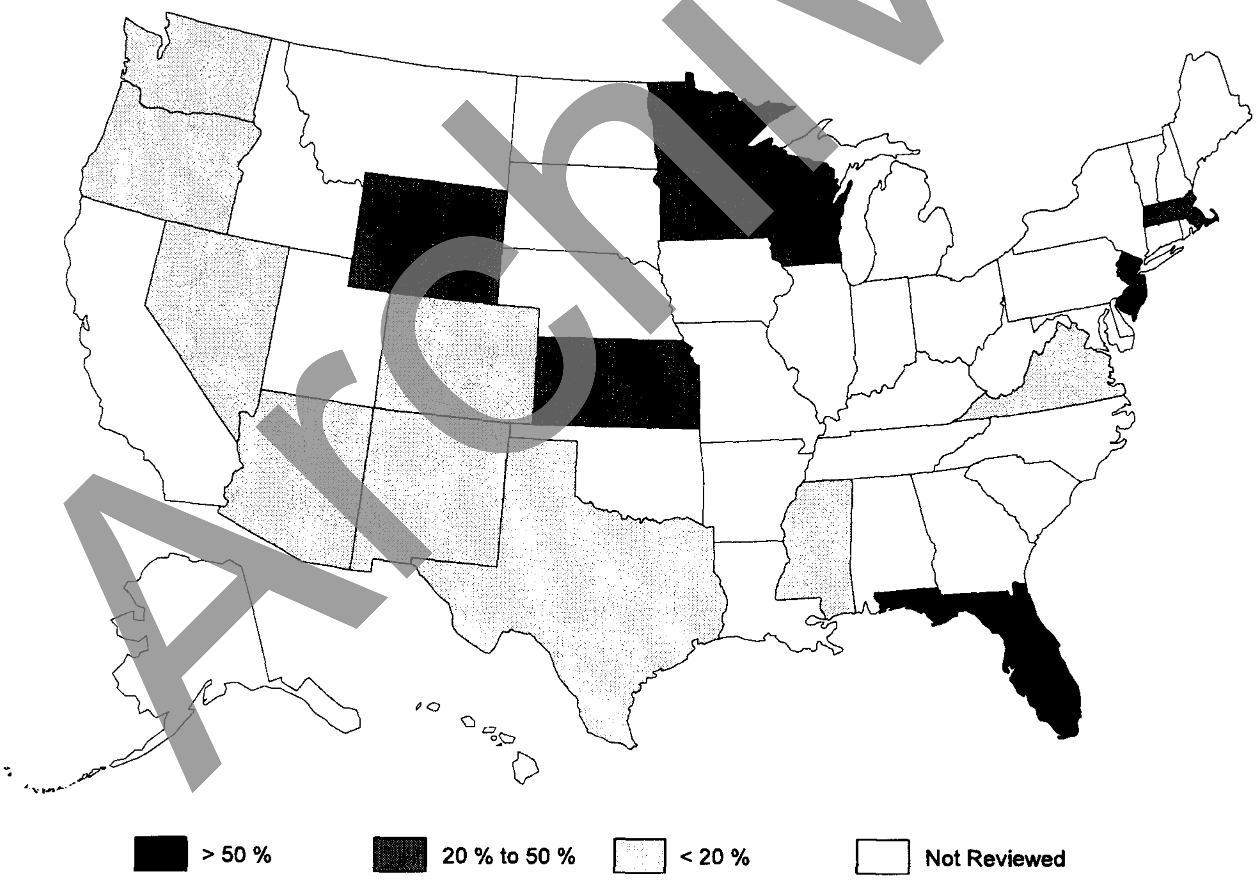

Figure 1. Percent of HMA production containing RAP.

A reference time period is not provided in figure 1 because it varied with each SHA's data. If data over a period of time was provided by a SHA, it was averaged to determine trends. Three categories were developed to display results. The NAPA survey showed that the national average of recycled HMA production to total production in 1986 was 23 percent.[2] Therefore, less than 20 percent was selected to show those States that were below that average. The 20 percent to 50 percent was selected to show those States that were at or above the average. Finally, greater than 50 percent was used to show those States in which recycled HMA was a major part of HMA production.

Figure 1 shows that recycled HMA is less than 20 percent of total HMA production in 9 of 17 States visited. Recycled HMA production was 20 percent to 50 percent of total production in six of the States visited. Recycled HMA production for the Florida DOT is greater than 50 percent of total HMA production. The Florida DOT's recycled HMA production has been in excess of 50 percent of total production since 1985.

For this report, recycled HMA is defined as a mixture containing any percentage of RAP. Therefore, an agency could put 10 percent RAP in all HMA and be shown in figure 1 as a large producer of recycled HMA. Another way to evaluate the extent of use is to compare the amount of RAP reused in recycled HMA production to the amount of pavement removal. This type of analysis may indicate whether stockpiles of RAP were being generated. Table 2 summarizes data collected regarding pavement removal and its reuse.

Estimation of the Amount of Pavement Removed

In most cases, pavement removal had to be estimated from quantities in summaries of annual contract bid quantities and prices. Summaries of contract bid quantities may not have represented the actual pavement removal in each contract because overruns and underruns were not yet reported for projects that were in progress. Pavement removal can be estimated and bid in a variety of methods, and the following assumptions and methods were used to calculate and report quantities shown in table 2.

- Summaries of quantities that included unit of measurement of surface area for specific depths for pavement removal were converted to mass. This conversion was made using an estimated density of 2.39 kg/m^2-mm.

- Some contracts had bid items with a unit measurement of surface area without further breakdown by depth. In this situation, agencies provided an average depth of milling to estimate mass. In most cases, a 50 mm depth was used in the estimation.

Table 2. Generation and use of RAP in recycled HMA[1].

STATE	PAVEMENT REMOVAL	RAP RECYCLED INTO HMA	% of REMOVED in RECYCLED HMA	Notes
Arizona	4,013,600 t	694,400 t	17 %	1990 - 1991
Colorado	226,200 t	173,800 t	77 %	Reference 7
Florida	1,652,400 t	1,240,600 t	75 %	1989 - 1990
Kansas	1,009,100 t	599,900 t	59 %	1991
Massachusetts	543,000 t	119,500 t	22 %	Reference 7
Minnesota	543,000 t	298,600 t	55 %	1991
Mississippi	149,400 t	Unknown		
Nevada	612,800 t	119,600 t	20 %	1983-1989
New Jersey	339,000 t	142,500 t	42 %	1991-1992
New Mexico	475,600 t	81,000 t	17 %	1990
Oregon	130,000 t	66,000 t	51 %	Reference 7
Pennsylvania	Unknown	Unknown		
Texas	1,754,200 t	123,100 t	7 %	1992
Virginia	36,800 t	Unknown		
Washington	Unknown	Unknown		
Wisconsin	724,000 t	253,400 t	35 %	Reference 7
Wyoming	724,900 t	Unknown		

Most SHAs were able to furnish data on the amount of pavement milling or pavement removed. However, some agencies did not track such quantities and could not determine them without exhaustive hours of labor. In this case, reference 7 was used to fill in gaps in the data. Unfortunately, complete data could not be obtained and is shown as unknown in table 2.

An accumulated total of pavement removal for those 12 SHAs showing complete data in table 2 is 12,022,900 t. Multiplying the accumulated total by the ratio 51/12 would show that 51.1 million t of pavement was removed. Data in table 2 does not represent equal time

[1] Quantities shown are for SHA projects and do not include RAP from DOT sources incorporated into HMA for non DOT projects.

periods or similar time frames. Therefore it would not be correct to estimate that 51.1 million t of RAP are generated annually.

One source of data that became available was the National Cooperative Highway Research Program (NCHRP) Synthesis (No.199), *Recycling and Use of Waste Materials and By-Products in Highway Construction*. The NCHRP Synthesis 199 included surveys of SHAs. A 100 percent response rate was received by the authors.[4][7] Table 4 in the technical appendix for the above-referenced synthesis provides a current status of RAP use in asphalt paving.[7] That table was developed from a survey of all SHAs.[7] Twenty-nine SHAs provided complete data on both generation and reuse of RAP for 1991.[7] Survey results showed that those 29 SHAs removed 7.6 million t of RAP. Collins and Ciesielski estimated that 45 million t of RAP were generated each year.[4]

Estimation of the Amount of RAP Reused in HMA Production

The accumulated total of RAP reused in recycled HMA for those same 12 SHAs (Table 2) is 3,912,400 t. Dividing this total by the amount of pavement removed (12,022,900 t) shows that roughly 33 percent of the pavement removed is reused in HMA production.

SUMMARY

The use of RAP in HMA production is not uniformly accepted throughout the United States. Some SHAs actively promote and produce recycled HMA. However, some agencies do not have a substantial recycled HMA program. Figure 1 shows that recycled HMA production is less than 20 percent of total production in 9 of the 17 states reviewed. Data in table 2 indicates that several SHAs use less than 50 percent of the pavement removed in recycled HMA production. Collins and Ciesielski showed 3 SHAs outside of those visited in this review do not use any RAP in HMA production.[7]

States with urbanized areas tend to produce more recycled HMA than rural States. There may be many reasons for this trend; however, the most obvious are more fixed HMA facilities, geometric constraints, such as roadway width, cross slope, and vertical clearance. A greater number of fixed facilities within a State reduces haul length of excess RAP. The value of RAP decreases as its handling and hauling costs increase. In some remote areas, the cost to haul RAP to the next project or nearest plant makes using RAP as a shoulder widening material or base course more cost-effective for the SHA. The Kansas DOT and the Wyoming DOT were exceptions to the previous generalization. As shown in figure 1, these States are above average in recycled HMA production. The Kansas DOT reuses up to 50 percent of the pavement it removes in recycled HMA production. One of the reasons for their greater use of recycled HMA is that the SHA assumes some of the risk in production. Both of these SHAs perform a detailed analysis to determine the cause of pavement distress. Once the decision to mill or remove the pavement is made, the layer to be removed is sampled and analyzed. A detailed laboratory mixture design is performed to specify all HMA ingredients and their proportions in contract documents prior to bidding. This includes the RAP content as well. In this way, all contractors bidding that project are aware that recycled HMA at a given percentage is expected to be used. The Kansas DOT and Wyoming DOT procedures, while not conforming to the trend of producer-designed and controlled HMA mixtures, effectively produce large quantities of recycled HMA in remote areas. A more detailed description of their procedures is contained in appendix A .

It can be concluded that 45 million t of RAP are generated annually with approximately 33 percent of the RAP being reused in HMA production. This does not mean that the highway community wastes the remaining 67 percent in landfills. Most agencies find other highway applications for excess RAP that is not included in recycled HMA. Research performed for the EPA and the FHWA found that more than 80 percent of the asphalt pavement removed is reused in highway applications and less than 20 percent is discarded.[6] Other applications for RAP include:

- Hot in-place recycling;
- Cold in-place recycling;
- Full-depth reclamation;
- As an aggregate for roadway and shoulder base;
- Shoulder surfacing and widening; and,
- Maintenance uses for driveways, surfacing under W-Beam traffic barriers, ditch linings, and pavement repairs.

The purpose of this review and data reported was strictly focused on recycled HMA. Information on other recycling techniques was outside the scope of this project.

CHAPTER 3. LIMITATIONS

One complaint shared by many producers was that SHAs' specifications set maximum RAP contents at unreasonably low limits. *Road & Bridges* magazine annually publishes a summary of specification limitations for the use of RAP in recycled HMA. The information in this magazine provides a good national overview of HMA specifications. The latest edition shows that all SHAs permit the use of RAP in HMA base and binder courses.[8] However, not all agencies permit the use of RAP in HMA surface course. Figure 2 was established from data in *Road & Bridges* magazine for HMA surface course.

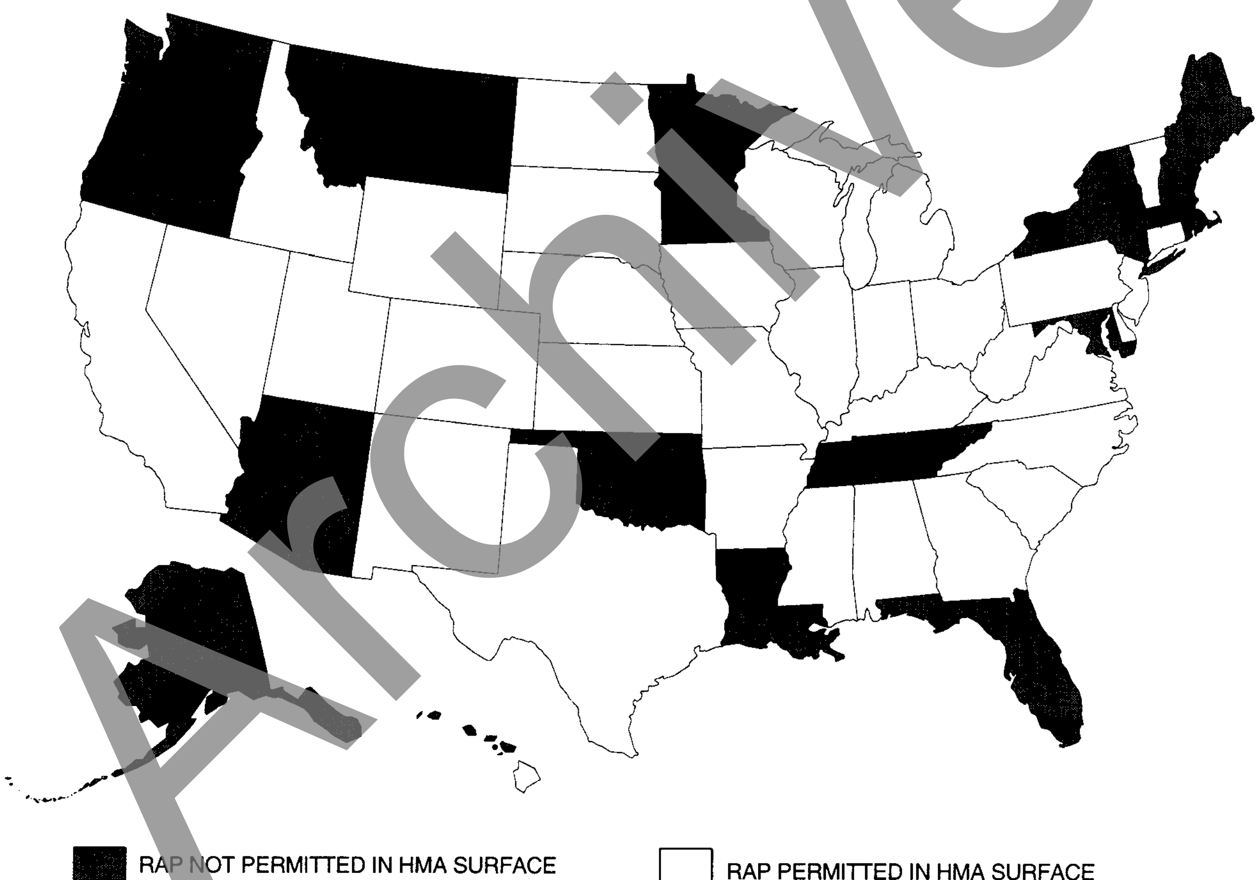

Figure 2. Use of RAP in HMA surface course.

Figure 1 shows that 17 SHAs' standard specifications do not permit RAP in the final surface course.[8] Five of these SHAs—the Florida DOT, Maryland State Highway Administration, Massachusetts Department of Public Works (DPW), Oregon DOT, and Washington State DOT—are shown as not permitting RAP in the surface course because an open-graded friction course (OGFC) is used for the final surface. Generally, aggregate gradations for OGFC have very little fine aggregate (5 to 15 percent passing the 2.36 mm sieve). The RAP has a large portion of fine aggregate and dust. Therefore, it is reasonable to expect these SHAs to restrict the use of RAP in OGFC. These SHAs permit RAP in other types of surface courses used on lower volume roadways. Taking away these 5 SHAs, 12 States do not permit the use of RAP in dense-graded surface courses. The Minnesota DOT is shown because it does not permit RAP in the surface course for high type pavements (mix type 61). However, the Minnesota DOT does permit RAP in surface courses for low volume roadways. It can be observed that some specifications do limit recycled HMA production and the reuse of RAP.

Detailed Review of Specifications of States Reviewed in TA 92-76

This project also included a detailed review of standard specifications, supplemental specifications, and special provisions of those SHAs participating in this review. Table 3 was developed to show specification limitations for RAP content in producer-designed mixtures.

Open implies that no restrictions are placed on the RAP content as long as the recycled HMA meets material properties for conventional HMA. *State Source* indicates that a dedicated stockpile of RAP, of known composition from a SHA pavement, is used in the recycled HMA. *Unknown Source* refers to RAP of unknown origination or composition or to stockpiles of RAP combined from many different sources.

Some SHAs do not permit the producer to make the decision to use RAP. These SHAs design the recycled HMA and specify the RAP content that the producer must use. Generally, the RAP content in a recycled HMA would be specified by the agency in the project special provisions. Table 4 summarizes RAP limitations for SHA-designed recycled HMA.

State Practices

Several SHAs permitted producers to use any source of RAP up to the maximum limits shown in table 3. These states included Florida, Massachusetts, Minnesota, Mississippi, Oregon, and Virginia. Field visits at plants and discussions with producers verified the information. Discussions with State engineers and producers indicated other SHAs had practices that placed further limitations on RAP contents that could not be summarized in tables 3 and 4. The following paragraphs briefly describe their recycled HMA program.

Table 3. Specification limits of RAP at producer's option.

STATE	SURFACE COURSE		BINDER COURSE		BASE COURSE	
	State Source	Unknown Source	State Source	Unknown Source	State Source	Unknown Source
Arizona	0[1]	0[1]	0[1]	0[1]	0[1]	0[1]
Colorado	30%	30%	30%	30%	30%	30%
Florida	50%[2]	50%[2]	50%	50%	60%	60%
Kansas	0	0	10%	10%	10%	10%
Massachusetts	10%	10%	20% B[3] 40% D[3]	20% B[3] 40% D[3]	20% B[3] 40% D[3]	20% B[3] 40% D[3]
Minnesota	30%[4]	30%[4]	30%	30%	50%	50%
Mississippi	15%	15%	30%	30%	30%	30%
Nevada	15%	0	15%	0	15%	0
New Jersey	50%	10%	50%	25%	50%	25%
New Mexico	0[1]	0[1]	0[1]	0[1]	0[1]	0[1]
Oregon	20%	20%	20%	20%	20%	20%
Pennsylvania	Open	15%	Open	15%	Open	15%
Texas	Open	0	Open	20%	Open	20%
Virginia	25%	25%	25%	25%	25%	25%
Washington	Open	Open	Open	Open	Open	Open
Wisconsin	Open	20%	Open	35%	Open	35%
Wyoming	0[1]	0[1]	0[1]	0[1]	0[1]	0[1]

[1] Producer is allowed to use RAP only on specific projects that are specified by the SHA.

[2] RAP is not allowed in friction course mixtures. RAP is allowed in surface course mixtures where a friction course mixture is not required (low traffic volumes).

[3] B refers to a batch plant and D refers to a dryer drum mixer plant.

[4] RAP is not allowed in Mix type 61 (high traffic volume facilities such as Interstate routes).

Table 4. Maximum limits of RAP—State design, source specified.

STATE	SURFACE COURSE	BINDER COURSE	BASE COURSE
Arizona	0%	40%	40%
Kansas	50%	50%	50%
Nevada	Open	Open	Open
New Mexico	Open	Open	Open
Wyoming	50%	50%	50%

Arizona DOT

Currently, the Arizona DOT does not permit RAP as a component of HMA surface mixtures. But, most of the surface courses are friction courses. Further, the Arizona DOT does not permit RAP in other mixtures unless it is specifically addressed in project special provisions. The RAP must be reclaimed from an Arizona DOT project. Unclassified RAP or RAP from sources outside Arizona DOT pavements are not permitted in any mixes. When recycled HMA is specified for a project, the Arizona DOT will perform the mix design and indicate the RAP content.

Colorado DOT

Producers are generally permitted to use RAP up to the maximum limits shown in table 3. Some district offices have placed further restrictions that permit only 15 percent RAP in recycled HMA.

Kansas DOT

The Kansas DOT generally designs the recycled HMA and specifies ingredient proportions. The RAP content is optimized up to the maximum limits shown in table 4. If recycling is not specified in the contract, the producer is permitted to use up to 10 percent of any source of RAP in routine HMA production. This permissive use specification does not apply to surface mixes.

Nevada DOT

The Nevada DOT's specifications allow producers the option of recycling the existing bituminous surface from a project as long as the RAP content does not exceed 15 percent. RAP from unknown sources is not permitted. Recycled HMA with RAP contents higher than 15 percent must be specified by the Nevada DOT in project special provisions. However, the Nevada DOT currently has not specified a recycled HMA with RAP content greater than 15 percent. Their experience has been that recycled HMA with higher RAP contents did not perform adequately in climates where performance-graded asphalt cement would require modification.

New Jersey DOT

The New Jersey DOT uses an open system and a closed system for recycled HMA production. The open system gives the contractor or the HMA producer the option to use up to 25 percent RAP in HMA base and binder courses and a maximum of 10 percent in HMA surface courses. The source of RAP in an open system is not classified. The closed system is specified by the New Jersey DOT when it is anticipated that the amount of milling will exceed 1820 t. The closed system gives the producer the option to use 26 percent to 50 percent RAP in HMA binder and base courses. The source of RAP for closed system projects is limited to pavement reclaimed from the rehabilitation project. Producers have made very little use of the closed system option in the past few years; almost all recycled HMA is produced in the open system.

New Mexico SHTD

Currently, producers do not have the option to use recycled HMA in place of conventional HMA. The New Mexico SHTD specifies when a project will be recycled HMA. Only RAP from a New Mexico SHTD project is permitted in recycled HMA.

Pennsylvania DOT

Producers have the option to use any source of RAP up to 15 percent in all mixes without further approval from Pennsylvania DOT. Only known sources of RAP are permitted in recycled HMA with higher RAP contents.

Texas DOT

Producers have the option of using up to 20 percent "unclassified" RAP in base and binder mixes. Only RAP from State-owned sources will be permitted in surface courses and recycled HMA with RAP contents greater than 20 percent. The Texas DOT will designate the source of RAP in those cases.

Washington State DOT

Currently, the Washington State DOT permits producers to include up to 20 percent RAP, without additional mix design, in all HMA mixes except Class D. Class D mix is an OGFC. Recycled mixes with RAP contents greater than 20 percent require a thorough mix design analysis and evaluation.

Wisconsin DOT

Producers can use any source of RAP up to 20 percent in surface courses and 35 percent in binder and base courses. Recycled mixes with higher RAP contents are limited to RAP from State highways.

Wyoming DOT

The Wyoming DOT specifies recycled HMA ingredients and proportions. The RAP content is optimized up to the maximum limitations shown in table 4.

SUMMARY

Almost half of the SHAs that participated in this review restricted the RAP content to 30 percent or less. Some states reduce the amount of RAP allowed when the source is not known. Table 3 shows that four SHAs reduce the maximum content of "unclassified" RAP in base and binder mixtures and five SHAs for surface mixtures. The use of "unclassified" RAP in HMA production is not permitted by 3 SHAs.

Most SHAs reviewed permit RAP in base and binder mixes, but table 3 shows that some SHAs still do not permit producers to add RAP at their option even if mixture properties are within specifications. Collins and Ciesielski found another three agencies that did not use RAP in any HMA production.[7] SHAs generally permit less RAP in surface mixtures than binder and base mixtures. Reasoning is that surface mixtures are subjected to more stress and wearing than binder and base mixtures.

There are practical limitations of the amount of RAP that can be incorporated into a recycled HMA. Some of these limitations include plant technology and the amount of fine material in the RAP. However, some specifications or special provisions provide further limitations on RAP usage. These limitations are an obstacle that limits recycled HMA production. In most cases, restrictions were based on past projects that did not perform well. However, it was found that there was limited research or analysis to explain the poor performance. Other agencies placed limitations on RAP based on their judgement. Some of the reasons for low limits of RAP in specifications include:

- The RAP variability is too high to use in HMA production, or recycle HMA production is too variable.
- Blending soft asphalt cement or rejuvenating agent with salvaged binder can be accomplished in the laboratory. However, some engineers do not believe that blending occurs during production and placement.
- The quality of recycled HMA has not been proven through performance evaluations.

CHAPTER 4. RAP VARIABILITY

Many engineers consider recycling RAP in HMA production as a means of using a waste product rather than producing a quality product. But RAP is just another component in recycled HMA that has to be monitored and controlled during production to achieve specified quality. The RAP consists of aggregate and asphalt cement similar to conventional HMA. Since variability of virgin aggregates can change based on source and producer, it should be reasonable to expect that RAP variability will change according to its source and removal and processing methods.

To illustrate the difference in RAP composition and variability on different projects, a literature search was performed to find RAP compositional data prior to recycling the old pavement. One source of information included a report by Kallas that provided compositional analysis of RAP from different sources used to develop recycled HMA mixture design process.[41] Table 5 summarizes this information.

Table 5. RAP composition of cores and stockpiles.

		% passing 2.36 mm		% passing 75 μm		Asphalt Cement Content	
	n	ave.	σ_{n-1}	ave.	σ_{n-1}	ave.	σ_{n-1}
California Road Cores[41]	12	54	8.3	9.9	2.01	5.4	0.71
California Stockpiled after milling[41]	5	69	6.5	11.8	0.34	5.2	0.04
North Carolina Road Cores[41]	12	69	3.2	6.1	0.66	5.7	0.11
North Carolina Stockpiled after milling[41]	5	72	0.9	8.0	0.11	5.7	0.11
Utah Road Cores[41]	12	52	3.8	8.7	2.60	6.5	0.28
Utah Stockpiled after milling[41]	10	58	2.8	9.9	1.15	6.2	0.44
Virginia Road Cores[41]	12	41	2.1	9.7	0.79	5.3	0.20
Virginia Stockpiled after milling[41]	6	52	1.1	13.0	0.30	5.2	0.12
Average σ of HMA Surface Course[42]			2.81		0.94		0.28

Two important conclusions can be drawn from data in table 5. These conclusions are: compositional data from roadway cores indicates worst-case variability; and, aggregate gradations become finer after removal, processing, and stockpiling. This indicates that producers can reduce RAP source variability by screening and crushing to separate stockpiles containing different sizes of RAP.

Other references were located that contained RAP compositional data prior to recycling. Table 6 summarizes data from those references (shown in brackets after stockpile location).

Table 6. RAP composition from other sources.

		% passing 2.36 mm		% passing 75 μm		Asphalt Cement Content	
	n	ave.	σ_{n-1}	ave.	σ_{n-1}	ave.	σ_{n-1}
Newton County Stockpile[43]	10	47.5	4.95	7.14	0.74	5.52	0.23
Forest Park Stockpile millings[43]	5	3.60	3.41	7.02	1.08	5.46	0.31
Forest Park Stockpile of chunks[43]	5	39.0	2.81	6.87	0.39	4.61	0.55
ReSaca Plant Stockpile[43]	10	36.4	2.20	8.72	1.36	5.08	0.21
Bryan County Stockpile[43]	10	42.9	4.63	4.75	0.71	4.83	0.42
Lowndes County[43]	10	49.3	4.82	7.36	0.75	5.60	0.48
New Jersey Cores[44]	23	50.5	3.20	7.0	1.11	5.91	0.48
Spartan Asphalt 1994 Stockpile[45]	70	58.1	3.5	9.0	0.82	3.8	0.30
Average σ of HMA Surface Course[42]			2.81		0.94		0.28

Granley reported on variations in bituminous construction for 26 projects producing HMA surface mixture.[42] Average standard deviations reported by Granley were used to indicate HMA production variability in tables 5 and 6. Tables 5 and 6 shows that some sources of RAP have more variability in composition than average HMA surface course production determined by Granley. Using these sources, the RAP content would have to be limited to produce recycled HMA to uniformity requirements in specifications. Tables 5 and 6 also indicate that some sources of RAP have less composition variability than average HMA surface course production determined by Granley. From these sources, the RAP content in recycled HMA would not be restricted based on its compositional variability.

Data in both tables point out the need for using samples of stockpiled RAP for final mixture design and analysis of recycled HMA. Tests on samples of stockpiles will quantify and qualify the composition of the RAP as well as other ingredient materials that are included in the HMA production. Once each ingredient material is quantified and qualified, then the mixture design process will optimize the proportion of each component. The RAP variability is just one item that is considered; the variability of each individual stockpile of virgin aggregate is also considered. Other items are important as well, such as the composite aggregate gradation of the RAP or the properties of the recovered asphalt cement in the RAP.

As an example, one can consider the use of the Virginia stockpiled RAP, shown in table 5, in the production of HMA surface course under current Virginia DOT specifications. Surface course mixture type 3C is often used on high-type facilities. The master gradation band for this mixture type, lot production tolerance, and total production variability requirements for full pay are shown in table 7. Acceptance of material for aggregate gradation and asphalt cement within a 1810 t lot are acceptable if the mean of test results is within tolerances of the approved job mix formula shown in table 7. Only the 2.36 mm and 75 µm sieves and asphalt cement content are shown in table 7 for brevity. The Virginia DOT specifications also require the producer to control the variability of its product. When mixture production exceeds 3620 t, then variability is determined based on standard deviation for each sieve and asphalt cement content. To receive 100 percent pay, the standard deviation of all tests has to be lower than the values in table 7.[38]

Table 7. Virginia DOT specification requirement for surface course SM-3C.[38]

Sieve Sizes	Master Gradation Band % passing	Lot Production Tolerance n = 4	Total Production Variability for Full Pay (σ_{n-1})
2.36 mm		± 4.0 %	< 3.0
75 µm	3-6	± 1.0 %	< 1.1
% AC		± 0.30%	< 0.27

Information on the Virginia stockpile of RAP is shown in table 5. The RAP content would not be restricted by comparing the stockpile standard deviations of aggregate gradation and asphalt cement content of the RAP to full pay production variability in table 7. However, the stockpiled RAP has 13 percent passing the 75 µm sieve (table 5). The SM-3C master gradation band for the 75 µm sieve is 3 percent to 6 percent passing. Assuming that the virgin aggregate was totally clean and no mineral filler would be added to the mix, then the maximum RAP content could be determined by dividing 6 by 13. The RAP content would be limited to 46 percent. Realistically, the RAP content would be lower to account for fines in the virgin aggregate, aggregate degradation during heating and mixing, and inclusion of other mineral fillers.

SUMMARY

There are many factors to consider in determining the maximum RAP content for given recycled HMA mixture. Besides satisfying mixture design properties one must consider variables such as the target gradation of the proposed job mix formula, average aggregate gradation and variability of individual aggregate stockpiles, average RAP composite aggregate gradation and its variability, requirement of lime or other mineral filler, and production tolerances or uniformity requirements included in SHA specifications.

Since each source of RAP will be different, random sampling and testing of the RAP stockpile must be performed to quantify and qualify the RAP. Samples of the stockpiled RAP should be used in the laboratory mixture design. Process should utilize the stockpiled RAP.

CHAPTER 5. ASPHALT CEMENT BLENDING

The recycled HMA mixture design process includes a step to select the type of new asphalt cement or recycling agent to use in the design.[46] Mixture design procedures are discussed in Appendix A. This part of the mixture design process is the most controversial and complicated to understand. Some engineers do not believe that blending between new and aged asphalt cement ever occurs. They believe that the old asphalt cement in the RAP is not part of the binder, and the new asphalt cement dominates properties of the recycled HMA. Others believe that the new asphalt cement will coat the new aggregate, resulting in one property, while new asphalt cement coats the old asphalt, resulting in another property. Engineers with these philosophies generally use RAP in limited quantities, usually less than 20 percent.

Several attempts have been made to determine the mixing efficiency of recycling agents or new asphalt cement within recycled HMA. These attempts have included laboratory testing of laboratory-prepared recycled mixtures and cores from in-service pavements. Laboratory tests have included staged extractions, dye chemistry techniques, creep testing, indirect tensile testing, and resilient modulus testing.

Holmgreen, Epps, Little, and Button found that recycling agents can be used to alter the consistency of field aged asphalts. They also found that the softening effect of recycling agents on the aged asphalts is time and temperature dependent.[50] The softening effects are also dependent on the viscosity of the aged binder.[51] Their results show that a substantial portion of the softening action has been completed by the time the mixture has been mixed, hauled, placed, and compacted.[50]

Numerous reports have demonstrated that laboratory-prepared and plant-mixed recycled mixtures have properties that are similar to conventional HMA when tested for creep, indirect tensile, and resilient modulus.[43][49][50][53][56][59][63] This would seem to indicate that thorough mixing between old asphalt cement and new asphalt or recycling agent occurs.

Dye Chemistry techniques consist of incorporating a small amount of dye chemical into the recycling agent and detecting the dye in the recycled mixture.[62] Through the use of dye print, Lee, Terrel, and Mahoney generally found that there was thorough mixing between the aged asphalt cement and the new binder in a hot-mix plant.[62]

All current available testing methods, devices, and techniques have shown that properly designed recycled mixtures can meet conventional design criteria including requiring the recycled binder to meet specification properties after production.

Compatibility between the recycling agent (or new asphalt cement) and the aged asphalt cement in the RAP is another important issue. Research has indicated that hardening rates of asphalt cement in recycled HMA are less than asphalt cement hardening rates in conventional HMA. This trend has been confirmed through long-term monitoring or recycling projects in Florida and Washington State. [56][57][59][60][61]

However, it should also be pointed out that several researchers have also shown that blended recycled binders may be more temperature susceptible than the original binder.[54][61][62][64] This work should not be discounted either.

References 54 and 62 have indicated that different recycling agents have different hardening rates. Reference 53 found that temperature susceptibility of an asphalt blend is a function of the modifier selected. Thus, the bottom line is the compatibility between new asphalt cement or recycling agent (or new asphalt cement), and the aged binder in the RAP should be checked during design and verified during production. It appears that recycling agents and new asphalt cements can be used successfully in recycled HMA production as long as design assumptions are verified from samples and testing during production. A few SHAs have included extractions and recoveries of the asphalt cement from samples during production. Their practices are discussed in appendix B.

CHAPTER 6. PERFORMANCE

A literature search was conducted as part of this effort to quantify recycled HMA performance. Field visits included a query of pavement management systems to obtain data on past recycling projects. Some SHA engineers were able to provide performance experiences not covered in literature and their pavement management systems. This chapter will synthesize documented performance information. A discussion of undocumented SHA performance experiences can be found in appendix C.

Washington State DOT

The Washington State DOT had completed 24 recycled HMA projects by January 1985.[59] In 1986, the Washington State DOT performed a detailed analysis of the first 16 recycling projects investigating asphalt cement, aggregate, and mixture properties. Peters, Geitz, and Walter reported results from that analysis as well as each project's in-service performance.[59][60] The scope of most of the projects was to remove a specified depth of existing asphalt pavement, replace the material with recycled HMA pavement, and place an OGFC wearing course. The depth of milling ranged from 30 mm to 70 mm with a typical depth of 45 mm for most projects.[59]

A field visit with the Washington State DOT was conducted in June 1993. As a part of this review, the Washington State DOT's pavement management system (PMS) was used to update performance histories of those 16 projects. The PMS provides data including: date of construction; accumulated traffic loadings; skid test results; depth of rutting; condition survey information; calculated pavement structural condition (PSC); and, performance models to predict when a project will reach a program rehabilitation (PSC=50). The PMS can also generate performance curve representing average conventional HMA performance for similar projects within the same district. Table 8 summarizes some of the updated PMS performance information for those 16 projects.

Table 8 shows that most (9 of 13) recycled HMA projects are predicted to perform equivalently or better than the average predicted performance of similar treatments in the same district. Two projects have already been rehabilitated after 10 years service. Data for the comparison of the performance on these projects to others of similar treatment was not provided. Both of these projects were on Interstate 90 between mileposts 239.11 and 255.29. A review of the PMS history data indicates that rutting in the OGFC may have resulted in the scheduled rehabilitation of these two projects. Their PSC value was 80, while their rut index was 19 for 1992.

Four of the projects are predicted to perform worse than the average of similar treatments in the same district. Two of these are by 1 year. The other two projects have significant differences in predicted performance. One project (SR 5) appears to be a result of heavy truck traffic and studded tire wear in the OGFC. The PSC value for this project is 97, while the rut index was 32 in 1992. The other (SR-527) has a predicted difference of 8 years.

Table 8. Performance summary of Washington State DOT recycled HMA recycling projects.

ROUTE	MILEPOSTS	RAP CONTENT	YEAR COMPLETE	80 kN ESAL (millions)	1993 PSC	PREDICTED PROGRAM REHAB DATE	REASON FOR REHAB	PREDICTED PROJECT SERVICE LIFE	AVERAGE CONVENTION. HMA SERVICE LIFE
I-90	121.92 to 126.14	72%	1977	4.3	58	4/93	Rut & PSC	16 years	15 years
I-90	102.61 to 106.34	79%	1978	7.3	86	93	Rut	15 years	15 years
I-90	239.11 to 255.29	65%	1982		80	9/92	Rut	10 years actual perf.	
SR-395	183.69 to 190.61	70%	1982	1.1	73	9/95	PSC	13 years	9 years
SR-2	240.77 to 245.40	40%	1982	0.4	60	8/92	PSC	10 years	9 years
I-90	126.14 to 137.20	75%	1982	3.3	76	9/95	PSC	13 years	13 years
I-90	164.25 to 175.62	75%	1982	2.6	51	2/93	PSC	11 years	12 years
I-90	191.89 to 200.35	65%	1982	2.7	81	3/98	PSC	16 years	13 years
I-90	244.90 to 254.31	71%	1982		80	9/92	Rut	10 years actual perf	
SR-9	5.35 to 7.15	8%	1982	0.6	80	1/98	PSC	16 years	
SR-97	144.64 to 149.56	9%	1982	0.4	76	8/94	PSC	12 years	9 years
I-90	175.62 to 179.05	35%	1983	2.8	85	5/98	PSC	15 years	13 years
SR-99	22.53 to 25.98	33%	1984	4.3	79	1/98	PSC	15 years	16 years
SR-5	88.02 to 102.70	70%	1984	11.3	97	1/93	Rut	9 years	18 years
SR-527	8.90 to 10.34	35%	1985	0.4	76	1/98	PSC	13 years	21 years

Overall, the predicted service lives of recycled HMA projects ranged from 9 to 16 years. The predicted average service life for conventional HMA Pavements for similar treatments ranged from 9 to 21 years. It can be concluded from a review of table 8, that the performance of the recycled HMA in those 16 projects is approximately equivalent to that of conventional HMA.

The first two Washington State DOT recycled HMA projects were constructed in 1977 and 1978. During construction, these projects were sampled, tested, and analyzed by numerous researchers.[53][58][75] A more detailed summary of test results and pavement performance of these projects is presented in appendix D.

Route 4 in Burlington, Connecticut[61][70]

This 1.1 km reconstruction project consisted of milling the old pavement to the base course. Full-depth HMA was placed over the base course. The AASHTO Interim Guidelines for Pavement Design indicated that a structural number of 3.38 was required to satisfy the performance period for the full-depth sections.[70] This project included test sections to evaluate recycled HMA. Test sections included 200 mm of recycled HMA containing 30 percent RAP, 200 mm of conventional HMA, 60 mm recycled HMA overlay containing 30 percent RAP, and 60 mm conventional HMA overlay.

Ganung and Larsen[61] reported on project performance after 6 years. Tests performed on the various sections during performance evaluation included skid testing, transverse profiles, condition surveys, and core studies. Transverse rut profiles showed no evidence of rutting.[61] Skid testing of all sections showed that skid numbers were about equal for all sections, with the exception of the 60 mm recycled HMA overlay. The lower values of that section were attributed to the effect of heavy turning movements at an intersection.[61]

Longitudinal and transverse cracking was monitored throughout the performance period. Figures 3 through 6 show development of cracking on sections for each roadway. Figures 3 and 4 do not indicate substantial differences between transverse cracking performance in the full-depth recycled HMA and conventional HMA test sections. The recycled HMA overlay test section appears to have performed worse over the evaluation period than the conventional HMA overlay on the westbound roadway. The recycled HMA overlay appears to have performed better over the evaluation period on the eastbound roadway. Figures 5 and 6 show that there appears to be a greater amount of longitudinal cracking in the recycled HMA test sections than in the conventional HMA sections. Ganung and Larsen did not draw definite conclusions and further data collection was recommended.[61]

Performance of Recycled Mixtures in State of Georgia[63]

Kandhal, Rao, and Young evaluated the performance of recycled HMA versus conventional HMA placed in Georgia. Evaluations included a direct comparison of sections of recycled HMA surface course with conventional HMA surface placed on the same project and an indirect comparison of projects using recycled HMA with projects using conventional HMA.

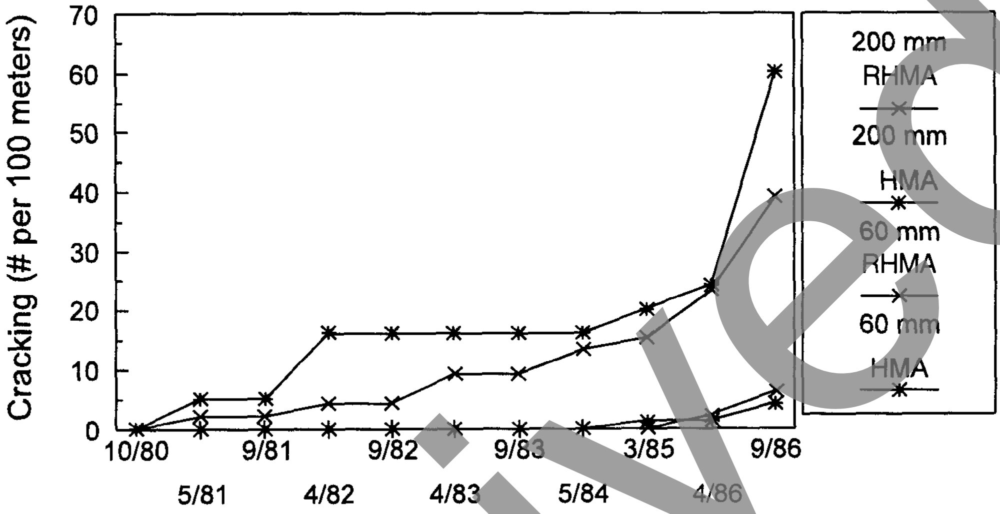

Figure 3.[23] Transverse cracking, eastbound roadway.

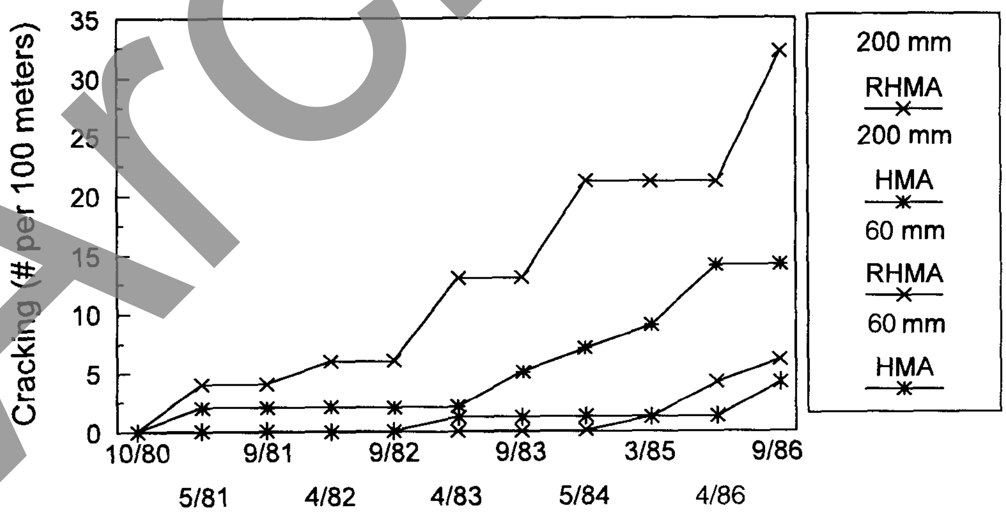

Figure 4.[23] Transverse cracking, westbound roadway.

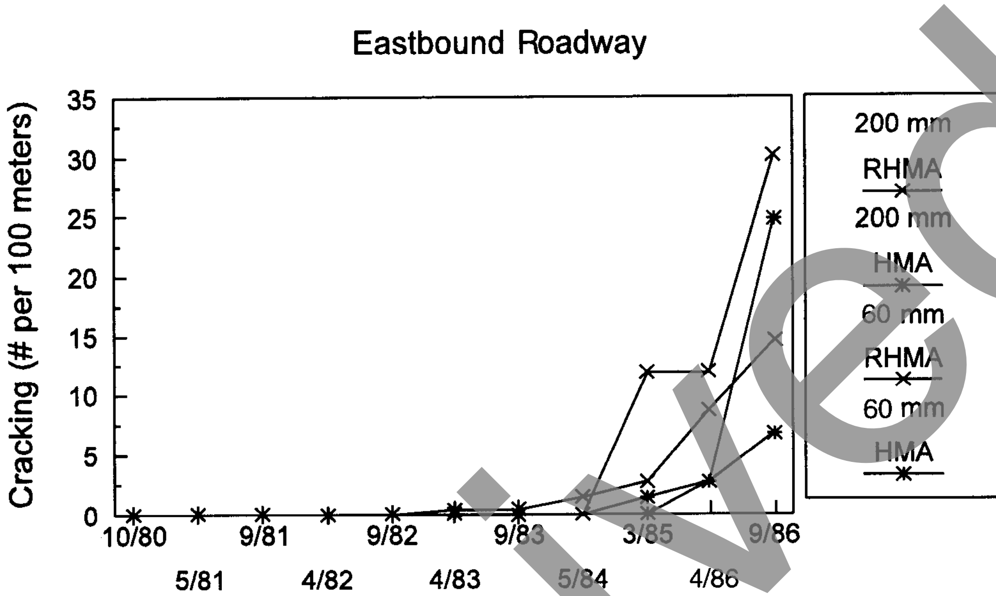

Figure 5.[23] Longitudinal cracking, eastbound roadway.

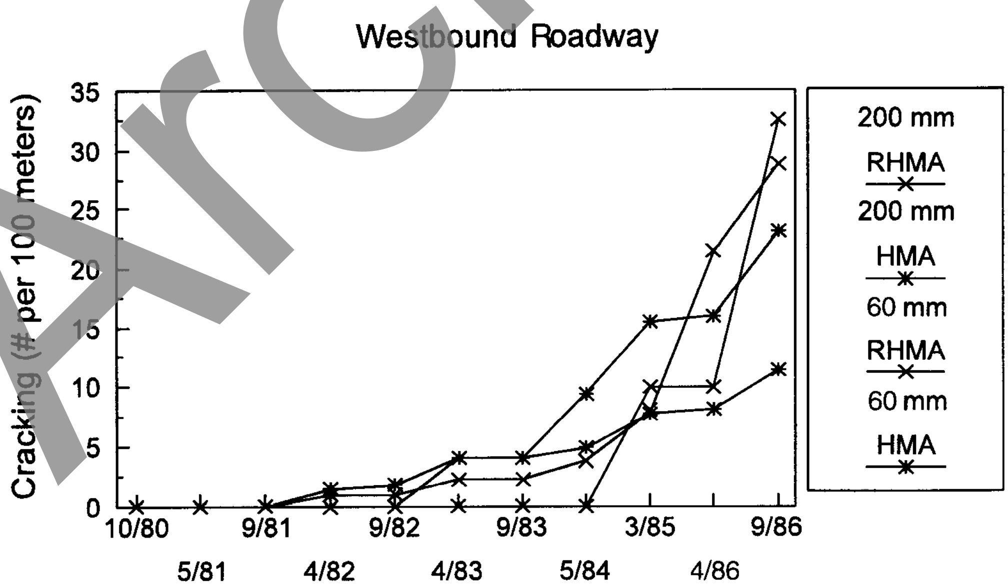

Figure 6.[23] Longitudinal cracking, westbound roadway.

Table 9 summarizes average mixture properties and recovered asphalt cement properties of samples from recycled HMA sections and control sections for projects included in the direct comparison.

A statistical analysis was performed for the properties in table 9. The report found no statistical difference between properties of recycled HMA and conventional HMA at the 5 percent level of significance.[63] No significant rutting, ravelling, or fatigue cracking was noted by distress surveys of recycled HMA or conventional HMA sections for projects in table 9.[63]

The report also included an indirect comparison of 15 conventional HMA projects with 18 recycled HMA projects.[63] Ages of conventional HMA projects varied from 1.5 to 4.75 years, and ages of recycled HMA projects varied from 1.25 to 5 years.[63] RAP contents for the recycled HMA projects varied from 10 percent to 40 percent, with 25 percent most common.[63] Comparisons were made for visual surface distress (performance), in-place air voids, recovered asphalt cement penetration at 25°C, and recovered asphalt cement absolute viscosity. Recycled HMA projects and conventional HMA projects were treated as two independent groups of unequal size for statistical analysis.[63] The authors found no significant difference in any indirect comparison when using the Independent Samples T-test at a 5 percent level of significance.[63] This report concluded that recycled pavements are generally performing as well as virgin pavements at the present time.[63]

Kansas DOT Reports

U.S. 56 in Edward and Pawnee Counties [72]

The first recycled HMA project was constructed in 1978 on U.S. 56 in Pawnee and Edward Counties. This project consisted of milling 135 mm of the existing cold-mixed asphalt pavement. A 210 mm recycled HMA layer was placed in 1978. A 20 mm conventional HMA surface was placed on top of the recycled HMA in 1979. A control section of patching and placing 100 mm of conventional HMA was placed in the project. The recycled HMA consisted of 50 percent RAP, 28 percent crushed limestone, and 22 percent sand gravel. Asphalt cement grade AC-5 was added at rates of 2.5 percent and 3 percent to the recycled HMA. The following cost comparisons were made at the completion of construction:[72]

TREATMENT	COST/KILOMETER
• Patching, widening, and 100 mm HMA	64,500
• Patching, widening, Petromat, and 100 mm HMA	73,500
• 135 mm cold milling, 210 mm RHMA, and 20 mm HMA	70,440

After 11 years of service, the ride quality remained acceptable.[73] Crack surveys conducted through 11 years indicated that the RHMA portion of the project had more reflected transverse and longitudinal cracks than the control section.[73] Figure 7 shows the total cracking for both test sections in the project. The project was overlaid in 1990.[73]

Table 9. Comparison of recycled HMA and conventional HMA:[63] average test results (standard deviation).

	Construction Details				Field Core Information						
Project	% RAP	Absolute Viscosity (Pa s)	% AC	% Voids (mat)	Age	%Voids (Mat)	Absolute Viscosity (Pa s)	G*/Sin(Delta) 64°C (kPa) Spec >2.2kPa	G*/Sin(Delta) 22°C (kPa) Spec <5000kPa	Indirect Tensile 25°C (kPa)	M_R 25°C (MPa)
18C	0	298.8	6.0	9.0	1.5	7.6 (0.45)	5581.0	20.8	2078	1766 (104)	7505
18R	15	298.8	5.7	9.3	1.5	8.2 (0.81)	5537.0	21.9	2012	1594 (145)	6572
22C	0	270.3	6.0	6.6	1.75	9.4 (0.70)	3309.2	12.1	781	1035 (28)	4942
22R	10	191.2	5.7	6.9	1.75	7.5 (0.89)	3677.3	11.9	655	980 (62)	4210
23C	0	280.7			1.5	3.6 (0.80)	3467.7	12.3	1030	1166 (124)	4816
23R	25	199.0	5.4	6.5	1.5	4.9 (0.52)	3300.2	10.3	721	1111 (117)	4728
25C	0	296.5	5.8	7.9	2.25	6.2 (1.07)	10,344.0	28.1	1789	1511 (166)	8289
25R	20	205.5	5.7	7.4	2.25	5.3 (0.70)	5934.1	16.1	1341	1346 (104)	5732
28C	0	304.7	6.0	8.3	1.5	8.3 (1.34)	4627.2	16.0	1102	1497 (69)	7104
28R	20	304.6	5.8	7.8	1.5	6.5 (0.99)	4990.7	16.9	1712	1428 (62)	9519

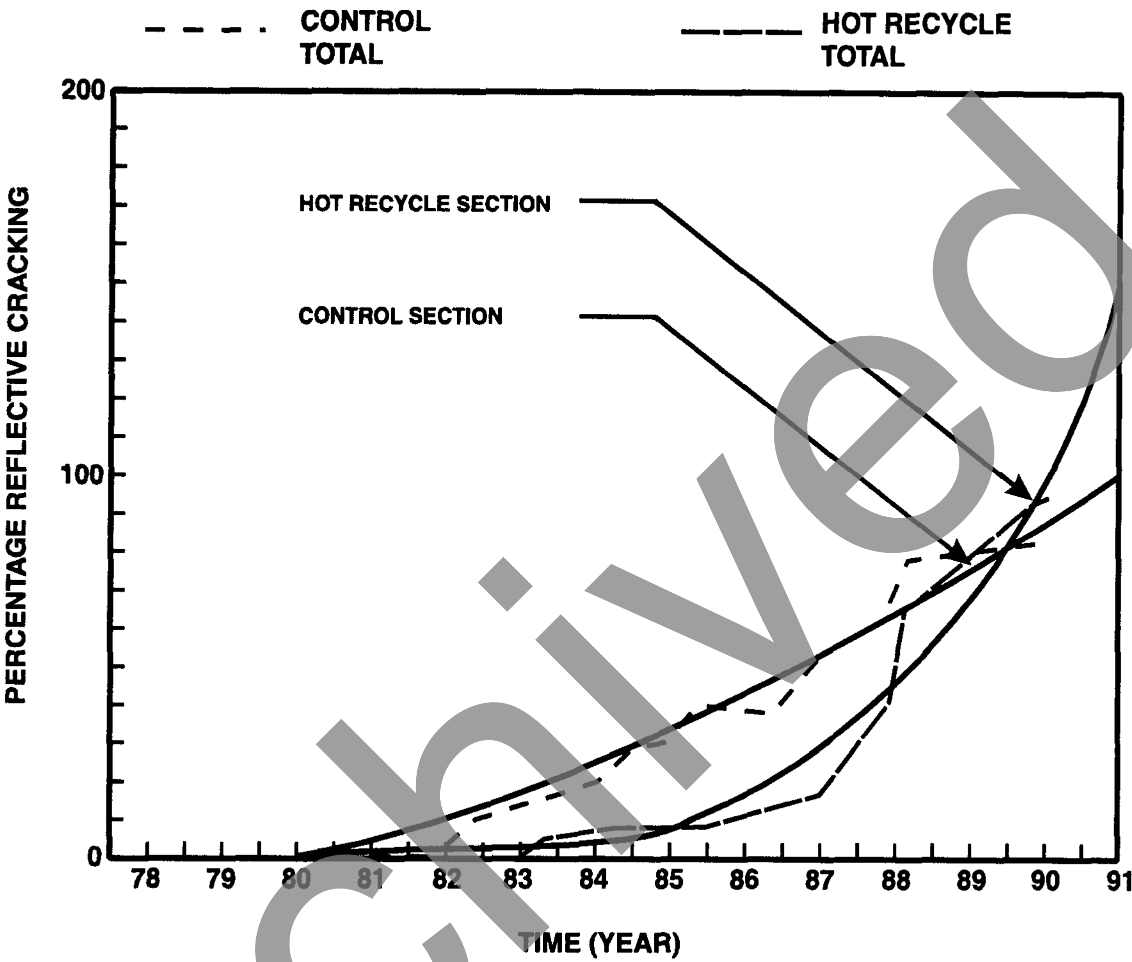

Figure 7.[35] Hot recycle, Pawnee County.

U.S. 56 in Gray County [72]

The second Kansas DOT recycled HMA project was performed on U.S. 56 in Gray County during 1978 and 1979. The project consisted of milling 100 mm of the existing 150 mm cold-mixed asphalt pavement. A 200 mm recycled HMA overlay was placed in three lifts with a 20 mm HMA surface course as the final layer. Recycled HMA was produced at 50, 60, and 70 percent RAP. Recycled HMA with 50 percent RAP was normally used. The existing pavement was removed in 50 mm lifts, and the lifts were stockpiled separately. Eventually the stockpiles were combined into one major stockpile. A 610 m control section consisting of all virgin HMA of the same thickness was constructed.[72]

Approximately 3.3 years after construction, both the recycled test section and the control section were performing comparably with less than 1 percent reflection cracking.[73]

K-96 in Scott Kansas [74]

A study was undertaken to construct and compare recycled HMA, cold in-place recycling (CIPR), and a control section. The original pavement consisted of 175 mm cold-mix asphalt. Three different sand seals were placed between original construction and time of rehabilitation, making the total asphalt pavement layer 200 mm.[74]

The predominant distress of the existing pavement was transverse thermal cracking with spacings varying between 0.9 m and 6.1 m. The five rehabilitation alternatives placed and evaluated included:[74]

- Cold mill 90 mm, 130 mm recycled HMA, and 30 mm HMA surface;
- Control 100 mm HMA overlay of the existing pavement;
- (Option A) CIPR 90 mm without additives, and 60 mm HMA overlay;
- (Option B) CIPR 90 mm, and 60 mm HMA overlay; and
- (Option C) Cold mill 55 mm, CIPR 90 mm, and 60 mm HMA overlay.

The CIPR sections were overlaid with half of the surface course thickness 1 day after construction. The second lift was placed 3 weeks later. Construction was completed in late summer 1979. Cost data for each section is shown in table 10.[74]

Table 10. Cost data for K-96 test sections.

Test Section	Cost/Lane-km	Estimated Life
Recycled HMA	68,990	13 years
Control	50,490	9 years
CIPR Option A	53,880	10 years
CIPR Option B	64,960	9 years
CIPR Option C	73,370	9 years

As noted in the report, the project originally specified milling and recycled HMA overlay. The CIPR options were added as extra work with the costs being negotiated. The study reported that CIPR costs are higher than those obtained through normal bidding procedures. The Kansas DOT performed crack surveys each spring and fall after construction. Figures 8 and 9 show the percent of original cracking for transverse and total cracking. The estimated lives were determined based on the crack surveys. Conclusions drawn from this study included: [74]

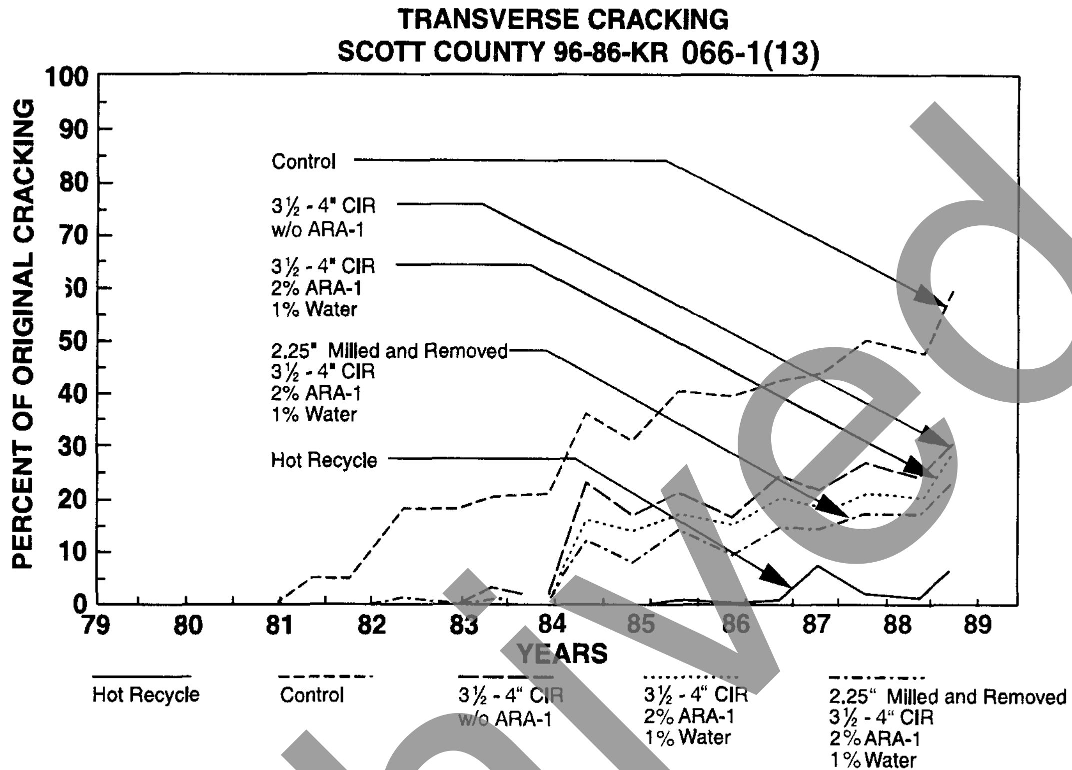

Figure 8. Comparison of transverse cracking within the five test sections.

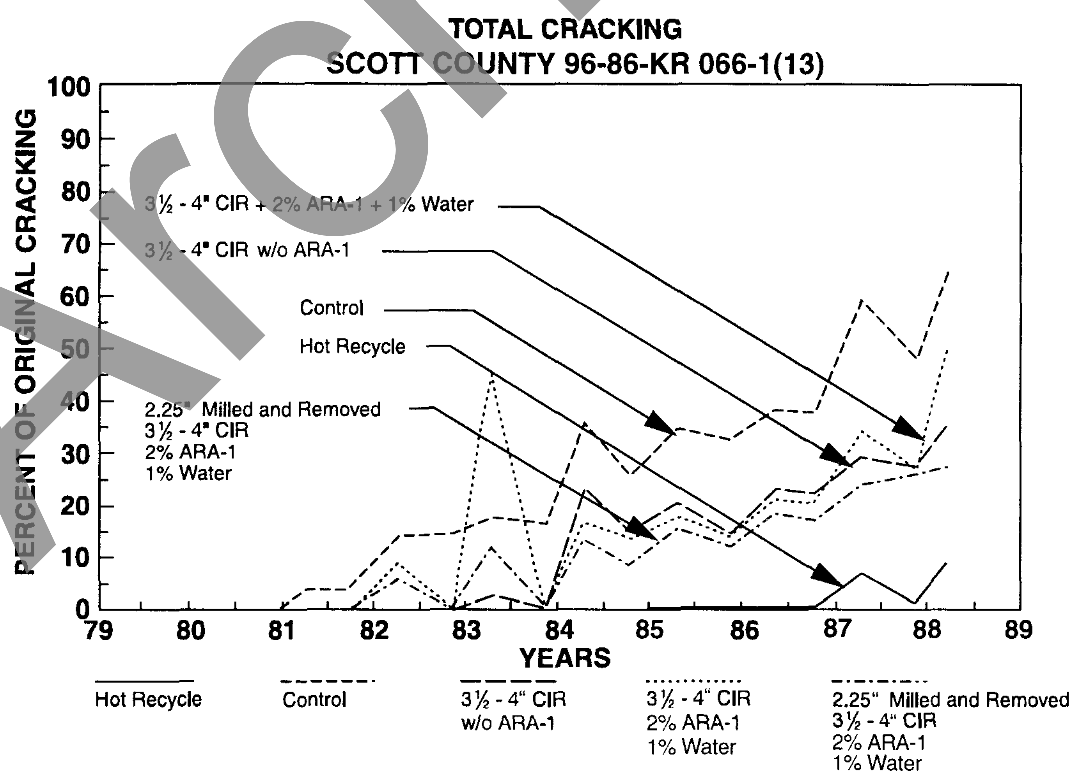

Figure 9. Comparison of the total cracking within the five test sections.

- Both the milled/recycled HMA and CIPR rehabilitation options were as cost-effective as the overlay option;
- Cold-milled and recycled HMA provided the best performance during the study period; and
- Cold milling prior to CIPR (Option C) to remove a greater depth of transverse crack further retards the percentage of reflective cracking.

Accelerated Testing of Recycled Asphaltic Concrete[71]

Ferreira, Servas, and Marias performed a comprehensive laboratory test program to determine the effect of varying proportions of reclaimed materials to new materials. All mixes were designed to meet the same aggregate gradation requirements. Tests performed included Marshall stability, creep modulus, resilient modulus, and indirect tensile strength. Laboratory analysis concluded that proportions of reclaimed material had no effect on the initial engineering properties of asphalt concrete mixes.[71] Accelerated testing was performed to determine fatigue and permanent deformation characteristics of recycled HMA.[71] In 1985, two trial sections containing varying amounts of RAP were constructed. One trial section was built on a relatively weak supporting base and the other trial section was built on a relatively strong supporting base. A 120 mm asphalt concrete layer was placed on each base. Each trial section contained different HMA sections with varying RAP contents (0 percent, 30 percent, 50 percent, and 70 percent).[71] These were the mixtures that were designed and tested in the laboratory analysis. A heavy vehicle simulator (HVS) applied a 60 kN single-wheel load with a tire pressure of 700 kPa. A mechanistic analysis was performed on the weakly supporting base section to predict expected fatigue life. The analysis predicted 1.5 million 80 kN axle loads as expected fatigue life.[71]

The HVS was applied to the weakly supported base section with 120 mm of recycled HMA containing 70 percent RAP.[71] Hairline cracks originating at the surface appeared after 118,000 repetitions (≈1 million 80 kN ESAL).[71] After 1.5 million 80 kN axles loads, the surface was completely cracked.[71] This was the only test section loaded with the HVS at the time of the report.[71] Preliminary findings from this research indicated that when recycled HMA met mixture design parameters for conventional HMA, the recycled HMA had the same engineering properties and performed as predicted when subjected to the HVS.[71]

SUMMARY

There is not an abundant supply of information that provides direct comparison of recycled with conventional HMA performance. States that routinely use RAP in HMA production were convinced early on that recycled HMA performance was equal to conventional HMA performance. For that reason performance information was no longer collected. Another reason for the lack of information is that use of RAP in binder and base courses which is not visible for visual condition surveys.

Appendix C summarized undocumented performance experiences of SHAs that participated in this review. It was the experience of these States that recycled HMA that was designed under established mixture design procedures and produced under appropriate quality control and acceptance measures will perform comparably to conventional HMA. Two SHAs experienced poor performance due to maximizing the RAP content without consideration of mix design. Their current procedure let an optimize mix design set the RAP content.

Another agency found that their recycled HMA base mixture outperformed their conventional HMA base mixture. The conventional HMA base mixture was a specified aggregate gradation with 4.5 percent asphalt cement. The recycled HMA base mixture was designed in the laboratory prior to production. That agency now requires a laboratory mixture design of its conventional HMA base mixture.

Most of the SHA indicated that recycled HMA performance is equivalent to conventional HMA when the recycled HMA meets mixtures requirements of conventional HMA. Available literature and information collected from pavement management systems appears to substantiate these claims. The data collected has shown that some recycled HMA has outperformed conventional HMA, while in other cases it has performed worse.
It is widely recognized that HMA performance has varied tremendously in the past. D'Angelo and Ferragut showed that some conventional HMA performance problems could well be related to laboratory prepared mixture properties not duplicating mixture properties of produced HMA.[85] Most of the highway community have accepted this concept and do some form of verification testing during production. It is accepted that good performing pavements must contain HMA mixtures that have been properly designed, produced with good quality control, and placed with no surface defects and adequate density.

The SHRP also recognized the lack of performance information for all HMA pavements. The long-term pavement performance (LTPP) studies initiated by the SHRP include studies on HMA performance. One LTPP project includes Specific Pavement Study (SPS)-5, Rehabilitation of Asphalt Concrete Pavements. One of the experimental variables of SPS-5 includes a direct evaluation of recycled HMA (with 30 percent RAP) performance to conventional HMA performance. The FHWA's LTPP Division is administering the data collection efforts for SPS projects. In-service monitoring will continue on SPS-5 projects until sufficient data is obtained for evaluation purposes.

The use of RAP in the Superpave binder and mixture design is an area where more research is required.

CHAPTER 7. CONCLUSIONS

1. **Disposal of excess pavement materials in landfills does not appear to be a nationwide problem.** Collins and Ciesielski's NCHRP Synthesis of Highway Practice 199 *Recycling and Use of Waste Materials and By-Products in Highway Construction* estimates that 45 million t of asphalt pavement are removed annually. A simple extrapolation of data collected during this project verified their estimate. Research for the EPA and the FHWA found that 80 percent of the pavement that is removed by SHAs is reused in highway applications such as recycled HMA, hot in-place recycling, cold in-place recycling, aggregate base material for roadways and shoulders, shoulder surfacing, embankment fill material, and maintenance uses.

2. **It is estimated that 33 percent of all asphalt pavement removed is recycled into HMA production.**

3. **The use of RAP in HMA production is not uniformly accepted throughout the US.** Some SHAs actively promote and use RAP in HMA production. However, there are SHAs that do not believe in the use of RAP in all HMA production. Collins and Ciesielski's NCHRP Synthesis of Highway Practice 199 *Recycling and Use of Waste Materials and By-Products in Highway Construction* found that three SHAs do not use RAP in any HMA production. This synthesis also shows that an additional nine SHAs do not permit the use of RAP in HMA surface courses.

4. **One major obstacle to increased RAP usage is limitations placed in Standard Specifications, Supplemental Specifications, and Special Provisions.** There are practical limitations on the amount of RAP that can be incorporated into a recycled HMA. Some of these limitations include plant technology and the amount of fine material in the RAP. However, some specifications or special provisions provide further limitations on RAP usage. Almost half of the SHAs reviewed set maximum RAP contents to 30 percent or less in all HMA mixtures. This applies to all HMA regardless of its application and properties of the RAP. It was found that some of these maximum RAP contents were set arbitrarily instead of being based on research or engineering criteria. Some SHAs still do not give the producer the option to use RAP in HMA production.

5. **Those SHAs that perform an evaluation of RAP and report its composition in plans, specifications, and estimates generally permit greater percentages of RAP in all HMA mixtures.** Only 7 of the 17 SHAs reviewed perform sampling and testing to determine RAP composition during the project development stage. Only four of those SHAs routinely perform such an evaluation for all major milling projects. These agencies' specifications do not have maximum RAP limits or restrict RAP contents to 50 percent in all HMA mixtures except OGFC.

6. **Another obstacle to increased RAP use is that many engineers believe that recycled HMA is inferior to conventional HMA.** Their expectations are based mostly on judgement instead of detailed engineering analysis or performance evaluations. Their beliefs for limiting use of RAP in HMA include:

   - RAP variability is too high to use in HMA production.
   - Aged asphalt cement in RAP cannot be restored to new asphalt cement properties during production.
   - The quality of recycled HMA has not been proven through long-term performance.

   Data collected during a literature search and a survey of plant producers demonstrates that not all RAP is too variable for use in quality HMA. Data in chapter 4 showed that some RAP stockpiles have variability that is less than could be expected of HMA production. Data also showed that some RAP had variability that was much greater than HMA production. Sources of RAP must be sampled, tested, and analyzed to determined the composition of the RAP and its uniformity.

   The RAP composition from pavement cores can provide contractors with information to establish prices for bidding purposes. Data in chapter 4 indicates that RAP variability determined from pavement cores usually represents worst-case variability. Contractors and producers can improve variability by milling, screening, crushing, and separating RAP into different stockpiles.

   Recycled HMA mixture design, including determination of the type and amount of new asphalt cement or recycling agent, was based on a substantial amount of research over the years. The viscosity blending chart in the Asphalt Institute's Manual Series 2 and Manual Series 20 provides a good estimation of the type of new asphalt cement or recycling agent to use in the laboratory mixture design process. Research has been performed that verified the applicability of the chart. Several research projects have attempted to verify the mixing efficiency of a recycling agent and aged asphalt cement in RAP. All current available testing methods, devices, and techniques have shown that recycling agents can alter aged asphalt cement in RAP so that the final blend meets specifications for new asphalt cement.

7. **Pavement performance and detailed evaluations indicate that recycled HMA that is designed and controlled during production will perform comparably to conventional HMA and can improve material properties of the existing pavement layer.**

   Pavement performance evaluations conducted by the Washington State DOT and updated with their PMS system shows that recycled HMA performs as well as conventional HMA. The Washington State DOT's first two recycling projects were experiments conducted on I-90 during 1977 and 1978 (see appendix D). The RAP content on both projects was in excess of 70 percent. The recycled HMA was designed using through laboratory evaluations. Quality control during production included sampling and testing all mixture design assumptions. This included extracting, recovering, and testing of the blended asphalt cement. Quality control testing showed that the recycled HMA was produced within normal HMA production tolerance. Sampling and testing the recycled pavement was also carried out 7 years after construction. Recycled HMA properties over time did not show any unusual signs of mixture aging. The average service life of these two projects was 16 years. The original HMA pavement layer that the recycled HMA replaced lasted only an average of 10 years. These original layers were removed and recycled at contents over 70 percent and provided an additional 6 years of service.

8. **Similar to poor-performing conventional HMA, poor recycled HMA performance can be related to poor mixture design procedures or use of control and acceptance procedures that do little to ensure the quality of the recycled HMA.** There is not a lot of literature that provides forensic analysis of recycled HMA that performed poorly. However, discussions with materials engineers indicate that poor performance can be attributed to the lack of proper design and QA, as follows:

   - Some SHAs have implemented **short cuts in the recycled HMA mixture design process**. These short cuts include:

     - Four of the 17 SHAs **permit the inclusion of RAP in HMA production without using the RAP in the laboratory mixture design process**. This includes mixes with RAP contents ranging from 10 percent to 40 percent. Only one of those four agencies performs any verification of the laboratory mixture design during production.

     - More than one-half (9 of 17) of the SHAs reviewed **do not consider the selection of the type of new asphalt cement or recycling agent in the recycled HMA when RAP is limited to low amounts**. Low amounts generally range from 10 percent RAP to 30 percent RAP. None of the SHAs routinely sample and test recovered asphalt cement from recycled HMA production.

     - Another four SHAs **specify the new asphalt cement to use in recycled HMA production regardless of the source of the RAP**. Two of these agencies do change the type of asphalt cement based on the percentage of RAP. Two of the agencies verify properties of the asphalt cement during production. However, the frequency of testing is generally once per production season.

   - Earlier recycling projects included **control and acceptance of only new components to the final mixture and did not include sampling and testing of the final recycled HMA mixture**. During the 1980s many SHAs included only cold feed sampling of new aggregates and application rate of new asphalt cement as the acceptance criteria. These SHAs now have revised their testing protocol so that control and acceptance are based on extractions of the final mixture; cold feed samples, nuclear gauge asphalt contents, with mixture design verification testing; or a combination of both.

- **Only one SHA includes routine production sampling and testing of recovered asphalt in a QA program**. Many SHAs are specifying or using new asphalt cement that has not been tested for compatibility with the asphalt cement in the RAP. Further, none of these SHAs routinely obtains production samples and tests the recovered asphalt cement.

9. **The recycled HMA mixture design procedure outlined in the Asphalt Institute's Manual Series No. 2 and No. 20 is a technically viable method for establishing ingredient proportions of a recycled mixture**. This procedure included a viscosity blending chart that estimates the type and amount of new asphalt cement or recycling agent that can be added to the mixture. This process is an estimation for plant production. Therefore, similar to conventional HMA, all recycled mixture design steps should be verified in a QA program during production to ensure quality. The FHWA's DP No. 74 showed that some conventional HMA performance problems could be related to laboratory prepared mixture properties not duplicating mixture properties of produced HMA.

10. **Recycled HMA that is designed and produced in a QA program that verifies mixture design assumptions to reasonable limits can be expected to perform comparably to conventional HMA**.

RECOMMENDATIONS

The following recommendations are provided to increase RAP usage and ensure HMA quality.

1. Sampling and testing of the pavement to be removed should be performed. Enough random samples should be taken to give an indication of variability of material properties. Test results and variability should be provided on plans, specifications, and estimates to provide contractors the best information. Producers in a few States use such information to determine preliminary RAP content to bid HMA prices. Reporting such composition and variability will also remove fear of the unknown and may encourage greater use.

2. States should consider revising their specifications so a given mix's RAP contents is based on a thorough mixture design process instead of arbitrary RAP limits.

3. Consideration should be given to permit up to 15 percent RAP in all mixtures without changing to a softer grade asphalt cement. This will minimize the amount of recovery and testing performed. This recommendation is in-line with the Asphalt Institutes' Manual Series No. 2 and No. 20 and is also provided in research performed by Kandhal, Rao, and Young (*Performance of Recycled Mixtures in State of Georgia, January 1994*). The laboratory mixture design should be established using the RAP as an ingredient.

4. With RAP contents greater than 15 percent, the selection of the new type of asphalt cement or recycling agent added to recycled HMA should be based on the viscosity blending chart or equivalent procedure or formula. Currently some States arbitrarily select new asphalt cement to add to recycled HMA containing high RAP contents. Some State materials engineers have shown that this has been a problem leading to greater frequency of transverse cracking or premature fatigue cracking.

5. Production sampling and testing programs need to verify all mixture design assumptions including the asphalt cement blend properties. Extractions and recoveries should be added to a QA program to ensure optimum performance of recycled HMA. It is recommended that such sampling and testing is added by producer sampling and testing in a QC program or by SHA sampling and testing for acceptance or verification. Test results should be used to adjust plant production. Production tolerances should be established by each agency for its environment.

6. Additional training should be provided to increase the awareness of proper mixture design and analysis, producer equipment and handling procedures, performance evaluations and quality control plans.

7. Follow-up production, construction, and performance evaluations of the Long-Term Pavement Performance Specific Pavement Study-5 and supplemental test sections should be provided to the highway community.

8. Research needs include the use of RAP with modified asphalt cements and use of RAP in the SHRP binder specifications and SuperPave™ mixture design and analysis system.

APPENDIX A. MIXTURE DESIGN PRACTICES

This appendix summarizes the current recycled HMA mixture design guidelines and also reviews state-of-the-practice for those SHAs visited during this review.

PRELIMINARY ENGINEERING

When the decision to remove part of the existing pavement is made, agencies can promote increased use of RAP by including its composition and variability in plans and special provisions. The decision to remove the existing pavement will be predicated on a review of historical data, visual condition surveys, and deflection testing. Historical data may include as-built construction plans, PMS past-condition surveys, or maintenance records. This data is analyzed to delineate substantial differences in pavement section, surface distress, or increased structural capacity. These differences are used to separate the project into units of differing construction materials or differing depths of milling. Using a random sampling method or plan, preliminary samples of the pavement to be removed can be taken from each different section. Samples would be trimmed to depth of removal prior to performing extractions and recoveries for testing. These tests are performed on the preliminary samples to quantify the RAP composition and its variability within each section. Producers have the knowledge and ability to use compositional data provided in plans to determine bid prices. Discussions with many producers in each of the States visited indicated that compositional information is indeed useful for establishing bids on projects. Almost all producers indicated that the asphalt cement content in the RAP was extremely important to know for bidding purposes. Test results should be available to contractors prior to bidding in Plans, Specifications, and Estimates (PS&E). Information that should be included in PS&E packages are:

- Aggregate gradation (AASHTO T 30);
- Asphalt cement content (AASHTO T 164);
- Absolute (AASHTO T 202) and kinematic viscosity (AASHTO T 201);
- Penetration at 25 °C (AASHTO T 49); and
- Ductility (AASHTO T 51).

Test results from random sampling can be used to provide an estimate of RAP variability within each section. Variability can be expressed as a range of test values or as the standard deviation of test values. Producers operating in States that have Quality Assurance (QA) specifications without RAP limits also stated that RAP compositional data is important for bidding purposes. Variability reported in RAP composition provides an indication of whether the RAP requires further processing. If a project has RAP with low variability, then a producer may establish a single dedicated stockpile for that source. Should the variability be high, then a producer may stockpile it with other sources of RAP that will be crushed at a later date. Two times the standard deviation of RAP test results can be compared against production tolerances as a quick approximation of whether the variability is high or low.

Some agencies do not want to sample and test pavements to report RAP composition in contract documents on the premise that RAP composition will change after removal, processing, and stockpiling. In fact, data in chapter 4 proves that point. Some agencies believe that reporting this information is a waste of testing and limited resources because the producer must establish the RAP composition in the stockpile to maintain production uniformity anyway. Another reason for not reporting composition in contract documents is the fear of a contractor claim should stockpile composition be different from the in-place pavement composition. These agencies also believe that producers do not have the knowledge to use such information in the development of bids.

Providing RAP compositional data can increase competition on given projects by permitting producers with mobile production plants the opportunity to evaluate and bid on projects. These plants do not have a ready supply of RAP. However, if the quality of the RAP is good enough and the quantity of RAP is large enough, then a producer may elect to bring a mobile facility. It is recognized that one could not provide compositional data on every milling project, especially those projects that have low tonnages of millings. The logical question is, "For what volume of milling should an agency perform sampling and testing to report compositional data in contract documents?" The Florida DOT, which generates and reuses a lot of RAP millings, will perform compositional testing any time the amount of milled material will be 900 t or more.

Some agencies have performed enough sampling and testing to determine correlation factors to convert core aggregate gradation to an estimated stockpile aggregate gradation. The Florida DOT, Kansas DOT, and Wyoming DOT routinely use recycled HMA and provide RAP compositional data from roadway samples in contract documents. Some of these DOTs provide the estimated RAP stockpiled gradation using correlation factors shown in table 11. The correlation factors are multipliers of the percent passing the sieve, with the exception of the Kansas DOT. The Kansas DOT's factors are subtracted from the percent retained on each sieve.

None of these DOTs mentioned claims due to changed conditions when the actual stockpile gradation differed from those shown in contract documents. Producers also did not indicate problems with compositional data shown in contract documents. In fact, some producers stated that they were more worried about virgin aggregate uniformity affecting pay than about RAP affecting pay.

PAVEMENT EVALUATION

A random sampling plan is developed to obtain preliminary samples of the existing pavement. The plan should include number of samples, sample size, and sample locations. Cores are usually taken for the full depth of the pavement structure. Frequency of sampling will depend on an estimate of project variability determined by analysis of historical data and condition surveys.

Table 11. Core gradation correlation factors.

Sieve Size	ARIZONA		FLORIDA			KANSAS	WYOMING
	Visc. 60°C Less than 5000 Pa	Visc 60°C Greater than 5000 Pa	Coarse Mix	Intermediate Mix	Fine Mix		
19 mm	1.00	1.00	1.00	1.00	1.00	3	1.05
12.5 mm	1.05	1.05	1.03	1.02	1.00	3	1.05
09.5 mm	1.05	1.05	1.06	1.03	1.00	3	1.05
6.3 mm	1.05	1.05					
4.75 mm	1.05	1.05	1.16	1.08	1.00	3	1.05
2.36 mm	1.05	1.10				3	1.05
2.00 mm	1.05	1.10	1.24	1.12	1.00		
1.18 mm	1.05	1.10				3	
600 μm	1.10	1.15				3	1.10
425 μm	1.10	1.15	1.27	1.13	1.00		
300 μm	1.10	1.15				2	
180 μm			1.49	1.25	1.12		
150 μm	1.15	1.25				2	1.15
75 μm	1.20	1.35	1.84	1.42	1.21	2	1.20

Reference 86 suggests the following procedure for randomly sampling a project that includes pavement milling. Using historical records, separate the pavement into construction units of similar composition. Divide each construction unit into six to eight sections of equal length. Randomly select one sampling location within each section. Each sample should be of sufficient size (6.8 kg minimum) for extraction, recovery, and testing. Test each sample individually.

The SHAs were canvassed regarding their pavement evaluation procedures during this project. The Florida and Wisconsin DOTs were the only agencies that provided RAP composition data in contract documents for all milling projects with significant quantities. The Arizona, Kansas, Nevada, and Wyoming DOTs only provide RAP compositional data in contract documents that specify the use of recycled HMA in the individual project. When milling is performed and the contractor has the option of reusing the material at low contents, those agencies do not perform compositional testing. Table 2 shows sampling frequency and sample size for those SHAs that perform pavement evaluations during the project development stage.

Table 12. Pavement evaluation sample frequency and size.

STATE	SAMPLE FREQUENCY	SAMPLE SIZE
Arizona	3 cores/1.6 lane-km	150 mm diameter for the full depth of structure
Florida	1 set of 3 cores/1.6 lane-km. Minimum 2 sets of 3 cores per lane.	150 mm diameter for the full depth of structure
Kansas	3 cores/1.6 lane-km Minimum 30 cores.	100 mm diameter for the full depth of structure
Nevada	1 core/760 lane-m	100 mm diameter for the full depth of structure
Texas	10 cores/project	150 mm diameter for the full depth of structure
Wisconsin	1 core/805 m	Surface area minimum of 230 cm^2
Wyoming	2 cores/km	150 mm diameter for the full depth of structure

Table 12 shows that most of these agencies core the full depth of the pavement. The sample size is either 100 mm or 150 mm diameter cores. The larger size cores are necessary to perform extraction on individual samples. After visual examination, all agencies trim cores to the proposed depth of removal. The following paragraphs provide a summary of procedures used for handling and testing material obtained from cores.

The Arizona DOT groups cores by different sections based on historical data or changes in depth of milling. Cores from the same section are crushed with a laboratory crusher and the material is combined. Samples are taken from the combined material, and an extraction is performed on each sample to determine the asphalt cement content and aggregate gradation. An abson recovery is performed on the extracted asphalt cement to determine its absolute viscosity. The Arizona DOT uses the results in a preliminary mix design and specifies the mix design and RAP content in contract documents for projects that include recycled HMA.

Through condition surveys and cores, the Florida DOT evaluates the need for milling the existing pavement. When it is determined that the existing pavement will be milled, the project is separated into different construction units. Three cores are obtained in each sample location at a frequency shown in table 12. All cores are trimmed for depth of removal. One of the three cores must be located in the wheel path, and another must be located either in between or outside of the wheel path. These two cores are sent to the central laboratory for an extraction and abson recovery. The central laboratory reports the average absolute viscosity of these cores, weighted by surface area. For example, for an absolute viscosity result from a set of cores, the reported value would be equal to one-third times the absolute viscosity determined from the wheel-path core plus two-thirds times the absolute viscosity in the nonwheel-path core. The justification for difference in viscosity is the difference in air voids in the mat due to traffic consolidation. Research has shown that the absolute viscosity of the asphalt cement will be higher as air voids increase.

The third core is delivered to the district laboratory. The district laboratory heats and hand breaks the core. An extraction is performed for reporting aggregate gradation and asphalt cement content. The Florida DOT reports average aggregate gradation of all samples, plus the range of test results; the average asphalt cement content of all samples; and, the average absolute viscosity from the weighted average determined from each set of cores. A target asphalt cement content for all mixes is also provided in the specifications for bidding purposes. These values are 6.0 percent for structural mixes and asphalt base course and 6.5 percent for other types of mixes. For all HMA production, producers perform mix designs that are verified by the Florida DOT.

The Kansas DOT groups cores for differing depths of milling. Cores are trimmed to proposed depth of milling. Cores are heated and hand broken and material is combined. Combined material is split with a mechanical splitter for sampling and testing RAP composition. Samples are extracted for asphalt cement content and aggregate gradation. The gradation is analyzed for percent of crushed faces. An abson recovery is performed on the extracted asphalt cement. The recovered asphalt cement is tested for absolute and kinematic viscosities, penetration at 4 °C and 25 °C, ductility at 25 °C, and softening point. An initial or preliminary mix design is performed by the Kansas DOT to specify the recycled HMA ingredients and their proportions in contract bid documents.

The Nevada DOT cuts cores to proposed depth of milling. Cores are heated and hand broken and the material is combined. Samples are taken from combined material to perform extractions to determine asphalt cement content and aggregate gradation. Abson recoveries are performed to determine the penetration at 25 °C and the absolute and kinematic viscosities of the asphalt cement. This information is used to select a preliminary gradation and type and amount of asphalt cement for contract bidding purposes. The RAP content in the recycled HMA will be specified in the plans or special provisions.

The Wisconsin DOT trims cores to proposed depth of removal. A laboratory crusher is used to process core samples. Crushed material is combined and two samples are taken from combined material. An extraction is performed on each sample to report an average asphalt cement content and an average aggregate gradation. Abson recoveries are performed to determine the average penetration at 25 °C. This information is provided in plans and special provisions for the contractor's information. The Wisconsin DOT may decide to specify recycled HMA for a given contract. In those cases, the RAP content will also be provided in the contract documents. Contractors are allowed to vary their RAP content minus 10 percent and plus 25 percent of the specified content.

The Wyoming DOT uses one of the two cores taken per section to determine the composition of the RAP. The other core is saved for mix design purposes. Cores for composition testing are heated and hand broken. Extractions are performed on samples to report aggregate gradation and asphalt cement content. Abson recoveries are performed to determine absolute viscosity. An initial or preliminary mix design is performed by the Wyoming DOT to specify the recycled HMA ingredients and their proportions in contract bid documents.

Each SHA's procedures differ in the way it samples and tests the existing pavement for project development. Most agencies sample and test the pavement when they specify recycled HMA and RAP content. All agencies used either 100 mm or 150 mm diameter cores to sample the existing pavement. Most agencies, except the Florida and Wyoming DOTs, break apart cores and combine material for sampling prior to extraction. These states run tests on extractions and recoveries of the combined material to report average test results. The Florida and Wyoming DOTs generally perform extractions and recoveries of individual core samples. Therefore, they can report average values from individual sample test results and evaluate variability of material properties. The Florida and Wyoming DOTs report test results in contract documents. Test results usually include extracted aggregate gradation, asphalt cement content, absolute viscosity, kinematic viscosity, and penetration at 25 °C. Some agencies include aggregate quality such as percentage of fractured faces.

PRELIMINARY MIX DESIGNS FOR PLAN PREPARATION

Quality assurance is not universally accepted or implemented by all SHAs. Some agencies still perform the necessary engineering to perform the mixture design and specify component proportions in contract documents. There are also some cases when an agency may wish to specify a RAP content in the recycled HMA or a certain range of RAP content to promote reuse of RAP. In these cases, the RAP content is optimized in a mixture design to minimize the excess that has to be dealt with later. Usually, these projects are located in remote areas and require mobilization of an HMA facility. Excess RAP must be stockpiled, wasted, or hauled with the plant after the project. Hauling RAP reduces the savings from a recycled HMA project. The Kansas and Wyoming DOTs have produced recycled HMA on many projects that fit this type of situation and have developed procedures that encourage recycling in spite of the location of the project. Their procedures are discussed below because of the large amount of recycled HMA produced according to this method.

Kansas DOT

The Kansas DOT calculates an initial mix design for the development of bid items and quantities for contract documents. The first step of the initial mix design process includes a back-calculation procedure to establish a virgin aggregate gradation and its production tolerances. This back-calculation process has been integrated in a computer spreadsheet that performs the following calculations.

- The average extracted RAP aggregate gradation is adjusted for an anticipated milled gradation using the core correlation factors in table 11.

- The average RAP aggregate gradation is multiplied by its percent of the total mix to determine the percent retained on each sieve that is contributed by the RAP. To optimize the RAP content, the initial starting point is the specification limit of 50 percent RAP.

- The percent retained on each sieve for the lower range of the master gradation band is added to the HMA production tolerance for the respective sieve. The percent retained on each sieve from the RAP contribution is subtracted from the master gradation band and HMA production tolerance. This total is then divided by the percent of virgin aggregate to the total mix. This gives a target lower range for the virgin aggregate gradation.

- Similarly, the HMA production tolerance for each sieve is subtracted from the percent retained on each sieve for the upper range of the HMA master gradation band. The percent retained on each sieve from the RAP contribution is subtracted from that number. This total is then divided by the percent virgin aggregate to the total mix. This gives a target upper range for the virgin aggregate gradation.

- The HMA production tolerance is applied to the upper and lower ranges of the target virgin aggregate band to give extreme limits for the virgin aggregate gradation band. The band width for each sieve is compared with a minimum band width that would be considered reasonable for an aggregate producer. Using the minimum band width for each sieve, the upper and lower ranges of the virgin aggregate gradation are adjusted.

- The adjusted lower and upper virgin aggregate ranges are combined with the average RAP gradation to determine if the calculated gradation will meet the HMA master gradation band. If the calculated gradation falls outside the HMA specification, the percentage of RAP is lowered and the entire back-calculation process is repeated until the calculated combined aggregate gradation meets the specification HMA master aggregate gradation band.

The second step of the initial mix design process uses theoretical equations to estimate the total asphalt cement content and the type and amount of asphalt cement or recycling agent. The estimated percent asphalt demand of the combined aggregates is determined by equation 1.

$$P_T = 0.035a + 0.045b + D + F \qquad \textbf{(1)}$$

Where,

P_T	=	Percent of total asphalt cement content by weight of mix.
a	=	Percent of mineral aggregate retained on the 2.36 mm sieve.
b	=	Percent of mineral aggregate passing the 2.36 mm sieve and retained on the 75 µm sieve.
c	=	Percent of mineral aggregate passing the 75 µm sieve.
D	=	0.15c for 11-15 percent passing the 75 µm sieve or
	=	0.18c for 6-10 percent passing the 75 µm sieve or

= 0.20c for 5 percent of less passing the 75 µm sieve.
F = O to 2.0 percent, based on absorption of light or heavy aggregate. The formula is based on an average specific gravity of 2.60 to 2.70. In the absence of other data value of 0.7 to 1.0 should cover most conditions.

Percentages in the formula are expressed as whole numbers.

The amount of new asphalt is then determined by equation 2.

$$P_N = P_T - \left[P_R x \frac{\%RAP}{100} \right] \tag{2}$$

Where,

P_N = Percent of new asphalt cement in the recycled mixture.
P_T = Percent of total asphalt cement in the recycled mixture.
P_R = Percent of asphalt cement in the RAP.

Percentages in the above formula are expressed in whole numbers.

The type of asphalt cement is determined by calculating the asphalt blending ratio (ABR) and equation 3. The ABR is the ratio of new asphalt cement or recycling agent to total asphalt cement of the recycled mixture.

$$\log P_{rvis} = \log P_{avis} + 100 \frac{\left[3.30 - \log P_{avis} \right]}{ABR} \tag{3}$$

Where,

P_{rvis} = absolute viscosity (poises) of new asphalt cement/recycling agent
P_{avis} = absolute viscosity (poises) of the asphalt cement in the RAP

The blending target absolute viscosity of a recycled binder is 200 Pa (2000 poises). The log of 2000 is 3.30. The lowest viscosity recycling agent used during production by the Kansas DOT is a RA 100. Should the theoretical calculations require a lower viscosity than a RA 100, then the program lowers the RAP content and the entire process is repeated until the new aggregate gradation criteria and new asphalt cement or recycling agent criteria are met.

The previously described process estimates the proportion of all ingredients in the recycled HMA. The percent RAP, type and amount of new asphalt cement or recycling agent, the amount of virgin aggregate, and the gradation band for the virgin aggregate are provided in the plans and specifications for bidding purposes. The Kansas DOT will perform a laboratory mix design after contract award when the plant and material stockpiles have been established. The laboratory mix design will establish final blend proportions for production during the project.

Wyoming DOT

The Wyoming DOT specifies all components of the recycled HMA and provides a list of available sources of the new aggregates. A laboratory mixture design is performed by the central laboratory and specified in contract documents. The starting point for the determination of aggregate blend percentages is the calculated RAP content that would use all of the project millings. This RAP content normally does not exceed 50 percent.

The average RAP aggregate gradation determined during the pavement evaluation is adjusted with the core correlation factors shown in table 11. For a given mixture, the specification master aggregate gradation band is used with the adjusted average RAP aggregate gradation to back calculate or determine a proposed virgin aggregate gradation band. The adjusted average RAP gradation is multiplied by the RAP content and subtracted from the maximum and minimum percent passing each sieve. The resultant maximum and minimum gradation is divided by the virgin aggregate percentage to obtain the maximum and minimum band for a proposed virgin aggregate gradation range. This range is analyzed to determine if it is reasonable for crushing operations. The RAP content is adjusted (lowered) until a reasonable range is obtained.

Once the virgin aggregate range is established, the mid-point on each sieve is determined to use to batch samples for mixture design. Samples of the virgin aggregate source are taken and crushed in the laboratory. Cores that were not extracted and tested in the pavement evaluation process are heated, broken down by hand, and combined. Samples of the broken down RAP are taken to batch the RAP by its specified percentage for mixture design samples. The Marshall mix design is performed on the recycled mixture. The optimum asphalt content is selected at 4 percent air voids. After the mix design analysis, the Marshall plug at each asphalt cement content is extracted to verify gradation and asphalt cement content. An abson recovery is performed on the extracted asphalt cement to verify properties of the blended asphalt cement. The Wyoming DOT performs mixture design verification during production on major projects.

PRODUCTION MIXTURE DESIGN

The production mixture design process consists of several steps to determine material components and their proportions. In general, this process includes the following steps.

- Obtaining samples of individual components from established stockpiles.
- Performing laboratory analysis.
  - Determining gradation and properties of each new aggregate.
  - Determining composition of the RAP and properties of the asphalt cement.
  - Determining initial aggregate, RAP, and asphalt cement proportions.

- Determining the type of new asphalt cement and/or recycling agent.
- Mixing, compacting, and testing trial mixtures.

- Selecting the optimum combination of materials that meets design criteria.
- Verifying properties of the recycled asphalt cement in the recycled mixture.

RAP Sampling and Testing

All mixture designs should be based on materials that have been established at the HMA facility. To establish a production job mix formula, the stockpiled RAP should be sampled and tested for aggregate gradation and asphalt cement content. This is especially true since it has been shown that removal, processing, and stockpiling will create differences in the RAP aggregate gradation. Reference 43 suggests obtaining 10 representative samples from different locations in the stockpile. The recommended procedure includes removing at least 150 mm of the material from the surface of the stockpile before obtaining the sample. This is done to minimize the effect of segregation. Samples are scalped off and material retained on the 50 mm sieve is discarded. Sample size is recommended to be at least 4.6 kg after scalping. One-half of each sample will be used for composition testing. The other half will be used later in the mixture design procedure. For compositional testing, reference 41 suggests that extractions for aggregate gradation and asphalt cement content be performed on each individual sample. Reference 41 recommends performing an abson recovery on five of the samples to determine properties of the asphalt cement. This sampling plan is similar to those proposed in references 43 and 87.

Almost all States reviewed required producers to establish the composition of the RAP in the stockpile. Most SHAs required producers to determine aggregate gradation and asphalt cement content in the RAP. When a SHA required properties of the asphalt cement, the SHA laboratory normally performed extraction and recovery of asphalt cement from samples supplied by field representatives or producers.

Producers' facilities were also reviewed during this project. None of the producers followed the suggested stockpile sampling process. Plant technicians were found to sample the stockpile as it was being constructed. This involved taking samples from trucks of milled material prior to unloading, or sampling from conveyor belts during crushing and processing. Sampling frequencies noted during this review varied from a sample from every fifth truck to one truck sample per day. Crushing operation sampling frequencies were found to vary from one sample per hour to one sample per day. The major reason for sampling the stockpile as it was constructed was the expedition of the sampling and testing process. One general observation was that many stockpiles constructed after crushing operations were conical in shape. Segregation of particles was noticeable in these stockpiles.

The RAP composition determined from conveyor belt samples may be different than RAP composition determined from stockpile samples. This may account for some of the control problems.

Most producers performed extractions to determine asphalt cement content and aggregate gradation. Records were reviewed to determine how producers determine the composition to use in the mixture design process. Most producers used average test values from more than one sample from the stockpile. However, some producers were found to use test results from only one sample. These technicians stated that RAP composition did not change much from day to day based on their experience. Information was not available to back up their claim. A few producers, operating under QA specifications, were found to have computer spreadsheet data on all the RAP stockpiles in their yard. Data included producers' average test values for aggregate gradation and asphalt cement content from stockpile samples, standard deviations of test results, and their in-place cost of the RAP.

Determination of RAP Content

Determination of the RAP content in recycled HMA was found to vary within the different States. These variations were based on whether the agency or producer designed the recycled mixture, the location of the project, and limitations in Standard Specifications and Special Provisions.

When SHAs performed mixture designs, the project was generally located in a remote area. Hauling excess RAP generated from these projects to other locations is not economically feasible. The SHAs mixture design procedures optimized the RAP content to minimize excess. In general, these projects routinely had the highest RAP content in recycled HMA.

The RAP contents in producer-designed mixtures varied across the board. A lot of the producers in QA specifications used specification maximum RAP contents in their mixture design. This generalization held true for those specifications that limit the RAP content to 35 percent or less. Table 3 in chapter 3 summarizes maximum RAP limitations in producer-designed recycled HMA. The number of recycled HMA job mix formulas containing the specification limit of RAP decreased when specifications limitations were greater than 35 percent.

Some producers estimated their RAP content in recycled mixtures based on RAP stockpiled in their yard and anticipated HMA production for the season. These producers wanted to minimize the number of recycled HMA mixture designs to limit overhead costs for testing to develop mixture designs. Generally, separate mixture designs are required for mixtures with different RAP contents. Maintaining the same RAP content in all recycled HMA surface, binder, and base mixture production throughout the year only requires three separate mixture designs. In a number of fixed facilities, the job mix design for a new production year consisted of submitting prior mix designs with QC data to obtain SHA approval. Therefore, there was very little testing overhead for mixture design submittals.

A few SHAs have modified their specifications to reduce the amount of mixture design testing for recycled HMA. These specifications permit the addition of RAP, up to certain percentages, in an approved conventional job mix formula. This addition would be without actually using the RAP in the laboratory mixture design process. The existing approved job mix formula for HMA would be modified so that the RAP gradation, asphalt cement content, and RAP content are also shown on the aggregate proportion sheets. The other aggregate proportions are adjusted so that the composite aggregate gradation remains unchanged. The new asphalt cement content would also be adjusted to accommodate the asphalt cement in the RAP. The type of asphalt cement would not change from the original job mix formula. The mix design would still be valid for production as long as the composite aggregate blend did not change and QC/QA tests stay within production tolerances.

Table 13 summarizes the SHAs with specifications or special provisions that permit producers to substitute RAP in an approved job mix formula.

Table 13. Inclusion of RAP in HMA without mix design testing.

STATE	MAXIMUM RAP LIMIT	MIX DESIGN VERIFICATION DURING PRODUCTION
Kansas	10%	Yes
Massachusetts	10% Surface 20% Binder/Base (Batch Plant) 40% Binder/Base (Drum Plant)	No
New Jersey	20%	Marshall Stability only
Washington	20%	No

Four of the 17 SHAs permit the inclusion of RAP without a formal mix design. The maximum RAP content that a producer can add without performing a mix design varies from 10 to 40 percent. However, adding 20 percent or less is most common. It is interesting to note that only one SHA verifies mixture properties during production. In the other States, as much as 20 percent RAP can be added without knowledge of its effect on mixture properties.

Selection of New Asphalt Cement and/or Recycling Agent

A method to select the type of recycling agent or new asphalt cement is to laboratory blend selected asphalt cements or recycling agents with the recovered asphalt cement from the RAP. The amount of recycling agent is varied to plot a curve of percentage of recycling agent to recycled blend absolute viscosity. Test method ASTM D 4887 can be used to blend the recovered asphalt cement with different types of recycling agents. Figure 10 shows a typical graph that can be plotted after performing ASTM D 4887 on a recycling agent-recovered asphalt cement blend. Various percentages of No. 2, No. 8, and No. 10 oils were blended with asphalt cement recovered from RAP to establish the curves in figure 10. The absolute viscosities of each combination were plotted on the graph to establish each curve.[47]

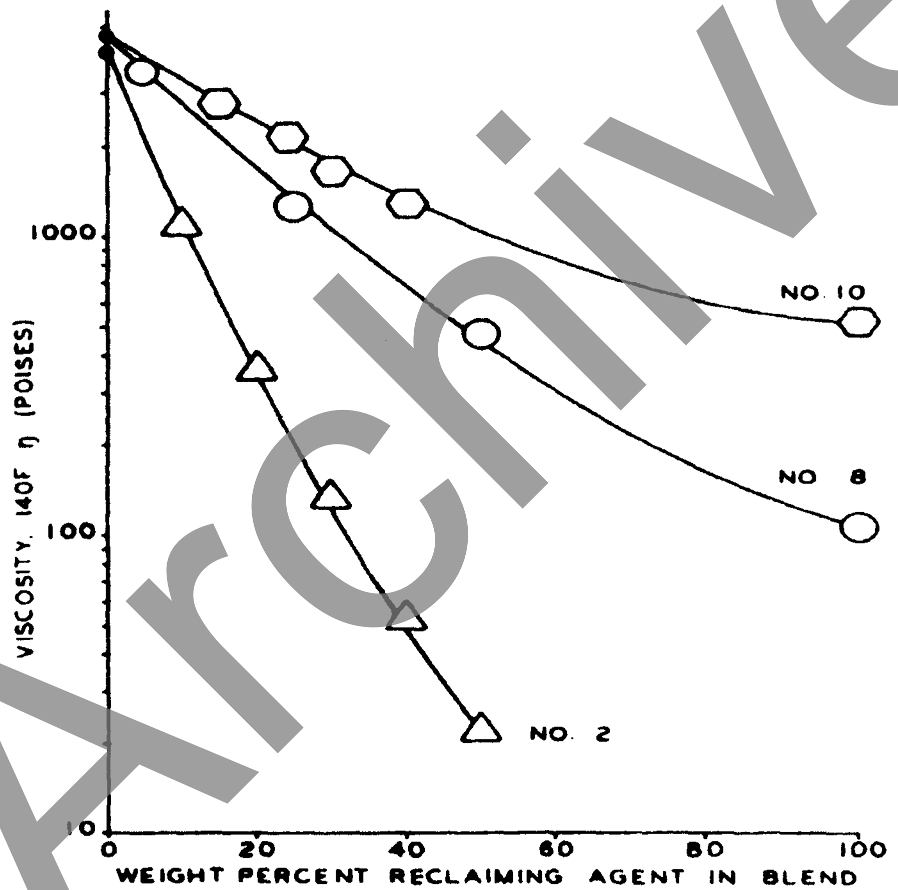

Figure 10. Effects of recycling agents on viscosity of asphalt.[8]

As shown in figure 10, a separate curve is developed for each combination of recycling agent and recovered asphalt cement. The amount of laboratory work involved with recovering asphalt cement from the RAP, blending different percentages of different recycling agents, and performing absolute viscosity testing for each sample is enormous. A simpler method of estimating the type and amount of recycling agent was needed.

To simplify the recycling agent selection process, a viscosity blending chart was developed to estimate the absolute viscosity of a recycled binder. Numerous studies conducted over time have shown that a wide range of aged asphalt cement and new asphalt or recycling agents can be blended and proportioned to meet AASHTO specifications for viscosity graded asphalt cements.[47][48][53][54][55][41] These studies included laboratory testing of artificially aged asphalt cement from various sources with a variety of recycling agents and soft asphalt cements.

These studies also included blending recycling agents and soft asphalt cements with aged binder extracted and recovered from old pavements. It was concluded that a viscosity blending chart is a reasonable approach for determining the type of new asphalt cement or recycling agent to use in the recycled HMA mixture design process.

The Asphalt Institute's MS-2[88] and MS-20[46] are commonly used for recycled HMA design. The new grade of asphalt cement or recycling agent is selected to blend with the aged asphalt cement to provide a final recycled binder that is comparable in properties to the standard paving grade asphalt cement used in conventional HMA specifications. In this estimation process, the absolute viscosities of the aged and standard paving grade asphalt cements and the mixture ratio of new asphalt cement to total asphalt cement are used to determine the absolute viscosity of the new asphalt cement or recycling agent. Equations 2 and 3 are the basis for a numerical solution for estimating the new asphalt cement to use in the mixture design procedure. Figure 11 is a graphical solution for estimating the new asphalt cement to use in the recycled HMA mixture design.

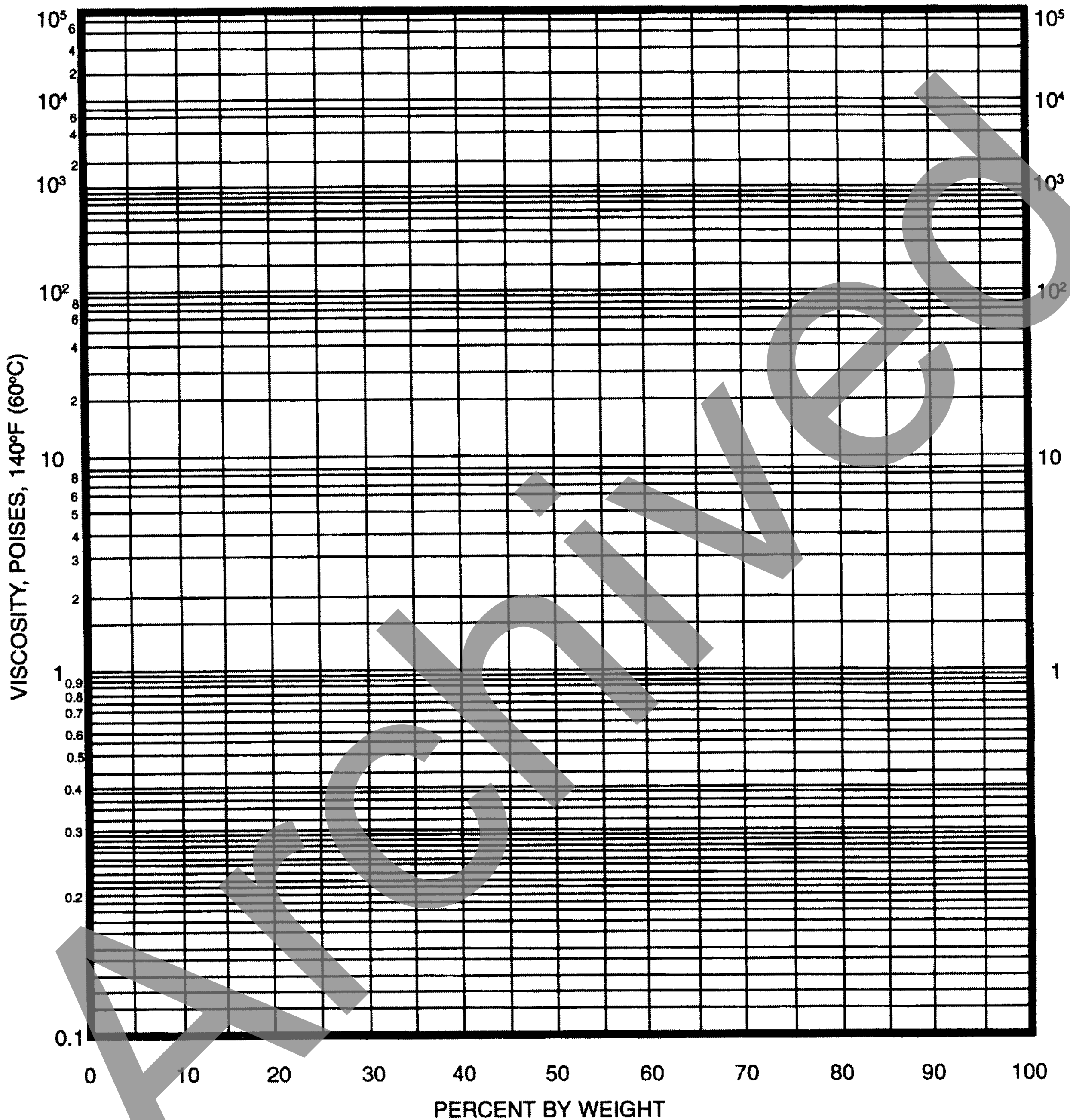

Figure 11. Viscosity blending chart.

It is interesting to note the following suggestion in the most recent revisions of the Asphalt Institute's MS-2 and MS-20:[87][88]

> It is suggested that when selecting a grade of asphalt cement for recycling that the following guide be used:
>
> Up to 20 percent RAP = No change in asphalt grade
> 21 percent RAP or More = Do not change more than 1 grade (i.e., from AC-20 to AC-10)

The background of this suggestion is not known, however, the selection advice for mixtures containing less than 20 percent RAP is close to recommendations provided by Kandhal, Rao, and Young.[63] Based on a limited performance evaluation of recycled HMA in Georgia, Kandhal, Rao, and Young recommended the consideration of permitting 10 to 15 percent RAP in all mixes without changing to a softer grade asphalt cement. Guidelines provided for recycled mixtures containing greater than 20 percent RAP should be used with extreme caution or at least verified by testing recovered asphalt cement from samples of produced material.

New asphalt cement selection procedures were reviewed in each of the 17 States. Table 14 lists those SHAs that do not change the grade of asphalt cement in recycled HMA. Table 14 also shows the RAP content to which that guidance applies.

More than one-half (9 out of 17) of the SHAs do not consider the selection of the type of new asphalt cement in the recycled HMA when the RAP content is limited to low amounts. It is believed that the properties of the final blend are not significantly affected by the properties of the aged asphalt cement in RAP at low contents. Interviews with SHA Materials Engineers indicated that these limits were established based on engineering judgement for particular conditions in their State. There is not general agreement on the amount of RAP that can be added without significantly affecting properties of the final blend. What is extremely interesting is that none of these SHAs require verification testing of recovered asphalt cement after recycled HMA production (appendix B).

Some SHAs use a rule of thumb process in the selection procedure of the new asphalt cement in the recycled HMA. Rule-of-thumb procedures may have been established by past research and would include something similar to using one grade softer asphalt cement in recycled HMA than would have been used in conventional HMA. Table 15 summarizes those SHAs that use rule-of-thumb procedures. The Minnesota and Virginia DOTs' specifications formally require the grade of asphalt cement to use in recycled HMA. The grade is usually one softer than that used in surface mixtures. The Minnesota DOT limits RAP content to 30 percent in surface and binder mixtures and 50 percent in base mixtures. The Virginia DOT limits RAP to 25 percent in all mixtures.

Table 14. States using the same grade asphalt cement in recycled HMA.

State	RAP Content
Colorado	30 percent
Kansas	10 percent
Mississippi	30 percent
Nevada	15 percent
New Jersey	25 percent
Oregon	20 percent
Pennsylvania	15 percent
Texas	20 percent
Washington	20 percent

Table 15. Rule of thumb selection procedures.

State	RAP CONTENT	TYPE OF NEW ASPHALT CEMENT
Massachusetts	15 % or less 20 % 30 % or more	AC-20 AC-10 AC-5
Minnesota	All	Pen. Grade 120/150
New Jersey	25 % or less more than 25 %	AC-20 AC-10
Virginia	All	AC-20

Some SHAs still sample, recover, and test extracted asphalt cement from the RAP to determine the type of new asphalt cement or recycling agent. Table 16 summarizes those agencies that perform detailed designs, the party responsible for selecting the new asphalt cement or recycling agent, selection procedure, and the softest asphalt cement or recycling agent that is used in recycled HMA.

Table 16. New recycling agent or asphalt cement selection.

STATE	Softest Asphalt Typically Used	Selecting Party	Selection Method
Arizona	AC-10	State	Modified Fig. 11
Florida	RA-1	State	Figure 11
Kansas	RA-100	State	Equation 3
Nevada	AC-5	State	Figure 11
New Mexico	Pen. grade	State	Equation 4
Pennsylvania	AC-5	State	Figure 11
Texas	RA-1	Producer	Figure 11
Washington	RA-5	State	Figure 11
Wisconsin	2 grades softer than AC used for HMA	State	Equation 4
Wyoming	AC-10	State	Figure 11

$$\log P_{rvis} = \log P_{avis} + 100 \frac{[3.30 - \log P_{avis}]}{ABR} \quad \textbf{(3)}$$

$$\log penAC_{tot} = ABR x [\log penAC_{new} - \log penAC_{RAP}] + \log penAC_{RAP} \quad \textbf{(4)}$$

Only producers in Texas are permitted to select the type of new asphalt cement and recycling agent. Producers proposing to use more than 20 percent RAP in recycled HMA for the Texas DOT must indicate the type of new asphalt cement or recycling agent on the proposed job mix formula. The Texas DOT requires that mixture design data include testing of laboratory blending of the recovered asphalt cement from RAP and the proposed new asphalt cement or recycling agent. The following test data is included on mixture design data sheets:

- Absolute viscosity.
- Absolute viscosity of the residue from the Thin Film Oven Test.
- Penetration at 25°C of the residue from the Thin Film Oven Test.
- Residue Viscosity Index.
- Aging Index.

The residue viscosity index is calculated by determining an equivalent viscosity at 25 °C from penetration testing in accordance with Tex-535-C. This equivalent viscosity is divided by the absolute viscosity of the residue from the Thin Film Oven Test. The laboratory blend must have a Residue Viscosity Index of less than or equal to 1500. The Aging Index must be less than or equal to 3.0. The Aging Index is calculated by dividing the absolute viscosity of the residue from Thin Film Oven Test by the absolute viscosity of the laboratory blend prior to aging.

Most of the agencies reviewed only permit the use of standard paving grade asphalt cements in recycled HMA. When these agencies select the new asphalt cement by the viscosity blending chart or equations, they are imposing another limitation on the maximum RAP permitted in a recycled HMA. Only four SHAs permit what would be classified as recycling agents (AASHTO R 14-88) in recycled HMA. These agencies are the Florida, Kansas, Texas, and Washington State DOTs. These States require that recycling agents meet properties of AASHTO R 14-88. In addition, the Florida DOT specifies that the recycling agent has a smoke point of at least 127 °C.

Most of the States reviewed indicated that recycling agents generally were not used because of reported temperature susceptibility problems or other poor performance in the past. Another reason for not using recycling agents was to limit the amount of testing performed in the mixture design process.

Mix Design Procedures

Once the initial ingredients and their proportions have been selected, the laboratory mix design process begins. The philosophy of current mix design procedures was found to be appropriate for recycled HMA.[46] Slight modifications were involved to include RAP in the process.

These modifications include:[88]

- Heating the RAP to and maintaining it at mixing temperatures. New aggregate normally is heated to mixing temperature plus 10 °C (50 °F).

- Dry mixing new aggregates and RAP (after weighing them out) to thoroughly blend the materials before adding new asphalt cement.

- Varying the total asphalt cement content by changing the amount of new asphalt cement or recycling agent and holding the weights of RAP and new aggregate constant.

- Verifying asphalt cement properties of the laboratory recycled blend after selection of optimum asphalt cement content. The ratio of new asphalt cement to total asphalt may be different at the optimum asphalt cement content than assumed during the estimation of initial ingredients. The set of plugs, at the optimum asphalt cement content, should be broken down for an extraction and recovery. The extraction verifies the aggregate gradation and asphalt cement content. A recovery is performed to verify properties of the recycled asphalt cement. Should the recovered asphalt cement not meet the properties desired, the new asphalt cement may have to be changed or the RAP content in the mix adjusted.

Except for these modifications, normal mix design procedures are followed. The optimum asphalt cement content and the job mix formula are established based on standard Marshall, Hveem, or other mixture design criteria.

Florida DOT

The producer is responsible for the recycled mixture design in Florida. The Florida DOT has developed a unique method of using roadway cores in a laboratory mixture design process that will account for the aggregate degradation during milling operations. The following procedures are used in handling the RAP and preparing combined aggregates:[86]

- Take ten 150 mm cores from the entire length of the project as indicated by the DOT.

- Trim cores to proposed depth of milling.

- Place cores in an oven at 110 °C until the cores can be broken down by hand without breaking the aggregate.

- Spread the broken down RAP into thin layers to air cool to room temperature.

- Separate the RAP using a nest of the following sieves: 19 mm, 12.5 mm, 9.5 mm, 4.75 mm, 2.00 mm, and a pan. The nesting of sieves is placed in a Gilson shaker for sieving. Determine the RAP gradation (not extracted gradation).

- Combine the RAP fractions with new aggregate components fractions to form individual batches for preparation of Marshall specimens at the trial combined aggregate gradation. The RAP gradation on the above sieves is adjusted to account for the asphalt cement content of the RAP. For example, if a Marshall specimen contained 1100 grams of aggregate and the RAP content of the mix was 50 percent, the RAP aggregate would have to account for 550 grams in the batch. If the asphalt cement content in the RAP was 5.0 percent, then 579 grams of the sieved RAP would be added to the specimen batch. The Florida DOT has found that sieving hand-broken RAP with a Gilson shaker will represent degradation occurring during milling. They have found that roughly 25 percent of the minus 2.0 mm, material will remain bonded to the coarse aggregate during sieving.

Combined aggregate is heated to specified temperature for mixing and compaction with the Marshall mix design. Extractions are performed on the set of Marshall specimens near the optimum asphalt cement content to verify aggregate gradation and asphalt cement content against the job mix formula. Recoveries of the extracted asphalt cement are performed to verify the absolute viscosity of the asphalt cement in the laboratory-recycled HMA.

The producer may use the procedure for establishing a job mix formula for production. The Florida DOT uses the procedure for verifying producers' job mix formulas when the RAP content includes project millings. When producer-supplied RAP is involved, the Florida DOT requires the producer to submit stockpile sampling for job mix formula verification.

SUMMARY

Some SHAs have implemented short cuts in the recycled HMA mixture design process. Some of these short cuts include:

- Four SHAs permit the inclusion of RAP in HMA production without using the RAP in the laboratory mixture design process. Only one of these SHAs performs any sort of verification of mixture design properties during production.

- Nine SHAs permit the use of the same grade of asphalt cement used in conventional HMA as the new binder in recycled HMA. Usually the RAP content is limited to a certain percentage in the recycled HMA. That percentage varies from 10 percent to as high as 30 percent. None of these SHAs verify asphalt cement properties in the recycled HMA through extraction and recovery.

- Four SHAs specify the type of asphalt cement to use with recycled HMA regardless of the RAP content. This applies to some mixtures containing up to 50 percent RAP. None of these SHAs routinely verify asphalt cement properties in the recycled HMA through extraction and recovery.

APPENDIX B. QUALITY ASSURANCE PRACTICES

Almost all of the SHAs reviewed expected recycled HMA to meet the specification requirements of conventional HMA. Each SHA acceptance or QA program consisted of the same sampling and testing used for conventional HMA. Some SHAs included additional tests on the recycled HMA to verify additional design steps in the recycled HMA mixture design process. Tests are generally performed on the aggregate, asphalt cement, and combined mixture. This Appendix will summarize recycled HMA acceptance or QA programs utilized by the States reviewed in this project. It should be noted that most SHAs do not utilize the metric system currently. The frequencies reported in this Appendix were hard conversions.

AGGREGATES

Table 17 summarizes sampling and testing plans used by SHAs to determine acceptability of composite aggregate blend in the recycled HMA. There were two basic composite aggregate sampling methods used, cold feed conveyor belt samples to test new aggregate and production samples to perform extractions to test composite aggregate gradation.

Control Sampling and Testing

Control sampling and testing is defined as sampling and testing performed by the producer to control its process and the quality of plant-produced material. Six SHAs require producers to perform control sampling and testing on recycled HMA. Two SHAs permit the use of cold samples to determine virgin aggregate gradation. One of these agencies also requires sampling of the RAP for extraction to determine RAP aggregate gradation. The other four SHAs require the producer to sample produced material and perform extraction testing to determine composite aggregate gradation. Two agencies permit the use of biodegradable solvents. The Pennsylvania DOT specification allows the producer to request a waiver of extraction testing when the plant is automated with recording devices and the RAP content is 15 percent or less. Hot bin samples are taken for control testing. Extraction testing is performed on recycled HMA containing more than 15 percent RAP.

Acceptance Sampling and Testing

Most SHAs require production samples and extraction testing to accept composite aggregate gradation of the recycled HMA. Sampling and testing frequencies were found to vary from one to three per day. Frequencies based on production rates varied from 1 per 400 t to 1 per 4500 t. Four SHAs permit the use of contractor's test results to accept the recycled HMA. Only one of those States performs routine verification testing of the contractor's test procedures and results.

Table 17. Recycled HMA aggregate assurance sampling and testing frequency.

STATE	CONTROL TESTING		ACCEPTANCE TESTING		VERIFICATION
	Cold Feed Samples	Mixture Extraction	Cold Feed Samples	Mixture Extraction	Mixture Extraction
Arizona	1/900 t[1]			3/shift	
Colorado			1/450 t		
Florida	1/900 t[1,3]	1/day[3]		1/900 t[3]	
Kansas			1/450 t		1/4500 t
Massachusetts				1/day[2]	
Minnesota	2/day			1/day	
Mississippi		1/½day[3]		1/day[3]	
Nevada			1/900 t		2 weekly
New Jersey				5/2700 t	
New Mexico				1/900 t[2]	
Oregon		1/900 t		1/4500 t	
Pennsylvania		1/day		≈ 1/90 t	
Texas					
Virginia				1/400 t[2]	1/9000 t
Washington				1/900 t	
Wisconsin				1/450 t[2]	
Wyoming			≈ 1/900 t		

Four SHAs sampled use cold feed samples and perform testing on the new aggregate for acceptance of the recycled HMA aggregate gradation. Three of these agencies (the Kansas, Nevada, and Wyoming DOTs) perform the analysis of the RAP and the recycled HMA mixture design. These agencies specify proportions of all ingredient materials along with the new aggregate gradation in contract documents. Therefore, aggregate gradation acceptance tests are only performed on the new aggregate component. The Kansas DOT and the Nevada DOT perform extractions of the recycled HMA to verify cold feed sample

[1] Includes a sample of the RAP and extraction testing

[2] Contractor's testing

[3] Biodegradable solvent extraction

test results and control adjustments to ingredient materials and plant production. The Kansas DOT samples the recycled HMA once every 4500 t to perform an extraction for verification. The Nevada DOT does not produces little of recycled HMA with RAP contents in excess of 15 percent. However their sampling frequency for verification testing would be twice weekly on major projects. The Wyoming DOT does not routinely perform extractions of recycled HMA to verify cold feed extractions. On major projects, a mobile laboratory is used to perform verification of mix design properties during production. Test results from mix design verification are used to control the plant and ingredient proportions.

The producer performs the mix design in Colorado. Samples of the new aggregate are taken from the cold feed conveyor belt. The Colorado DOT does not perform extraction testing to verify cold feed gradations of recycled HMA. It should be noted that RAP content in recycled HMA is limited to 30 percent by specifications in Colorado. Some districts have further established maximum RAP content to 15 percent. The Colorado DOT performs mix design verification testing on a routine basis to cover the absence of extractions for aggregate gradation.

ASPHALT CEMENT CONTENT

Table 18 summarizes sampling and testing plans for the determination of the asphalt cement content in recycled HMA. Only a few SHAs (3 out of 17) require the producer to perform an extraction to determine the asphalt cement content for producer control testing. Sampling frequencies for extraction control testing vary from one sample per day to one sample per 900 t.

Most SHAs still use extraction testing to accept the asphalt cement content in recycled HMA. Frequencies for sampling the recycled HMA for extraction acceptance testing varied from one sample per day to one sample per 4500 t.

A growing concern regarding the determination of asphalt cement content is the use of chlorinated solvents for extraction testing. A number of SHAs are using alternative strategies to determine the asphalt cement content or acceptability of the recycled HMA. The purpose of these methods is to either reduce the frequency of extraction testing or eliminate extraction testing.

Some SHAs are moving to the use of nuclear gauges for the determination of asphalt cement in recycled HMA. During this review, 4 out of the 17 SHAs accepted the asphalt cement content in the recycled HMA based on nuclear gauge test results. Nuclear gauges must be calibrated specifically for each job mix formula. The use of the nuclear gauge will still require sampling and extraction testing of the RAP to determine the asphalt cement content in the RAP. The Wyoming DOT uses RAP compositional information from their intensive sampling and testing of each specific project during project development.

Table 18. Recycled HMA asphalt cement sampling and testing frequency.

STATE	ASPHALT CEMENT CONTENT			MIXTURE DESIGN PROPERTIES
	Contractor Control	State Acceptance	Extraction Verification	Verification
Arizona		3/shift		
Colorado		1/450 t[4]		1/9000 t
Florida	1/day	1/905 t		1/3620 t
Kansas			1/4500 t	1/day
Massachusetts		1/day[5]		
Minnesota	2/day	1/day		1/1000 t[5] 1/day (MNDOT)
Mississippi	3/day[4]	1/day[4]		3/day
Nevada		1/900 t[4]	2 weekly	
New Jersey		5/2700 t		
New Mexico		1/900 t[5]		
Oregon	1/900 t	1/4500		
Pennsylvania	1/day	≈ 1/100 t		
Texas				
Virginia		1/450 t[5]	1/9000 t	1/900 t
Washington		1/900 t		
Wisconsin		1/450 t[5]		1/450 t
Wyoming		≈ 1/900 t[4]		

The Mississippi DOT is correlated with compositional data determined from RAP samples from the established stockpile. Stockpile samples are split. One-half of the split is submitted to the Materials Office for extraction testing to determine asphalt cement content. The other half of the split is used to batch materials into the producers gauge and the District Materials Office gauge. The average asphalt cement content determined by extraction is used to determine the amount of asphalt cement added, through the RAP, to the nuclear gauge sample container.

[4] Determined by nuclear gauge

[5] Contractor's testing

Two methods were found to be used in the verification of the asphalt cement content determined by nuclear gauge. These methods included verification with extraction testing and verification through mixture design property testing. The Nevada DOT verifies the asphalt cement content, determined by nuclear gauge, in recycled HMA containing greater than 15 percent RAP with extraction testing. The sampling and testing rate for extraction testing is approximately two samples per week. These test results are used to determine whether or not the nuclear gauge needs to be recalibrated. The Colorado DOT and the Mississippi DOT use the gauge in conjunction with a mixture design property acceptance plan during production. An investigation of asphalt cement content would be performed only when laboratory voids properties did not meet specifications or got out of control. The Wyoming DOT also performs mixture design verification during production on major projects.

Another method of reducing or eliminating extraction testing is the acceptance of asphalt cement content based on printed tickets. The Pennsylvania DOT specification allows the producer to request a waiver of extraction testing when the plant is automated with recording devices and the RAP content is 15 percent or less. Hot bin samples are taken for aggregate control testing. Extraction testing is performed on recycled HMA containing more than 15 percent RAP. Asphalt cement content production tolerances for control and acceptance testing are reduced to ± 0.2 percent from the job mix formula target when printed tickets are utilized.

The New Jersey DOT accepts recycled HMA based on asphalt cement content, aggregate gradation, and stability. Acceptance is based on individual lots consisting of five sublots. One sample is taken within each sublot. The location of entry of the RAP in the plant determines testing protocol. When the RAP is entered directly in the weigh hopper, printed tickets may be utilized for four of the sublots. An extraction is performed on the fifth sublot sample. The lot average production tolerance is reduced from ± 0.45 percent to ± 0.15 percent when printed tickets are utilized. The lot tolerance of individual tests is also reduced from ± 1.5 percent to ± 0.4 percent. Should the RAP be entered in the bottom of the hot elevator, extraction testing is performed on each sublot test.

A third method is the Blast Furnace Oven. This procedure is currently undergoing a round robin test evaluation.

Job Mix Formula Tolerances

Most of the SHAs required the recycled HMA to be produced to the same production tolerances of the required job mix formula. However, one SHA did increase its production tolerances for the incorporation of higher percentages of RAP. When recycled HMA is produced for the Washington State DOT binder and base courses, the production tolerance is adjusted for the RAP content in the mix. Production tolerances for this State are shown in table 19.

Table 19. Production tolerances for recycled HMA.

Sieve	RAP Content 0 to 20 percent	RAP Content 21 percent to 49 percent	RAP Content 50 percent or greater
9.5 mm	within master gradation band		
6.26 mm	± 6 percent	± 6 percent	± 6 percent
2.00 mm	± 5 percent	± 5 percent	± 5 percent
0.425 mm	± 4 percent	± 4 percent	± 4 percent
75 μm	± 2.0 percent	± 2.0 percent	± 2.5 percent
percent AC	± 0.5 percent	± 0.7 percent	± 1.0 percent

When the RAP content exceeds 20 percent but is less than 50 percent, the tolerance for asphalt cement content moves to ± 0.7 percent. When the RAP content exceeds 50 percent, the asphalt cement content tolerances increase to ± 1.0 percent and the amount of material passing the 75 μm sieve increases from ± 2.0 percent to ± 2.5 percent. Generally, this practice is not recommended; the FHWA recommends that recycled HMA be designed and produced in accordance with quality HMA operations.

ASPHALT CEMENT PROPERTIES

Sampling the recycled HMA and recovering the extracted asphalt cement is highly recommended to be included in a recycled HMA QA program. The number of SHAs that were found to verify properties of the recovered asphalt cement during production was very low. Only 4 out of the 17 SHAs had specification requirements on the final recycled asphalt cement. Specification requirements on properties of the asphalt cement from production samples are shown in table 20.

Table 20. Specifications for recovered asphalt cement properties.

State	Penetration (25°C)	Viscosity (60°C)	Ductility (25°C)
Florida		400 pa s minimum 800 pa s maximum	
Massachusetts	50 minimum	800 pa s maximum	
Texas	30 minimum 55 maximum		
Virginia	35 minimum		40 cm minimum

Only the Florida DOT was found to routinely performe sampling and testing to determine properties of the recycled asphalt cement. The Florida DOT's Materials Office recovers extracted asphalt cement from random samples taken from the recycled HMA every 1800 t. Tests for absolute viscosity are performed on the recovered asphalt cement. Should test results fall outside the range shown in table 20, the Florida DOT's Materials Office will recommend changes in the new binder type or amount.

The Massachusetts DPW requires producers to perform an Abson recovery of extracted asphalt cement for recycling once per season. Tests results must show compliance with requirements listed in table 20. This is used to verify the producers' selection of the type of asphalt cement used in the production of the recycled HMA. The Massachusetts DPW would like to institute a program that requires testing recovered asphalt cement on a 2700 t frequency. However, there is a lot of resistance from the hot mix industry. The main concern is costs associated with additional testing. The Virginia DOT samples HMA every 90,500 t to extract and recover asphalt cement for testing in compliance with requirements listed in table 20.

SUMMARY

Almost all SHAs require recycled HMA mixtures to be produced to the same quality or mixture properties required of conventional HMA. This includes production tolerances on aggregate gradation and asphalt cement content.

Most of the SHAs that either specify the type of new asphalt cement without regard to RAP content or use rule of thumb guidance, similar to MS-2, do not verify properties of recovered asphalt cement during recycled HMA production. Only the Florida DOT was found to routinely perform QC or verification testing of the asphalt cement in the recycled HMA. The performance of recycled HMA in Florida has been good. The Bituminous Materials and Research Engineer attributes much of the success to the verification testing of all mixture design properties, including testing recovered asphalt cement.

The Washington State DOT recycled HMA mixture properties and performance data presented in Appendix D is another indication that recycled HMA that is designed and controlled to conventional HMA mixture properties and production tolerances will perform comparably to conventional HMA.

Past research has indicated that different recycling agents have different hardening rates.[54][62] Other research found that temperature susceptibility of an asphalt blend is a function of modifier selected.[53] Compatibility between new asphalt cement or recycling agent and the aged binder in the RAP should be checked during design and verified during production. It is recommended that production sampling and testing programs be set up to verify all the mix design assumptions, including the properties of the asphalt cement blend.

APPENDIX C. SHA PERFORMANCE EXPERIENCES

Many SHAs were found to have conducted performance evaluations of recycled HMA. However, many of these evaluations have not been documented through research reports and have been reported internally within the SHAs. This chapter will summarize performance information obtained through visits with SHAs engineers.

ARIZONA DOT

The Arizona DOT was one of the initial leaders in the development and use of recycled HMA. However, the extent of use of recycled HMA has declined in recent years due to poor performance of recycled mixtures. An informal evaluation of these poor performing recycled HMA pavements by the Arizona DOT showed that these projects had several items in common:

- The total HMA layer was less than 75 mm (3 in);
- The recycled HMA had RAP contents of 40 to 50 percent;
- All the pavements had heavy truck loadings;
- Projects were constructed in the early- and mid-1980s; and
- All mixtures had very high Marshall stabilities.

The poor performance of the recycled mixes during the early 1980s was attributed to maximizing RAP contents instead of basing its proportion on a thorough mixture design evaluation. The Arizona DOT believes that practice resulted in high stability mixes that were very stiff layers. When these stiff mixes were placed in thin layers, tensile cracks developed in the overlay requiring early rehabilitation. A site visit was conducted on Interstate 10 (I-10) during the visit with the Arizona DOT. Sections of I-10 between mileposts 30 and 60 were examples of the poor-performing recycled HMA. Different sections within this stretch of I-10 had been rehabilitated between 1985 and 1987. The primary distress, prior to rehabilitation, consisted of fatigue cracking and rutting. Table 21 summarizes rehabilitation project data and recent condition survey data from the Arizona DOT's PMS.

Within this stretch of I-10, rehabilitation projects consisted of milling either the travel lane or full width for a specified depth and replacing the milled material with recycled HMA and an asphalt concrete friction course. In some projects, an additional overlay was added. The primary distress of concern noted during this review was fatigue cracking in the travel lane. Cracking in the inside wheel path was more severe than in the outside wheel path. In the maintenance column, the amount of funds expended per mile per year are recorded. Pavement condition is rated poor when maintenance expenditures exceed $420 per km/year. Recycled HMA projects between mileposts 42 and 60 are considered poor with maintenance requirements ranging from between $1250 to $2500 per km/year. These projects can be compared to the 1984 rehabilitation project between mileposts 0 and 10. The maintenance funding expended on this segment is $375 per km/year even though the

Table 21. Pavement management system data—Interstate 10.

Milepost	Date Last Action	Milling Depth (mm)		Depth of New HMA (mm)		Depth of RHMA (mm)		Depth of ACFC (mm)		CRACK %	Ride Mays M. IRI	Skid	Rut (mm)	Maint. $/km/year
		TL	PL	TL	PL	TL	PL	TL	PL					
0-10.0	1984	90	90	75	75			19	19	10	65	55	6	375
10-31.2	1979	75	75	53	53			19	19	6	80	55	5	1875
24.0-30.0	1989									6	65	55	5	1875
30.0-36.5	1988	100	100			140	140			5	65	42	5	40
36.5-37.3	1988	3	3			110	110			5	65	42	5	40
37.3-42.0	1988	4	4			140	140			5	65	42	5	40
42.0-45.35	1987	3	2.5			110	100	12.5	12.5	5	65	60	6	1250
45.35-46.45	1987	4	2.5			140	100	12.5	12.5	5	65	60	6	1250
46.45-47.15	1987	3				110	40	12.5	12.5	5	65	60	6	1250
47.15-48.0	1987		5.5 E				125 E		12.5 E	15	110	60	8	2500
48.0-49.31	1987		3 W				63 W		12.5 W	15	110	60	8	2500
49.31-50.9	1987		3.5 W				75 W		12.5 W	15	110	60	8	2500
50.9-52.5	1985	5.5	0.5			160	40	12.5	12.5	15	110	60	8	2500
52.5-59.0	1985	5.5	5.5			125	125	12.5	12.5	15	110	60	8	2500

Condition Ratings		CRACK %	Ride Mays M. IRI	Skid	Rut (mm)	Maint. $/km/year
	Good	< 10	< 93	≥ 43	≤ 6	0-210
	Fair	10-30	94-142	35-42	7-12	211-420
	Poor	> 30	≥ 143	≤35	≥ 13	> 420

project has been in service 3 years longer. The only difference is the overlay in this segment consisted of conventional HMA. These recycled mixes were high stability mixes that were very stiff.

The performance of the recycled HMA placed in 1988, mileposts 30.0 to 42.0, is shown in good condition. This is about the time period the Arizona DOT began requiring recycled HMA to meet conventional HMA mixture design criteria.

Jimenez and Meier performed an analysis of recycled HMA produced between 1978 and 1985 to evaluate recycled HMA mix design procedures for the Arizona DOT.[78] Seven projects were evaluated in this study, and RAP contents ranged from 50 percent in four projects, 70 percent in two projects to 100 percent in two projects. A Cyclogen recycling agent was used in the 70 percent and 100 percent RAP-content recycled mixtures. An asphalt cement was used in the recycled mixtures containing 50 percent RAP. The analysis of recycled HMA with 100 percent RAP and 70 percent RAP in their study showed that the in-place mat air voids were significantly lower than the laboratory mix design air voids of 4.1 percent. The in-place air voids were, typically, less than 2 percent. Recycled mixtures with 50 percent RAP had in-place air voids in the 3-to 7-percent range.[78]

Jimenez and Meier's report recommended that the Arizona DOT consider using a ratio other than the 50 percent proportioning of RAP and virgin aggregate. They recommended that the ratio of the materials should be dependent on the quantity and variability of the RAP. The report also recommended that the Arizona DOT continue using AC-10 and AC-20 asphalt cements as recycling agents instead of rejuvenating agents.[78]

The Arizona DOT's experience shows that recycled HMA that is not designed through established procedures will not perform satisfactorily. The past recycling design was to add RAP without any consideration of mixture properties. Currently, the Arizona DOT is very selective on potential recycling projects. Recycled HMA will not be placed in the surface course. It will also not be used when the HMA course thickness is less than 75 mm.

The Arizona DOT currently performs a detailed mixture design when recycled HMA is specified on a project. This detailed design includes the selection of the new binder based on properties of the recovered asphalt cement from the RAP, the new asphalt cement, and specification requirements for standard asphalt cement.

FLORIDA DOT

Recycled HMA has been used in Florida since 1978. The performance of recycled HMA has been reported to be as good as conventional HMA. A rehabilitation technique, milling, and replacing with recycled HMA outperforms the technique of placing a leveling course and conventional overlay. Reflective cracking is eliminated by milling the full-depth of the cracked layer.

The Florida DOT has not constructed projects with test and control sections. However, preliminary evaluations, mixture designs, laboratory evaluations of cores from the constructed pavement, and deflection testing of recycled HMA all indicate comparable performance or better. The Florida DOT has a good specification and sampling and testing program to control and accept recycled HMA. These plans include monitoring all phases of mixture design including verification of the blending between the new asphalt cement and aged binder in the RAP. The Florida DOT routinely samples production to recover asphalt cement and test its properties. The Florida DOT has accepted the use of recycled HMA and did not need to verify its applicability through performance evaluations.

MASSACHUSETTS DPW

The Massachusetts DPW's first recycled HMA project was a section of I-290 beginning at the Lake Quinsigamond Bridge in Shrewsbury and extending easterly about 8.6 km.[79] This project was controlled through a lot of research investigation including monitoring properties of recovered asphalt cement after production.

The original pavement consisted of a 40 mm HMA top surface course, 75 mm HMA binder course, 140 mm HMA base, 300 mm gravel sub-base, and 600 mm frost-free material. Original construction was completed in 1970. The roadway was opened to traffic during 1970.[79] At the time of rehabilitation, 1982, the pavement showed considerable random and transverse cracking along with longitudinal joint separation. Coring showed that the depth of cracks extended down to the HMA binder course. Extraction analysis, recovery, and testing of the aged asphalt cement indicated that penetration of the asphalt cement ranged from 13 to 21.[79]

The rehabilitation design consisted of removing 50 mm of the existing pavement for the easterly two-thirds of the project and replacing it with 120 mm recycled HMA binder surfaced with 20 mm OGFC. The western portion of the project included removing 75 mm of the old pavement and replacing it with 95 mm recycled HMA binder surfaced with 20 mm OGFC.[79] The recycled HMA was produced in a batch plant using 35 percent RAP. A blend of 60 percent AC-5 and 40 percent AC-20 was added at the rate of 3.5 percent by weight of the mix. However, during production, results of tests of the recovered asphalt cement indicated that ductility and penetration results were not within specified limits. Asphalt cement addition was changed during production to 80 percent AC-5 and 20 percent AC-20 to obtain better properties of the recovered asphalt cement from the recycled mixture.[79] The recycled HMA was completed in late 1982 and the OGFC was completed during mid-1983.[79]

A site visit of this project was conducted during May 1993. There was no evidence of transverse cracking or rutting throughout the pavement section. The rehabilitated pavement structure has been in service for 11 years, and the OGFC has been in service for 10 years. The original pavement structure was rehabilitated after 12 years of service due to transverse cracking and lane joint separation. Although the 1982 rehabilitation project added additional pavement structure, the environmental distress in the original structure had not reappeared or new distress was not evident. The pavement has not been sampled and tested to determine why it has had better environmental performance; however, it can be surmised that controlling the properties of the recovered asphalt cement during production played an important role. It is obvious that the rehabilitation will outperform the original construction in length of service. Therefore, the Massachusetts DPW concluded that RAP can be recycled into a quality HMA. Currently, the Massachusetts DPW permits RAP in all HMA mixtures at the producer's option. The properties of recovered asphalt cement from recycled HMA are monitored at least once during each production season.

MINNESOTA DOT

The Minnesota DOT's first recycled HMA project was constructed in Maplewood in 1976.[80] This is where the "Maplewood" or "Minnesota" heat transfer process of hot mix recycling in a batch plant was first developed. This project was a 4-lane urban section that included reconstruction of the original pavement. The existing pavement was removed and a full depth recycled HMA was placed. The reconstructed pavement structure consisted of a 175-mm recycled HMA base, a 40-mm recycled HMA binder, and a 19-mm surface wearing course. The RAP content of the recycled HMA was 50 percent. A control section of full-depth conventional HMA was also placed at this project. The recycled HMA base on the eastbound roadway was placed in three lifts, the recycled HMA base was placed in one lift on the westbound roadway. Benkelman beam deflections were taken in summer 1977. These measurements showed similar deflections between the conventional HMA section and the recycled HMA section.[81] The pavement structure with the recycled HMA base course placed in one lift had a higher average deflection than the roadway with the base placed in three lifts.[81] Performance evaluations between the control and recycled sections were conducted prior to a mill and overlay project in 1991. The evaluation consisted of visual examination and cores of both the recycled and conventional HMA sections. The service life (15 years) of the recycled HMA was comparable to the conventional HMA control section.

The Minnesota DOT initiated a research project to evaluate the performance of recycled HMA. Initially, the objective was to characterize its performance in relation to conventional HMA. The research project was initiated because the performance of recycled HMA has varied quite a bit throughout the State, and some of the districts had placed further restrictions on the use of RAP. Some district offices reported good pavement performance with recycled HMA. Other district offices reported poor performance based on rapid deterioration of transverse cracks. Coring revealed that the base course was stripping at the transverse cracks.

Past projects were reviewed for comparison between recycled HMA and conventional HMA control sections. Each project had to meet the following criteria:

1. The recycled HMA and conventional HMA had to be designed through mixture design.

2. Lifts of base and binder had to be the same material.

Early recycled HMA projects generally performed better than conventional HMA projects placed during the same time period. The main reason for this trend was the recycled HMA was developed through mix design procedures. During that timeframe, conventional HMA bases were not designed. Typically, a standard 4.5 percent asphalt cement content was specified regardless of aggregate source and gradations. Therefore, mixtures that were based on engineering criteria performed better than those that were not based on any engineering criteria.

The Minnesota DOT did not construct very many projects that met the above criteria. Only a few projects were constructed with control sections. One such project site was constructed in 1988 and reviewed in August 1992. The project was TH 19, from milepost 111.26 to milepost 112.2, between Winthrop and Gaylord. Visual observation of the pavement surface indicated the frequency of transverse temperature cracking was slightly greater in the recycled HMA base section than in the conventional HMA section. The severity of cracks in both sections was low, as cracks were tight and there was not any spalling at the cracks. The cracks had been sealed by Minnesota DOT maintenance crews. Evaluation of the pavement has not been performed to determine reasons for difference in performance.

The Minnesota DOT does not perform asphalt cement analysis as part of their recycled HMA design. A 120/150 penetration graded asphalt cement is used in recycled HMA regardless of RAP source and RAP content. Extraction and recovery of asphalt cement from recycled HMA production is not performed either. Therefore compatibility between binders is assumed and not verified. This may contribute to the wide variety of recycled HMA performance within the State.

NEVADA DOT

Performance of recycled HMA pavements in Nevada has not been good, although its performance is considered equal to conventional HMA. The first project constructed in 1974 (I-15 with 100 percent RAP) required heavy maintenance and was finally removed in 1986. The Nevada DOT has had problems with HMA performance in the higher altitude environments. The Nevada DOT is using more polymer modified binders and the West Coast User-Producer performance-based binder specification. Recycled HMA is not used where performance graded asphalt cements require modifiers.

NEW JERSEY DOT

The first recycling project performed in New Jersey was the rehabilitation of Route 130 in 1979. The recycled mixture contained 50 percent RAP and was produced in a batch plant. The RAP was a surface course milled from Route 1. The recycled mixture was placed as a 40 mm surface course on the outside shoulders on Route 130. A 366 m test section of 40 mm recycled HMA surface course was placed full width of the pavement structure.[82] After a 3-year performance period, no transverse cracking was found in the shoulders. In the 366 m recycled HMA pavement surface test section, only four joints had shown reflective cracking. In the control section of virgin HMA overlay, 27 joints had reflected cracks in the overlay.[82]

This project shows that recycled HMA performs equivalently to conventional HMA to mitigate reflection cracking of underlying pavement structures.

PENNSYLVANIA DOT

A Pennsylvania DOT research project performed an evaluation of recycled HMA in six rehabilitation projects.[83] Each rehabilitation project consisted of milling a depth of existing bituminous overlay of portland cement concrete (PCC) pavement and placing an HMA overlay. PCC pavement on each project was originally constructed between 1920 and 1937. The original PCC pavements were substandard width, and rehabilitation projects included an HMA base widening of the PCC pavement. Recycled mix was placed as a part of the overlay in the rehabilitation process. All recycled mixes were designed and evaluated by the Pennsylvania DOT Materials and Testing Division. Pertinent project information is provided in table 22. The information in the table is taken from reference 83 and condition data supplied by the Pennsylvania DOT PMS.

A June 1993 field review of these projects indicated that primary distresses on all projects are transverse and longitudinal reflection cracking. Most of the reflection cracks were shown in the PMS data as medium-to-high severity on a low-to-medium extent of a segment, with low extent less than 10 percent and medium extent 10 to 30 percent of the pavement. The reflection cracking probably would not trigger a rehabilitation action.

Test sections of conventional HMA overlays were not constructed and reported on in this study. It is not likely that the conventional HMA overlay would have delayed reflection cracking. The main conclusion that can be obtained from this report is that distress was not due to the HMA properties. In cases of overlays of jointed plain concrete or jointed reinforced concrete pavements, where ultimately reflection cracking will occur, savings in a rehabilitation project can be accomplished by using recycled HMA in the overlay.

Table 22.[83] Summary of recycled HMA in six Pennsylvania DOT rehabilitation projects.

ROUTE	REHAB COMPLETE	BASE WIDENING Thickness mm	OVERLAY THICKNESS mm Recycled Base	Recycled Binder	Virgin Surface	RAP CONTENT in RHMA	80kN ESAL	RIDE	Cracks Severity/ Extent
281	9/84	200	0	50	40	50%	417	Fair to Good	Med-High/ Low-med
Appl 5462 & 721	9/83	170	WL	60	40	15%	97	Fair to Poor	Med-High/ Low-Med
178	9/83	0	200	50	40	20%	?	Poor	Med-High/ Low-Med
137	7/83	190	WL	50	40	15%	82	Fair to Poor	Low/ High
146	12/83	0	90	40	40	15%	245	Fair to Good	Med/ Med-High
130	7/84	0	180	50	40	10%	152	Fair to Poor	Med-High/ Low-Med

WISCONSIN DOT

The Wisconsin DOT's first recycling project was constructed in 1978. During the mid-1980s the Wisconsin DOT was one of the leading users of recycled HMA. However, recently recycled HMA production has tailed off as shown in figure 12.

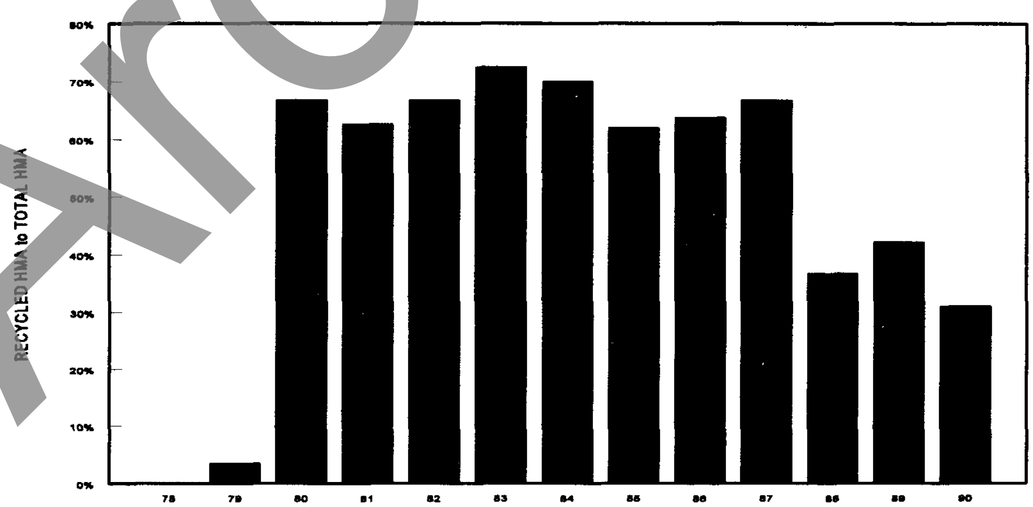

Figure 12. Wisconsin DOT hot mix asphalt production.

There are a couple of reasons for the decline. Some districts have been having problems with transverse temperature cracking. This distress has been showing up 2 to 4 years after placement of the recycled HMA. Seal coats are generally required to be placed by maintenance forces. Specifications have been revised to improve HMA performance. During the early 1980s, the mixture design practice for recycled HMA was to specify the amount of RAP to maximize its utilization. Routinely, RAP was incorporated between 35 and 50 percent by weight of the mixture. A mixture design was performed to specify mix and materials properties. For control and acceptances purposes, only the new aggregate and asphalt cement was sampled and tested. The Wisconsin DOT had cored 56 projects constructed between 1980 and 1985 to determine reasons for the variety of performance. The cores have been tested; however, an analysis of test data was not performed.

The Wisconsin DOT revised their recycled HMA specifications in 1990. This specification required recycled HMA to meet conventional HMA mixture properties. Sampling and performing extraction testing of produced mixture was also required. The Wisconsin DOT constructed a few experimental projects during the revised specification implementation to compare recycled HMA production under the new specification to conventional HMA production. One such experimental project was visited in 1993 during a trip to Wisconsin. The project was located on State Trunk Highway 12 and 16 in Juneau County. Five test sections were constructed as part of the project. Table 23 summarizes these test sections.

Table 23. State Trunk Highway 12 and 16.

Section	Surface Course	Binder Course
12-1	45 mm conventional	45 mm conventional
12-1A	45 mm conventional	45 mm conventional
12-2	45 mm conventional	45 mm recycled
12-2A	45 mm conventional	45 mm recycled
12-3	45 mm recycled	45 mm recycled

All of the test sections were constructed over a jointed plain concrete pavement. During the site visit, none of the test sections exhibited pavement distress. Test section 12-3 had a greater degree of truckload segregation (chevrons) than the rest of the sections. It was also noted that not all of the sections were receiving an equal amount of traffic loadings. Tractor trailers were hauling aggregate to a project or development through some of the test sections. The trucks were turning off State Trunk Highway 12 and 16 halfway through the experimental project. The trucks would return to the Trunk Highway for the unloaded return trip.

The Wisconsin DOT has since revised its specifications to Quality Management for HMA production. The performance of recycled HMA has varied in the past. Some projects have performed well and others have performed poorly. The Wisconsin DOT attributes poor performance to the maximization of the RAP content and the lack of necessary quality control of mixtures during production. The Wisconsin DOT expects both recycled HMA and conventional HMA to perform better under recent specification revisions. The RAP content in recycled HMA will be based on mixture properties through mixture design and verification testing during production.

WYOMING DOT

A limited number of documented studies have been performed on recycled HMA. After the first two projects, the Wyoming DOT was convinced that recycling HMA was a technically viable alternative. The Wyoming DOT also found that it is feasible to recycle an existing pavement that is stripping. This was demonstrated in the first two recycling projects undertaken. The first project was 5 miles long and located on I-80 between Rawlins and Laramie. The original pavement had to be rehabilitated in 1977 after 7 years of service due to lack of adhesion between the asphalt cement and the aggregate.[84] The existing plant mix was removed and replaced with recycled HMA. Recycled HMA was designed to include 85 percent RAP, 15 percent new aggregate, and 1.0 percent lime. New asphalt cement was added at a rate of 0.5 percent.[84] The Wyoming DOT Materials Office reported that this project performed for 12 years prior to milling and second generation recycling.

The second project on I-80 was recycled in 1978.[68] This project was approximately 9 miles in length. The existing pavement was removed and replaced with recycled HMA. The recycled HMA included 70 percent RAP, 30 percent new aggregate, and 1.0 percent lime. The lime was applied in slurry to the RAP. New asphalt cement was added at a rate of 1.0 percent. This project was still in service as of June 1992.

These two projects convinced the Wyoming DOT that recycled HMA could be expected to perform equivalently to conventional HMA.

SUMMARY

Some SHAs' experiences have indicated good performance of recycled HMA. Other SHAs' experiences have indicated poor performance of recycled HMA. Some SHAs have not performed any evaluations of recycled HMA because its production is limited or the RAP content in recycled HMA is minimal.

D'Angelo and Ferragut showed that conventional HMA performance problems could well be related to laboratory prepared mixture properties not duplicating mixture properties of produced HMA.[85] Most of the highway community have accepted this concept and do some form of verification testing during production.

It was the experience of these States that recycled HMA that was designed under established mixture design procedures and produced under appropriate quality control and acceptance measures will perform comparably to conventional HMA. Two SHAs experienced poor performance due to maximizing the RAP content without consideration of mix design. Their current procedures let an optimize mix design set the RAP content. Another agency found that their recycled HMA base mixture outperformed their conventional HMA base mixture. The conventional HMA base mixture was a specified aggregate gradation with 4.5 percent asphalt cement. The recycled HMA base mixture was designed in the laboratory prior to production. That agency now requires a laboratory mixture design of its conventional HMA base mixture.

Most of the SHAs indicated that recycled HMA performance is equivalent to conventional HMA when the recycled HMA meets mixtures requirements of conventional HMA. The use of polymer modified asphalt cement with recycled HMA is an area where more research is required.

APPENDIX D. WASHINGTON STATE DOT CASE STUDY

The Washington State DOT began recycling HMA in August 1977 near Ellensburg, Washington.[58] That project was a rehabilitation project of Interstate 90 (I-90) from Renslow to Ryegrass. Since this was one of the first recycling projects, samples from that project were tested and analyzed by numerous researchers.[58][53][75] The Washington State DOT had completed 24 recycled HMA projects by January 1985.[59] The Washington State DOT performed a detailed analysis of the first 16 recycling projects in 1986 investigating asphalt cement, aggregate, and mixture properties. Peters, Geitz, and Walter reported results from that analysis as well as in-service performance of the recycled HMA.[59][60] A field visit with the Washington State DOT, as a part of this Technology Assessment Project, was conducted in June 1993. As a part of this review, the Washington State DOT's pavement management system (PMS) was used to update performance histories of those 16 projects. This appendix will summarize the first two projects in some detail. The first two projects were constructed in 1977 and 1978 using the Washington State DOT PMS. This appendix will include perhaps the longest performance evaluation of any given research project.

INTERSTATE 90 (I-90), FROM RENSLOW TO RYEGRASS, MILEPOSTS 121.92 TO 126.14

The original construction of this pavement was completed in July 1967 and was opened to traffic in November 1968. The pavement section consisted of 45 mm (0.15 ft) of asphalt concrete wearing course; 60 mm (0.20 ft) leveling course; and, 135 mm (0.45 ft) of asphalt concrete base (class E).[58] The condition of the pavement prior to recycling was as described on page 4 of reference 58:

> The condition of the pavement before recycling showed much structural cracking in the wheel paths and extensive transverse cracking across both lanes and shoulders. The structural cracking extended through the wearing and sometimes into the leveling courses, but not into the base course, leading us to believe these were not base failures but structural deficiencies in the asphalt concrete. Transverse cracking extended completely through the 0.80 feet of asphalt concrete pavement.

The 1977 rehabilitation project consisted of removing 45 mm of the existing pavement and replacing it with recycled HMA. A 18 mm open-graded friction course overlaid the recycled HMA.[58] A test section using the recycled HMA as the surface course was also constructed. A CMI Roto-Mill cold milling machine removed the existing pavement and the milled material was stockpiled at the plant. The milled material was recycled through a standard 8840 kg batch plant modified by adding an additional dryer drum and cold feed equipment.[58] The additional dryer drum was used to heat new aggregate to 127 °C to 157 °C. The superheated aggregate was then proportioned with the RAP on a separate cold feed.[58] The combined aggregate and RAP was fed through the plant dryer drum for mixing with additional heat.[58] The target mixture temperature out of the drum was 149 °C.[58] The heated mixture was fed to the top of the batch plant for its final proportioning and mixing with the recycling agent.[58]

Mix Design

The mix design used in production consisted of 71.75 percent RAP, 27.5 percent 16.0 mm to 6.3 mm aggregate, 0.75 percent Cyclepave, and no new asphalt cement.[58] The recycling agent application rate was selected to provide a recycled binder comparable to an AR-4000W asphalt cement. The recycling agent application rate provided a laboratory recycled binder with an absolute viscosity of 188 Pa.[58] Table 24 provides data on RAP composition and recycled HMA production control test results.

Table 24.[58] Interstate 90, Renslow to Ryegrass: compositional data for RAP and recycled HMA.

Gradation	Stockpiled RAP (n=18) Average	Stockpiled RAP (n=18) Range	Production Samples (n=28) Average	Production Samples (n=28) Range
25 mm	100	100	100	100
16 mm	100	100	100	100
12.5 mm	100	99 - 100	97	95 - 99
9.5 mm	96	95 - 98	84	76 - 89
6.3 mm	84	77 - 88	65	54 - 70
2.0 mm	45	40 - 52	37	33 - 40
425 µm	21	19 - 26	19	17 - 20
180 µm	15	12 - 17	14	13 - 15
75 µm	8.5	6.6 - 10.2	8.4	7.8 - 9.1
Asphalt Cement Content	6.2	5.3 - 7.2	5.6	4.8 - 6.6
Asphalt Cement Properties	* n=16 ** n=3		* n=27 ** n=3	
Pen 4 °C **	7	5 - 8	19	18 - 21
Pen 25 °C *	15	10 - 17	48	32 - 60
Viscosity (Pa), 15 °C **	1.2×10^8	$0.95 - 1.6 \times 10^8$	6.2×10^6	$5.3 - 7.2 \times 10^6$
Viscosity (Pa), 60°C *	3052.1	2156.3 - 5091.0	389.4	246.6 - 740.8
Viscosity (cst), 135 °C **	966	828 -1155	365	332 - 403

Mixture Properties

Mixture design verification tests were performed on 27 samples during production. Those test results are summarized below.[60]

	Average	Range
Air Voids	2.2%	0 - 4.2%
Hveem Stability	19	9 - 32
Cohesion	343	170 - 580

Density testing was also conducted during construction. In-place air voids are summarized below.[58]

	Eastbound		Westbound	
	Lane 1	Lane 2	Lane 1	Lane 2
Average	8.4	6.9	6.9	5.5
Range	3.0 - 10.9	2.9 - 10.0	3.0 - 11.0	0.3 - 9.3

Cores from the old pavement and the recycled pavement were tested and evaluated by Epps, Little, Holmgreen, and Terrel.[53] Their analysis indicated the following:[53]

- The slope of the resilient modulus-temperature curve is about the same for both the recycled HMA and the old pavement.
- Resilient modulus testing and indirect tension testing indicated that the mixture was not moisture susceptible.
- Recycled cores had larger Hveem stabilities than old pavement cores. However Hveem stabilities were less than 30.

The Washington State DOT continued to monitor the performance of the recycled HMA placed under the I-90 Renslow to Ryegrass project. In 1986, the Washington State DOT reported on the status of the project.[60] Included in this report were summaries of properties of the asphalt cement and the recycled mixture. The pavement had been in service approximately 8 years at the reporting date.

Tables 25 and 26 provide average properties of the recycled asphalt cement extracted and recovered from samples taken over time. It was reported that cores were taken from the pavement, broken up, and combined prior to sampling for extraction and recovery purposes. Test values reported in tables 25 and 26 are averaged from multiple samples. The number of samples tested is also shown in these tables. For comparison purposes, the current specification requirements for an AR-4000W graded asphalt cement are also included in these tables.

Table 25.[60] Interstate 90, Renslow to Ryegrass: average asphalt cement properties from recycled HMA, overlaid section.

Asphalt Cement Properties	Specification AR-4000W Test on Residue from RTFC	Recovered Asphalt from cores after construction (years)					
		0 n=24	1 n=16	2 n=18	3	5 n=6	7 n=6
Absolute Viscosity, Pa	250-500	290.0	339.4	356.4		446.7	448.7
Penetration 25°C	45 min.	58 40-75	50 39-62	51 40-60		48 45-51	37 26-43

Data in table 25 shows that binder in the recycled HMA did not age very much over time. Average properties of the recycled binder would have met specification requirements for absolute viscosity and penetration for an AR-4000W graded asphalt cement up to the fifth year. The average test result for penetration at 25 °C failed to meet the AR-4000W grade asphalt cement specification in the seventh year.

Table 26.[60] Interstate 90, Renslow to Ryegrass: average asphalt cement properties from recycled HMA, nonoverlaid section.

Asphalt Cement Properties	Specification AR-4000W Test on Residue from RTFC	Recovered Asphalt from cores after construction (years)					
		0 n=24	1 n=6	2 n=4	3 n=4	5 n=1	7 n=1
Absolute Viscosity, Pa	250-500	290.0	429	415.9	482.9	309.3	491.5
Kinematic Viscosity	275 min.	349	391	426	422		
Penetration 25°C	45 min.	58 40-75	45 43-47	44 40-47	46 40-52	53	62
Ductility, 7°C	10 min.	32.6	11				14

Data in table 26 shows that the recycled binder in the nonoverlaid test section had aging characteristics similar to the binder from the remainder of the project, which was overlaid with an OGFC. In the nonoverlaid section, average test results for the recycled binder would have met the AR-4000W grade asphalt cement specifications for all 7 years, with the exception of the average test result for penetration at 25°C in the second year after construction. Observation of data in table 3 for the aging characteristics measured by penetration at 25°C may appear contrary to common sense. The data shows the penetration increasing from the 3rd year to the 7th year indicating a softening effect over time. One would normally expect the binder to age and become stiffer resulting in lower penetration values.

Reference is made to the number of samples tested each year. Because data in the fifth and seventh years are from one sample, it can not be assumed to be an accurate predictor of the population average. The other test results are averages for multiple samples; more samples represent a better estimation of the population average. Figures 13 and 14 show the average and range of test results for absolute viscosity for the I-90 Renslow to Ryegrass project.[60]

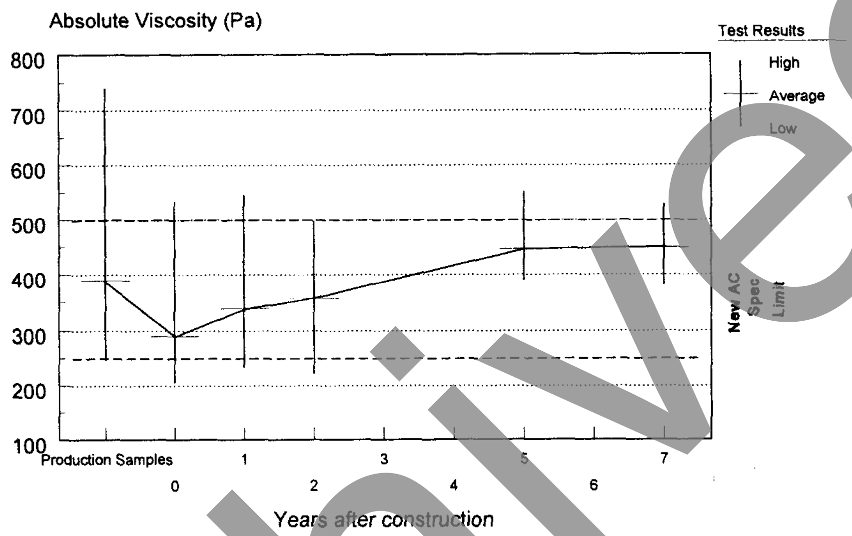

Figure 13. Interstate 90, Renslow to Ryegrass: overlaid section.

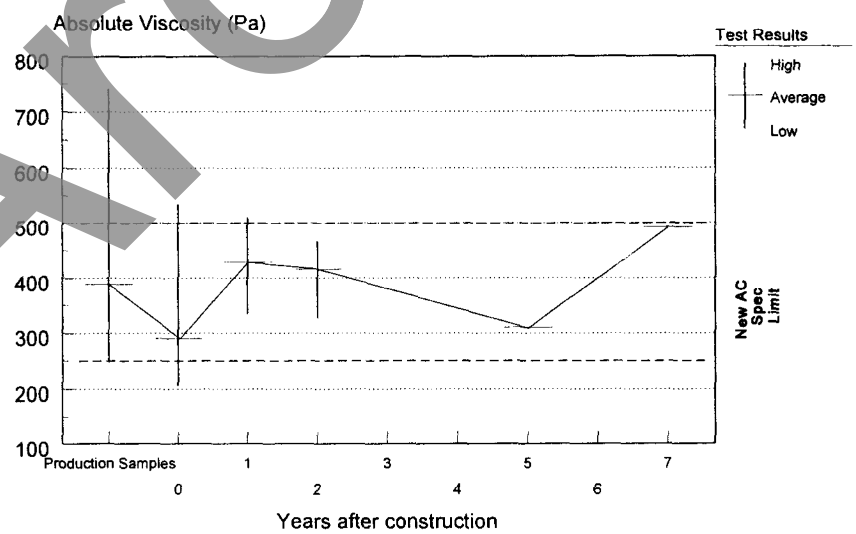

Figure 14. Interstate 90, Renslow to Ryegrass: nonoverlaid section.

Reference 60 provided test results by number of samples and range of test values. Figure 14 gives one an indication of the variability of the test results for recovered asphalt cement absolute viscosity. Figure 13 shows that average test results for absolute viscosity over time would have met specification requirements for the new asphalt cement added to conventional HMA. Figure 14 shows aging characteristics of the recycled asphalt cement in the recycled HMA acting as the final surface course. Data in this figure is not as meaningful because the absolute viscosity determined in the fifth and seventh years was from one sample test.

One item to note from these figures is the range of absolute viscosity determined from production samples. The lowest absolute viscosity reported during production was 246.6 Pa and the highest absolute viscosity reported was 740.8 Pa. The mixture design for this project included 71.75 percent RAP, 27.5 percent 16.0 mm to 6.3 mm new aggregate, and 0.75 percent Cyclepave recycling agent. It should also be pointed out that this was the Washington State DOT's first recycling project.

Peters, Gietz, and Walter concluded that recovered viscosities from recycled HMA were comparable to those from conventional HMA. They also concluded that this project had lower viscosities over pavement life than could be expected of conventional HMA.[59] While properties of the recycled asphalt cement did not show any aging characteristics, properties of the asphalt cement have only been indirectly related to pavement performance. The resilient modulus is a measure of mixture stiffness and should show aging characteristics of the recycled HMA over time. The resilient modulus should increase as the HMA mixture ages. The Washington State DOT also sampled the recycled HMA over time and tested those samples for resilient modulus. Table 27 summarizes resilient modulus testing for core samples taken from the recycled HMA in both overlaid and the nonoverlaid test sections. Peters, Gietz, and Walter concluded that resilient modulus values for recycled HMA on this project were comparable initially and over time to those of conventional HMA.[59]

Table 27.[60] Average resilient modulus, 25 °C, 0.10 second load duration.[60]

I-90 Section	Resilient Modulus Plant Mix Samples (n=18)	Average Resilient Modulus (Range), Years After Construction, MPA Core Samples			
		0 (n=24)	1 (n=16,6)	5 (n=4,1)	7 (n=7,3)
Overlaid			1720 (900-2970)	2070 (1410-3140)	3330 (1080-7590)
Not Overlaid	5796 (828-13,800)	2140 (1380-3105)	2690 (2000-3730)	1680	3720

The Washington State DOT found that properties of the recycled binder and recycled HMA mixture were similar to conventional HMA for this project. Their testing and analysis would tend to indicate that the recycled HMA should perform as well if not better than average conventional HMA.

Project Performance

A pavement condition survey is performed on all routes in Washington State. The Washington State DOT records various forms of pavement distress and enters the data into their PMS. Distress survey data is used to calculate a pavement structural condition (PSC) rating for all sections. The PSC ranges from 100, best condition, to 0, worst condition. The PSC is calculated by subtracting deduct points from 100 as shown in the following formula.[76]

$$PSC = 100 - 15.8x\sqrt{EC} \quad (5)$$

The "EC" is equivalent cracking that is based on type and severity of distress. Equivalent cracking is a composite of alligator cracking, longitudinal cracking, transverse cracking, and patching.[76] The equation was derived so that 10 percent high-severity alligator cracking in the wheel path would result in a PSC of 50, and 40 percent high-severity alligator cracking in the wheel path would result in a PSC of 0.[76]

The Washington State DOT PMS also contains a performance model curve to estimate project performance. The performance model curve is used to predict when a project will reach a PSC of 50.[76] A PSC of 50 normally triggers a rehabilitation program action. The Washington State DOT PMS performance curve is shown in equation 6.[76]

$$PSC = C - mA^{P} \qquad (6)$$

A = Years since construction or last rehabilitation
C = PSC at construction
m = slope coefficient
P = constant to control degree of curve

A regression analysis is performed on data for each project to select "m" and "P" to generate project-specific performance curves.

The Washington State DOT PMS provided historical data for the I-90 Renslow to Ryegrass project. Figure 15 shows the average PSC for all sections within the project over time. The dark heavy line in figure 15 represents the PMS performance curve for the project determined by a regression analysis of average PSC data with equation 6. This performance curve estimates that the project will reach a program rehabilitation (PSC = 50) in the middle of 1993. This project was advertised for rehabilitation in April 1993. The effective service life of the recycled HMA placed during the rehabilitation project is 16 years.

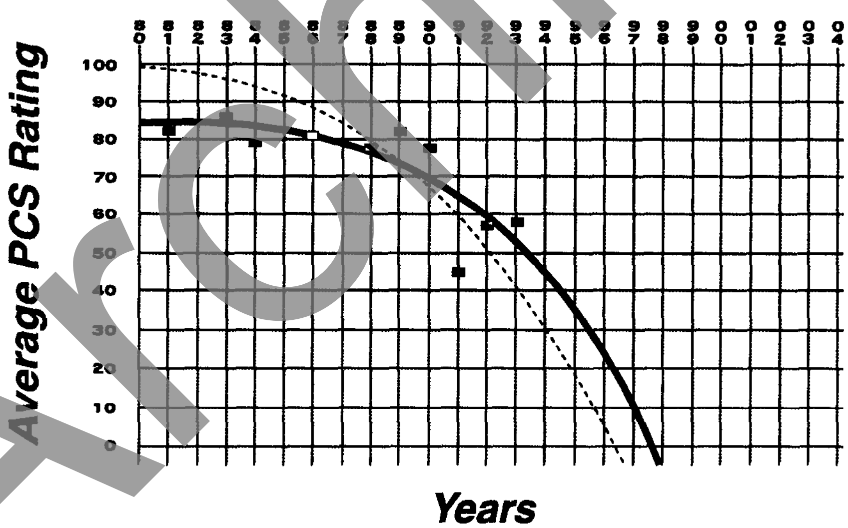

Figure 15. Interstate 90, Renslow to Ryegrass: pavement structural condition.

The thin-lined performance curve in figure 15 represents the average performance of projects with similar treatments within the same district. This provides an indirect comparison of the recycled HMA layer performance to average conventional HMA layer performance. The I-90 Renslow to Ryegrass recycling project was estimated to provide an additional year of service over conventional HMA. At the time of the last distress survey, the last (1993) condition survey information for sections within the I-90 Renslow to Ryegrass project.

Table 28. Interstate 90, Renslow to Ryegrass: 1993 pavement condition survey data.

	Mile Post Section (Distress Severity)			
Distress	122-123	123-124	124-125	125-126
Alligator Cracking (% wheel path)	5% low	5% low	5% low	5% low
Patching (% wheel path)	0%	15% med	30% med	0%
Ravelling (% lane area)	50% low	50% low	25% med	50% low
Longitudinal Cracking (% segment length)	30% low	30% low	30% low	30% low
Transverse Cracking (#)	2 med	2 med	2 med	2 low
Flushing (% lane area)	0%	0%	0%	0%
IRI (mm/m)	2.23	2.19	1.9	2.21
Rut (mm)	18	13	13	11
PSC	75	51	32	78

Figures 16 and 17 provide ride and rutting performance over time, respectively. The data in table 28 and figures 16 and 17 indicate that I-90 from Renslow to Ryegrass should be rehabilitated due to rutting in the OGFC. The structural condition of a couple of sections within the project would also warrant program rehabilitation. Figure 18 and table 28 show an average 14 mm rut depth for the project. The Washington State DOT Pavement Management Engineer explained that rut depths are normally attributed to studded tire wear in the OGFC. The last distress survey shown in table 28 indicates that patching in sections between mileposts 123-124 and 124-125 contributed to lower PSC for those two sections.

The HMA placed during the original construction provided 10 years of service to traffic. The recycling of the original HMA resulted in an improved HMA that provided 16 years of service to traffic.

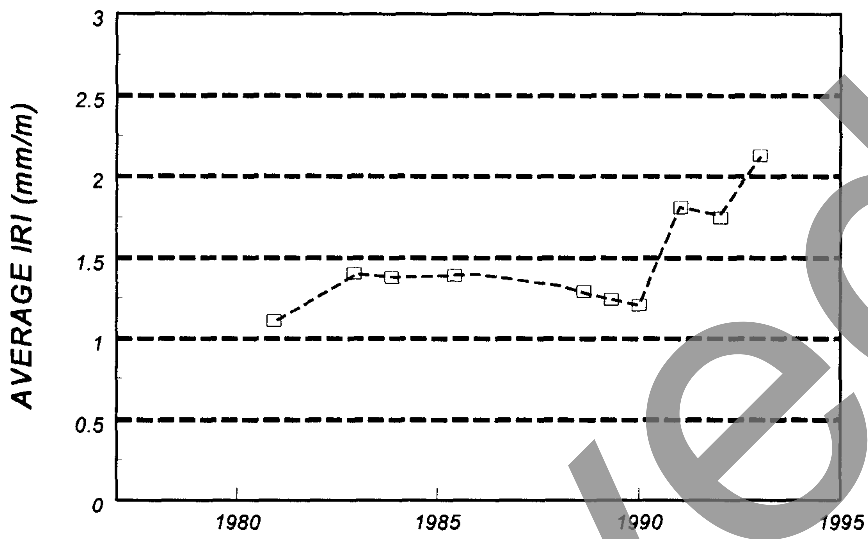

Figure 16. Interstate 90, Renslow: average ride index.

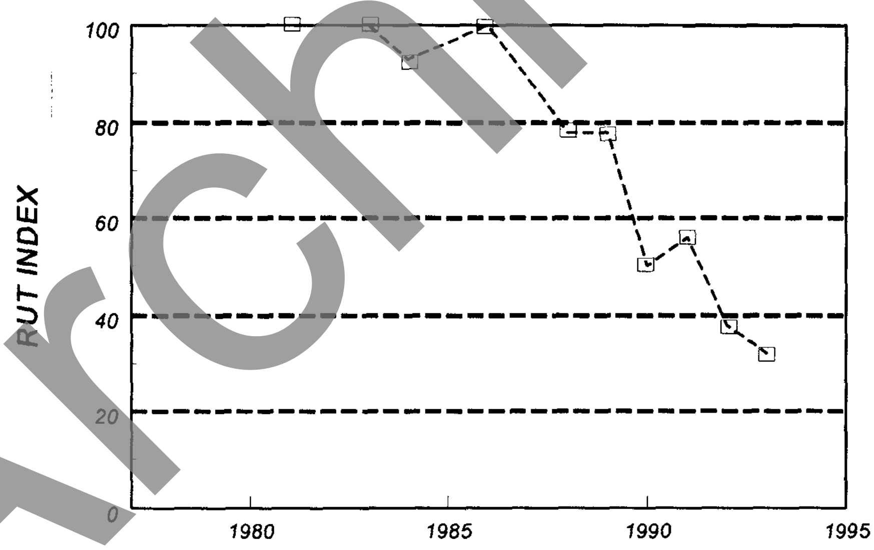

Figure 17. Interstate 90, Renslow: average rut index.

I-90, YAKIMA RIVER TO W. ELLENSBURG, MILEPOSTS 102.61 TO 106.34

The Washington State DOT's second recycled HMA project was constructed in 1978 on Interstate 90 from the Yakima River to west of Ellensburg. The original pavement was completed in 1969. The original pavement under this section of I-90 was similar in structure to the Renslow to Ryegrass project. In 1978, the PSC rating for this section of I-90 was 53, requiring rehabilitation.[59] The original HMA service life was approximately 9 years.

The rehabilitation project consisted of milling 45 mm of the existing pavement and replacing it with a recycled HMA. An 18 mm OGFC was placed on top of the completed recycled HMA. Two different mix designs were used on this project. The RAP content in the recycled HMA was approximately 79 percent.[59] Cyclogen 'L' was used as a recycling agent. Its application rate varied depending on the roadway. The recycled HMA placed on the westbound roadway contained 30 percent recycling agent to the total binder. The recycled HMA placed on the eastbound roadway contained 25 percent recycling agent to total binder. A test section on the eastbound roadway was placed using only the recycled HMA as the wearing course.[59]

Table 29 summarizes production test results for recycled HMA placed under this project. Test results indicated that the mixture met specification requirements of conventional HMA at that time. The range of test values does not indicate that the recycled HMA had unusual variability due to large RAP contents.

Table 29.[60] Interstate 90, Yakima River to West Ellensburg: compositional data for recycled HMA.

Gradation	Eastbound Roadway (n=4)		Westbound Roadway (n=4)	
	Average	Range	Average	Range
25 mm	100	100	100	100
16 mm	100	100	100	100
12.5 mm	98	98-99	99	98-100
9.5 mm	88	88-90	88	86-90
6.3 mm	64	61-66	62	61-65
2.0 mm	32	31-33	33	32-35
425 µm	16	15-16	16	16-18
180 µm	10	10-11	12	11-13
75 µm	7.4	7.0-7.8	7.6	7.5-7.8
% AC	5.0	4.8-5.1	4.8	4.8-4.9
AC Properties	n=4, *n=1		n=4, *n=1	
Pen 4°C*	26		35	
Pen 25 °C	66	60-71	80	78-81
Viscosity (Pa s), 15 °C*	2.7×10^6		1.5×10^6	
Viscosity (Pa s), 60°C	222.7	212.3-236.7	153.8	136.5-160.5
Viscosity (cst), 135 °C*	300		272	

Tables 30, 31, and 32 provide average properties of recovered asphalt cement various years after construction from this project. The AR-4000W grade asphalt cement specification requirements for the aged residue from the Rolling Thin Film Oven Test are also included in these tables. Data in those tables show that recovered asphalt cement from roadway samples would have met specification requirements for AR-4000W graded asphalt cement initially and over time. Recovered asphalt cement from the nonoverlaid test section on the eastbound roadway would also have met AR-4000W grade asphalt cement requirements over the 6-year evaluation period with the exception of average penetration at 25 °C at 6 years.

Table 30.[60] Interstate 90, from Yakima to West Ellensburg interchange: eastbound roadway, not overlaid.

Asphalt Cement Properties	Specification AR-4000W Test on Residue from RTFC	Recovered Asphalt from cores after construction (years) Average Range			
		0 n=4	1	2	6 n=3
Absolute Viscosity	250-500	302.8 281.2-341.7	277.1 254.7-295.4	400.1 296.7-583.8	469.7 362.9-536.7
Kinematic Viscosity	275 min.	339	327	393	
Penetration 25°C	45 min.	55 51-58	61 58-64	51 39-57	39 27-50
Ductility, 7°C	10 min.	60			23

Table 31.[60] Interstate 90, from Yakima to West Ellensburg interchange: eastbound roadway, overlaid with OGFC.

Asphalt Cement Properties	Specification AR-4000W Test on Residue from RTFC	Recovered Asphalt from cores after construction (years) Average Range			
		0 n=7	1	2	6 n=6
Absolute Viscosity Pa s	250-500	292.8 214.4-354.3	233.1 171.0-317.9	298.1 225.1-392.7	359.0 272.8-467.5
Kinematic Viscosity	275 min.	344	303	346	
Penetration 25°C	45 min.	58 51-66	66 52-82	59 51-70	51 44-57
Ductility, 7°C	10 min.				43

Table 32.[60] Interstate 90, from Yakima to West Ellensburg interchange: westbound roadway, overlaid with OGFC.

Asphalt Cement Properties	Specification AR-4000W Test on Residue from RTFC	Recovered Asphalt from cores after construction (years) Average Range			
		0 n=3	1	2	6
Absolute Viscosity	250-500	185.2 160.8-201.0	180.1 132.6-240.2	283.7 217.7-366.4	292.0 178.0-456.1
Kinematic Viscosity	275 min.	280	302	332	
Penetration 25°C	45 min.	77 73-83	78 62-91	63 56-70	63 43-79
Ductility, 7°C	10 min.	60			46

Cores were taken from the roadway to measure the recycled HMA mixture properties over time. Table 33 summarizes the results of resilient modulus testing of roadway samples.

Table 33.[60] Average resilient modulus, 25 °C, 10 second load duration.

Section	Average Resilient Modulus, (Range) Years After Construction, MPA Core Samples		
	0	4	6
Eastbound not overlaid	1520 (1310-1730)		2160 (1710-2430)
Eastbound, overlaid	1380 (760-1800)	2400 (1600-2900)	1230 (860-1670)
Westbound overlaid	1310 (1040-1520)		1410 (1270-1520)

Table 33 indicates that the recycled HMA did not age significantly over the 6-year evaluation period. Peters, Gietz, and Walter concluded that resilient modulus values for recycled HMA on this project were comparable initially and over time to those of conventional HMA.[59]

Project Performance

The Washington State DOT PMS was used to generate an updated performance history for the I-90 Yakima River to W. Ellensburg project. As of 1993, the project has carried 7.3 million 80 kN ESAL. Figure 18 provides the average PSC for all sections over time. The dark line represents the project performance curve developed by regression analysis of equation 6 with data collected over time. The PMS estimates the pavement should provide adequate structural service until the mid-1997. It is estimated that the PSC will reach the rehabilitation program level of 50 at that time. The PMS also estimates the average performance of HMA with similar thickness in the same district would reach a PSC of 50 in 1993. The thin line on figure 18 represents that estimation. Thus the estimated structural life of the recycled layer is 4 years longer than average HMA.

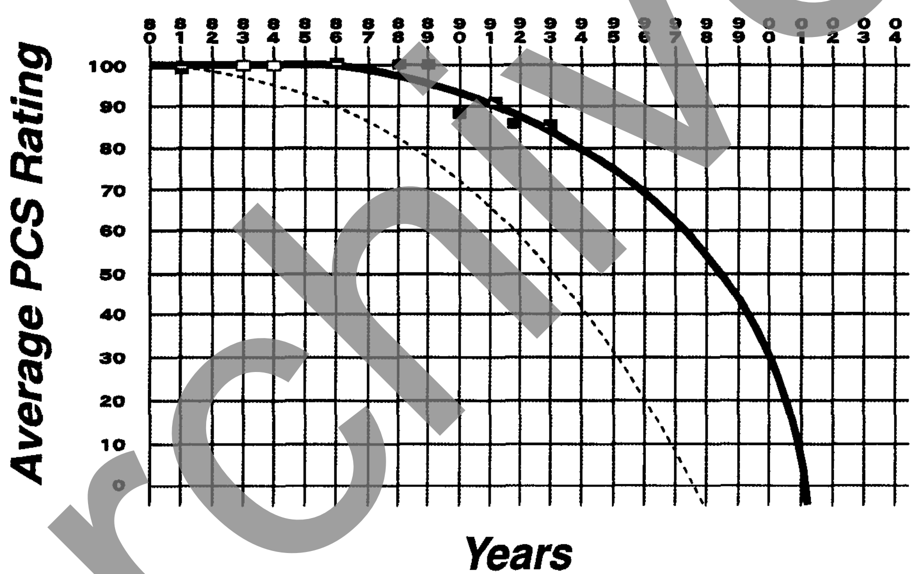

Figure 18. Interstate 90, Yakima River to West Ellensburg: pavement structural condition.

The PMS established a rehabilitation program date in mid-1993 for this project. Data from the 1993 condition survey provides a reason for rehabilitating the section. Table 34 contains pavement condition survey data collected in 1993 for all sections within the project. The table shows that over one-half of the project has approximately 12 mm of rutting. Thus, it appears that rutting in the OGFC is driving the rehabilitation of this project at the current time. Figures 19 and 20 provide average ride and rutting performance for this project.

The HMA placed during original construction provided 6 years of service to traffic. The recycling of the original HMA layer resulted in an improved HMA that provided 15 years of service to traffic.

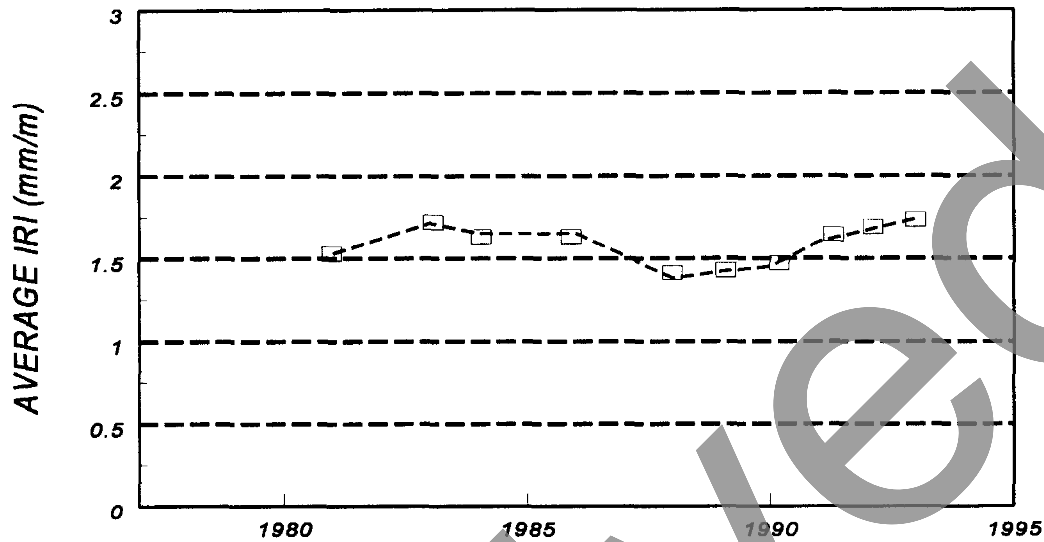

Figure 19. Interstate 90, Yakima average ride index.

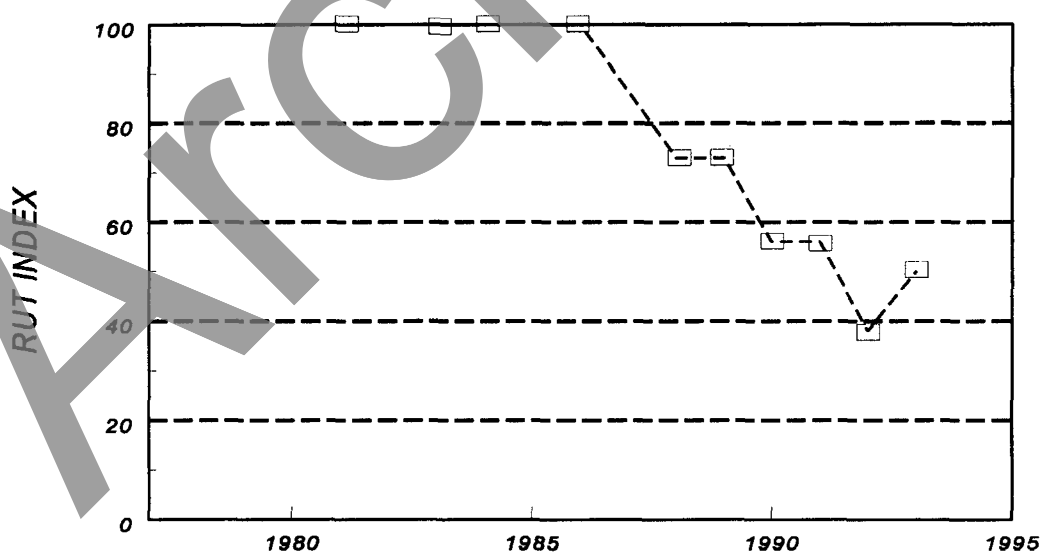

Figure 20. Interstate 90, Yakima average rut index.

Table 34. Interstate 90, Yakima River to West Ellensburg: 1993 pavement condition survey data.

	Mile Post Section (Distress Severity)					
	102.61-103.19	103.19-103.3	103.3-104.0	104.0-104.71	104.71-104.79	104.79-106.01
Alligator Cracking (% wheel path)	5% low	0%	0%	0%	15% low	0%
Patching (% wheel path)	0%	0%	0%	0%	0%	0%
Ravelling (% lane area)	0%	0%	0%	50% low	5% low	50% low
Longitudinal Cracking (% segment length)	30%	30%	30% low	30% low	0%	30% low
Transverse Cracking (#)	0%	2 low	0%	0%	0%	2 low
Flushing (% lane area)	25% low	25% low	25% low	0%	0%	0%
IRI (mm/m)	1.74	1.02	1.66	1.96	1.85	1.74
Rut (mm)	6	5	13	12	3	11
PSC	79	86	88	88	83	86

SUMMARY

Sampling and testing during production and over time for both projects show that recycling agents can be used in recycled HMA containing large RAP contents. Test data indicate that asphalt cement recovered from properly designed recycled HMA can meet virgin asphalt cement properties. Test data also demonstrate that the asphalt cement recovered from properly designed recycled HMA does not age at a much greater rate than asphalt cement recovered from conventional HMA. In fact, Peters, Gietz, and Walter concluded that asphalt cement properties from the recycled HMA in both projects were comparable initially and over time to those of conventional HMA.[59]

Sampling and testing of both projects initially and over time also indicated that mixture properties (resilient modulus) do not age significantly over time. It should be pointed out that the recycled layers were overlaid with an OGFC. Again, Peters, Gietz, and Walter concluded that resilient modulus values for recycled HMA on both projects were comparable initially and over time to those of conventional HMA.[59]

Finally, performance monitoring by the Washington State DOT PMS of these two projects shows that properly designed and controlled recycled HMA can perform as well as conventional HMA and can improve the performance of in-place materials.

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