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Participant's Reference Book

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16. Abstract

Recycling or reuse of existing asphalt pavement materials to produce new pavement materials has the following advantages: (a) reduced costs of construction, (b) conservation of aggregate and binder, (c) preservation of the existing pavement geometrics, (d) preservation of the environment, and (e) conservation of energy. This document was prepared to provide the following information on recycling of asphalt pavements: (a) performance data, (b) legislation/specification limits, (c) selection of pavement for recycling and recycling strategies, (d) economics of recycling, and (e) structural design of recycled pavements. The following recycling methods have been included: hot-mix asphalt recycling (both batch and drum plants), asphalt surface recycling, hot-in-place recycling, cold-mix asphalt recycling, and full depth reclamation. Materials and mix design, construction methods and equipment, case histories and quality control/quality assurance have been discussed for all recycling methods.

This participant's reference book was developed to support a 2-day workshop on pavement recycling guidelines for state and local governments.

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FOREWORD

Recycling of existing asphalt pavements for pavement rehabilitation or reconstruction has the following advantages: (a) reduced costs of construction, (b) conservation of asphalt and aggregate, (c) preservation of the existing pavement geometrics, (d) preservation of the environment, and (e) conservation of energy. Recycling is no longer considered an experimental process by many highway agencies. These agencies permit recycling alternate on a routine basis in their standard highway construction specifications and/or special provisions. There is a need to train government highway officials and engineers in pavement recycling so that its use becomes wide spread and benefits are realized at all levels.

This participant's reference book has been developed to support a 2-day workshop on all aspects of recycling of asphalt pavements.

The objectives of this 2-day training course are to provide participants with:

1. An understanding of the various methods and technology (hot and cold) of recycling asphalt pavements.
2. The ability to determine when asphalt recycling is a viable pavement rehabilitation alternative.
3. The knowledge of how to select the most appropriate asphalt recycling method.
4. Information on equipment, construction methods, and QC/QA involved in recycling.

The 2-day training will provide an in-depth technical knowledge of the following recycling methods: hot mix asphalt recycling (both batch and drum plants), hot in-place recycling, cold-mix asphalt recycling (both in-place and central plant), and full depth reclamation of asphalt pavements. The training will also include the following topics: performance data of recycled mixes, selection of pavements for recycling and recycling strategies, and economics of recycling. Although mix design and structural design of recycled pavement are not included in the 2-day workshop, information on these topics are included in the participant's handbook and a set of visual aids is available for mix design and pavement design engineers.

The training can be divided into independent, self contained session modules capable of being added or deleted depending on the participants' needs and time constraints. For example, session modules can be put together to address the following audience: (1) administrators, (2) pavement design engineers, (3) mix design engineers/technicians, and (4) construction engineers/inspectors.

Each chapter in this participant's reference book represents a corresponding workshop session in the 2-day workshop. Some repetitions in a few chapters are inevitable because some participants may not be interested to read all chapters if they are attending a specialized, shorter version of the 2-day workshop. Each chapter contains a list of references at the end for further reading if so desired.

Mr. Mike Moravec of FHWA's Office of Technology Applications is the Contracting Officer's Technical Representative for this project. This manual was co-authored by:

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CHAPTER 1. INTRODUCTION TO PAVEMENT RECYCLING

Recycling or reuse of pavement material is a very simple but powerful concept. Recycling of existing pavement materials to produce new pavement materials results in considerable savings of material, money, and energy. At the same time, recycling of existing material also helps to solve disposal problems. Because of the reuse of existing material, pavement geometrics and thickness can also be maintained during construction. In some cases, traffic disruption is less than that for other rehabilitation techniques. The specific benefits of recycling can be summarized as follows:

1. Reduced costs of construction.
2. Conservation of aggregate and binders.
3. Preservation of the existing pavement geometrics.
4. Preservation of the environment.
5. Conservation of energy.
6. Less user delay.

RECYCLING AS A REHABILITATION ALTERNATIVE

Several studies[1,2] have shown that it costs highway agencies less if the pavements are kept at a certain acceptable level of serviceability. According to World Bank Sources,[2] each $1.00 spent during the first 40 percent drop in quality will cost $4.00 to $5.00 if delayed until the pavement loses 80 percent of its original quality (figure 1-1). Rehabilitation is needed to maintain the pavement at a certain condition. Rehabilitation of pavement is also needed due to the following reasons:

1. Inadequate ride quality.
2. Excessive pavement distress.
3. Reduced surface friction.
4. Excessive maintenance requirement.
5. Unacceptable user costs.
6. Inadequate structural capacity for planned use or projected traffic.

Recycling is only one of the several rehabilitation alternatives available for asphalt pavements.[3] Some of the other common methods are thick or thin hot mix asphalt (HMA) overlay. The choice of rehabilitation alternative depends on observed pavement distress, laboratory and field evaluation of existing material, and design parameters.[4] Also, maintenance of geometrics and original thickness of pavements, especially in underpasses, influence the choice of rehabilitation method. However, recycling has some unique advantages which are not available with other types of rehabilitation techniques. For example, recycling can result in savings, help in conservation of natural resources, and can maintain pavement geometrics as well as thickness. Different recycling methods are now available to address specific pavement distress and structural needs.

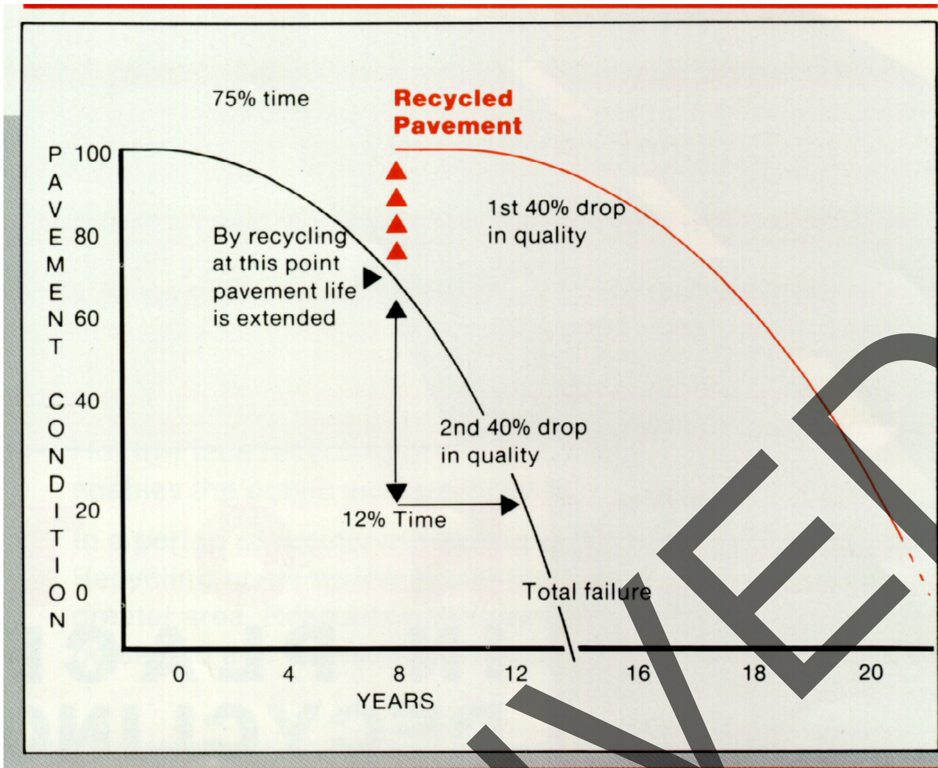

Figure 1-1. Plot of pavement condition versus time.[2]

RECYCLING METHODS AND PROCESSES

The Asphalt Recycling and Reclaiming Association[5] defines four different types of recycling methods: (1) hot recycling; (2) hot in-place recycling; (3) cold in-place recycling; and (4) full depth reclamation.

1. Hot mix asphalt recycling is the process in which reclaimed asphalt pavement (RAP) materials are combined with new materials, sometimes along with a recycling agent, to produce hot mix asphalt (HMA) mixtures. Both batch and drum type hot mix plants are used to produce recycled mix. The RAP material can be obtained by milling or ripping and crushing operation. The mix placement and compaction equipment and procedures are the same as for regular HMA.

   Typically, 10 to 30 percent RAP is used in recycled hot mixes. Figure 1-2 shows introduction of RAP material in a drum plant. The advantages of hot mix recycling include equal or better performance compared to conventional HMA, and capability to correct most surface defects, deformation, and cracking.

2. Hot in-place recycling (HIR) consists of a method in which the existing pavement is heated and softened, and then scarified/milled to a specified depth. New HMA (with/without RAP) and/or recycling agent may be added to the scarified RAP material during the recycling process. HIR can be performed either as a single pass or as a multiple pass operation. In single pass operation, the scarified in-place material can be combined with new material if needed or desired. In multiple pass operation, the restored RAP material is recompacted first,

Figure 1-2. Introduction of RAP material in a drum plant.

Figure 1-3. Surface recycling.

and a new wearing surface is applied later. The depth of treatment varies between 20 to 50 mm (¾ in to 2 in). The Asphalt Recycling and Reclaiming Association (ARRA) has identified three HIR processes; (1) surface recycling, (b) repaving, and (c) remixing. Figure 1-3 shows a surface recycling operation. This is a type of HIR operation in which the existing asphalt surface is heated and scarified to a specified depth. The scarified material is combined with aggregate and/or recycling agent. The mix is then compacted. A new overlay may or may not be placed in the recycled mix. In the second type of HIR method, repaving, the surface recycling method is combined with a simultaneous overlay of new hot mix asphalt (HMA). Figure 1-4 shows a HIR operation with the application of an overlay. Both the scarified mix and the new HMA are rolled at the same time. In the case of remixing (figure 1-5), the scarified RAP material is mixed with virgin HMA in a pugmill, and the recycled mix is laid down as a single mix. The advantages of hot in-place recycling are that surface cracks can be eliminated, ruts and shoves and bumps can be corrected, aged asphalt is rejuvenated, aggregate gradation and asphalt content can be modified, traffic interruption is minimal, and hauling costs are minimized.

3. Cold in-place recycling (CIR) involves reuse of the existing pavement material without the application of heat. Except for any recycling agent, no transportation of materials is usually required, and aggregate can be added, therefore hauling cost is very low. Normally, an asphalt emulsion is added as a recycling agent or binder. The emulsion is proportioned as a percentage by weight of the RAP. Fly ash or cement or quicklime may also be added. These additives are effective for over asphalted and low stability mixes. The process includes pulverizing the existing pavement, sizing of the RAP, application of recycling agent, placement, and compaction. The use of a recycling train, which consists of pulverizing, screening, crushing and mixing units, is quite common. The processed material is deposited in a windrow from the mixing device, where it is picked up, placed, and compacted with conventional hot mix asphalt laydown and rolling equipment. The depth of treatment is typically from 75 to 100 mm (3 to 4 in). The advantages of cold in-place recycling include significant structural treatment of most pavement distress, improvement of ride quality, minimum hauling and air quality problems, and capability of pavement widening. Figure 1-6 shows a typical CIR operation with a milling machine, a crusher and screening plant, and a mix-paver.

4. Full depth reclamation (FDR) has been defined as a recycling method where all of the asphalt pavement section and a predetermined amount of underlying base material is treated to produce a stabilized base course. It is basically a cold mix recycling process in which different types of additives such as asphalt emulsions and chemical agents such as calcium chloride, portland cement, fly ash, and lime, are added to obtain an improved base. The four main steps in this process are pulverization, introduction of additive, compaction, and application of a surface or a wearing course. If the in-place material is not sufficient to provide the desired depth of the treated base, new materials may be imported and included in the processing. New aggregates can also be added to the in-place material to obtain a particular gradation of material. This method of recycling is normally performed to a depth of 100 mm to 300 mm (4 to 12 in).[6] Figure 1-7 shows a full depth reclamation train in action. The train consists of recycling machine hooked to a water tanker and steel drum roller with pad foot shell. The advantages of full depth reclamation are that most pavement distresses are treated, hauling costs are minimized, significant structural improvements can be made

Figure 1-4. Hot in-place recycling operation with application of overlay (repaving).

Figure 1-5. Remixing.

Figure 1-6. Cold in-place recycling.

Figure 1-7. Full depth reclamation.

(especially in base), material disposal problems are eliminated, and ride quality is improved.

PAVEMENT DISTRESS

The majority of pavement distress can be categorized as surface distress or deformation or cracks, or a combination of these three. Surface distress, such as raveling (figure 1-8) or bleeding (figure 1-9) or aggregate polishing (figure 1-10) can be treated with either hot mix or hot in-place recycling. Deformation in the form of corrugation (figure 1-11) can be treated with hot mix or hot in-place recycling, whereas rutting (figure 1-12) can be treated with hot or cold in-place recycling or full depth reclamation, depending on the location of the problem in the pavement structure. Pavements with cracks such as those caused by shrinkage from low temperatures (figure 1-13) and/or hardening of asphalt can be rehabilitated with cold in-place recycling or full depth reclamation. Depending on the severity and extent of distress, a variety of recycling options is available for rehabilitation of deteriorated pavements. The selection of a specific type of recycling method depends on engineering considerations, such as distress, structural strength, availability of equipment, availability of experienced contractors, cost and construction impact on traffic. These considerations are discussed in detail in chapter 3.

Figure 1-8. Raveling.

SUMMARY

Recycling is one of the several alternatives available for rehabilitation of pavements. Other methods include overlay and complete removal and replacement. Recycling is increasingly being used because of the following advantages: (a) reduced cost of construction, (b) conservation of aggregate and binders, (c) preservation of existing pavement geometrics, (d)

Figure 1-9. Bleeding.

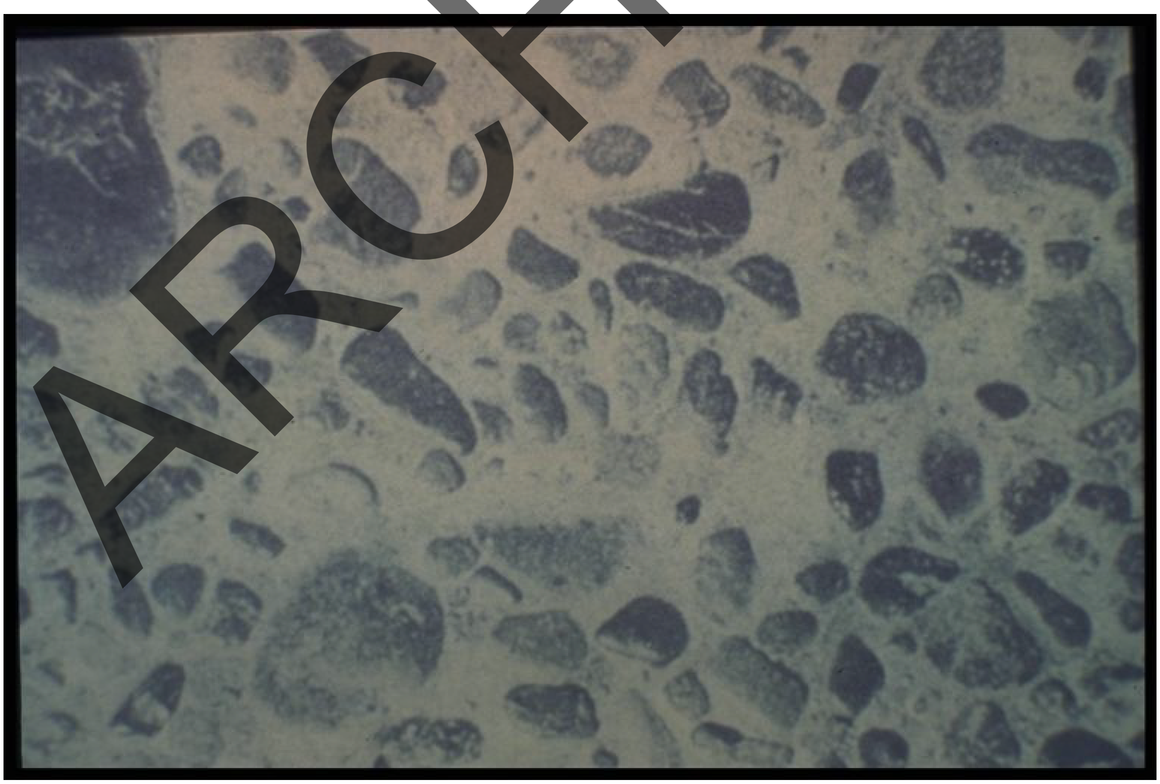

Figure 1-10. Aggregate polishing.

Figure 1-11. Corrugation.

Figure 1-12. Rutting.

Figure 1-13. Transverse cracks.

preservation of environment, and (e) conservation of energy. Different recycling techniques are available to address specific pavement distress and/or pavement structural requirements. The four primary recycling methods most commonly used are hot mix recycling, hot in-place recycling, cold in-place recycling, and full depth reclamation. The choice of a particular technique depends on engineering considerations (such as pavement distress and structural strength), availability of necessary equipment, availability of experienced contractor, initial cost, construction impact on traffic, and long term maintenance costs.

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CHAPTER 2. PERFORMANCE DATA OF RECYCLED MIXTURES

INTRODUCTION

Use of recycled asphalt pavements has increased appreciably since its inception in 1915 and revival in the mid-1970s, when Arab oil embargo caused inflation of construction costs. Experience gained over the years by different states has shown that asphalt pavement recycling is a technically viable rehabilitation technique. Properly designed recycled asphalt pavements have performed similar to and in many cases better than the conventional overlays. A literature search was conducted to collect the results of performance evaluation of recycled projects in the different states. The objective of this session is to present the laboratory and field performance data on recycled asphalt pavements.

PERFORMANCE OF HOT MIX ASPHALT RECYCLING

Hot mix asphalt recycling has been used extensively and routinely in the U.S. during the last several years. It is no longer considered an experimental operation because recycled HMA pavements have generally performed equal to or better than conventional HMA pavements. Therefore, very few experimental projects which have evaluated the relative performance of recycled and conventional HMA pavements, have been reported in the literature. A limited number of projects (mostly constructed in the 1970s) are reported here.

Florida

Florida has been using recycled HMA since 1978. Pavements constructed by milling and replacement by recycled HMA are reported to be performing better than pavements constructed of conventional overlay and leveling courses. Reflective cracks have been removed successfully by full-depth milling of cracked layers. Laboratory and in-place evaluation of recycled HMA has indicated similar or better performance compared to conventional HMA.[(1)] A comprehensive specification and sampling and testing program is used by Florida DOT for recycling HMA. The plans include monitoring all phases of mixture design including verification of the blending between the new asphalt cement and aged binder in the recycled asphalt pavement (RAP). Samples are taken during production routinely to recover asphalt cement and test its properties.

Georgia

An evaluation study consisted of performance evaluation of recycled and conventional HMA surface courses in each of five projects ranging in age between 1½ and 2¼ years. The RAP content in these mixes was mostly 25 percent with a range of 10 to 40 percent.[(2)] Both virgin and the recycled sections were reported to be performing satisfactorily after 1½ to 2¼ years of service with no significant rutting, raveling and weathering, and fatigue cracking. The recycled sections had an average rut depth of 2 mm (0.08 in), with no raveling or alligator cracking, and very few transverse and longitudinal cracks.[(2)] Statistical analysis revealed no significant difference in the properties of in-service HMA mix and recovered asphalt cement, and performance of recycled and conventional HMA test sections in these five projects.[(2)] Figures 2-1 and 2-2 show

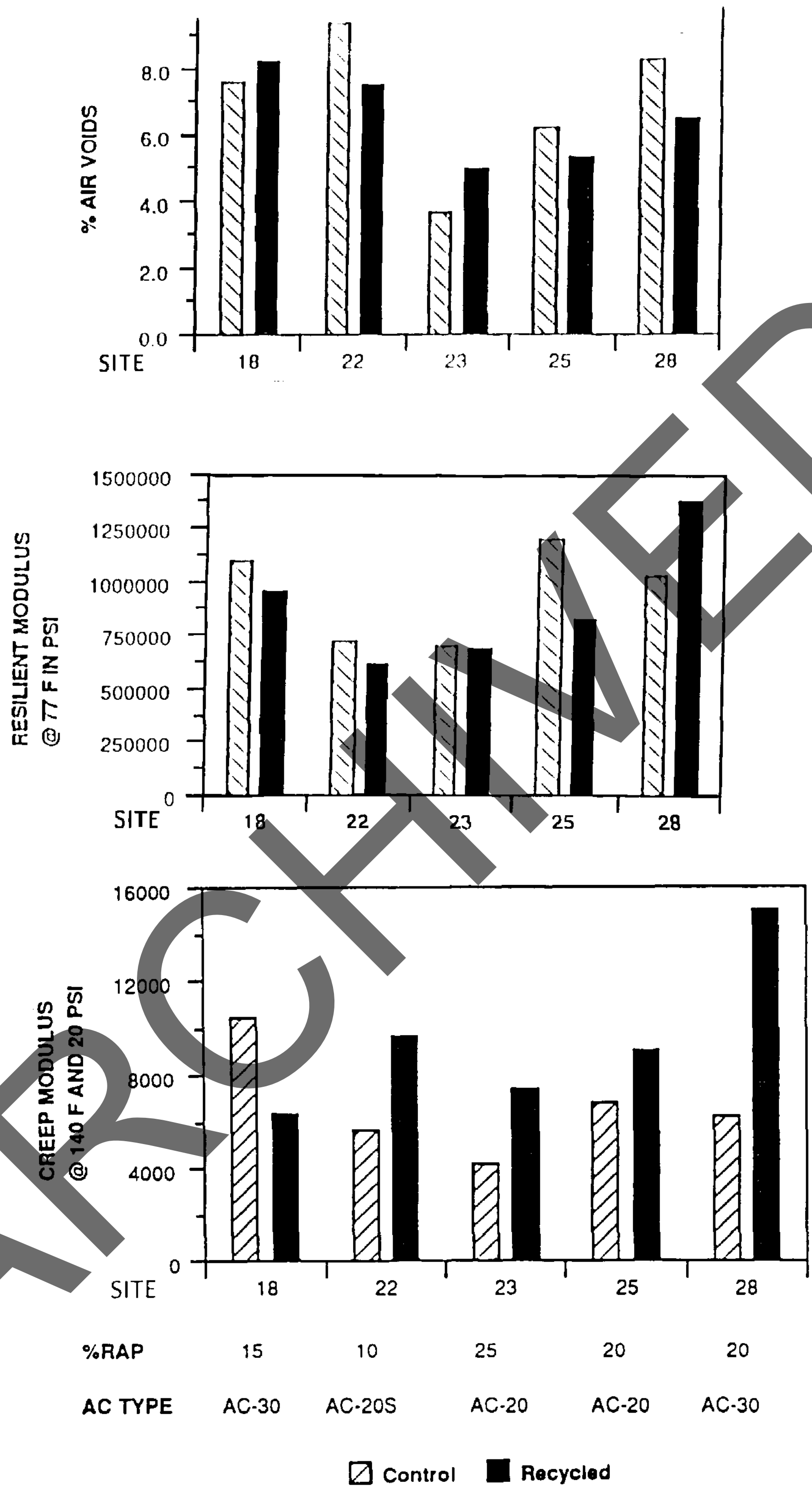

Figure 2-1. Comparison of air voids, resilient modulus, and creep modulus of in-place cores from control and recycled mixes.

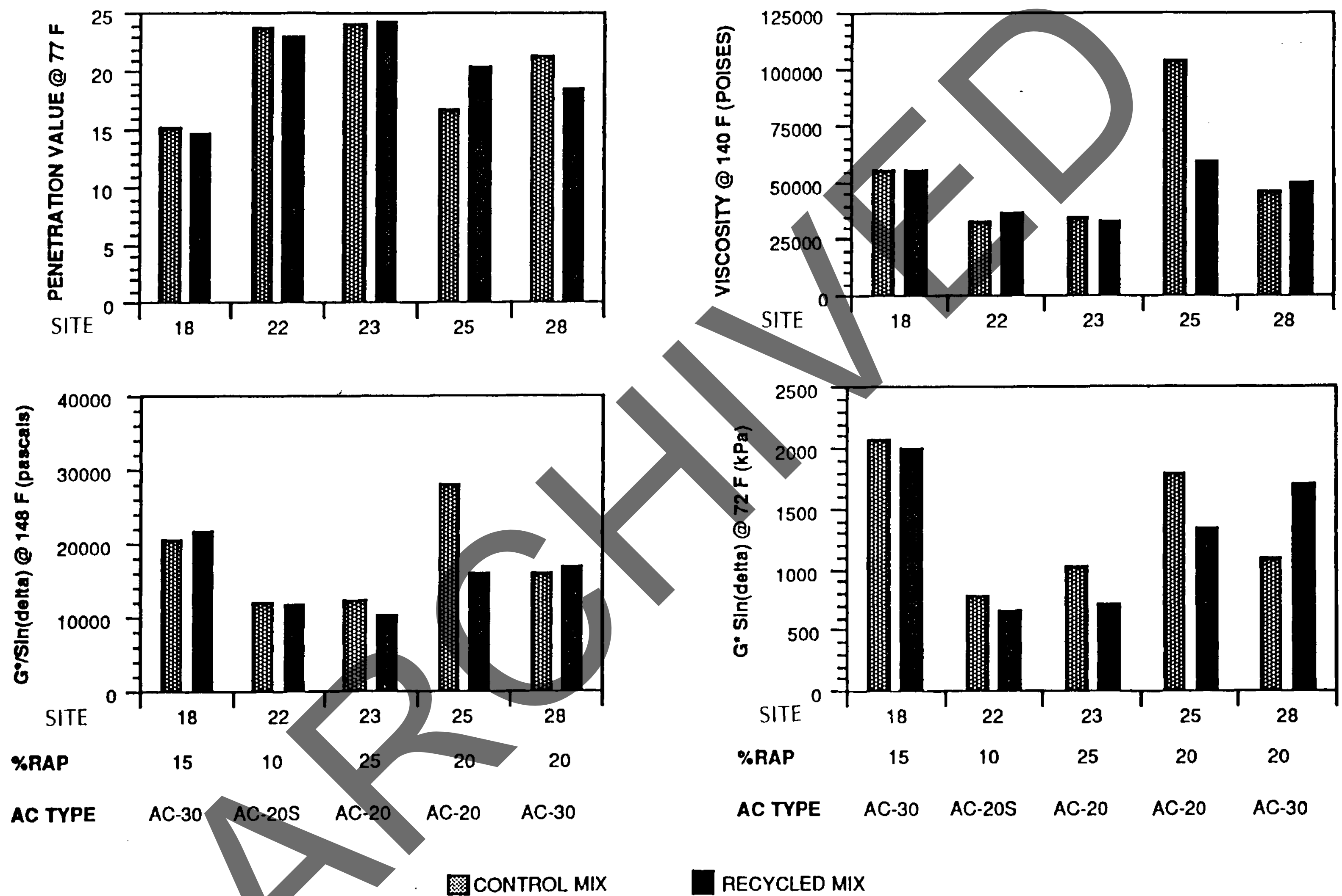

Figure 2-2. Comparison of binder properties of in-place cores from control and recycled mixes.

comparisons of air voids and resilient modulus of pavement cores, creep moduli of recompacted mixes, and properties of recovered asphalt binder from conventional (control) and recycled HMA sections. It was concluded rutting properties were similar based on creep moduli, and the extent of asphalt aging was equal for control and recycled mix based on the properties (both conventional as well as Superpave) of the recovered asphalt binder.

Kansas

In a project undertaken to evaluate performance of hot recycled mix, a 30-mm (1.2-in) HMA conventional surface course was constructed over a 125-mm (5-in) recycled HMA binder course, after cold milling 90 mm (3.5 in) of the existing pavement. A control section of 100 mm (4 in) conventional HMA overlay was also constructed. The Kansas DOT performed crack surveys each spring and fall after construction. Transverse crack and total crack evaluations were carried out for seven years after construction. Both with respect to transverse cracks and total cracks, the recycled HMA section had much better performance than the control section.(3)

Louisiana

A study(4) carried out to evaluate ten recycled pavements (about six to nine year old) constructed in the late seventies reported that both recycled binder and wearing courses performed similar to conventional pavements. The pavements, containing 20-50 percent RAP material, were compared to conventional HMA pavements in terms of pavement condition, serviceability, structural analysis, and mixture and binder properties. In general, no significant difference was observed between the pavement condition and serviceability ratings (from Mays Ridemeter and distress survey) of the recycled and conventional HMA pavements. Structural parameters (from deflection, subgrade modulus, surface curvature, and structural number) were found to be similar for the recycled and conventional HMA pavements. Penetration, viscosity, and ductility tests conducted on recovered binders showed no significant difference between the recycled and conventional HMA pavements.

Massachusetts

A rehabilitation project on a randomly cracked 8.6 km (5.3 mile) stretch of I-290 comprised of removing 50 mm (2 in) of existing pavement for the easterly two thirds of the project and replacing it with 120-mm (4¾-in) recycled HMA binder course and a 20-mm (¾-in) open-graded friction course (OGFC). The top 75 mm (3 in) in the western part of the pavement was removed and was replaced with a 95-mm (3¾-in) recycled HMA binder and a 20-mm (¾-in) OGFC. The recycled HMA had 35 percent RAP and was produced in a batch plant. During production, the original mix design of 60 percent AC-5 and 40 percent AC-20 was modified to 80 percent AC-5 and 20 percent AC-20 to conform to the asphalt cement ductility and penetration specifications.(5) Evaluations after 11 years of construction showed no signs of cracking or rutting in the pavement sections. The Massachusetts Department of Public Works concluded that it is quite possible to use RAP to produce HMA which conforms to specifications.(1)

Minnesota

The first recycled HMA project was constructed in 1976 on a 4-lane urban highway, in which the original pavement was recycled and replaced with a 175-mm (6.9-in) recycled HMA base, a 40-mm (1.6-in) recycled HMA binder and a 20-mm (¾-in) surface wearing course. The recycled HMA contained 50 percent RAP material. The recycled HMA base on the eastbound roadway was placed in three lifts, and the recycled HMA base in the westbound roadway was placed in one lift. A control section of full-depth conventional HMA section was also placed.(6) Benkelman beam deflections taken after one year of service showed similar measurements in the test sections with recycled and conventional HMA.(7) This indicates that the structural strengths of recycled and conventional HMA are comparable. The pavement with recycled HMA base placed on one lift had a higher average deflection than the pavement with the recycled HMA base placed in three lifts. Visual examination of testing of cores taken in 1991 showed that the recycled mix had a service life comparable to the life of conventional HMA.(7)

Washington

In a 1977 rehabilitation project, 45 mm (1¾ in) of an existing pavement was removed and replaced with recycled HMA. A 20-mm (¾-in) open-graded friction course was placed over the recycled HMA. A test section using the recycled HMA as the surface course was also constructed.(8) The mix consisted of about 72 percent RAP material, 0.75 percent recycling agent and no new asphalt cement. The recycling agent application rate was selected to provide a recycled binder comparable to an AR-4000W asphalt cement. Asphalt cement was extracted from field cores obtained after each of eight years after construction. It was reported that the binder in the recycled HMA did not age very much over time, and that the 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 Washington DOT also sampled the recycled HMA over time and tested those samples for mix strength in terms of resilient modulus. It was concluded that resilient modulus values for recycled HMA were comparable initially and over time to those of conventional HMA.(9) The recycled pavement had a 16 year actual service life as compared to 10 years of service life for the original HMA.

The second recycled HMA pavement constructed in 1978 consisted of milling 45 mm (1.8 in) of the existing pavement and replacing it with a recycled HMA. It was overlaid by an 18-mm (0.7-in) open graded friction course.(9) The RAP content was approximately 70 percent. The recycled HMA contained 25 to 30 percent of recycling agent, designed to meet the AR-4000W grade asphalt cement specification. A test section on the eastbound roadway was placed using only the recycled HMA as the wearing course. Performance evaluations were made for a period of six years. Data from recovered asphalt cement showed that the asphalt cement would have met specification requirements for AR-4000W grade initially and over time. Resilient modulus data indicated that the recycled HMA did not age significantly over the evaluation period.(9) The improved HMA after recycling provided actual 15 years of service as compared to 6 years for the original HMA.(1)

Wyoming

The first two recycled HMA projects were constructed on two sections of I-80 in the late seventies. In the first project the existing mix on the pavement was removed and replaced with recycled HMA containing 85 percent of RAP.[10] The mix contained 0.5 percent new asphalt binder and 1.0 percent lime. The pavement performed for 12 years before rehabilitation. The second recycled mix used on I-80 had 70 percent RAP material[11] and 1.0 percent new asphalt binder. The project was performing satisfactorily as reported in June, 1992.[1]

PERFORMANCE OF HOT IN-PLACE RECYCLING (HIR)

Performance of HIR pavements is generally satisfactory based on the reports by most of the states where it has been used. It should be noted, however, that the HIR technology and associated equipment have significantly improved during the last several years resulting in further improvement in pavement performance. Both good and poor performing pavements have been constructed in some states. The projects rated poor in performance have generally been considered as bad candidates for HIR. The performance of some HIR pavements in Canada and in New York is discussed below followed by the general performance based on a nationwide survey.

Canada

A recent reference[12] described the results of a study carried out in 1996 to evaluate the performance of ten HIR test sections constructed in Alberta since 1990. All of these sections were constructed using the two stage hot in-place recycling (HIR) processes in which the top 50 mm (2 in) was removed by heating and milling in two stages—the top 25 mm (1 in) in the first step and the bottom 25 mm (1 in) in the next step. The recycled mix was laid down as a single course with one pass of a recycling train. The field work for performance evaluation consisted of obtaining randomly located in-place cores and visual condition survey. The material properties determined in the laboratory included density, asphalt content, gradation of aggregate, penetration and absolute viscosity of recovered asphalt cement, binder film thickness and asphalt absorption. In general, the observations for all of the sections were as follows:

1. The intensity of full lane width transverse cracks in all but one section was slight. Severe cracking was observed in one section only, and the authors observed that the cracks were related to the full depth HMA pavement and were not related to the HIR process. The slight transverse cracks were considered as reflected cracks and not related to the HIR process.
2. Crack deterioration or spalling along cracks were not evident at any of the sites.
3. The average 1996 rut depths were reported to be between 3 mm (0.1 in) and 7 mm (0.3 in). Pavements with greater traffic loadings were found to have higher rut depth. The authors indicate the causes of relatively greater amounts of rutting in one section to be high asphalt content and increased thickness.
4. No significant in-place aging of binder was observed for the test sections in the six-year performance period. In most of the cases, the recovered binder penetration values were found to have remained unchanged (or increased) over the six-year performance period.
5. The air voids were found to have stabilized after four years of service.

Figures 2-3 and 2-4 show before and after recycling photographs of a pavement in Canada.

New York

Eight hot in-place recycled projects were completed in New York from 1987 to 1992. All of these projects were reported to be performing satisfactorily in 1992.[(13)] Of the eight projects, six were on Interstates with average daily traffic volumes of 9,000 to 62,000 vehicles.

A nationwide survey[(14)] has indicated excellent to good performance of hot in-place recycled pavements in 22 states as listed in table 2-1. Most states which reported fair to poor performance could identify an assignable cause such as poor project selection. Some specific HIR projects which have been reported to give satisfactory pavement performance are listed in table 2-2.[(14)]

PERFORMANCE OF COLD MIX AND COLD IN-PLACE ASPHALT RECYCLING

A comprehensive nationwide information on performance of cold mix asphalt recycling is not available. Some reports which contain performance evaluation of cold recycled asphalt pavements, are available in the literature. However, these reports do not use a common method of defining performance. The general performance data reported by states that have constructed a number of projects indicate that performance has been mostly good or very good, particularly with respect to cracking.[(15)]

California

In an evaluation study of thirteen cold recycled asphalt pavements constructed between 1979 and 1983, about 70 percent of the projects were found to have good performance.[(16)] The poor performance of the rest of the projects was attributed to incomplete mix design and nonuniform distribution of the binder.

Indiana

Roughness, deflection, and visual evaluation made after one year of construction (1986) indicated better performance for a cold in-place recycled mix section compared to a conventional resurfaced pavement.[(17)] Transverse reflection cracks and longitudinal cracks were found in the conventional HMA pavement but not in the cold recycled mix section.

Maine

A three-year performance evaluation indicated that reflective cracking and frost problems had been minimized by the use of full depth reclamation procedure.[(18)]

Nevada

Examination of cores and visual condition surveys done after seven years of service revealed areas of bleeding and minor cracking in one cold recycled project.[(15)] A large portion of the project was found to have no distress. The authors mention that the bleeding was probably

Figure 2-3. Pavement before recycling.

Figure 2-4. Pavement after HIR.

Table 2-1. Results of U.S. survey on hot in-place recycling (HIPR).(modified from 14)

State	Methods Used			Milling Depth Range, mm (in.)	Class of Highways for HIPR			Surface Seal or Overlay Commonly Placed Over HIPR Pavement	Performance of HIPR Pavements			
	Heater Scarifi-cation	Repave	Remix		Major	Secondary	Low Volume		Excellent	Good	Fair	Poor
Alabama		x	x	50 (2)	x		x		x (remix)			
Alaska	x				x					x		
Arizona	x			25 (1)	x	x		x				x
Arkansas			x	25-32 (1-1¼)		x				x		x
California	x		x	(19-38) ¾-1½	x	x	x			x		x
Colorado	x	x		38-50 (1½-2)	x	x	x			x		
Connecticut		x		38-50 (1½-2)	x							
Delaware												
Florida	x	x	x	38 (1½)	x	x		x		x		
Georgia			x									
Hawaii												
Idaho	x		x	50 (2)	x							
Illinois		x		25-38 (1-1½)			x	x		x	x	x
Indiana												
Iowa	x			<25 (< 1)			x	x				x
Kansas	x			25 (1)	x	x	x	x		x		

Table 2-1. Results of U.S. survey on hot in-place recycling (HIPR) (continued).(modified from 14)

State	Methods Used			Milling Depth Range, mm (in.)	Class of Highways for HIPR			Surface Seal or Overlay Commonly Placed Over HIPR Pavement	Performance of HIPR Pavements			
	Heater Scarification	Repave	Remix		Major	Secondary	Low Volume		Excellent	Good	Fair	Poor
Kentucky												
Louisiana	x	x	x	19-38 (¾-1½)	x	x		x (for heater scar)		x		x
Maine												
Massachusetts												
Maryland			x	38-50 (1½-2)	x	x				x		
Michigan		x				x				x		
Minnesota		x			x			x		x		x
Mississippi		x	x	38 (1½)	x			x		x		
Missouri												
Montana		x		25-44 (1-1¾)	x	x	x	x (interstate)			x	
Nebraska												
Nevada		x		32 (1¼)				x		x		
New Hampshire		x			x			x		x		
New Jersey												
New Mexico												

Table 2-1. Results of U.S. survey on hot in-place recycling (HIPR) (continued).(modified from 14)

State	Methods Used			Milling Depth Range, mm (in.)	Class of Highways for HIPR			Surface Seal or Overlay Commonly Placed Over HIPR Pavement	Performance of HIPR Pavements			
	Heater Scarification	Repave	Remix		Major	Secondary	Low Volume		Excellent	Good	Fair	Poor
New York			x	25-38 (1-1½)	x					x		
N. Carolina												
N. Dakota												
Ohio	x		x	38 (1½)	x (remix)	x (heater scar.)		x (with heat scar)		x (heater scar)		
Oklahoma		x		25 (1)	x			x				
Oregon												
Pennsylvania			x		x	x					x	
Rhode Island												
S. Carolina			x	25 (1)	x				x			
S. Dakota												
Tennessee		x	x		x	x		x		x		
Texas	x	x	x	25-38 (1-1½)	x	x				x		
Utah		x		25 (1)	x	x		x		x		
Vermont			x		x			x				x
Virginia	x			38 (1½)			x	x			x	
Washington	x					x				x		
Wyoming												

Table 2-2. Summary of selected case histories of hot in-place recycled pavement.(modified from 14)

Agency/ Date Recycled	Description of Job	Condition of Old Pavement	HIPR Process Used	Milling Depth/ Overlay Depth	Rejuvenating Agent	Mix Temperature	Performance/ Remarks
Repaving Process							
FAA Carrabelle, FL 1990	Thompson Field Airport. 30 m x 212m (98.4 ft x 695.6 ft) runway	Unknown	Repaver	25 mm/25 mm (1 in/1 in)	Unknown	Unknown	Officials pleased that job met specs and appeared cost effective and had short down time.
Florida DOT 1979	US41, Ft. Myers, FL 3.9 km (2.4 mi), 6-lane ADT-39,000	Rutting, cracking, low friction; pavement structure was OK.	Cutler Repaver	25 mm/19 mm (1 in/0.75 in)	EA-SS-1 0.27 1/m^2(0.06 gal/yd)	79.4ºC to 121ºC (175º F to 250ºF)	PSI** increased from 3.43 to 3.89. After 14 years pavement has 12 mm ruts, hairline cracking, and fair ride quality. Overall performance good.
Louisiana DOT 1980	Metairie RD from US 61-IH-10 5.8 Km (3.6 mi) curb and gutter section	Cracking, rutting	Cutler Repaver	25 mm/20 mm (1 in/0.8 in)	CSS-1, 0.45 1/m^2 (0.09 gal/yd^2)	Unknown	Eliminated cracks, and restored cross slope, and minor improvement of longitudinal undulations. Began raveling in 6 mo. Generally, satisfactory after 5 years.
Louisiana DOT 1986	11.4 km (7.1 mi) of US 71	Overlay on PCCP*** had reflection cracks with severe spalling which gave poor ride quality.	Cutler Repaver	25 mm/38 mm (1 in/1½ in)	ARA-1, 0.63 1/m^2 (0.13 gal/yd^2)	Mat 65ºC to 129ºC (150-265ºF) with 102ºC (215ºF) avg. behind paver	Difficult to achieve density. Low mat temp. Recycled section performing about equivalent to control section.
City of Phoenix 1990	City collector street. 8000 m² (10,000 yd^2)	Severe alligator cracking with longitudinal cracking distortions, bleeding and raveling	Cutler Repaver	19 mm/25 mm (0.75 in/1 in)	Yes, Type and quantity Unknown	Unknown	Early performance good. Low pollution favorable to city officials.
Lee County, Iowa 1990	Rural roads. X-38 and X-48	Oxidized surface, cracking, 13 mm (0.5 in) ruts	Cutler Repaver	19 mm/25 mm (0.75 in/1 in)	Elf ETR-1 at 0.36 1/m^2 (0.08 gal/yd^2)		Early performance good. Officials pleased with relatively little traffic disruption.

Table 2-2. Summary of selected case histories of hot in-place recycled pavement (continued).(modified from 14)

Agency/ Date Recycled	Description of Job	Condition of Old Pavement	HIPR Process Used	Milling Depth/ Overlay Depth	Rejuvenating Agent	Mix Temperature	Performance/ Remarks
Repaving Process							
FAA Texarkana, TX 1986	Airport. 2011 m (6598 ft²) and 25 yr old	Aged, brittle mix. Low friction.	Cutler Repaver	25 mm/25 mm (1 in/1 in)	Type unknown. 0.54 1/m² (0.11 gal/yd²)	110ºC (230ºF)	After 6 yrs a few surface cracks have appeared in isolated places. Otherwise, performance is excellent.
Connecticut DOT 1981	Rt. 15 at Westport, CT. 4.7 km (2.9 mi), 4-lane divided	Rutting. Otherwise fairly good condition	Cutler Repaver	25 mm/25 mm (1 in/1 in)	AE-300R 0.36 1/m² (0.07 gal/yd²)	121ºC ± 22ºC (250ºF ± 30ºF) by spec.	Some reflection cracking. HIPR same as control. Recycling cost about 16% more than conventional.
Transport Canada 1988	Prince George Airport, British Columbia	Extensive longitudinal, transverse, and random cracking w/ raveling. Annual crack sealing no longer cost effective.	Taisei Rotec Remixer	50 mm/50 mm -- (2 in/2 in). No new aggregate added to RAP.	Cyclogen-L at 0.36 1/m² (0.08 gal/yd²) Varied based on observing flushing during heating	110ºC-150ºC (230ºF - 302ºF) was specified. Maintained at low end.	Extraction tests verified excellent control of rejuvenator application rate. Asphaltenes decreased by 24%; polar compounds increased 143%, which indicates improved durability.
Defence Construction Canada 1989	Airfield pavements at Canadian Forces Base, Edmonton, Alberta, 330,000 m² (412,500 yd²)	Severe raveling and thermal cracking. Badly weathered, oxidized appearance	Artec Remixer Only a small area was remixed	40 mm/50 mm (1.6 in/2 in) overlaid later; or 40 mm/19 mm (1.6 in/0.75 in) repave	RJO #3 at 0.4 1/m² (0.08 gal/yd²)	120ºC (248ºF) behind paver was targeted value	Equipment was capable of heater-scarification, repaving, and remixing. Early performance of pavement has been good. Author states that pavement flushing is a concern, and that more inspection and testing will be required for all HIPR.
Texas DOT 1991	IH-10 and SH-87 near Beaumont	Severe rutting, age-hardened mix. Raising elevation by overlaying was impractical	Wirtgen Remixer	25 mm to 31mm (1 in/1.2 in)	ARA-1	About 116ºC (240ºF)	No drop off during construction enhances safety. Early performance satisfactory.

Table 2-2. Summary of selected case histories of hot in-place recycled pavement (continued).(modified from 14)

Agency/ Date Recycled	Description of Job	Condition of Old Pavement	HIPR Process Used	Milling Depth/ Overlay Depth	Rejuvenating Agent Mix Temperature	Performance/ Remarks
Repaving Process						
Tennessee DOT 1990	Northern-most 9.7 km (6 miles) of IH-75 in Tennessee	Severe rutting and other forms of distress	Wirtgen Remixer	75 mm + 24 kg/m^2 of new mix	AES-300RP (polymer) at 0.63 1/m^2 (0.13 gal/yd^2) 107ºC (225ºF)	Officials pleased with density, stability, asphalt content, and gradation. Overall early performance very good.
Alabama DOT 1989	6.4 km (4 mile) stretch of US 78 near Fruithurst	Cracking and rutting. Unsightly.	Wirtgen Remixer	38 mm + 14 Kg/m^2 (1.5 in + 24.6 lb/yd^2) of new mix	Unknown Near 148ºC (300ºF)	Minimal traffic disruption was important. Early performance OK.
Mississippi SHD 1990	55 lane-km (34 lane-mi) of IH-59 in Lauderdale County	Highly polished with some rutting.	Wirtgen Remixer	38 mm + 15 kg/m^2 (1.5 in + 26.4 lb/yd^2) of new mix	Yes, unknown 110ºC (230ºF)	Early performance OK. DOT pleased with project.
Texas DOT 1990	IH-35 in La Salle County near Cotulla	Surface was severely age-hardened with cracking and rutting.	Wirtgen Remixer	50 mm + 8 kg/m^2 (1.5 in + 26.4 lb/yd^2) of new mix	None used. Asphalt was in new mix. Unknown	Officials believe process is promising. Early performance is OK.
Canadian Dept. Of National Defense* 1989	Lancaster Park Airfield near Edmonton 4250m (13944 ft)	Unknown	Artec Repaver and Remixer	38 mm + 19 - 50 mm (1.5 in + 0.75 - 2 in) overlay; 38 mm + 41 kg/m^2 (1.5 in + 72.2 lb/yd^2) new mix	Shell RJO-3 at 0.19 1/m^2 (0.04 gal/yd^2) Unknown	Specs on density, temperature, penetration, scar, depth and smoothness of surface were met. An acceptable economic alternative.
British Columbia Ministry of Highways* 1989	Trans-Canada Highway (Rt 1) near Vancouver, 126 lane-km (78 lane-mi)	Rutting, surface cracking and other age-related distress	Artec and Taisei Remixers	38 mm to 63 mm (1.5 in + 52.8 lb/yd^2) (no new material added)	Unknown 105ºC (221ºF) minimum	All specs were met. Ministry was satisfied with final results. Appears to be an acceptable economic alternative. Reduced traffic disruption.

Table 2-2. Summary of selected case histories of hot in-place recycled pavement (continued). (modified from 14)

Agency/ Date Recycled	Description of Job	Condition of Old Pavement	HIPR Process Used	Milling Depth/ Overlay Depth	Rejuvenating Agent Mix Temperature	Performance/ Remarks
Repaving Process						
Texas DOT 1989	IH-20 from Louisiana, border to FM450, 51 km (32 mi), ADT-18,000 20% trucks	Poor ride quality and some raveling. An other portion was overasphalted.	Wirtgen Remixer	38 mm + 30 kg/m² (1.5 in + 52.8 lb/yd²) new mix	ARA-1 at 0 to 0.71 1/m² (0 to 0.15 gal/yd²) 110ºC (230ºF)	Officials pleases with early performance. Pleased with safety aspects of process. Good ride quality.
Texas DOT 1987	US 259 in Lone Star. Major arterial carrying heavy trucks	Oxidized, Block cracking. 25 mm (1-inch) ruts at inter-sections	Cutler Remixer	38 mm + 17 kg/m² (1.5 in + 29.9 lb/yd²) new mix	AC-5 used with new mix 93ºC (200ºF) behind screed	Early performance OK. Pleased with economics.
Oregon DOT 1987	82nd Ave from N.E. Wasco to S.E. Division a 5-lane major arterial	Rutting, Cracking, very poor drainage	Taisei Remixer	Up to 50 mm (2 in) + various mew mix	Non-emulsified product Unknown	Officials very happy with project outcome. Ride quality and early performance good.
South Carolina DOT 1983	SC 291 from US 29 to N. St. in Greenville, 1.2 km (0.74 mi), 6-lane, ADT-37,300	Unknown	Wirtgen Remixer	41 kg/m² (72.2 lb/yd²) surface mixed with 18 kg/m² (31.7 lb/yd²) virgin mat	Exxon AC-2.5 used in virgin mix Mat behind screed 110ºC (230ºF)	Stability, density and workability compare well with virgin mix. Durability of mix is a concern.
Louisiana DOT 1990	US 90 from LA 99 to Jennings	Poor ride quality due to cracks reflected form underlying PCCP***	Wirtgen Remixer	38 mm + 30 kg/m² (1.5 in + 52.8 lb/yd²) new mix	ARA-1 at 0.9 1/m². (0.19 gal/yd²) AES-300RP used in a short section 107ºC - 148ºC (225ºF - 300ºF)	Initial economic benefit realized. Early performance OK.

caused by improper seal coat quality control or design. Examination of another three year old project showed no distress other than joint raveling.[15]

New Mexico

A total of 120 cold in-place asphalt recycling projects have been constructed in New Mexico since 1984. A recent performance evaluation of 45 projects located throughout New Mexico[19] shows that all of the pavements are providing acceptable performance levels. The projects evaluated were from 4 to 12 years old jobs. The traffic levels ranged from about 3,000 to 10,000 AADT and average daily load in terms of 80 KN ESALS ranged from about 8 to 4,000. Both condition rating by visual inspection and evaluation of cores were made for the projects. Pavement condition surveys have indicated that these pavements will far exceed their assumed service life of 10 years. More than 90 percent of the projects were found to be in excellent condition, and the rest were in fair to good condition. Comparison of density of cores obtained at the time of construction and at the time of evaluation indicated no significant change in air voids.

New York

A total of four cold in-place asphalt recycling projects were constructed in New York from 1990 to 1992. The four rural road projects total 57 lane miles, with an average traffic volume range of 500 to 4300 vehicles per day. All the projects were reported to be performing extremely well in 1992.[13] Figures 2-5 through 2-8 show before and after recycling photographs of two pavements in rural New York.

Oregon

Results from evaluation of 52 cold in-place recycled pavements indicated that 47 of the projects had good or very good performance, and only five had poor performance.[20,21,22,23] The traffic volume in these pavements varied from low to high. Three different types of treatments have been used in the Oregon projects: 1) Recycling performed on a uniform pavement built to specifications, 2) Recycling performed on pavement with significant maintenance patches over a uniform pavement, 3) Recycling performed on low-volume highways where considerable variation in pavement structure exists.

The performance data obtained from these projects have been used by Oregon DOT to revise its mixture design and construction operations as well as selection of binder for cold in-place recycling operation. By 1990, more than 450 miles of recycled mix have been placed in Oregon.[15] The following causes were responsible for the poor performance of the five pavements:

1. Too high a recycle agent content in the early years. Contents more than 2 percent with 7 to 10 percent diluent were shown to create excessive softening.
2. Placing a tight seal or dense wearing course too soon, resulting in trapping of water and diluent, followed by stripping and rutting.
3. Depth of recycle stopped at a delaminated layer of old pavement, resulting in loss of bond.
4. Failure to provide some type of seal before freeze/thaw conditions.

Figure 2-5. Pavement before recycling.

Figure 2-6. Pavement after CIR.

Figure 2-7. Pavement before recycling.

Figure 2-8. Pavement after CIR.

A comparison of ride quality data obtained from pavement prior to recycling, and recycled pavement showed that major improvement can be achieved with cold in-place recycling. This ride quality comparison is shown in figure 2-9.

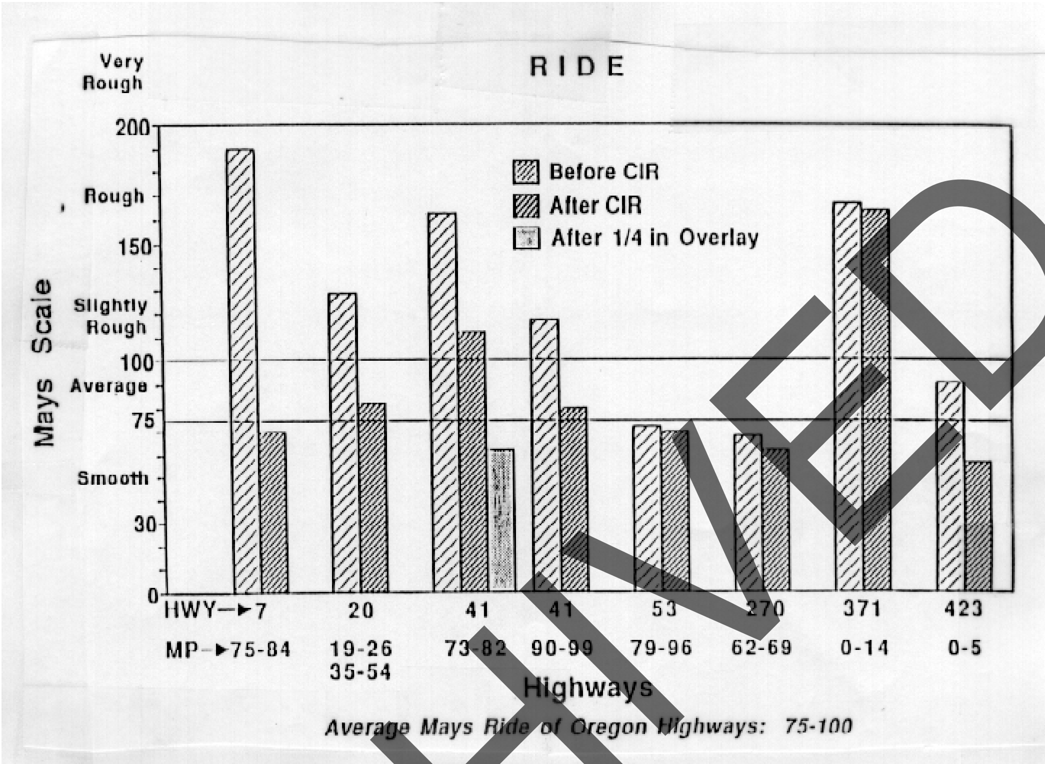

Figure 2-9. Pre- and post-construction ride data from 1986 Oregon project.[21]

Pennsylvania

Details of construction and performance data for some cold in-place recycled pavements have been presented in literature.[24] The first recycling job was on a pavement with a poor base showing considerable amount of patches and alligator cracking. The existing road was milled to a depth of 75 mm (3 in), and the resulting RAP was transferred to a mobile mixer-paver (Motopaver) by a truck. The RAP was mixed with 2 percent MS-2 emulsion (approximately 0.02 liter per kg (5 gallon per ton) of the RAP by weight) in the pugmill and laid through a screed. The recycled mix was laid to give a compacted base course of 125 mm (5 in) thickness. This base course was overlaid with a 40-mm (1.5-in) thick HMA surface course after remaining open to the traffic for a couple of weeks. The road, which carried a lot of truck traffic, was reported to be performing well.[24,25] Photographs of the pavement before and after recycling are shown in figures 2-10 and 2-11. Another cold in-place recycling project was completed on a narrow, badly cracked, heavily patched road in 1983. The existing roadway (figure 2-12) was milled and recycled to a depth of 75 mm (3 in). A CSS -1h emulsion was used in this project. The recycled pavement was provided with a single seal coat only, and was reported to be in very good condition after the 1983-84 winter (figure 2-13). However, inspection in 1986 revealed a loss of seal coat and developing potholes[25] (figure 2-14). The section in which 100 percent RAP was used was found to have more potholes than the section in which a 50/50 blend of RAP and virgin

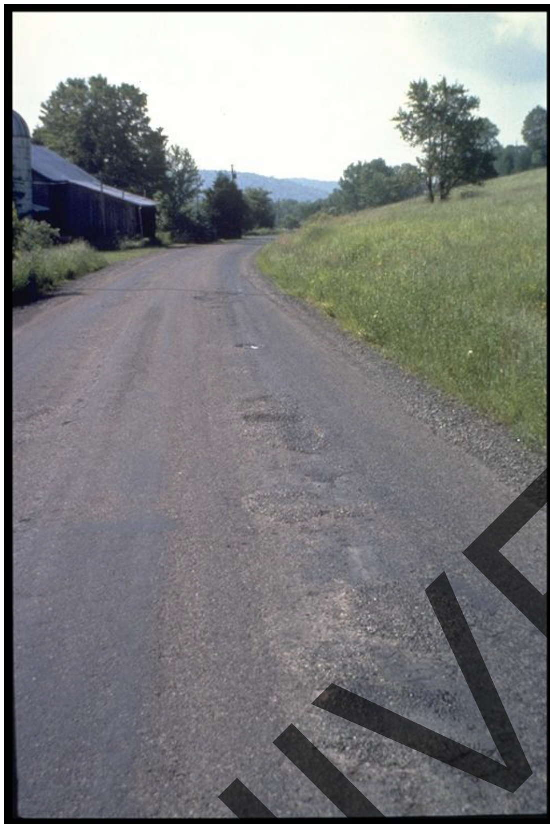

Figure 2-10. Pavement before recycling.

Figure 2-11. Pavement after CIR.

Figure 2-12. Pavement before recycling.

Figure 2-13. Pavement in good condition after CIR.

Figure 2-14. Pavement in poor condition after CIR.

aggregate was used. The authors have also reported five other cold in-place recycling projects in northeast Pennsylvania. About two-three percent CMS-2 emulsion by weight of the RAP was used. The compacted recycled base course appeared quite dense and was covered with a single seal coat. The authors mention that since a cold recycled mix is not adequately water and abrasion resistant, a single coat may not be adequate to protect it. Potholes developed on these projects after the loss of the first seal coat. The authors have recommended the use of at least a double seal coat in cold recycled jobs. After two years of service, three projects were patched and a double surface treatment was applied. The condition of the pavements were reported to be good in 1986.[25]

PERFORMANCE OF FULL DEPTH RECLAMATION

Since in most of the cases full depth reclaimed bases are covered with HMA courses, it is very difficult to obtain long term performance data for these layers. However, the experience of several state and local agencies regarding full depth reclamation have been favorable. Depending on the type of additive used in full depth reclamation, strong and durable bases have been obtained and in many cases occurrence of pot holes and related deterioration have been avoided. With the help of falling weight deflector meter tests, full depth reclamation has been shown to increase the material strength (resilient modules), and capability to distribute loads.[26,27] Figures 15 and 16 show two photographs of before and after recycling pavements in New Hampshire.

SUMMARY

The experience of the different states indicates that in most cases the performance of the recycled

Figure 2-15. View before recycling.

Figure 2-16. View after FDR.

asphalt pavements has been superior to or comparable to conventional asphalt pavements. However, it was also observed that recycled pavements performed well only when good project selection criteria were followed, and they were designed properly and constructed under good quality control and acceptance conditions. Hence, the conclusion from this literature review is that, as in the case of conventional asphalt pavements, recycled asphalt mixtures must be designed to meet proper specifications, produced with good quality control, and placed properly with no defects or irregularities.

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CHAPTER 3. SELECTION OF PAVEMENT FOR RECYCLING AND RECYCLING STRATEGIES

INTRODUCTION

All pavements deteriorate over time due to traffic and environmental factors. Rehabilitation is needed to maintain the pavement at a certain condition. As mentioned in chapter 1, rehabilitation may be required for any one or more of the following reasons:[1]

1. Inadequate ride quality.
2. Excessive pavement distress.
3. Reduced coefficient of friction between tire and pavement.
4. Excessive maintenance requirement.
5. Unacceptable user costs.
6. Inadequate structural capacity for planned use.
7. Inadequate capacity to carry projected traffic volumes.

There are large numbers of rehabilitation alternatives available for asphalt pavements.[1] As shown in figure 3-1 recycling is only one of the several rehabilitation alternatives.[2] Some of the other common methods are thick or thin hot mix asphalt (HMA) overlay. The HMA overlays may be dense graded or open graded, as shown in figures 3-2 and 3-3 respectively. Cold milling (figure 3-4) is also used as a rehabilitation technique. The choice of the rehabilitation alternative depends on observed pavement distress, laboratory and field evaluation of existing material, and design information.[2] Also, maintenance of geometrics and original thickness of pavements, especially in underpasses, influence the choice of rehabilitation method. HMA overlays can be used with or without milling or recycling. Except asphalt surface recycling, all other recycling methods such as hot mix or hot in-place or cold in-place recycling, have the potential to improve the structural capacity of pavements. In addition to this, recycling has some unique advantages which are not available with other types of rehabilitation techniques.

Some of these advantages are:

1. When properly used, recycling can result in substantial savings over the use of new materials. Also, the cost of haulage can be avoided if recycling is performed in-place. The need for economic consideration is felt now, more than ever, because of tightening budgets and ever increasing costs of materials.
2. Recycling can help in conservation of natural resources by cutting down the need for new materials. This translates to substantial savings in aggregate resources and demand for asphalt binder, especially during supply interruptions. Even though there may be an abundant supply of aggregates, the distribution of these sources does not always coincide with the location of need. A pavement recycled by cold process may need about one to three percent of asphalt binder compared to about six percent for a new asphalt concrete pavement This amounts to savings of about 10 gallons of asphalt binder per ton of the mix.[3] Cold recycling can also substantially reduce energy consumption by the pavement industry.

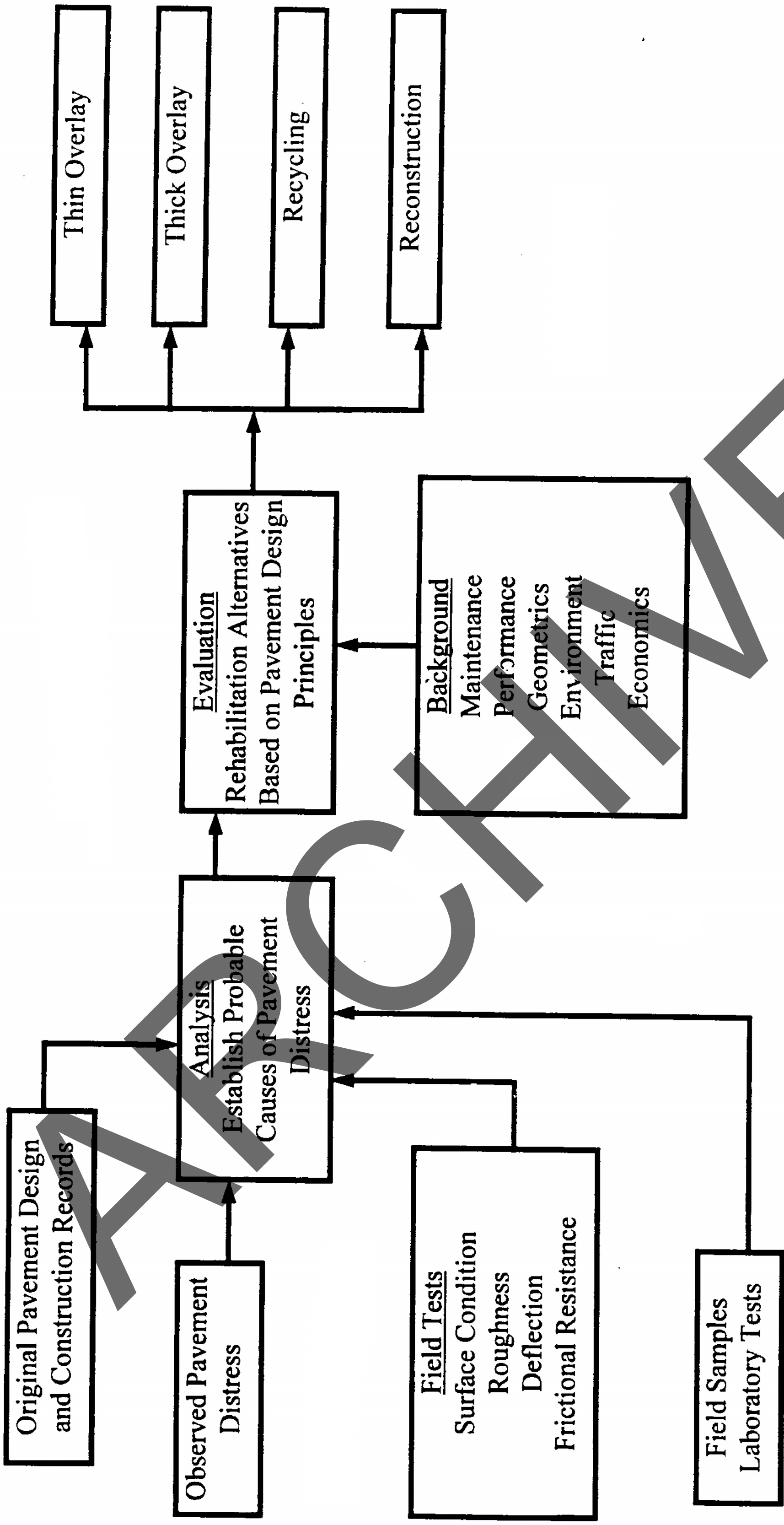

Figure 3-1. Rehabilitation alternatives.

Figure 3-2. Dense-graded HMA overlay.

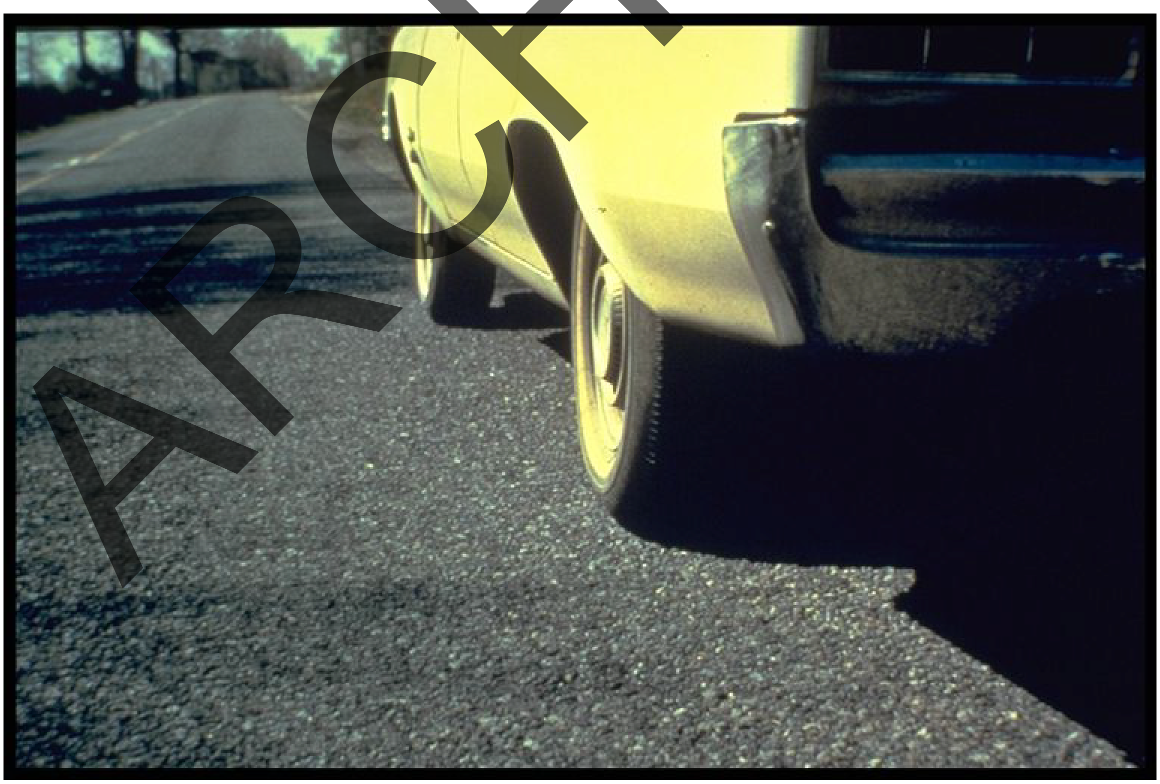

Figure 3-3. Open-graded HMA overlay.

Figure 3-4. Cold milling.

3. Recycled materials have proven to be at least equal to new materials in quality. An HMA overlay on recycled base may perform better than an HMA overlay on the existing surface, even though they are of the same thickness, because the former, being less stiff, can substantially reduce the potential of reflective cracking through the surface course.
4. Recycling can maintain pavement geometrics as well as pavement thickness. The existing pavement structure can be strengthened by recycling without adding substantial overlays. In some cases, the traffic disruption is lesser than that for other rehabilitation techniques.

Over the years recycling has become one of the most attractive pavement rehabilitation alternatives. With the continuous accumulation of performance data, field and laboratory evaluations of recycled mixes, and with the simultaneous development of realistic performance-oriented guidelines it is expected that recycling will continue to be the most attractive rehabilitation technique.

Since recycling can also be combined with the use of overlays, the process of selection of rehabilitation technique involves recycling methods as well as recycling with overlay or without overlay, or some treatment without recycling. Table 3-1[4] shows the different pavement maintenance and rehabilitation method available for asphalt concrete pavements to address specific pavement distress problems. Structural recycling refers to both hot and cold recycling. The choice of rehabilitation technique should be based on engineering considerations, economic considerations, and energy considerations. A discussion of these three considerations follows.

Table 3-1. Pavement maintenance and rehabilitation alternatives.(4)

PROBLEM	POSSIBLE CAUSE				MAINTENANCE[1]				REHABILITATION[2]					
	Structural Failure	Mix Composition	Temp.or Moisture Changes	Const.	Patching & Routine Maintenance	Fog Seal	Surface Treatment	Slurry Seal	Surface Recycling	Thin Overlay	Open Graded Surface	Structural Overlay	Structural Recycling	Recon-struction[3]
Alligator Cracking	x				x[4]		x[5]	x[5]				x	x	x
Edge Joint Cracks	x		x	x	x									
Reflection Cracks					x		x[5]	x[5]			x[6]	x	x	
Shrinkage Cracking		x	x				x	x	x		x[6]	x	x	
Slippage Cracks				x	x									
Rutting	x	x		x					x	x[7]		x	x	x
Corrugation	x	x		x					x	x[8]		x	x	x
Depressions	x			x	x								x	x
Upheaval			x		x								x	x
Potholes	x		x	x	x						x			
Raveling		x		x		x[5]	x	x	x	x				
Flushing Asphalt		x		x			x		x		x			
Polished Aggregate		x	x				x		x	x	x			
Loss of Cover Aggregate		x					x							

Notes:
[1]Refer to Asphalt in Pavement Maintenance (MS-16), The Asphalt Institute, for details
[2]When cracking exceeds 40 percent of the surface area of the pavement
[3]If problem is extensive enough
[4]Deep patch-permanent repair
[5]Temporary repair
[6]When accompanied by surface recycling
[7]When rutting is minor
[8]Over planed surface

Engineering Consideration

The choice of a rehabilitation technique should be based primarily on the condition and performance history of the existing pavement. The major factors should include the following:[5]

1. The present condition of pavement, based on ride quality and type
2. The type, extent and severity of distress
3. The structural condition of the pavement
4. The environmental conditions of the region, primarily temperature and rainfall
5. Drainage conditions of pavement, including surface and subsurface drainage
6. Construction considerations, including restriction imposed by bridges (limited overhead clearance), and other structures such as curbs and gutters, drainage structures, shoulders, median barriers and guardrails
7. The design life required for treatment
8. The material used in original construction and planned for overlays
9. The age of the pavement
10. The type, frequency and cost of past maintenance activities.

The most common factors considered are (1) the present condition of pavement with regard to distress, (2) traffic in terms of equivalent 18-kip axle loads estimated for design period, and (3) structural capacity of existing pavement.[6]

Before choosing a rehabilitation alternative, the designer must evaluate environmental and drainage factors, and practical limitations imposed by contiguous structures. Since different rehabilitation techniques can produce pavements with different life cycle, the designer should consider the expected life of the pavement as well as funds available and user convenience. Design considerations are also dependent on the type of original surface (for example, PCC or asphalt) on which the new overlay will be placed. There is also the question of whether to use a separating course between the old surface and the new overlay. And finally, perhaps the most important consideration should be made of the type, amount and severity of distress conditions of the existing pavement. Since different recycling techniques can remedy different types of distresses, the most appropriate method should be considered.

Overlay design methods for improving the structural capacity of the existing pavement are discussed in chapter 18. These methods, together with methods for the design of new pavements, are also used to determine thickness requirements for recycled pavements.

Economic Consideration

Recycling techniques can be evaluated on the basis of the cost of the pavements. The cost, or worth, of a pavement can be defined in two ways: (1) present worth (PW), or the present value, and (2) equivalent uniform annual costs (EUAC). Present worth is defined as the money needed at present to fund all costs of the pavement. The equivalent uniform annual cost (EUAC) is an equivalent amount of money spread out over the analysis period.

The advantage of EUAC method is that alternatives with different lives can be conveniently compared, and prices for alternatives are in dollar value ranges that can be easily comprehended.

Life cycle costs of the rehabilitation alternatives must also be considered in economic analysis. The life cycle is the period of time of actual use before replacement, reconstruction, or extensive rehabilitation is required. Life cycle costs include the initial construction cost as well as the cost of maintenance activities during the life cycle.

Appendix A contains a detailed discussion of economic considerations including an example of life cycle cost analysis.

Energy Considerations

Even though recycling of pavements was performed as early as 1915, it was not until the mid-1970s that widespread attention was paid to recycling because of the oil embargo. Recycling of HMA pavements results in a considerable conservation of energy by reducing cost of hauling and production of materials. However, the amount of savings depend on the particular type of recycling used. Energy considerations required for selection of a recycling method include the following operations which consume energy: material manufacture, material transportation, mix production, mix transportation, and mix placement and compaction.

The following energy requirement data for resurfacing and recycling operations have been reported:[3]

1. Heater Planer - 3.5-7.0 kWh/m^2 - 1.90 cm (10,000-20,000 Btu/yd^2-3/4 in).
2. Heater scarify - 3.5-7.0 kWh/m^2 - 1.90 cm (10,000-20,000 Btu/yd^2-3/4 in).
3. Hot milling - 0.27-0.55 kWh/m^2-cm (2,000-4,000 Btu/yd^2-in).
4. Cold milling - 0.14-0.35 kWh/m^2-cm (1,000-2,500 Btu/yd^2-in).
5. In-place recycling - 2.1-2.7 kWh/m^2-cm (15,000-20,000 Btu/yd^2-in).
6. Hot central plant recycling - 2.7-3.4 kWh/m^2-cm (20,000-25,000 Btu/yd^2-in).

The energy requirements for operations 1 to 4 only include energy associated with the equipment used for pavement removal. The preferred approach for calculation of the energy requirements of recycling operations is to use a step-by-step procedure for each phase of the operation using energy data.[3]

Considerations for Final Selection

The following factors should be considered prior to final selection of the rehabilitation alternative:

1. Availability of equipment.
2. Availability of experienced contractor.
3. First cost.
4. Life cycle cost.
5. Traffic control.
6. Length of construction.
7. Impact on adjacent business.
8. Utility relocation and interference.

Selection of a Recycling Method

If recycling is chosen as a rehabilitation alternative, there is a variety of recycling methods available for rehabilitation of HMA pavements. The primary options are hot mix recycling, hot in-place recycling (HIR), cold in-place recycling (CIR), and full depth reclamation (FDR). These recycling methods offer a number of advantages, which include the following.[7]

1. Allow the use of existing material with the elimination of disposal problems.
2. The asphalt mix may be improved through changes to the aggregate and/or asphalt binder.
3. The pavement profile may be corrected and the ride improved.
4. Cost reductions may be achieved over conventional rehabilitation methods.

The following section is divided into two parts. In the first part, each of the different recycling methods is discussed along with its advantages and disadvantages. In the next part, general guidelines for selection of a recycling process are presented.

Hot mix recycling or hot recycling is a method in which the RAP is combined with new aggregate and an asphalt cement or recycling agent to produce hot mix asphalt (HMA). Both batch and drum type hot mix plants are used to produce recycled mix. The RAP is obtained from pavement milling with a rotary drum cold planing machine and may be further processed by ripping and crushing operations, if needed. The mix laydown and compaction equipment and procedures are same as for conventional HMA. The ratio of RAP to new aggregates depends on the mix design, on the type of hot mix asphalt plants, and on the quality of stack emission generated. Typical RAP to aggregate proportions vary between 10:90 to 30:70, although a maximum of 50:50 have been reported for drum mix plants. The use of microwave technology has allowed the use of a higher amount of RAP, because the RAP can be preheated. The advantages of hot mix recycling are as follows.[8]

1. Significant structural improvements can be obtained with little or no change in thickness by improving the existing asphalt materials.
2. Additional right-of-way is not needed.
3. Surface and base distortion problems can be corrected
4. Performance of recycled mix is as good as conventional HMA mix.

Hot in-place recycling is a method which is performed on site with the RAP material obtained from the existing pavement. The deteriorated asphalt pavement is heated and softened to allow it to be scarified or mixed to a specified depth. If required, new hot mix material and/or recycling agent is added to the RAP material. In this method, the existing pavement is typically processed to a depth of 20 mm (¾ in) to 40 mm (1½ in). The process can be carried out as a single-pass or as a multiple-pass operation. In the single-pass operation, the scarified existing pavement material is combined with new material, if needed, and compacted. In a multiple-pass operation, the scarified material is recompacted and then the new wearing surface is applied after a prescribed interval. The advantages offered by this method include the following:[9]

1. Cracks are interrupted and filled.
2. Aggregate which has lost the asphalt binder coating through stripping, is remixed and recoated.

3. Ruts and holes are filled, shoves and bumps are leveled, drainage and crowns are re-established.
4. Flexibility is restored by chemically rejuvenating the aged and brittle pavement.
5. Aggregate gradation and asphalt content may be modified by some variations of this process.
6. Enhances highway safety through increased frictional resistance.
7. Reduces interruptions in traffic flow when compared to other conventional rehabilitation techniques.
8. Hauling costs can be minimized.
9. Aggregate and asphalt binders are conserved.

In the cold in-place recycling method, existing pavement materials are used along with recycling agent. The depth of treatment is typically from 75-100 mm (3-4 in). Although, in some cases, virgin aggregate may be added to the recycled material to change or improve the RAP characteristics, normally this procedure is carried out without transportation of any material except the recycling agent. The technique consists of pulverization of the existing pavement, sizing of the RAP, addition of recycling agent and the placement and compaction of the recycled mix. The newly developed recycling trains consist of large cold milling machine with a screening and crushing unit, and a mixing device attached to it. Conventional HMA laydown and compaction equipment are used to pick up the processed material from windrow, and subsequent placement and compaction. The advantages of cold in-place recycling include the following:[10]

1. Significant pavement structural improvements may be achieved without changes in horizontal and vertical geometry and without shoulder reconstruction.
2. All types and degrees of pavement distress can be treated.
3. Reflection cracking normally is eliminated if the depth of pulverization and reprocessing is adequate.
4. Pavement ride quality is improved.
5. Hauling costs can be minimized.
6. Old pavement profile, crown, and cross slope may be improved.
7. Production rate is high.
8. Only thin HMA overlay or chip seal surfacing is required on most projects.
9. Engineering costs are low.
10. Aggregate and asphalt binder are conserved.
11. Energy is conserved.
12. Air quality problems resulting from dust, fumes, and smoke are minimized.
13. Frost susceptibility may be reduced.
14. Pavement widening operations may be accommodated.

Full depth reclamation is a recycling technique in which all of the HMA layer and a predetermined amount of underlying materials are treated to produce a stabilized base course. The different types of additives which can be used for improving the quality of the base include asphalt emulsion and chemical agents such as calcium chloride, portland cement, fly ash, and lime. In some cases, new material is added to obtain a required depth of the improved base. In general, the technique consists of pulverization, introduction of additive, shaping, compaction, and application of a surface or wearing course. The advantages offered by full depth reclamation include the following:[11]

1. Cost effective method for creating improved sections and ride quality.

2. Eliminates potential reflective cracking of new overlays.
3. Recycles existing materials saving natural resources and energy.
4. Process is accomplished in-place.
5. Heating, mixing, and hauling costs of conventional maintenance techniques can be eliminated.
6. Roadway cross section can be maintained or adjusted; grade can be lowered in curbed sections to regain curbs or reshaped in poor draining sections to improve drainage.
7. Emergency and local traffic can usually continue to use roadway during construction.
8. Eliminate material disposal concerns.
9. Improved resistance to frost penetration of subgrade.
10. Savings realized by reducing total pavement thickness.

All of the different recycling techniques offer some advantages over conventional rehabilitation techniques. However, the choice of a particular recycling method should be primarily on the basis of the type of distress shown by the existing pavement. This is because all of the recycling methods are not equally suited for treating different types of distress, and hence the choice must be made for the particular method which is capable of rectifying the existing distress conditions. The applicability of a particular recycling technique not only depends on the pavement defect, but also on the extent and severity of the distress. For this reason, a comprehensive evaluation of the existing pavement is necessary before attempting any recycling process. Once the type, extent and diversity of distresses have been identified, candidate recycling procedures should be evaluated on the basis of their effectiveness and cost. The type of distresses recognized by ARRA are discussed in the following sections.[9] Attempt should be made to quantify pavement distress by using available methods such as SHRP pavement distress manual SHRP-LTPP/FR-90-001.[12]

Pavement distresses can be primarily grouped into six categories: (1) surface defects, (2) deformation, (3) cracking, (4) maintenance patching, (5) base/subgrade problems, and (6) poor ride/roughness.[1] The different terms are explained in the following sections.

(1) Surface defects: This type of defect includes raveling, bleeding (flushing), and skid hazard (slipperiness). Raveling is the progressive deterioration of the pavement surface caused by the loss of aggregate particles. Initially fine particles are lost followed by coarse aggregate becoming dislodged as the condition becomes more severe. Figure 3-5 shows a pavement with raveling. The cause of raveling is poor quality mixture, inadequate compaction, and excessive hardening of the binder. In the case of bleeding, an excessive amount of asphalt migrates to the pavement when the application rate was too high or cover aggregate loss has occurred. Figure 3-6 shows a bleeding surface. Loss of frictional resistance (skid hazard or slipperiness) occurs as a result of polished aggregate and resulting smooth pavement surface. This condition is particularly hazardous when the pavement is wet and has a film of water on the surface.

(2) Deformation: The different types of deformation include corrugations (wash boarding), wheelpath rutting and shoving. Corrugations are ripples formed laterally across an asphalt pavement surface. These occur as a result of lack of stability of the HMA at location where traffic starts and stops or on hills where vehicles brake downgrade. Figure 3-7 shows corrugation on a HMA pavement. The causes of the lack of stability are too much or too soft asphalt, a high sand content and excessive presence of smooth and rounded aggregate in the mix.

Figure 3-5. Raveling.

Figure 3-6. Surface bleeding.

Shoving occurs as localized bulging of the pavement surface. A typical example is shown in figure 3-8. The cause of this type of distress is a lack of mix stability.

Rutting is the occurrence of longitudinal surface depressions or channels in the wheel path. Figure 3-9 shows an example of rutting. This distress may be caused by an unstable mixture with very low air voids or excessive wheel loads and tire pressure.

(3) Cracking: The different types of load and non-load associated cracks include alligator cracks, wheel path cracks, pavement edge cracks, slippage cracks, block cracks, longitudinal joint cracks, transverse cracks, and reflection cracks.

Alligator cracking is shown in figure 3-10. These are interconnected cracks that create a series of small pieces resembling an alligator's skin or chicken wire. This type of distress may be caused by excessive deflection of the pavement surface over an unstable subgrade or base courses of the pavement, or due to repeated loads that exceed the load-carrying capability of the pavement.

Wheel path cracks appear as fractures or separation within the wheel paths. The cracking begins as single or multiple longitudinal cracks and progresses with time to a pattern resembling alligator cracking.

Pavement edge cracks are longitudinal cracks within 0.3 to 0.6 mm (1 to 2 ft) of the outer edge of the pavement or at the joint between a pavement and widening. The cracking is due to the lack of lateral (shoulder) support, base weakness frost action, and inadequate drainage.

Slippage cracks are typically crescent or half-moon shaped cracks produced when vehicles brake or turn which cause the pavement surface to slide or push. This is caused by a low strength HMA or a lack of bond between surface and lower courses.

Block cracks are interconnected large cracks with sharp angles or corners. Figure 3-11 shows a typical block cracking. Such cracks occur due to shrinkage of asphalt mix because of volume changes in the base or subgrade.

Longitudinal joint cracks develop at construction joints because of poorly paved joint or improper construction technique. A typical example is shown in figure 3-12.

Transverse cracks occur across the pavement centerline and are caused by shrinkage from temperature changes and/or hardening of asphalt. Figure 3-13 shows a pavement with transverse cracks.

Reflection cracks are cracks in asphalt overlays caused by cracks in the pavement structure underneath. A typical example is shown in figure 3-14.

(4) Maintenance Patching: A patch is an area of distressed pavement which has been repaired with new mixture (deep or pothole patching) or the placement of a thin overlay (skin patching).

The patching may be only a seal coating of the distressed area (spray patching). Figure 3-15 shows an example of maintenance patching.

Figure 3-7. Corrugation.

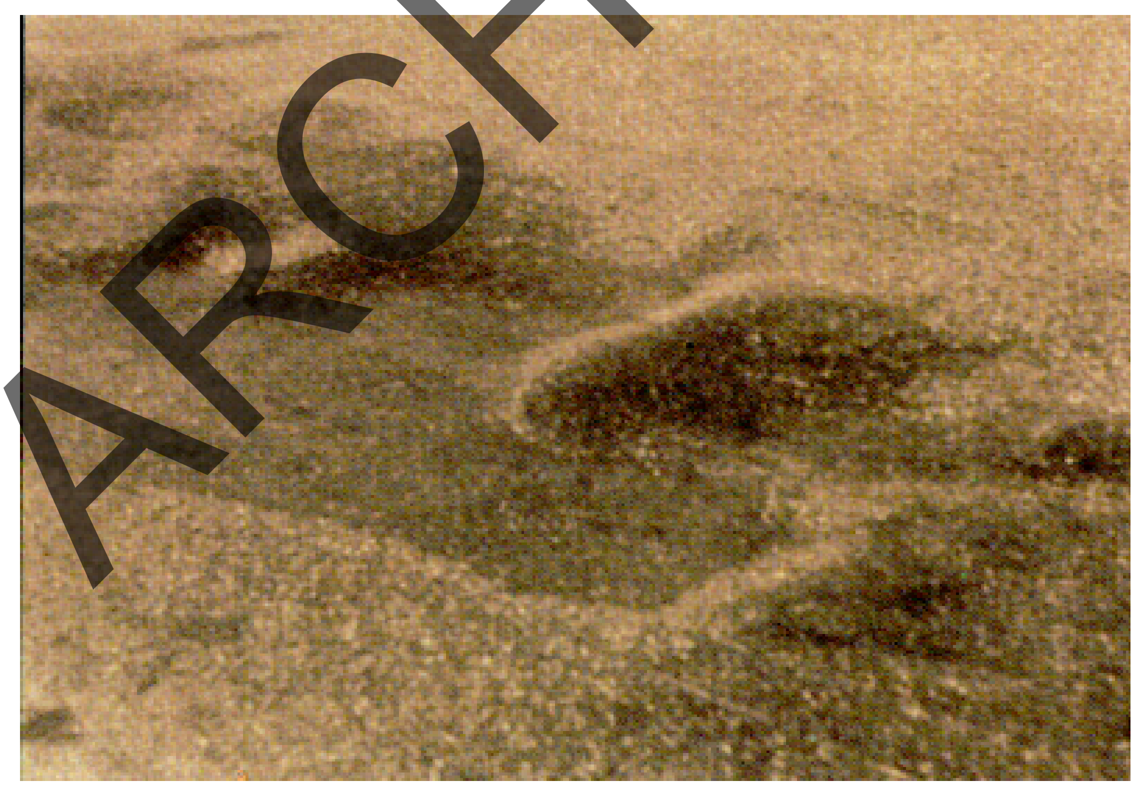

Figure 3-8. Shoving.

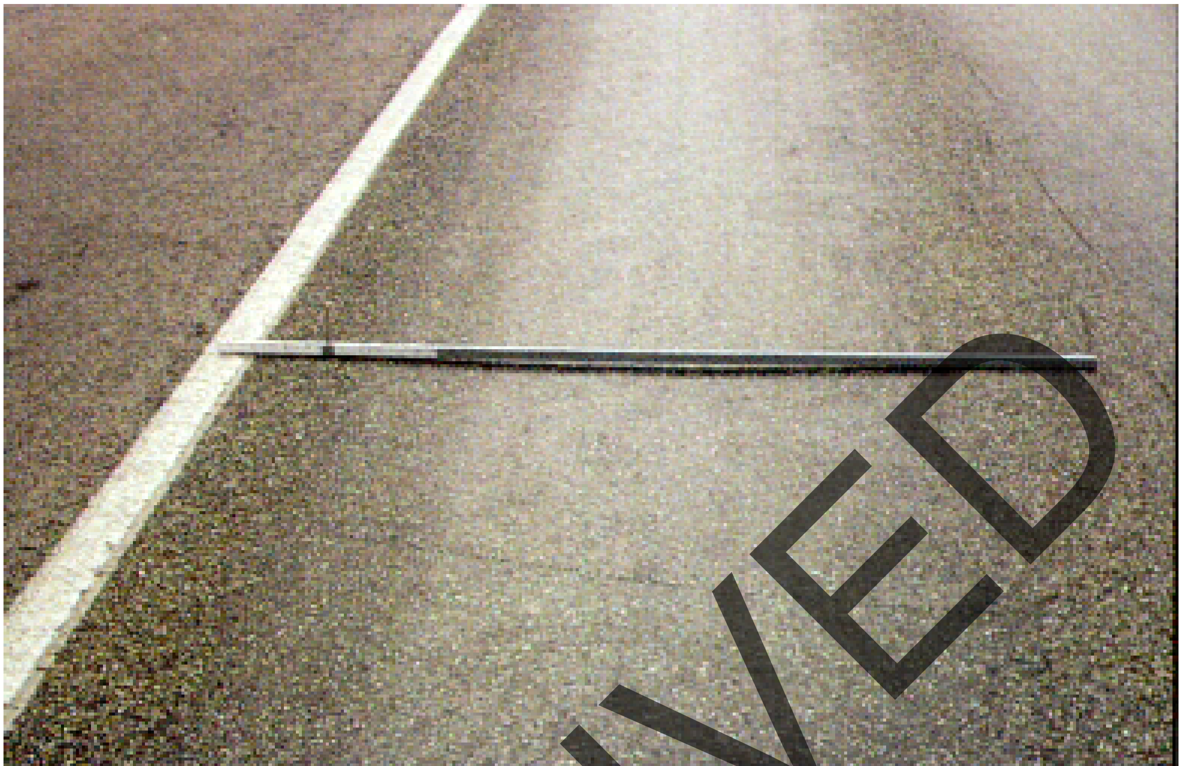

Figure 3-9. Rutting.

Figure 3-10. Alligator cracking.

Figure 3-11. Block cracking.

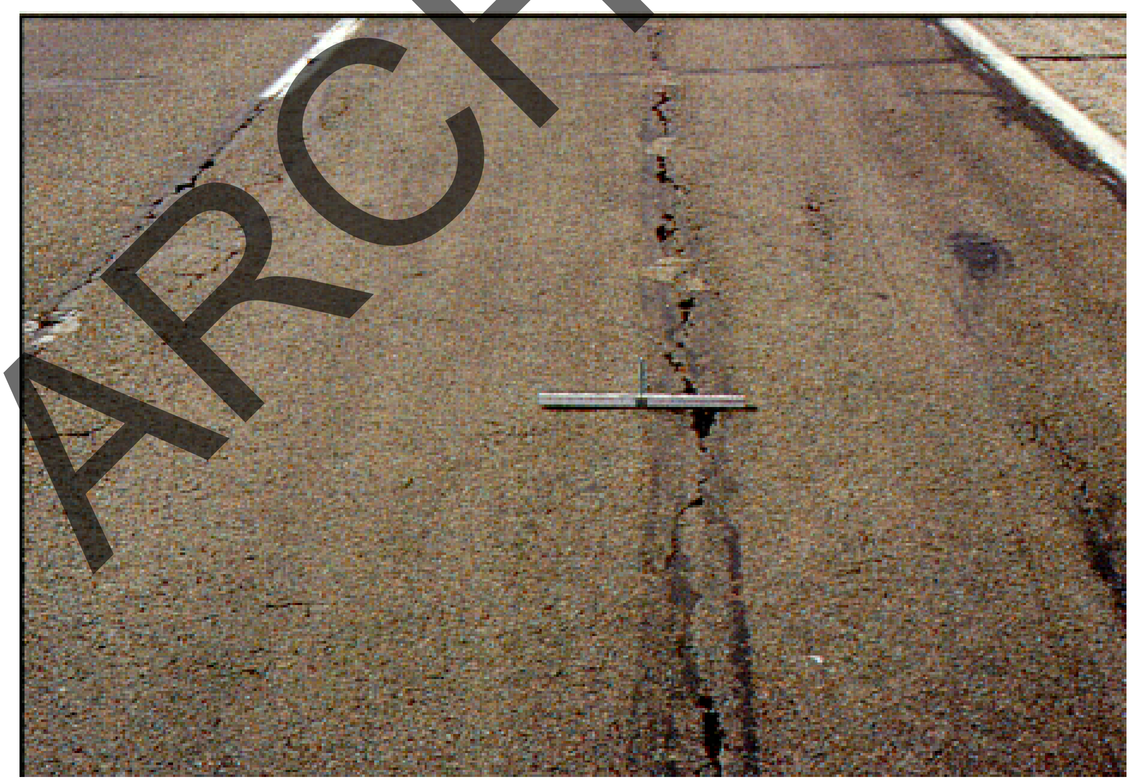

Figure 3-12. Longitudinal joint cracking.

Figure 3-13. Transverse cracking.

Figure 3-14. Reflection cracking.

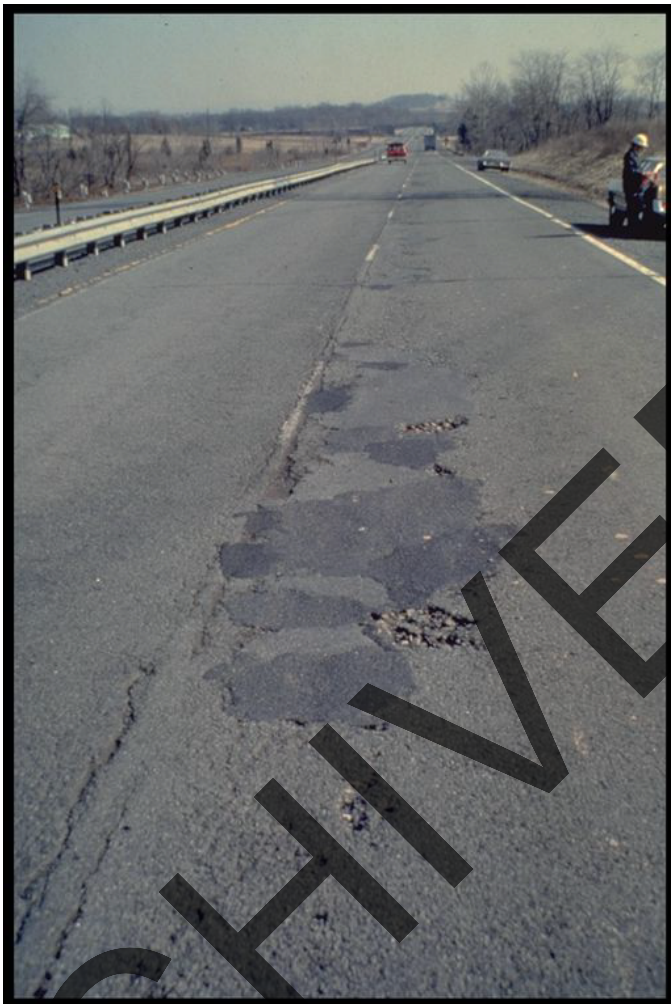

Figure 3-15. Maintenance patching.

(5) Problem Base/Subgrade: An unstabilized or poorly drained base or subgrade can result in severe cracking, settlement and rutting of an asphalt pavement. A wet, soft base or subgrade can result in very low strength and possible pumping/displacement of materials to the surface through cracks in the pavement.

(6) Ride Quality/Roughness: General unevenness is defined as the overall ride quality with consideration given to the general smoothness of the pavement. Depressions are low areas which were created during the paving operation or caused by localized settlement.

High spots are high areas in the pavement caused by paving operation or frost heaving or swelling of the subgrade soil.

Based on these distresses, the ARRA recommends table 3-2 as a guideline for selecting a recycling alternative. A detailed discussion of applicability for the use of different recycling techniques and considerations is presented in table 3-3.

Table 3.2. Guide for selection of recycling method.(7)

Type of Pavement Distress	Hot Recycling	Hot In-Place Recycling	Cold In-Place Recycling	Full Depth Reclamation
Surface Defects				
Raveling	x	x[2]		
Bleeding (flushing)	x	x[5]		
Slipperiness	x	x[2]		
Deformation				
Corrugations (washboarding)	x	x[5]		
Rutting - shallow[3]	x	x[5]		
Rutting - deep	x		x[6]	x[6,7]
Cracking/Load Associated				
Alligator	x		x	x
Longitudinal - wheel path	x	x[8]	x	x
Pavement edge	x		x	x
Slippage	x	x[9]		
Cracking/Non-Load Associated				
Block (shrinkage)	x		x	x
Longitudinal-joint	x	x[10]		
Transverse (thermal)	x		x	x
Reflection	x		x	x
Maintenance Patching				
Spray	x[11]		x[11]	x
Skin	x[11]		x[11]	x
Pothole	x		x	x
Deep (hot mix)	x		x	x
Problem Base/Subgrade (Soft, Wet)				x
Ride Quality/Roughness				
General unevenness	x	x		
Depressions (settlement)	x[12]	x[12]		x[13]
High spots (heaving)	x[12]	x[12]		x[14]

Notes:

1. A pavement in which asphalt mixtures are used for all courses above the subgrade or an improved subgrade having portland cement, lime, lime-fly ash, fly ash or calcium chloride modification.
2. Applicable if the surface course thickness does not exceed 1½".
3. Rutting is limited to the upper portion of the pavement structure (top 1½ - 2").
4. Rutting is originating from the lower portion of the pavement (below surface course and includes base and subgrade).
5. May be a temporary correction if entire layer affected not removed or treated by the addition of special asphalt mixtures.
6. The addition of new aggregate may be required for unstable mixes.
7. The chemical stabilization of the subgrade may be required if the soil is soft, wet.
8. Applicable if the cracking is limited to the surface course of the pavement.
9. Applicable if the treatment is to a depth below the layer where the slippage is occuring.
10. Applicable if the cracking is limited to the surface course of the pavement.
11. In some instances, spray and skin patches may be removed by cold planing prior to these treatments (considered if very asphalt rich, bleeding).
12. May be only a temporary correction if the distress related to a subgrade problem.
13. Used if depressions due to a soft, wet subgrade condition.
14. Used if the high spots caused by frost heave or swelling of an expansive subgrade soil.

Table 3-3. Applicability and consideration for different recycling procedures.

Process	Applicability	Considerations
1. Hot Mix Recycling	Can be used to treat surface defects, deformation, load and non-load associated cracks, and maintenance patching. Material obtained from an existing pavement can be stockpiled for future use. Also, stockpiled RAP material can be carefully blended in a plant with other materials to achieve proper mix.	Percentage of RAP that can be used depends on recycling mix properties and the type of hot mix plant. RAP/virgin material blend is typically 10:90 to 30:70, with a maximum of 50:50 (drum plant).
2. Hot In-Place Recycling	Can be used to treat surface defects, corrugation and surface rutting, and longitudinal and slippage cracking up to 50 mm (2 in) depth. The existing pavement material can be used fully, resulting in a minimal demand for virgin materials. Hence, substantial savings in transportation cost can be realized. This method can reduce rehabilitation time significantly, and is particularly suitable for busy highways or streets which cannot be kept closed for a long time.	Hot in-place recycling can involve significant amounts of heavy machinery and equipment. Because of high mobilization costs, there should be enough work in a particular area (either for a single project or for a number of projects) to make this process cost effective. Also, since this method frequently involves long equipment trains, it may not be suitable for local residential streets with very limited space for maneuvering of equipment . This process can produce air quality problems, for pavements with a significant amount of patches made with liquid bituminous materials and/or crack sealing material.
3. Cold In-Place Recycling	Can be used to treat rutting in asphalt layers below the surface; load associated block and thermal cracks; and maintenance patching. The existing pavement material can be used fully and, therefore, substantial savings can be achieved by avoiding transportation of new materials. Also, since no heat is used in this technique, there are no air quality concerns associated with it, and savings are also realized in energy and money. This method can improve the structural capacity on an existing pavement. Also, disturbance to traffic is limited and can be used for busy highways which cannot be kept closed for a long time.	In most cases cold in-place recycled materials require a curing period, followed by an application of a wearing course. Although smaller machines are available, this technique can involve long trains which may not be suitable for local residential streets with very limited space for maneuvering of equipment.

Table 3-3. Applicability and consideration for different recycling procedures (continued).

Process	Applicability	Considerations
4. Full Depth Reclamation (FDR)	Can be used to treat rutting in layers below the surface, including base; load associated, block and thermal cracking; and maintenance patching. This technique is particularly suitable for pavements with base problems or insufficient structural capacity. Since this is basically a cold in-place process, it has all the advantages of cold in-place recycling, including savings in transportation cost and energy and no occurrence of air quality problems due to emissions. Different manufacturers have large single machines which can complete this process in a single pass.	Full depth reclamation usually results in a new base, which must be covered with an appropriate wearing course. As in cold in-place recycling, a significant amount of curing period may be required. At present, there is a lack of proper construction guidelines and specifications for FDR, and the whole process must be supervised by an experienced person. Since in this method, a part of non-asphalt layer is also recycled, the resulting mix must be carefully monitored for any contamination by undesirable material (such as vegetation or large chunks of RAP).

SUMMARY

Recycling is one of the many alternatives available for rehabilitation of pavements. Rehabilitation is required to keep pavements at a serviceable condition in terms of surface roughness, distress or frictional resistance. Without rehabilitation, pavements can deteriorate at a faster rate and ultimately cost much more to maintain than pavements maintained at a certain level of serviceability with the help of proper rehabilitation. Different rehabilitation alternatives include various types of seal coats. The particular choice of the rehabilitation technique should be based on life cycle costs and the one with the lowest life cycle cost should be considered. But simultaneously, engineering considerations should also be made. The important engineering consideration include present quality of pavement, type, extent and severity of distress, the amount of traffic, and the structural condition of the pavement. Economic considerations can be made by evaluating the cost of the pavement by any of the different methods such as present worth or equivalent uniform annual cost. The user costs and salvage value of the pavement should be accounted for. Consideration to energy requirements can also be made by calculating energy expenditure for each phase of operation. The choice of a particular technique also depends on availability of equipment, experienced contractor, initial cost, and construction impact on traffic. Except asphalt surface recycling, all other types of recycling can substantially improve the structural capacity of a pavement. In addition, recycling offers substantial savings in cost of material and haulage, helps in resource conservation, can improve pavement performance, and help maintain original pavement geometries and thickness. Recycling can be combined with overlays also. The relative advantages and disadvantages of the different recycling alternatives should be considered before making a decision. Among other things, the merits and demerits should include considerations about economy, removal of distress, effective quality control and traffic disruptions.

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CHAPTER 4. ECONOMICS OF RECYCLING

INTRODUCTION

Although started as a method of reusing waste materials, recycling of asphalt pavement has proved to be a cost effective method of pavement rehabilitation. When properly selected, all the different types of recycling methods are usually cheaper than the conventional rehabilitation methods, even though the relative savings will depend on the kind of recycling technique used. The primary saving in hot and cold mix recycling comes from savings in the cost of virgin asphalt cement, whereas the savings in hot in-place recycling comes by elimination of transpor-tation cost and use of very little amount of virgin material. The major savings in the case of cold in-place recycling comes by eliminating the need for fuel or emission control system, since the process is done at ambient temperature, elimination of transportation costs, and the addition of only a small percentage of virgin asphalt binder. The objective of this session is to present the economics associated with the use of recycled asphalt materials. Expenditures and cost comparisons with the use of conventional HMA mixes are summarized from available literature.

Estimated price associated with pavement construction, reconstruction and recycling operations are presented in this chapter. These prices have been collected from available literature. Whenever possible, prices collected from literature published in or after 1990 are generally reported. It should be noted that recycling costs have changed over the years because of continual developments in the recycling technology and equipment. If costs for these operations are available from state or local agency records or from local contractors, they should be used instead since a large price variation can be expected depending on the location of the project and the time of construction.

As presented here, the pavement cost is defined as the amount of monies that a contractor must spend for labor, materials, equipment, subcontractors, and overhead to construct, rehabilitate or maintain a pavement structure.[1]

COST AND SAVINGS ASSOCIATED WITH HOT MIX RECYCLING

The cost associated with recycling can be presented on a material cost as well as construction cost basis. Although construction cost may be a more valid approach, an example of material cost comparison is also presented here. This example shows the amount of savings that can be made by using recycled asphalt pavement (RAP) instead of using virgin material.[2] Considering $5 per ton and $120 per ton as average costs of aggregate and liquid asphalt, respectively, the cost of a 100 percent virgin mix with 6 percent asphalt comes out to be $11.90 (see table 4-1). If the contractor uses a half-lane milling machine and hauls the RAP back to the HMA plant, his/her total cost for RAP is $3.70 per ton, considering $1.70 per ton for machine and labor for milling, and $2.00 per ton for trucking cost. Hence the savings, compared to using virgin material, is $8.20 per ton, as shown in table 4-1. Table 4-2 shows the savings in using different percentages of RAP. It should be noted that these savings are in first cost. Limiting life cycle costs, if any, must be considered when using excessive amounts of RAP in recycled mixes. Typical cost savings with hot mix recycling are shown in tables 4-3 and 4-4.

Table 4-1. Comparison of cost for virgin and RAP mix.[2]

Item	Cost per ton ($)	Percent used (%)	Total Cost ($) per ton
Aggregate	5.00	94	4.70
Asphalt Binder	120.00	6	7.20
Virgin Mix			11.90
RAP			
Trucking	2.00		2.00
Milling	1.70		1.70
RAP Mix			3.70
Savings in using 1 ton of RAP instead of 1 ton of virgin mix			8.20

Table 4-2. Savings by using RAP (based on reference 2).

Percent of RAP	Cost/Ton	Savings, $/ton	Savings, %
0%	11.90		
20%	10.26	1.64	14
30%	9.44	2.46	21
40%	8.62	3.28	28
50%	7.80	4.10	34

HOT IN-PLACE RECYCLING

There are three primary types of hot in-place recycling, as recognized by the Asphalt Recycling and Reclaiming Association (ARRA). These are: surface recycling, repaving, and remixing.

Surface recycling to a depth of 25 mm (1 in) and addition of a recycling agent costs approximately $1.25/m^2 ($1.00/yd^2).[3] A cost of approximately $2.05/m^2 ($1.64/yd^2) is required for an additional 25-mm (1-in) overlay. Hence the total cost of recycling and overlaying by two-pass method will be approximately $3.3/m^2 ($2.64/yd^2).[3] In the repaving method, placement of a 25-mm (1-in) overlay along with recycling of the top 25 mm (1 in) of an existing pavement will cost approximately $3.62/m^2 ($2.90/yd^2).[4,5] A maximum of 25 percent cost savings over cold milling and conventional overlaying procedure has been reported.[6] The cost of cutting 25 mm (1 in) and remixing with 10 to 20 percent of virgin aggregate is approximately $2.24/m^2 ($1.79/yd^2).[6] Typical remixing price in Canada is reported to be between $2.78 and $3.70/m^2 for a 50-mm treatment depth (between $2.22 and $2.96/yd^2 for a 2-in treatment depth).[7]

Table 4-3. Summary of cost savings - FHWA survey (1984).

Area	Total Tonnage (1000) 1984	Average Savings Per Ton ($)	Average % Savings vs. 100% New Material(s)	Total Savings ($1000)
Northeast	500	2.80	10	1,400
Southeast	4,000	5.67	20	22,300
North-central	12,000	5.26	18	62,600
South-central	2,000	5.32	20	10,000
Central-western	1,600	5.12	21	8,200
Total	20,000	---	---	104,500
Average	---	4.83	18	---

Table 4-4. Typical cost savings.

Agency	Year(s)	% Average Savings
Florida DOT	1981-1983	24-26
Saskatchwan	1985	20-30
U.S. Corps of Engineers	1986	16
Wisconsin DOT	1980-1985	39-49

In a 101,156 m^2 (121,000 yd^2) repaving job in Florida, it was found that the recycling process used 2.6 trillion joules (2.5 billion BTU) less energy than that required by a conventional method. This was found equivalent to an energy savings of 32 percent.(8)

Table 4-5(6) presents a recent summary of cost and savings data and case histories. The estimated savings over conventional construction methods ranges from 17 to 50 percent.(6)

COLD IN-PLACE RECYCLING

The reported costs of cold in-place recycling are shown in Table 4-6.(8) The representative cost varies from approximately \$1.71/m^2 (\$1.37/yd^2) to \$9.87/m^2 (\$7.90/yd^2) depending upon many factors such as depth of recycling, equipment type, and thickness of overlay. The reported relative savings of using cold in-place recycling in lieu of conventional construction methods are also shown in table 4-6. The initial savings have varied from 6 to 67 percent.

The mean cost from Oregon DOT cold in-place recycling projects in the 1989-1990 period was reported to be $2.51/m^2$ ($2.0/yd^2$) for a 50-mm (2-in) cold in-place recycling with a chip seal, and about $1.80/m^2$ ($1.44/yd^2$) without a chip seal.[9]

The mean cost for 48 New Mexico cold-in-place recycling projects ranged from $0.13 to $0.44/m-cm^2$ ($0.27 to $0.92/yd-in^2$), with a mean of $0.26/m-cm^2$ ($0.54/yd-in^2$).[9] Recycling cost increases with an increase in the use of virgin aggregates.

On a per square meter per cm basis cost of recycling is reduced with an increase in depth of cold in-place recycling. For the New Mexico state projects, the mean cost per square meter per centimeter have been reported to be $0.31 for 75 mm ($0.64/yd-in^2$ for 3 in), $0.27 for 85 mm ($0.56/yd^2$-in for 3.4 in), $0.25 for 10 cm ($0.52/yd^2$-in for 4 in), and $0.21 for 11.3 cm ($0.44/yd^2$-in for 4.5 in) of cold in-place recycling.[9]

A recent study shows that the CIR savings in New Mexico amount to approximately $1.90/m^2$ ($1.52/yd^2$) in initial cost and $2.05/m^2$ ($1.64/yd^2$) on the basis of life cycle costs. Figure 4-1 shows typical sections resulting from conventional rehabilitation and recycling operations. Cost figures based on initial cost and life cycle cost are also indicated in the figure. The savings on a life cycle basis results from reduced frequency of maintenance for CIR pavements. Generally, maintenance for cracking is required after every four years for mill and overlay projects, whereas maintenance for cracking is required after eight years for CIR projects.

FULL DEPTH RECLAMATION

Cost comparisons of conventional rehabilitation technique and recycling with full depth reclamation and HMA wearing course are given in table 4-7.[10] In this case, the cost of recycling ($7.25/m^2$, $5.80/yd^2$) is less than one half of the conventional reconstruction technique ($16.12/m^2$, $12.90/yd^2$).

GENERAL BENEFITS OF RECYCLING

Apart from savings in materials, recycling saves money by avoiding transportation cost and cost of filling up landfill space. Recycling reuses non-renewable resources. Hence it should be considered even if the cost of recycling is equal to the cost of conventional rehabilitation. Also, in some cases where overlays are restricted to maintaining underpasses, or avoiding raising guard rails, recycling is a better option compared to conventional rehabilitation methods.

Table 4-5. Summary of selected case histories of hot in-place recycled pavements.[6]

Agency/ Date Recycled	Cost Information	Description of Job	HIR Process Used	Milling Depth/ Overlay Depth	Rejuvenating Agent	Mix Temperature
Repaving Process						
FAA, Carrabelle, FL 1990	\$4.28/m^2 (\$3.42/yd^2)	Thompson Field Airport. 30 m x 1212m (98 ft x 696 ft) runway	Repave	25 mm/25 mm (1 in/1 in)	Unknown	Unknown
Florida DOT 1979	\$2.99/m^2 (3.39/yd^2). A savings of 25% estimated	US 41, Ft. Myers, FL 3.9 km (2.4 mile), 6-lane. ADT- 39,000	Cutler Repave	25mm/19mm (1 in/3/4 in)	EA-SS-1 0.27 1/m^2 (0.06 gal/yd^2)	79º-121ºC(175ºF to 250ºF)
City of Phoenix 1990	\$3.59/m^2	City collector street. 800 m^2 (10,000 yd^2)	Cutler Repave	19mm/25mm (3/4 in/1 in)	Yes, Type and quantity Unknown	Unknown
Lee County, Iowa 1990	\$3.41/m^2	Rural roads X-38 and X-48	Cutler Repave	19mm/25mm (3/4 in/1 in)	Elf ETR-1 at 0.36 1/m^2 (0.08 gal/yd^2)	105ºC (221ºF)
Connecticut DOT 1981	\$4.33/m^2. 16% more than control	Rt. 15 at Westport, Connecticut 4.7 km (2.9 mile), 4-lane divided	Cutler Repave	25mm/25mm (1 in/1 in)	AE-300R 0.36 1/m^2	250ºF ± 30ºF by spec.
FAA Texarkana, Texas 1986	50 percent savings reported	Airport- 2011 m^2 (6598 ft^2) and 25 yr old	Cutler Repave	25mm/25mm (1in/1 in)	Type unknown 0.54 1/m^2 (0.11 gal/yd^2)	110ºC (230ºF)
Remixing Process						
Defense Construction Canada* 1989	\$3.58/m^2 for the 40mm/19mm -- \$4.17/m^2 for conv. 50 mm overlay	Airfield pavements at Canadian Forces Base, Edmonton, Alberta, 330,000 m^2 (412,500 yd^2)	Artec Remixer -- Only a small area was remixed	40mm/50mm (1.6 in/2 in) overlaid later; or 40mm/19mm (1.6 in/0.75 in) repave	RJO #3 at 0.4 1/m^2 (0.08 gal/yd^2)	120ºC (248ºF) behind paver was targeted value
Texas DOT 1991	\$2.15/m^2 for recycling portion only	IH-10 and SH-87 near Beaumont	Wirtgen Remixer	25mm to 31mm	ARA-1	About 116^{0}C(240ºF)

Table 4-5. Summary of selected case histories of hot in-place recycled pavements (continued).[6]

Agency/ Date Recycled	Cost Information	Description of Job	HIR Process Used	Milling Depth/ Overlay Depth	Rejuvenating Agent	Mix Temperature
Repaving Process						
Mississippi SHD 1990	Unknown. 40% savings reported	55 lane-km (34 lane-mile) of IH-59 in Lauderdale County	Wirtgen Remixer	38 mm + 15 kg/m^2 of new mix	Yes, unknown	110ºC (230ºF)
British Columbia Ministry of Highways* 1989	$1.70/m^2 for recycling only	Trans-Canada Highway (Rt 1) near Vancouver, 126 lane-km (78 lane-mile)	Artec and Taisei Remixers	38 mm to 63 mm (no new material added)	Unknown	105ºC (221^{0}F) minimum
Texas DOT 1987	$3.05/m^2 a savings of 34% over conventional	US 259 in Lone Star. Major arterial carrying heavy trucks	Cutler Remixer	38 mm + 17 kg/m^2 new mix	AC-5 used with new mix	93ºF (200ºF) behind screed
Texas DOT 1989	$2.57/m^2 including 30 kg/m^2 of new mix	IH-20 from Louisiana, border to FM450, 51 km, ADT-18,000 20% Trucks	Wirtgen Remixer	38 mm + 30 kg/m^2 new mix	ARA-1 at 0 to 0.71 1/m^2	110ºC (230ºF)
Oregon DOT 1987	17% savings estimated	82nd Ave from N.E. Wasco to S.E. Division a 5-lane major arterial	Taisei Remixer	Up to 50mm + various new mix	Non-emulsified product	Unknown
Texas DOT 1981	$1.59/m^2 including recycling, rejuv. agent and admixture	US 59 near Lufkin, 20,000 ADT	Wirtgen Remixer	50-38 mm + 20% new mix	ARA-1 at 0.1 0.45 1/m^2 (0.09 gal/yd^2)	107ºC (225ºF)
Louisiana DOT 1990	$4.59/m^2 including recycling, rejuv. agent and admixture	US 90 from LA 99 to Jennings	Wirtgen Remixer	38 mm + 30 kg/m^2 new mix	ARA-1 at 0.9 l/m^2. Elf AES-300RP used in a short section	

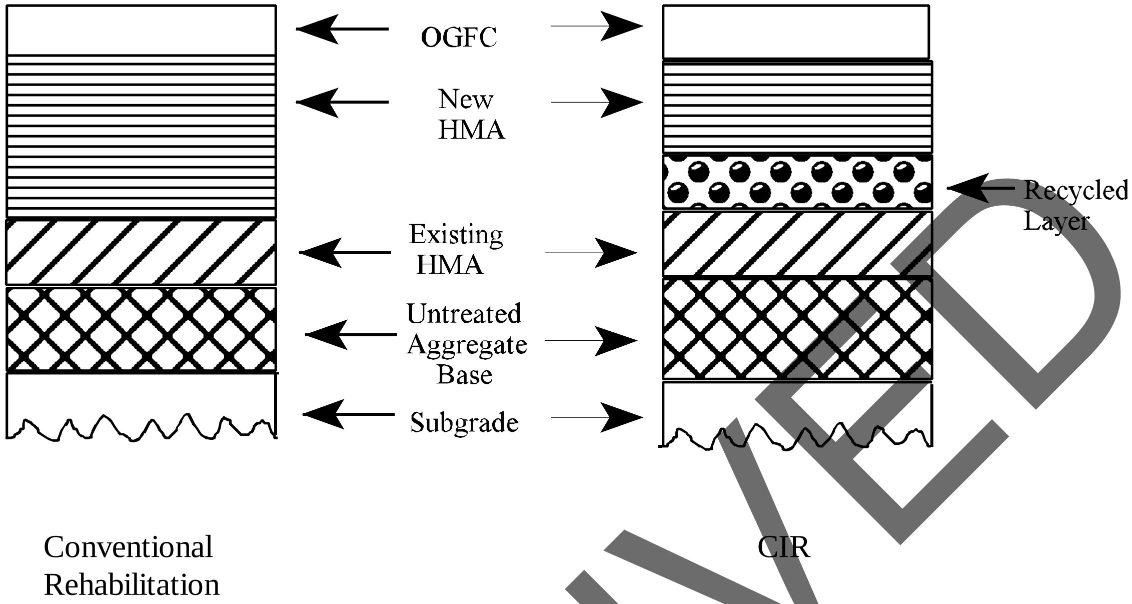
Note:
* Cost for jobs in Canada given in Canadian dollars.

Table 4-6. Full and partial depth cold in-place recycling cost differences.[8]

Agency	Year	Cost Difference (%)[a]		Cold In-Place Recycling ($)	
		Range	Rep. Value	Range	Rep. Value ($)
California	1979-83	15-43	31	16.16-26.73/Mg (14.71-24.32/ton)	22.15/Mg (20.16/ton)
California			37		24.17/Mg (22.00/ton)
California	1980		21		6.46/m^2 (5.17/yd^2)
Illinois	1982				4.75/m^2 (3.80/yd^2)
Indiana	1976			13.13-24.17/Mg (11.95-22.00/ton)	
Iowa	1988		67		7.58/Mg (6.90/ton)
Kansas	1977		53		
Kansas	1988				
Missouri	1978		50		
Montana	1978		21		23.72/Mg (21.59/ton)
New Mexico[b]	1984-86			1.31-2.5/m^2 (1.05-2.00/yd^2)	1.75/m^2 (1.40/yd^2)
N. Carolina[c]	1977		6		4.99/m^2 (3.99/yd^2)
Oklahoma	1979				4.32/m^2 (3.46/yd^2)
Oregon	1984		24	1.99-3.02/m^2 (1.81-2.42/ yd^2)	2.50/m^2 (2.00/yd^2)
Pennsylvania	1983		16		
Vermont	1978		28		9.87/m^2 (7.90/yd^2)
Vermont	1982		31		1.71/m^2 (1.37/yd^2)
Wisconsin	1978				0.14/m^2-cm (0.29/yd^2-in)
FHWA					5.9/m^2 (4.72/yd^2)

Notes:

[a] Relative to commonly used rehabilitation alternatives used by identified states.
[b] Personal communication with D. Hanson (1987).
[c] Cost increase on one project.



Initial Construction Cost:

Savings	Maximum	Minimum	Average
$/lane-km	14,296	1,593	7,094
$/square-m	2.81	0.53	1.90

Life Cycle Cost:

Rehab. Option	Initial Costs ($)	Maintenance Cost ($)	Total Cost ($)
Mill and Overlay (total)	8.780	0.314	9.090
CIR (total)	6.880	0.159	7.040
Cost Savings with CIR	1.900	0.155	2.050

Figure 4-1. Typical sections for conventional and recycled pavement.

Table 4-7. Cost comparison (full depth reclamation versus conventional reconstruction).[10]

Option	Cost
Fully reconstruct road: 1) excavate existing 75 mm (3 in) pavement and 45 cm (18 in) base gravel; 2) Place, grade and compact 45 cm (18 in) new gravel; 3) Pave with 65 mm (2½ in) HMA	\$16.12/m^2 (\$12.19/yd^2)
Full Depth Reclamation: 1) Full depth reclamation of existing pavement and base gravel with addition (twice) of liquid calcium chloride; 2) Add 50 mm (2 in) additional gravel; 3) Pave with 65 mm (2½ in) HMA	\$7.25/m^2 (\$5.80/yd^2)

SUMMARY

A review of current literature shows that savings up to 40, 50, 55 and 67 percent can be achieved by using hot mix, hot in-place, cold in-place recycling, and full depth reclamation, respectively. These savings are achieved when one of the recycling methods is used in place of conventional method or some other recycling method. In addition to the material and construction cost savings, significant amount of cost savings (in terms of user costs) can be realized by the reduced interruptions in traffic flow when compared with conventional rehabilitation techniques. Recycling can be used to rejuvenate a pavement or correct mix deficiency and conserve material and energy—options not available with the conventional paving techniques. A conventional overlay may require upgrading shoulders to maintain profile, raising guard rails to maintain the minimum safety standard, and restrict overlays below the bridges to maintain underpass height. On the other hand, recycling can effectively be used to maintain the highway geometry and thus resulting in substantial overall savings as well.

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CHAPTER 5. HOT MIX ASPHALT RECYCLING - BATCH PLANT (CONSTRUCTION METHODS AND EQUIPMENT)

INTRODUCTION

When properly designed and constructed, recycled hot mix asphalt (HMA) has proved to be at least equal to conventional HMA mixes. Of the various types of recycling options available, hot mix recycling is considered as a very useful and proven method. It can be used to correct mix design problems in existing pavements and make them better, to correct and maintain horizontal geometrics, or as a rehabilitation alternative where curb and bridge clearances are a problem. Hot mix recycling can use the same materials repeatedly, needs minor modification to existing equipment, eliminates disposal problem, and can be done in compliance with existing air pollution control standards.

Hot mix recycling, or hot recycling has been defined as a method by which reclaimed asphalt pavement (RAP) is combined with new aggregate and an asphalt cement or recycling agent to produce hot mix asphalt (HMA). The RAP may be obtained by pavement milling with rotary drum cold milling machine or from a ripping/crushing operation.[1]

REMOVAL OF THE EXISTING PAVEMENT

The two commonly used methods for removal of existing pavement are cold milling, and ripping and crushing. Each of the methods is described in the following sections.

Cold Milling

Of the two available methods for removing an existing pavement, cold milling is the most widely used today. The advent of cold milling has revolutionized the recycling of asphalt pavements. Cold milling has been defined[2] as the method of automatically controlled removal of pavement to a desired depth with specially designed equipment, and restoration of the surface to a specified grade and slope, free of bumps, ruts, and other imperfections. The Asphalt Recycling and Reclaiming Association (ARRA) guideline specification for cold milling requires that the milling machine be power operated, self propelled and self sufficient in power, traction and stability to remove a thickness of HMA surface to a specified depth. The machine should be able to provide a uniform profile and cross slope, and capable of accurately and automatically establishing profile grades within ± 3 mm (within ± 1/8 in) along each edge of the machine by referencing from the existing pavement by means of a ski or matching shoe, or from an independent grade line. A 12.2-m (40-ft) ski has been recommended by Brock.[3] The machine should have an automatic system for controlling grade elevation and cross slope. The machine should be equipped with a means to effectively control dust generated by cutting operation.[2] The ARRA has defined five classes of cold milling: (1) Class I consists of milling the existing surface to the extent necessary to remove surface irregularities, (2) Class II consists of milling the existing surface to a uniform depth as shown in the plans, (3) Class III consists of milling the existing surface to a uniform depth and cross slope as shown in the plans and/or special provisions, (4) Class IV consists of milling the entire depth of existing surfacing from the underlying base or subgrade, (5) Class V consists of milling to a variable depth of the existing surfacing as shown in the plans and/or special provisions.

The ARRA recommends that the surface resulting from cold milling operations should have uniform, discontinuous longitudinal striations or other uniform pattern and should not be gauged or torn.(2) Figure 5-1 shows a typical surface resulting from cold milling.(3) Milling should either stay above an interface or cut into the next layer. Milling to interface can result in delamination; shallow and flat depressions; and slabby RAP pieces.

Class I and II cold milling are recommended to be measured by the square meter (square yard) for specified thickness or by the square meter-mm (square yard-inch) for the actual square meters (square yards) milled times the mm (in) of depth milled. All other classes of cold milling should be measured by the Mg (ton).(2)

The basis of payment for cold milling should be the contract unit price per square meter (square yard) or per Mg (ton). The bid price should be full compensation for furnishing labor, materials, equipments, tools, and incidentals to complete the work.(2)

Improvements to the design of the milling teeth have helped in tremendous advancement of cold-milling machines since the seventies. Figure 5-2(4) shows the modern cold milling teeth. Improvement in size and power has lowered cold milling costs significantly. For example, for a 100-mm (4-in) cold milling the present cost can be as low as 30 percent of what it was in the seventies.(3) A front-load machine can pick up conveyor spillage automatically. A built-in broom system can be used to pick up most of the large pieces of the planed material and automatically load onto its drum and back onto the conveyor system. Crushing of RAP is achieved at the same time as milling.

Cold milling machines are available in various sizes and capacities (horse power). A full line of milling machines are available to suit different production requirements. The milling width can be from one meter to a full lane and the milling depth can be from 20 cm to 38 cm (8 to 15 in). Figures 5-3 and 5-4 show a one meter and a full lane cold milling machine, respectively.

Ripping and Crushing

The alternative to cold milling is ripping and crushing operations with earthmoving equipment, scarifiers, grid rollers or rippers (figures 5-5 and 5-6). The material is loaded into trucks and hauled for crushing. The type of ripping equipment to be used depends on the maximum size of the RAP that the crusher can handle. This method is particularly applicable where an existing roadway is to be upgraded for heavier traffic and is of uniform material.(5)

The major advantage of cold milling over ripping and crushing is that crushing of RAP is achieved at the same time and hence results in higher production rate. There is also no heat, and minimal dust is produced. However, unlike ripping and crushing, cold milling produces a greater amount of fines.(4)

Figure 5-1. A typical surface resulting from cold milling.

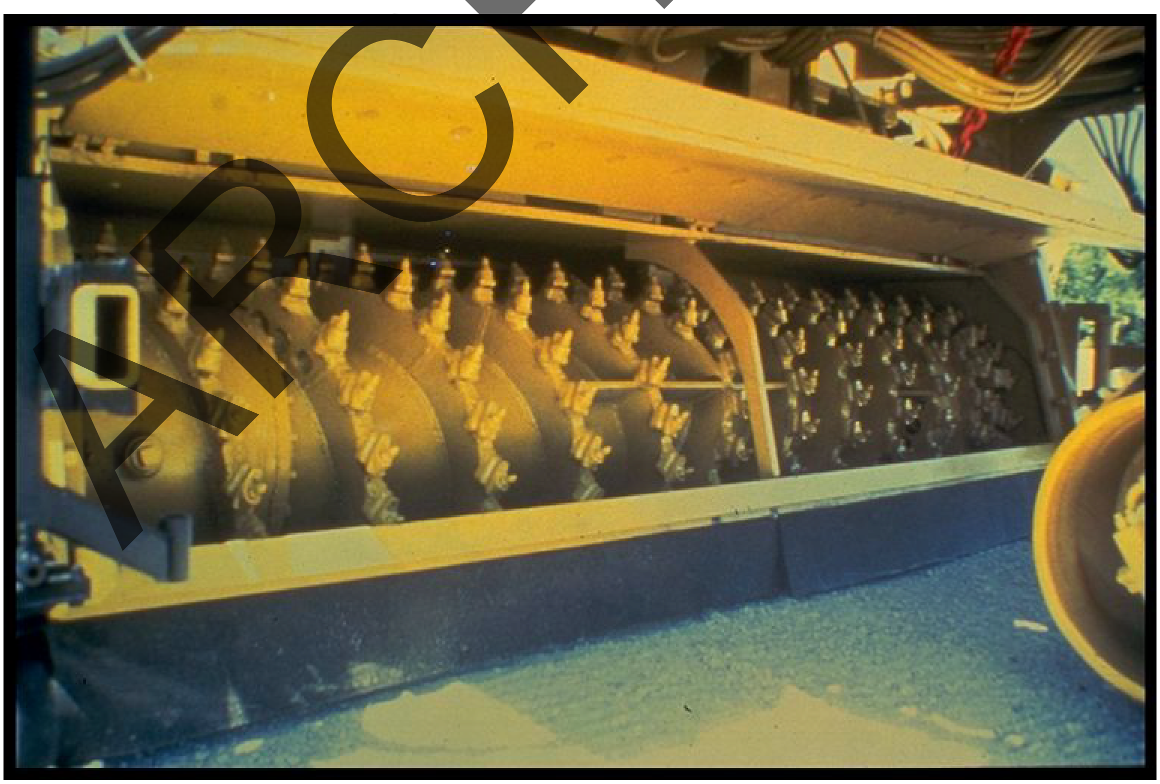

Figure 5-2. Teeth on drum of cold-milling machine.

Figure 5-3. A one-meter cold milling machine.

Figure 5-4. A full lane cold milling machine.

Figure 5-5. Pavement ripping with dozer.

Figure 5-6. Dozer with rear-mounted ripper tooth.

Figure 5-7. Ripping and crushing operation.

CRUSHING AND STOCKPILING

The objective of crushing is to reduce the RAP to the maximum acceptable particle size. One example of such a limit is that at least 95 percent of the RAP pass the 50 mm (2 in) sieve.[6] Cold milling machines can crush the RAP in-place, whereas in the ripping/crushing operation, front-end loaders are generally used to break up the pavement material so that it can be loaded into a truck for crushing at a central plant. The amount of aggregate degradation by cold milling is a function of the aggregate top-size and gradation of the HMA pavement.[4] For crushing in a central plant, different types of crushers are available, for example, compression crushers and impact crushers. A "RAP-breaker" or "lump-breaker" is also used between bin and the belt for size reduction (figure 5-8).

Impact crushers are most widely used in recycling. This is because compression crushers, such as jaw crushers (figure 5-9) sometimes get plugged up with RAP material. Impact crushers are used both as primary and secondary crushers. In a horizontal impact crusher (figure 5-10), solid breaking bars fixed to a solid rotor crush RAP particles against a striker plate. It can be used as both primary and secondary crusher, and can also be used as a secondary crusher along with a jaw (primary) crusher. In the case of hammermill impact crushers, the breaking bars pivot on a rotor creating a swing-hammer type action (figure 5-11). It can be used both as a primary or as a secondary crusher (with a jaw crusher). Sometimes a combination of jaw and roll crushers (figure 5-12) can be used effectively for sizing RAP material. The jaw crushes the slabs down to a more manageable size, which is then reduced to usable size by a secondary roll crusher. Typically, jaw/roll crushers are used in conjunction with a double deck screen for producing two products for full depth RAP: a fine product (typically <12.5 mm) and a coarse product (12.5 - 19.0 mm).

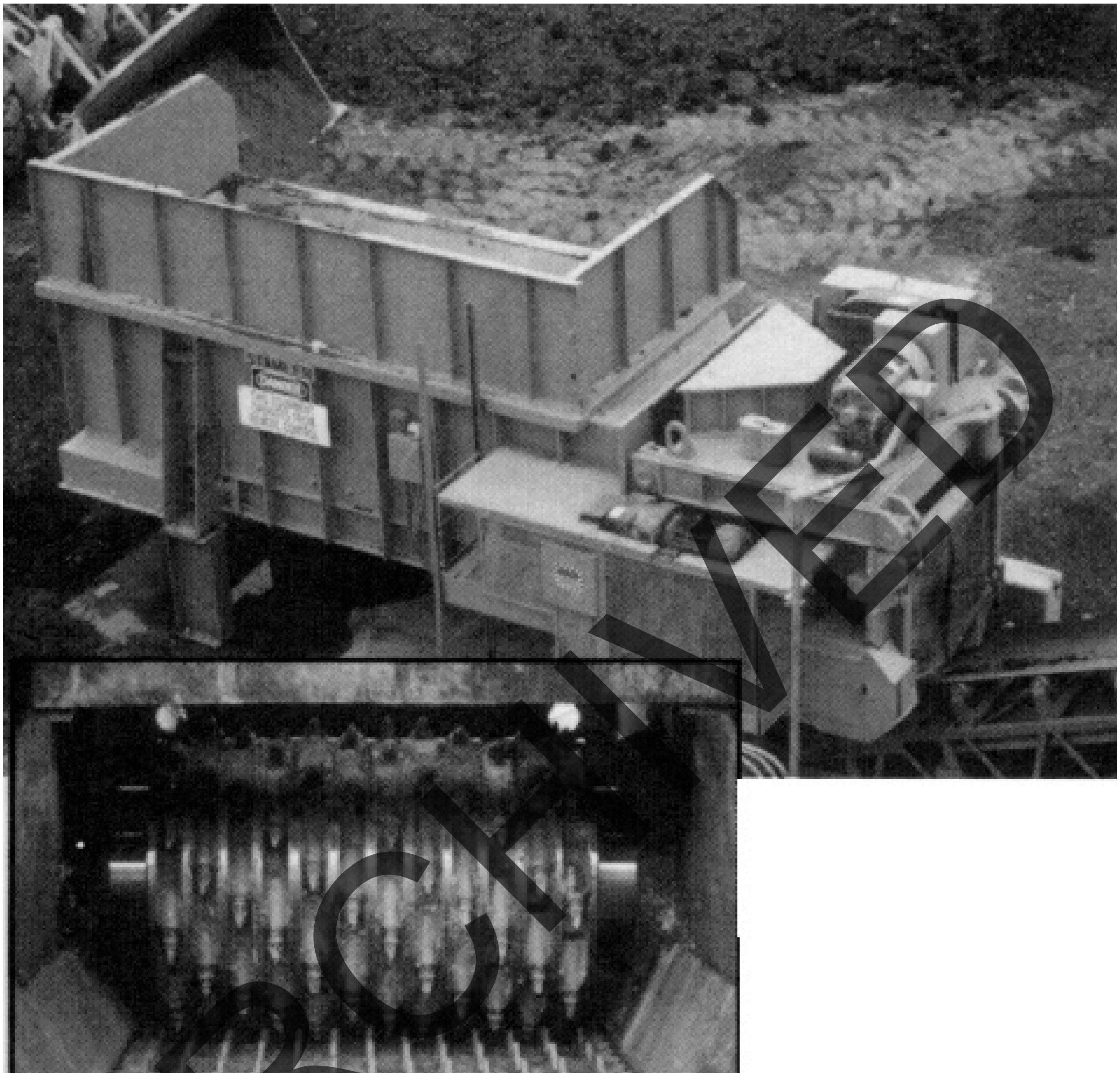

Figure 5-8. RAP breaker.

Both jaw and roll crushers can “pancake” the RAP, especially on warm, humid days. Pancaking is the formation of a flat, dense mass of RAP or crusher surface. It does not affect the quality of the processed material. This is not a problem with horizontal or hammermill crushers.[7]

To produce a homogeneous RAP product, the RAP material is first blended thoroughly with a front end loader or a bulldozer and then crushed to downsize the top stone size in the RAP to one smaller than the top size in the HMA being produced (for example, 16 mm for a 19.5 mm top size mix). This is to ensure that the asphalt aggregate blend is broken as much as possible and there is no oversize material. When a crusher is available at site at all times, smaller quantities are typically crushed, sampled for consistency, and then used. Crushing in smaller quantities makes it easier to sample the crushed product for consistency and keep the crushed product identified. Also, smaller piles can be used quickly before they have a chance to gain moisture from being stored outside, which increases drying costs and limits RAP percentage that can be used.

Figure 5-9. Jaw crusher.

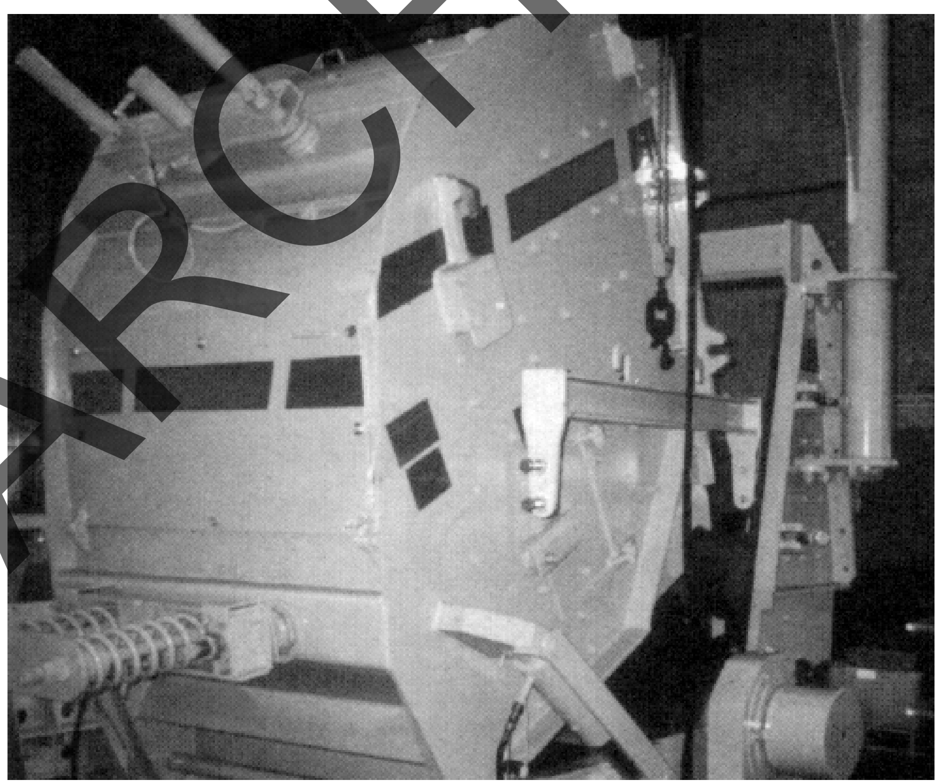

Figure 5-10. Horizontal impact crusher.

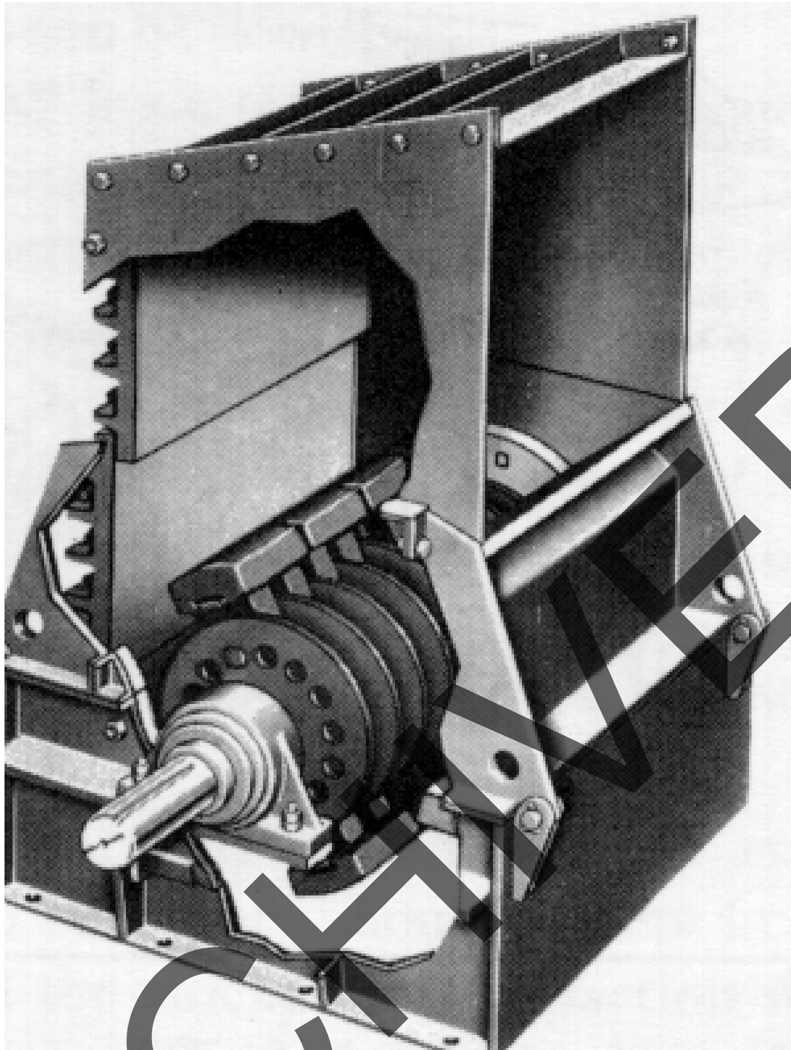

Figure 5-11. Hammermill crusher.

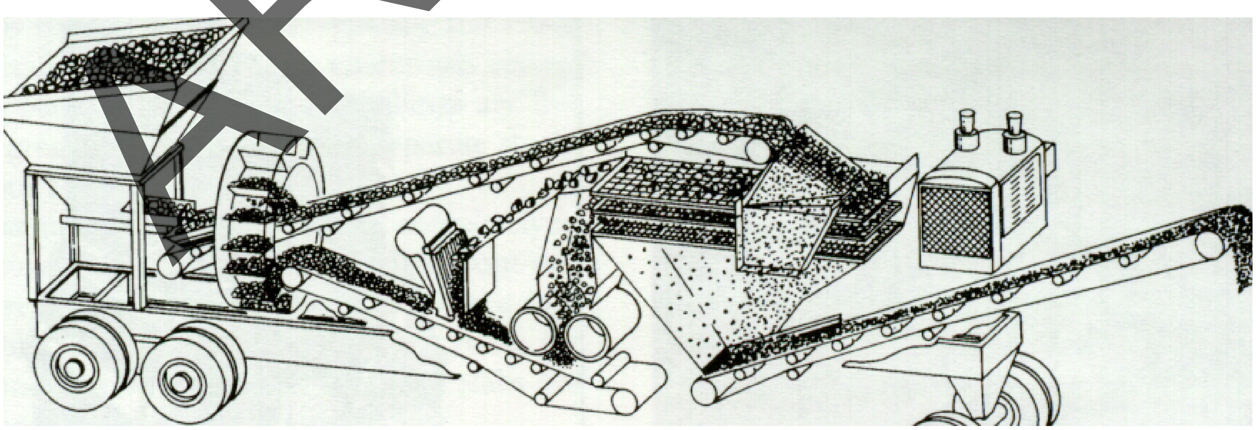

Figure 5-12. Combination crusher.

Care should be taken to avoid removing the fines from the reclaimed HMA pavement since the fines retain much of the aged asphalt that is to be recycled. The crusher should not also produce an increase in fine size material or new fractured faces which can require more virgin binder material and hence increase in cost.[6]

RAP from different sources and containing different asphalt content and aggregates with different gradations should be stockpiled separately. RAP can be stockpiled either before or after processing and a front end loader or a radial stacker can be used for the purpose. Figure 5-13[4] shows a radial stacker used for stockpiling RAP. The two major problems associated with stockpiling are consolidation and moisture retention.

In the past, it was believed that low, horizontal stockpiles are better than high and conical stockpiles which can result in re-agglomeration of RAP. However, experience has proven that actually large, conical stockpiles are better[7] and that RAP does not recompact in large piles. Actually, there is a tendency to form a crust over the 20-25cm (8-10 in) of pile depth. This crust can be easily broken by a front end loader. Also, the crust tends to shed water and prevent the rest of the pile from recompacting. In the case of a low, horizontal stockpile also this 20-25 cm (8-10 in) crust is present. However, it is more difficult for the front-end loader operators to work around a low pile. The stockpile should be built on a solid surface to prevent contamination or compaction of the underlying surface. The finer particles in the processed RAP material tend to absorb and retain moisture. This increases the moisture content of the material and hence the energy required to drive it off during production. The heat primarily comes from the heated uncoated aggregates, and since there is a limit up to which the aggregates can be heated, either the amount of RAP or the production rate has to be sacrificed if there is an increase in moisture

Figure 5-13. Radial stackers for building up RAP stockpiles.

content.(4) Figure 5-14 shows a plot of moisture content versus temperature required for drying to produce recycled HMA. It shows that there is a significant increase in drying temperature per degree increase in moisture content. An increase in moisture content of the RAP by even 0.5 percent will hinder HMA production capabilities seriously.(5) Hence, proper drainage of the stockpile should be provided. Tall conical stockpiles provide better drainage compared to low, flat stockpiles. Depending on the annual moisture level in the region, use of protective coverings such as tarps and even structures should be also be evaluated.(8) Figure 5-15(7) shows a shed used for storing RAP.

MODIFICATIONS TO BATCH PLANT FOR RECYCLING

Modifications are required in the batch plant to recycle RAP since attempts to introduce RAP directly with the virgin aggregates result in excessive smoke and material build-up problems in the dryer, hot elevator and screen tower.(4) The most widely used method for batch plant hot-mix recycling is the "Maplewood Method."(5) Other recycling processes used in batch plant are described later. Figure 5-15 shows the schematic of the "Maplewood Method." Even though variations exist, basically a separate cold feed bin introduces the RAP into the weigh hopper or the pugmill by a chute and belt conveyor. There the RAP is joined by the virgin material coming from the cold feed bins through the dryer and the screen decks. The temperature to which the virgin aggregates are superheated depend on the properties of the RAP material.

Exhaust capacity of pugmill or weigh hopper is important since a significant amount of steam is generated when the dry virgin aggregates come in contact with relatively moist and cold RAP. The steam produced can either be exhausted by the RAP charging chute or an exhaust duct fitted to the pugmill or weigh hopper. Many producers vent their pugmills or weigh hoppers into the drier exhaust stream. This is done by enclosing the pugmill and ducting into the exhaust steam equipment.(5)

Depending on the method used to convey the RAP to the weigh hopper or the pugmill, different modifications are needed to recycle HMA. The following modifications are needed.(9)

Aggregate Dryer

Since a relatively lesser amount of virgin aggregate is superheated in HMA recycling, some modifications are needed in the dryer. An adequate veil must be maintained in front of the burner flame. A cooling period at the end of each production period may be necessary to prevent warping of the drum at high temperatures.

Dryer Exhaust System

Modification of this system is necessary to prevent damage of baghouse collectors from the high temperature exhaust gases which result from superheating of virgin aggregates. Several methods may be adopted to lower the temperature of the exhaust gas. These include redesign of dryer flights, use of longer duct work, addition of cooling air or water spray into the exhaust system.

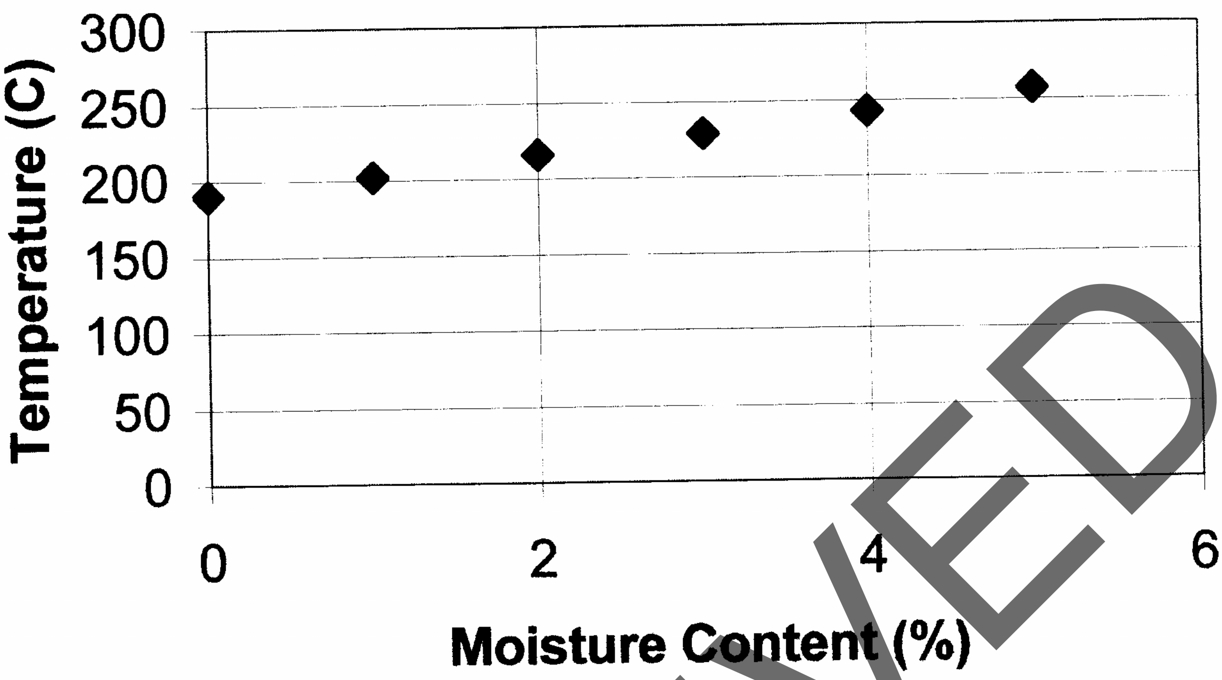

Figure 5-14. Plot of moisture content vs. drying temperature.

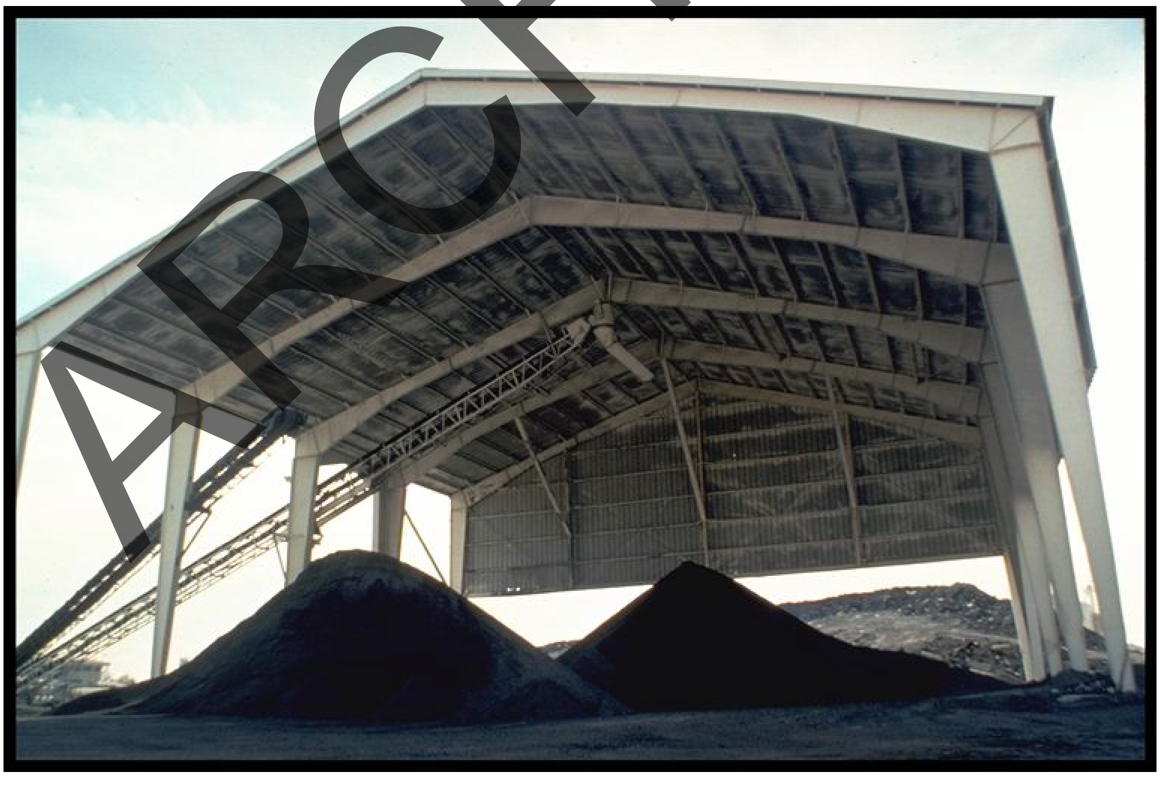

Figure 5-15. Structure for protecting and minimizing moisture in RAP or aggregates.

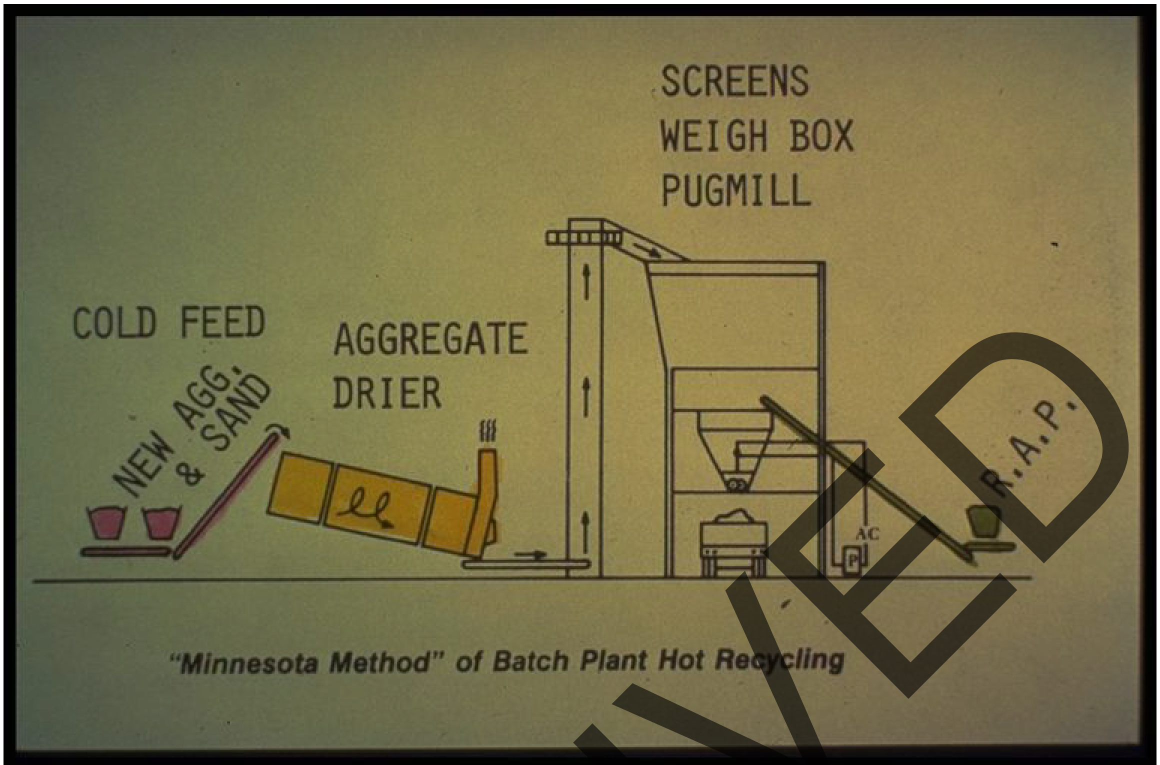

Figure 5-16. Maplewood method of batch plant hot recycling.

Screen Deck

To prevent excessive increase in temperature, special lubricants may have to be used in the screen bearings located inside the duct housing.

Hot Bins

Depending on the size of the bin and the material storage time, the outside of the hot bins may have to be insulated to prevent drops in the superheated aggregate temperature.

Binder Feeder

The asphalt binder feeder system should be modified to include a recycling agent discharge system, either into the asphalt weigh bucket or the pugmill. However, this is required only if a recycling agent is used in the process.

RAP Cold Feed Bin

To avoid accumulation and bridging of the RAP material, the cold feed bin should be relatively small with steep sides and a large discharge opening (figure 5-17).

RAP Feeder and Conveying System

To ensure continuous operation, the feeding and the conveying systems should have sufficient

Figure 5-17. RAP cold feed bin.

capacity to deliver RAP into the weighing hopper without any delay. Also, if a special surge bin is not provided above the hopper, the conveyor system should be equipped with a heavy-duty motor to ensure continuous starting and stopping.

Entrance Chute to the Weighing Hopper

The entrance chute to the weighing hopper should be as steep as possible, of constant width and provided with a counterweight draft gate to prevent the escape of dust when the RAP is introduced. The entrance chute should be capable of introducing the material at the center of the weighing hopper.

Venting for Weighing Hopper and Pugmill

Adequate venting for the weighing hopper and the pugmill should be provided to prevent build up of moisture and dust emissions during mixing operations. The dust entrainment by the steam from the RAP can be prevented by reducing the dry-mixing time also. The amount of steam produced depends on the moisture content of RAP and the amount of RAP per batch of mix. Higher the amount of moisture, and higher the amount of RAP per batch, higher is the amount of steam produced.

Storage Silos

Storage silos may be used to store the hot mix after it leaves the pugmill, so that it gets sufficient time to attain temperature equilibrium throughout the mix.[6] This is because the transfer of heat from the superheated aggregate to the relatively cold RAP may not be completed in the relatively short mixing time, especially since in many cases the mixing times are not altered from normal mixing times used for virgin HMA mixes.

RECYCLING PROCESSES IN BATCH PLANT

In the recycling process the virgin aggregates must be superheated to a certain temperature to transfer heat and dry the RAP material. Table 5-1[7] shows the temperatures to which the virgin aggregates must be heated for different discharge temperatures of recycled mix and RAP moisture content.

The different methods of batch plant operation for recycling are given below.[3,7]

Method 1. The method is illustrated in figure 5-18. The superheated virgin aggregates and the cold RAP are introduced into the boot of the hot elevator. The mixed material is screened and stored in hot bins. The scavenger system in the batch tower pulls off the water evaporated from the RAP. There is no resulting emission problem in this operation.

However, unless the screen cloth in the bottom deck exceeds 5 to 6 mm (3/16 to 1/4 in), relatively low percentage of RAP may be used in this process without blinding the screens (especially 6.4 mm screen). It is necessary to avoid excessive moisture in RAP to prevent blinding of the screens.

Method 2. The batch tower is required to have a fifth hot bin in this method. The procedure is shown in figure 5-19. The virgin aggregate is screened, superheated and then deposited at the

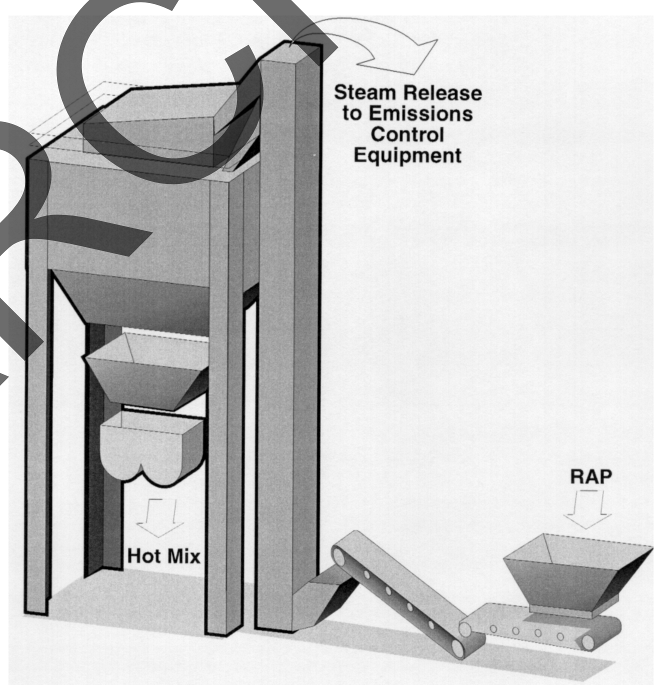

Figure 5-18. RAP into batch plant hot elevator.

Table 5-1. Required aggregate temperatures for recycling.[7]

Reclaimed Material	Moisture Content (Percent)	Recycled Mix Discharge Temperature, ºC(ºF)			
		104ºC (220ºF)	115ºC (240ºF)	167ºC (260ºF)	138ºC (280ºF)
A. Ratio: 10% RAP/ 90% Aggregate	0	121(250)	138(280)	152(305)	163(325)
	1	127(260)	143(290)	154(310)	168(335)
	2	132(270)	146(295)	157(315)	171(340)
	3	138(280)	149(300)	163(325)	174(345)
	4	141(285)	152(305)	166(330)	177(350)
	5	193(290)	157(315)	168(335)	182(360)
B. Ratio: 20% RAP/ 80% Aggregate	0	138(280)	154(310)	168(335)	182(360)
	1	146(295)	160(320)	177(350)	191(375)
	2	154(310)	168(335)	182(360)	196(385)
	3	163(325)	177(350)	191(375)	204(400)
	4	171(340)	185(365)	199(390)	213(415)
	5	179(355)	193(380)	207(405)	221(430)
C. Ratio: 30% RAP/ 70% Aggregate	0	157(315)	179(345)	191(375)	207(405)
	1	168(335)	185(365)	202(395)	218(425)
	2	182(360)	199(390)	216(420)	232(450)
	3	196(385)	213(415)	229(445)	246(475)
	4	210(410)	227(440)	243(470)	260(500)
	5	224(435)	241(465)	257(495)	274(525)
D. Ratio: 40% RAP/ 60% Aggregate	0	179(355)	199(390)	218(425)	138(460)
	1	199(390)	218(425)	238(460)	257(495)
	2	218(425)	238(460)	257(495)	277(530)
	3	243(470)	260(500)	279(535)	299(570)
	4	260(500)	279(535)	299(570)	321(610)
	5	285(545)	302(575)	321(610)	341(645)

Table 5-1. Required aggregate temperatures for recycling[7] (continued).

Reclaimed Material	Moisture Content (Percent)	Recycled Mix Discharge Temperature, °C (°F)			
		104°C (220°F)	115°C (240°F)	167°C (260°F)	138°C (280°F)
E. Ratio: 50% RAP/ 50% Aggregate	0	210(410)	235(455)	257(495)	282(540)
	1	240(465)	268(515)	288(550)	310(590)
	2	271(520)	293(560)	318(605)	243(650)
	3	302(575)	327(620)	349(660)	374(705)
	4	338(640)	360(680)	379(715)	409(760)
	5	365(690)	390(735)	413(775)	438(820)

Note:
11°C (20ºF) loss between dryer and pugmill assumed in these calculations.

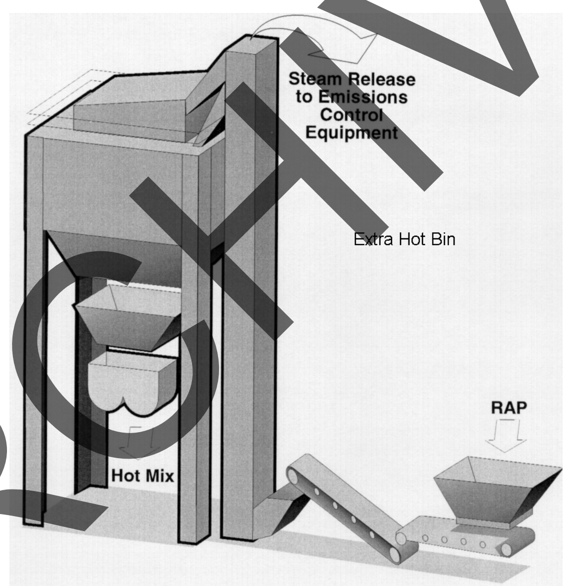

Figure 5-19. Batch tower fifth hot bin for RAP.

boot of the hot elevator along with the cold RAP. The blended material is introduced in the fifth hot bin without going through the screens in the tower. This method allows the use of up to 40 percent RAP and also switching from RAP mixes to virgin mixes without emptying the hot bins since the materials in the hot bin are not superheated. (Note that the figures for Method 1 and 2 are the same. This is because the procedures are similar, except for the fifth bin in Method 2).

Method 3. In this so called "Maplewood Method," which is most commonly used (figure 5-20), the cold pre-screened RAP is delivered directly into the weigh hopper of the batch tower along

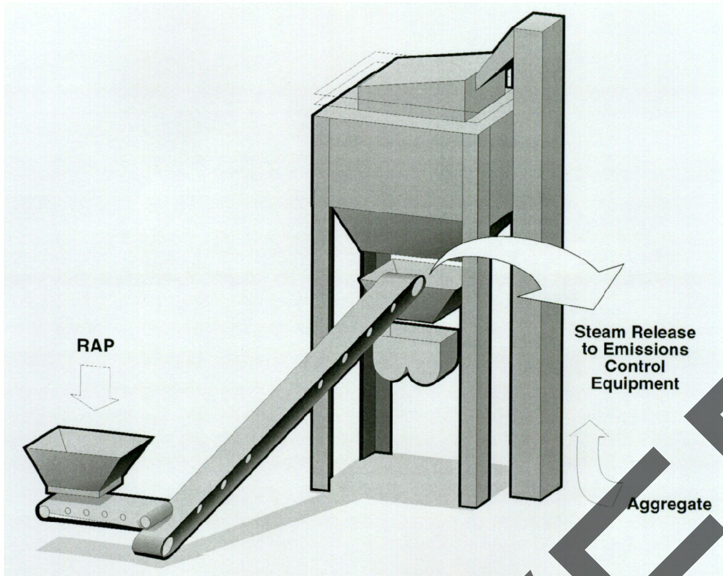

Figure 5-20. RAP directly into weigh hopper.

with the superheated virgin aggregate from a hot bin. The RAP is delivered from a RAP bin through an inclined conveyor having automatic plant controls. In this process, the RAP material may be added after material from bin 1 is added to the weigh hopper and before the material from bins 2, 3 and 4 are added to the weigh hopper. In this way the RAP is sandwiched between the hot virgin aggregates and gets more time to heat up. A mild explosion results from instant evaporation of the RAP moisture when the unmixed aggregates are discharged into the pugmill.

To scavenge the mixer during the steam generation a baghouse with considerable capacity is required unless the dump time of the weigh hopper is increased. Another less practical method is to build a large chamber behind the plant. The chamber serves as a surge container into which the exploding steam can escape.

Method 4. This is a new control feed system (figure 5-21) in which the RAP is fed onto a third scale to obtain a set amount of RAP. After the RAP is weighed, it is dropped into a bin with a feeder. The feeder introduces the RAP into the pugmill over a 20 to 30 seconds period. This method allows relatively more control of the generated steam by slowing down the batch cycle.

Method 5. This expensive system (figure 5-22) preheats the RAP in a separate dryer before mixing it with the virgin aggregates. Heated RAP materials are then conveyed to a separate, heated storage bin which has its own weigh hopper on a typical batching tower. RAP materials are weighed as a separate ingredient, then conveyed to the pugmill for production of recycled mix. Variations in moisture content and oxygen available from the RAP heater make system control difficult. However, 35 to 40 percent RAP have been used with this method.

Amount of RAP Used

Factors controlling the percentage of RAP are the temperature to which new aggregates must be

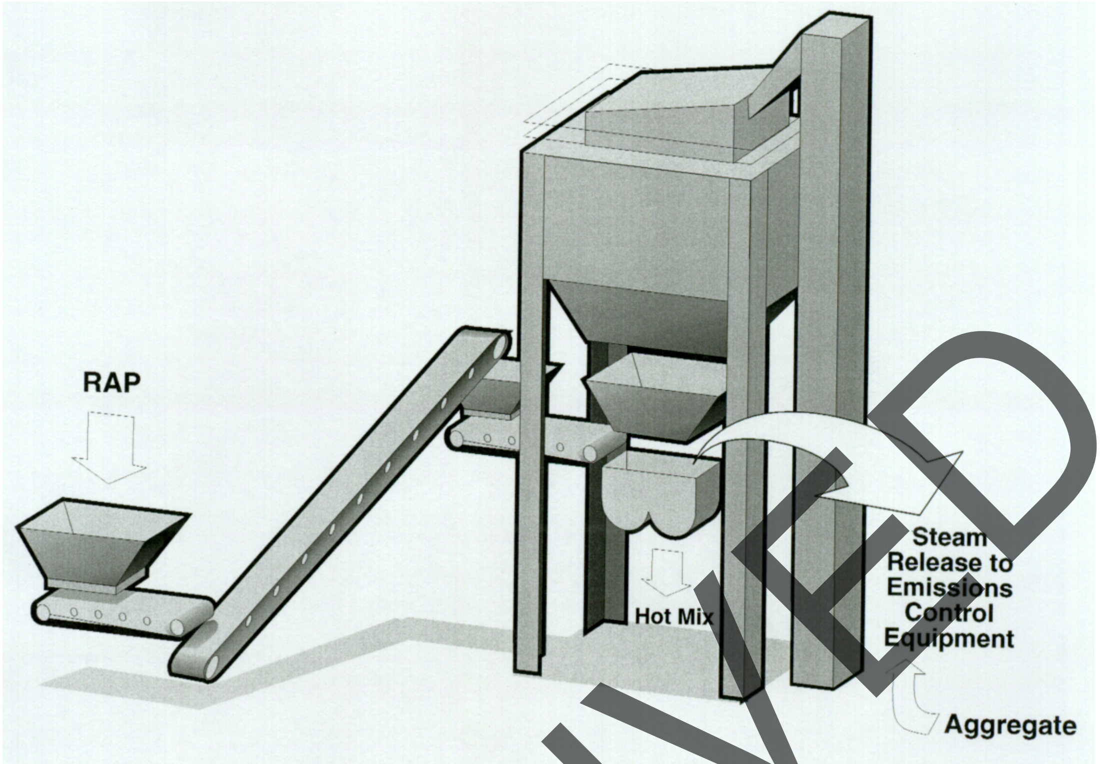

Figure 5-21. Controlled feed to weigh hopper.

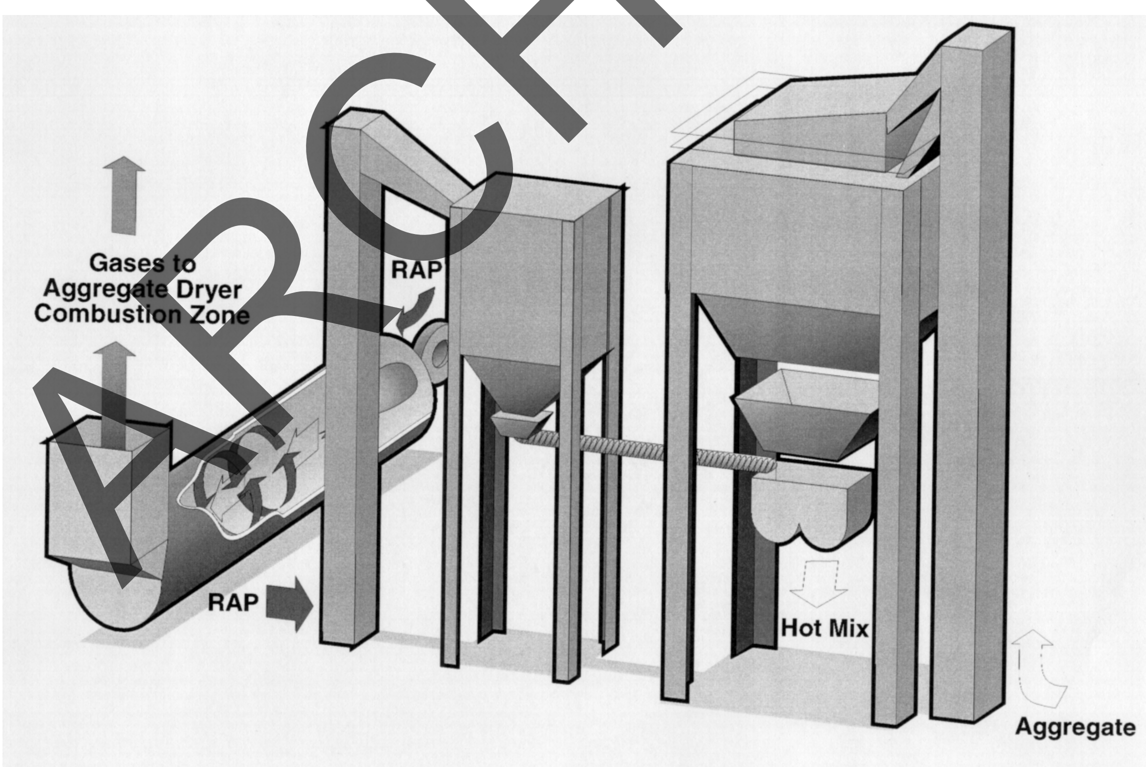

Figure 5-22. RAP heater for batch plant.

heated, moisture content of RAP, temperature of the RAP in stockpile, desired recycled HMA mix temperature, HMA production rate, exhaust capacity of pugmill or weigh hopper, and the percentage of material passing the 0.075 mm screen in the RAP.[5] According to the Asphalt Recycling and Reclaiming Association, the practical limit for hot mix recycling in a batch plant is 20 percent RAP, although up to 40 percent RAP can be used. However, as high as 50 percent RAP has been used if the moisture content of the RAP is minimal and the RAP is fed to the plant at the ambient temperature. Generally, 30 to 35 percent RAP is considered to be the practical limit with 10 to 20 percent RAP being a typical range.

Figures 5-23 through 5-25 show plots of RAP percentage allowed in base, binder and surface courses.[10] In base course, the percentage of RAP allowed ranges from 15 to 100, with a large number of states (27.1 percent) allowing 50 percent. A substantial number of states (22.9 percent) have no limit on the amount of RAP that can be used. For binder course the percentages range from 15 to 100. Approximately equal number of states (25.1 and 20.8 percent) allow 50 percent and unlimited amount respectively. A small number of states (2.1 percent) do not allow RAP in batch plant for binder course. For surface course, the allowable percentage ranges from none to 100. A significant percent of states (22.9 percent) do not allow any RAP, whereas 16.6 percent of the states allow unlimited RAP. Some states have special provisions for allowing RAP in the surface mixes.

SUMMARY

Hot mix recycling has been proven to be a viable rehabilitation technique. When designed and

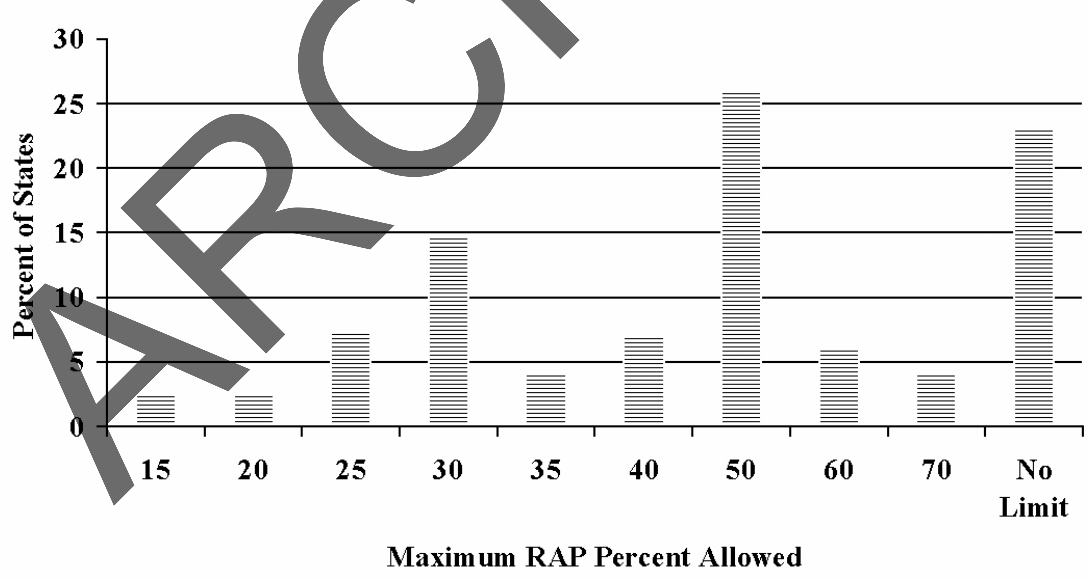

Figure 5-23. Maximum RAP percent allowed for batch plant mix in base course.

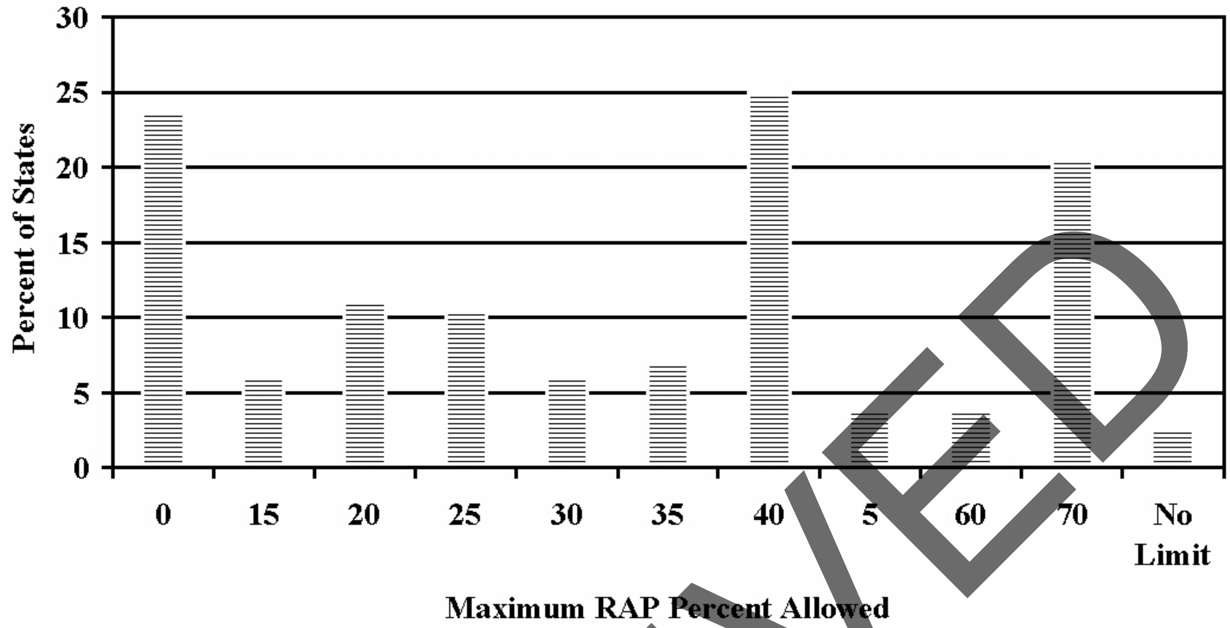

Figure 5-24. Maximum RAP percent allowed for batch plant mix in binder course.

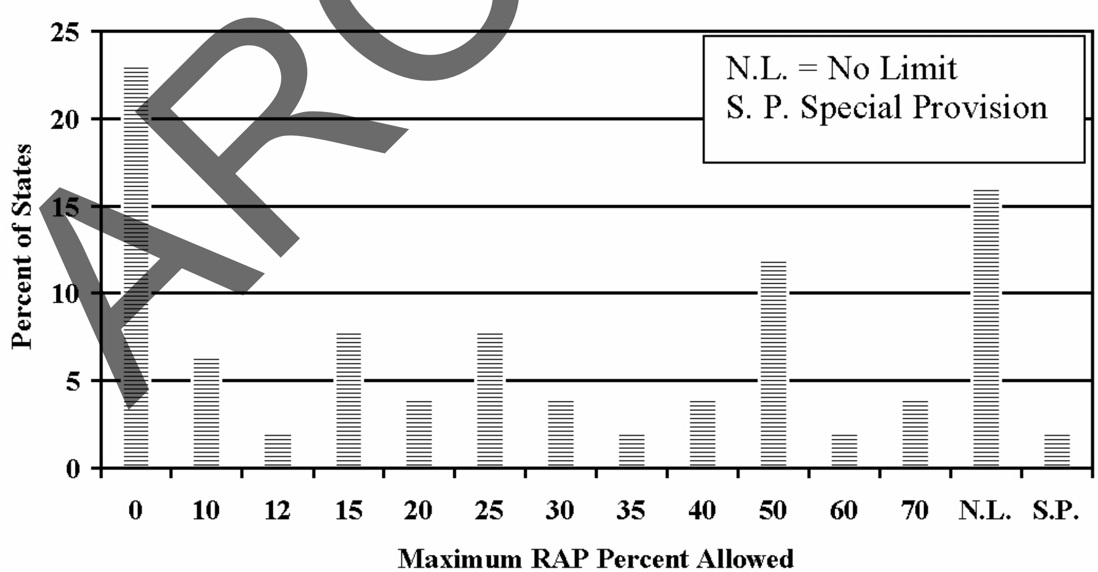

Figure 5-25. Maximum RAP percent allowed for batch plant mix in surface course.

constructed properly, hot mix recycled pavements have performed similar to or better than conventional HMA pavements. The method of hot mix recycling includes removal of existing HMA pavement, crushing, stockpiling of RAP, mixing, lay down, and compaction. Except for lay down and compaction, which are similar to conventional hot mix construction, the other processes require some modification to existing plants or some new equipments. The most commonly used method of hot recycling in batch plants is the heat transfer method. The virgin aggregates are superheated to a certain temperature to transfer heat and dry the RAP material. Proper care should be taken in crushing to smaller sizes, and stockpiling the RAP to prevent contamination, consolidation or moisture retention. Production of recycled hot mix must be made under strict quality control to ensure satisfactory performance of the mix.

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CHAPTER 6. HOT-MIX ASPHALT RECYCLING - DRUM PLANT (CONSTRUCTION METHODS AND EQUIPMENT)

INTRODUCTION

Recycled Asphalt Pavement (RAP) material, obtained by pavement milling or ripping and crushing, can be combined with new aggregate and an asphalt cement or recycling agent to produce hot mix asphalt (HMA). The process of hot mix recycling, with its comparatively low cost, and potential of producing quality mix, has proved to be a viable rehabilitation alternative. As in the case of conventional hot mix asphalt (HMA), hot mix recycling can be done in both batch (central) and drum mix plants. However, hot mix recycling in a drum mix plant offers some advantages over recycling in a batch plant which was discussed in chapter 5. These advantages are:(1)

1. Portability: Drum mix plants are more portable and require shorter plant setup time compared to batch plants.
2. Versatility: A relatively higher percentage of RAP can be used in a drum mix plant compared to a batch plant.
3. Production: Plant production rates are relatively unaffected by RAP percentages (up to a certain limit).
4. Mixing: A more homogeneous mix is produced in a drum mix plant since the RAP is heated and mixed with the virgin aggregate and asphalt binder for a longer period of time compared to the mix in a batch plant.

RECYCLING PROCESSES IN DRUM PLANTS

The Reclaimed Asphalt Pavement (RAP) material cannot be processed in normal drum mix plants since excessive "blue smoke" is produced when the RAP comes in contact with the burner flame. The condition is further aggravated by build-up of fine aggregates and asphalt binder on metal flights and end plates.(2) It has been suggested(3) that most of the smoke problem is caused by the light oils in soft grade of asphalt binder used to rejuvenate the aged asphalt in the RAP. Although the smoke problem could be solved by various processes such as lowering HMA plant's production rate, increasing water content of the RAP, lowering discharge temperature of the recycled mix, introducing additional combustion air and decreasing percentage of RAP, it was found that a more effective way to rectify the problem was to modify the drum mix plant.(4)

Center Entry Method

Although variations exist in the process, basically the center entry method is the most widely used method for hot mix recycling in a drum mix plant. In this method, shown in Figure 6-1,(5) the RAP is introduced into the drum downstream of the burner flame to mix with the superheated new aggregates. The hot virgin aggregates heat up the RAP material by conduction. The RAP is protected from coming in direct contact with the burner flame by a dense veil of aggregate added prior to the point where the RAP is added. It is very important to have the veil of virgin aggregate. Otherwise, overheating of RAP can result in "blue smoke," and it may not be possible to use the design amount of RAP material. Sometimes special flight design, steel ring dams, or

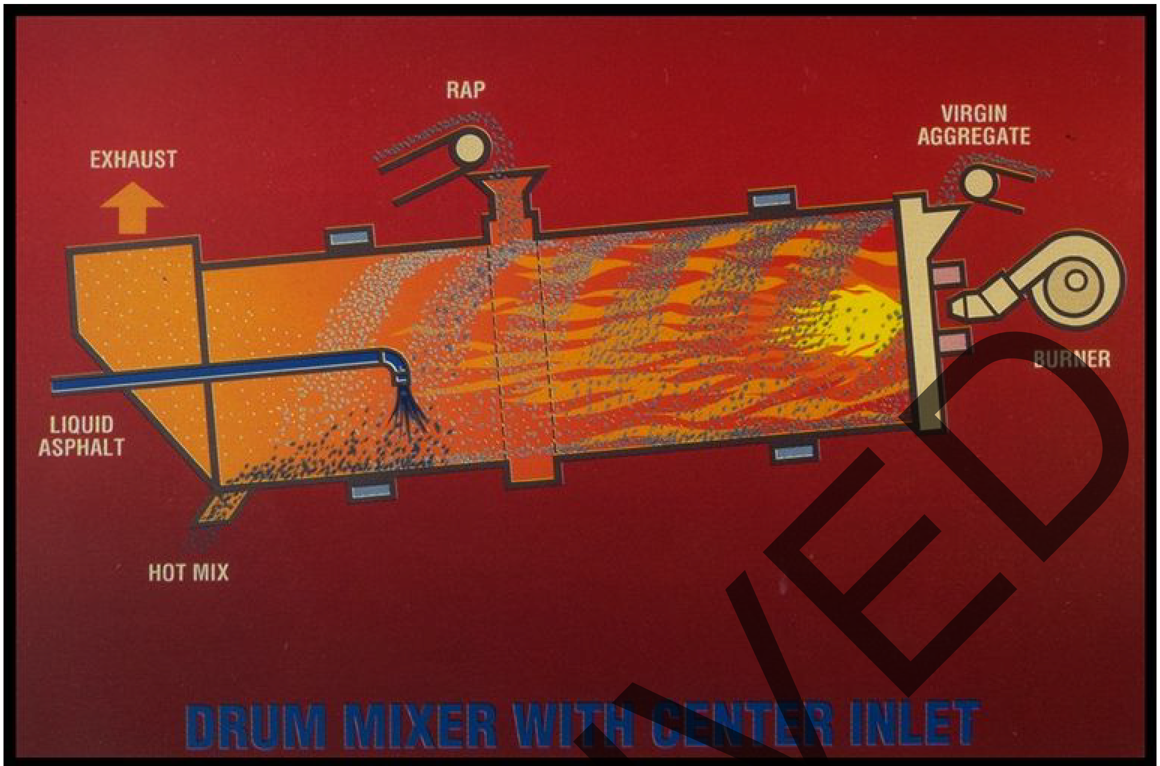

Figure 6-1. Schematic of drum mixer with center entry.

circular steel flame shields are utilized to force the RAP to mix with the virgin aggregates before being subjected to the high gas treatment. These techniques eliminate "blue-smoke" problem.

Figure 6-2 shows a drum mix plant with center entry. The virgin aggregate is kept in the hot zone of the drum and superheated to about 260°C (500°F). Kicker flights or dams are included in the middle of the drum to increase the aggregate dwell time in the first half of the drum. The superheated aggregate is used to heat the RAP materials. The aggregate temperature drops as the RAP material is heated and its moisture evaporated. The recycled mix is brought up to discharge temperature in the last portion of the drum. The parallel flow drum mixers were effectively used for recycling in the '70s and '80s. However, the plants had difficulty in complying with the growing number of restrictive emission standards. In some cases, the problem was caused by the production of steam that distilled light oil from the virgin asphalt binders and RAP.[7] The important factors contributing to the problem of emission are high moisture content of the aggregates, higher amount of fines in the RAP material and a relatively long time of exposure of the asphalt binder to the steam in the gas stream.[3] Several modified versions of the drum mix plant have been built to counter the emission problem. In general, in these methods the exposing of the asphalt binder to the steam in the exhaust gas stream has been eliminated, and this has eliminated the emission of light ends to the baghouse, except the minute amounts of light oil emitted from recycled material when a high percentage of RAP is used. Different types of drum mix plants are described below.

In a parallel-flow drum mixer with an isolated mixing area, the mixing device is welded to the dryer shell so that it rotates with the dryer (figure 6-3). The gas stream is removed from the dryer prior to the aggregate/RAP mixture entering the mixing area. Some designs vent to the mixing

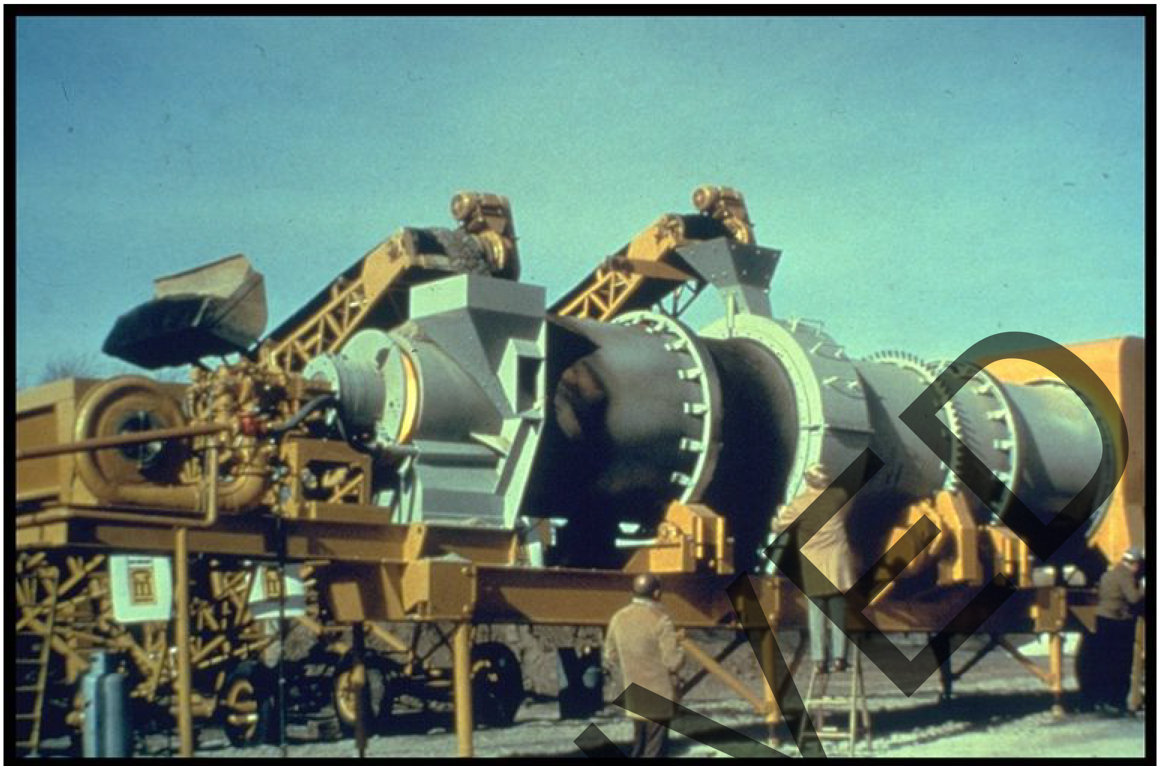

Figure 6-2. Drum mix plant with center entry.

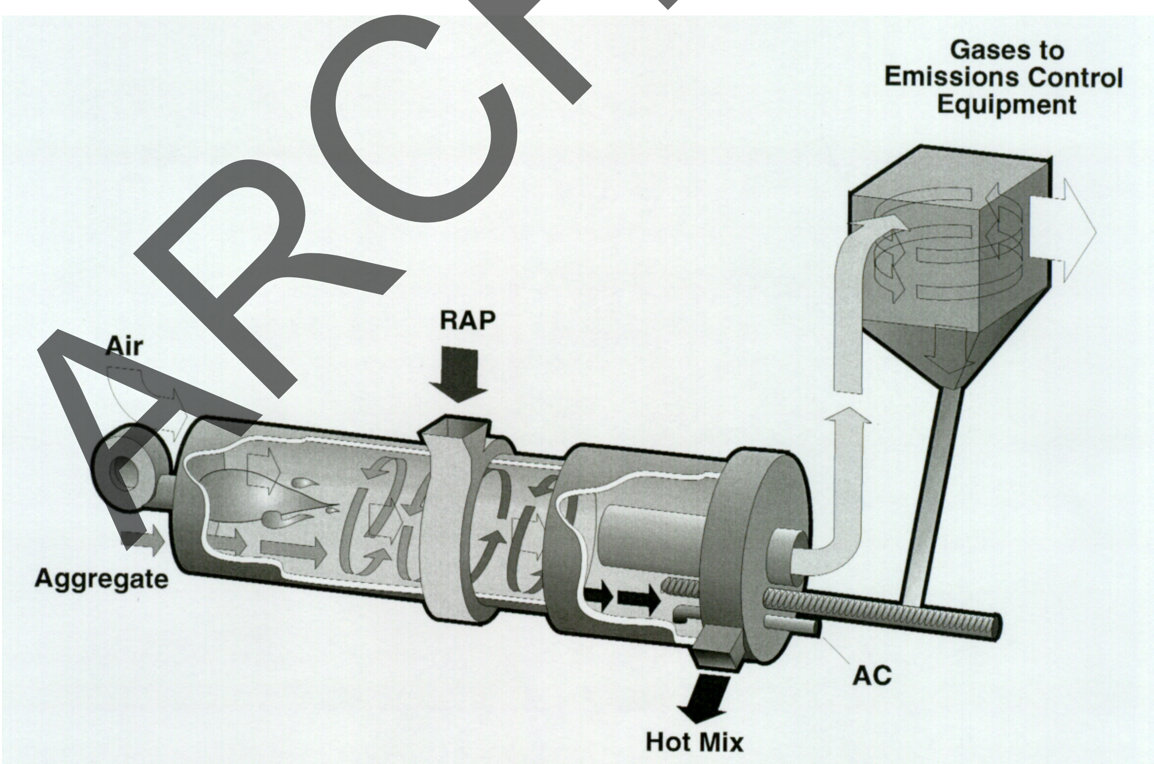

Figure 6-3. RAP in a parallel-flow drum with isolated mixing area.

area back to the combustion area of the dryer. This equipment requires a primary collector for capture of the larger dust particles. The particles collected are typically returned to the mixing area of the dryer with a screw conveyor.

In a parallel-flow drum mixer with counterflow RAP drying tube, the RAP is introduced into a cooler portion of the dryer and travels against the gas stream to mix with the virgin aggregates in the area where the aggregate/RAP mixture enters the mixing area of the dryer (figure 6-4). In this type of drum hydrocarbon levels are greatly reduced from the gas stream because the new liquid asphalt is shielded from direct exposure to the gas stream, and the aggregate is superheated for some conductive heat transfer to the RAP while the convective heat transfer of the RAP occurs in a cooler portion of the dryer.

In another type of parallel-flow dryer drum, the RAP is introduced in a separate continuous mixing device (figure 6-5). RAP is heated conductively in the mixing device. In this type of drum, RAP percentages are affected by the physical space available for conductive heat transfer in the mixing device. The superheated virgin aggregates must heat the RAP, and time and space are required for the moisture to be released from the RAP. To avoid the occurrence of hydrocarbons in steam, the vapor and steam are directed back into the combustion area of the aggregate dryer which effectively burns any hydrocarbon left in that separate gas stream. However, the virgin aggregate are superheated in a parallel flow configuration, and the exhaust gas temperature is not lower than the aggregate temperature. Hence, the percentage of RAP that can be achieved with this approach can be limited by air pollution control equipment on the facility.

The excessively high gas temperature can be avoided by changing the dryer configuration to a counterflow dryer design (aggregate travels against gas flow (figure 6-6). A heat exchange chamber can be added to the aggregate dryer to heat the RAP with virgin aggregates in the combustion area of the dryer (figure 6-7). Higher RAP percentages are possible because RAP has a longer residence time with the superheated virgin aggregates, and because RAP is heated conductively with aggregate in the vicinity of the hottest part of the dryer shell.

In a counterflow drum mixer, a mixtured dryer and a continuous mixing drum is combined in one unit (figure 6-8). In this type of drum mixer, the virgin aggregate is heated convectively, the RAP is heated conductively, and the virgin asphalt binder, recycled fines from primary and secondary collector, and other additives are added in the mixing section that is attached and rotating with the shell.

In a unitized counterflow dryer and continuous mixer (figure 6-9), a counterflow aggregate dryer is combined with a continuous pugmill mixing device. The aggregate passes through the inside of the counterflow dryer, and then is discharged with a fixed outer mixing shell where the mixing paddles move the virgin aggregate “uphill” through a mixing bed from between the rotating drying shell and the fixed rotor mixing shell. RAP is introduced at this point, along with virgin asphalt binder, recycled fines and additives, to produce HMA. This concept has been utilized in the “double barrel” drum, discussed later.

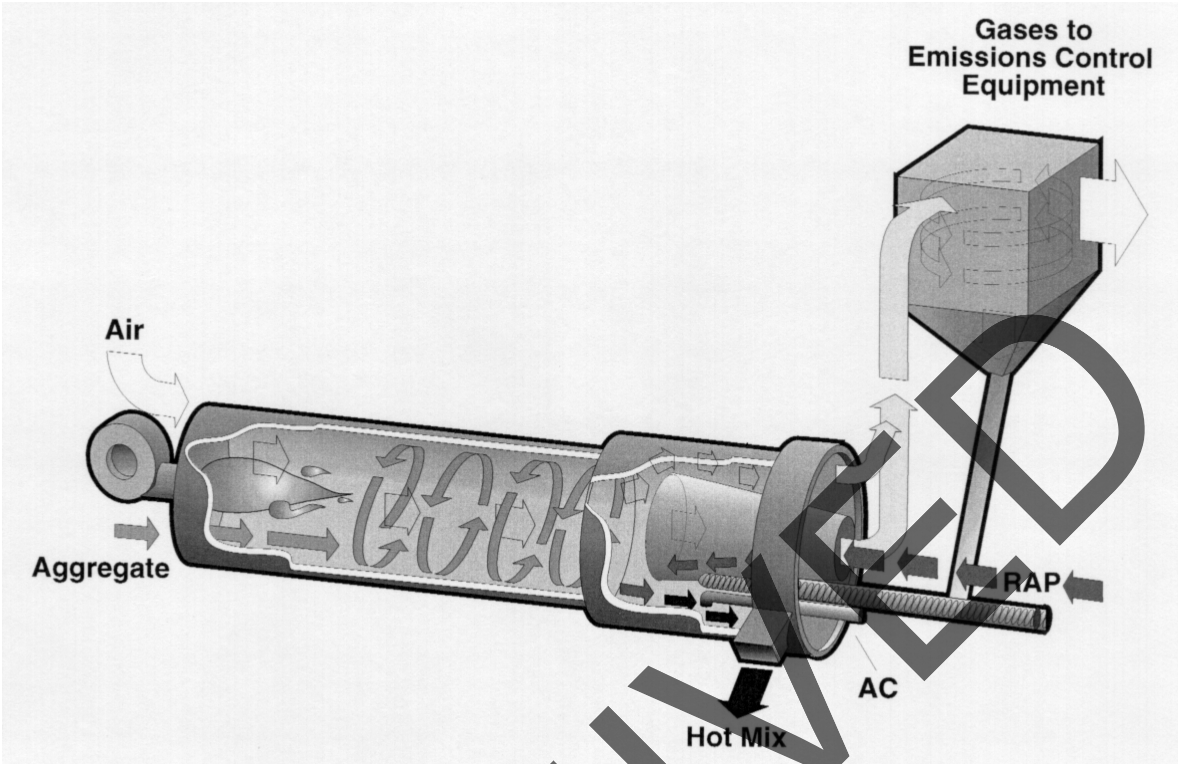

Figure 6-4. RAP in a drum mixer with counter-flow drying tube.

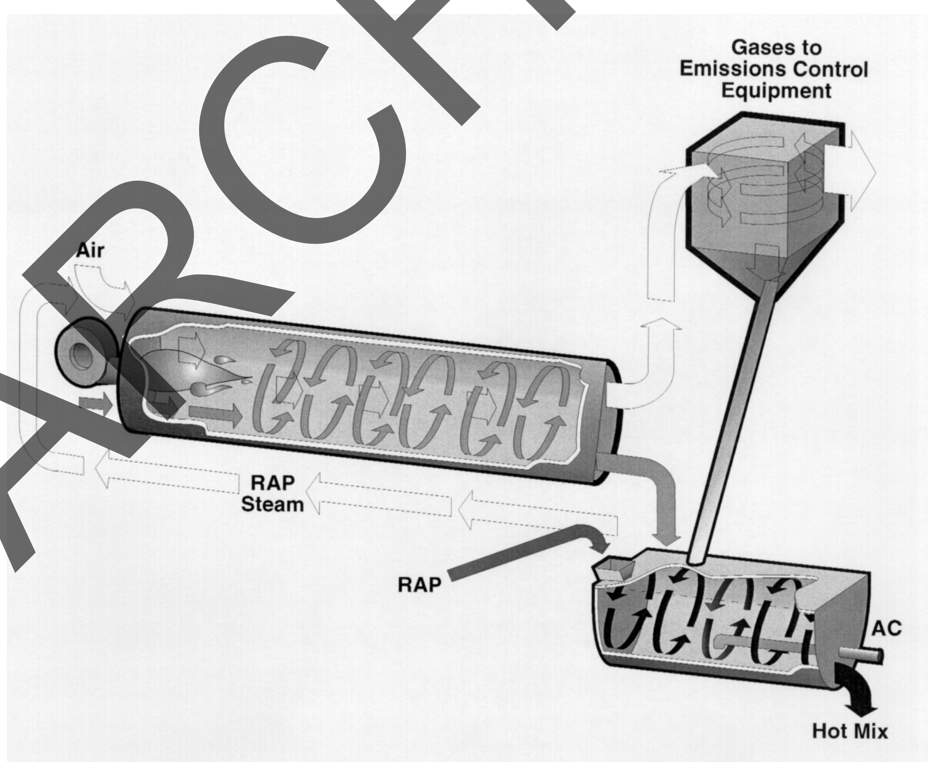

Figure 6-5. Parallel-flow dryer with RAP added in continuous mixer.

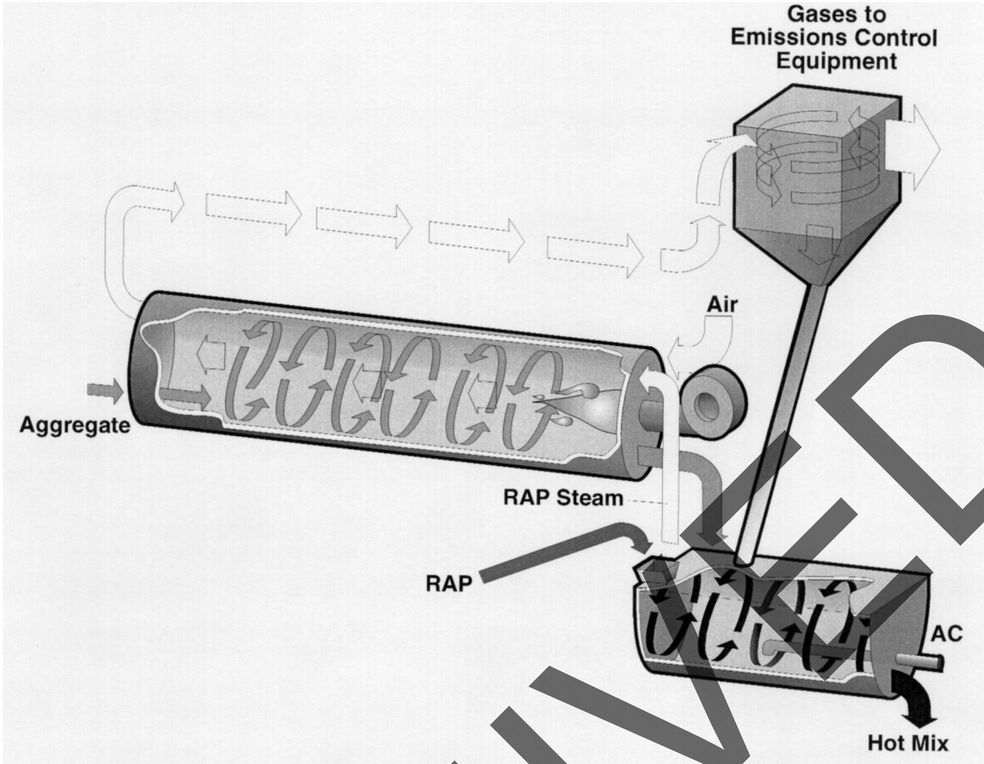

Figure 6-6. Counter-flow dryer with RAP added in continuous mixer.

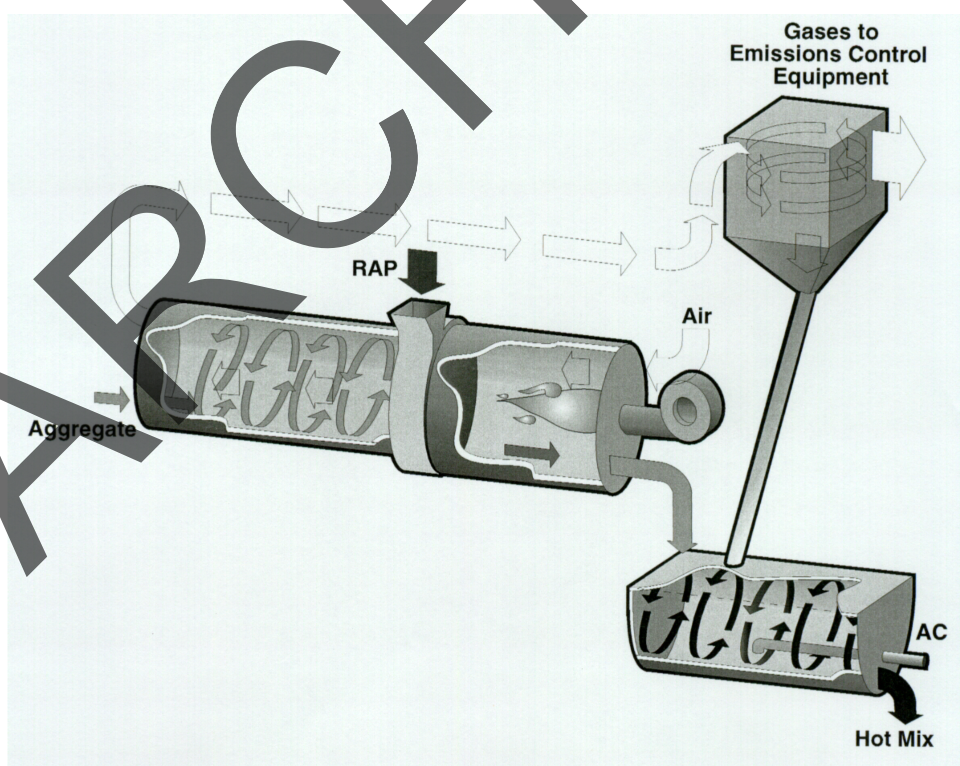

Figure 6-7. RAP added in counter-flow dryer.

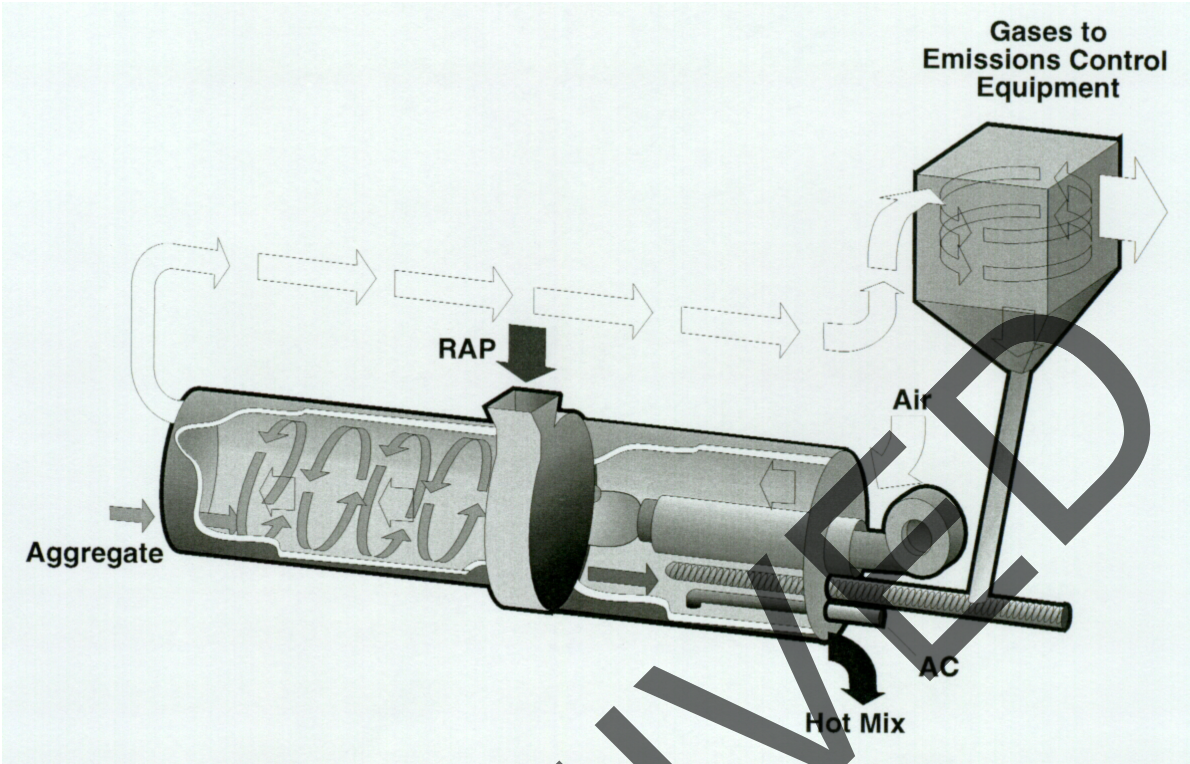

Figure 6-8. RAP in a counter-flow drum mixer.

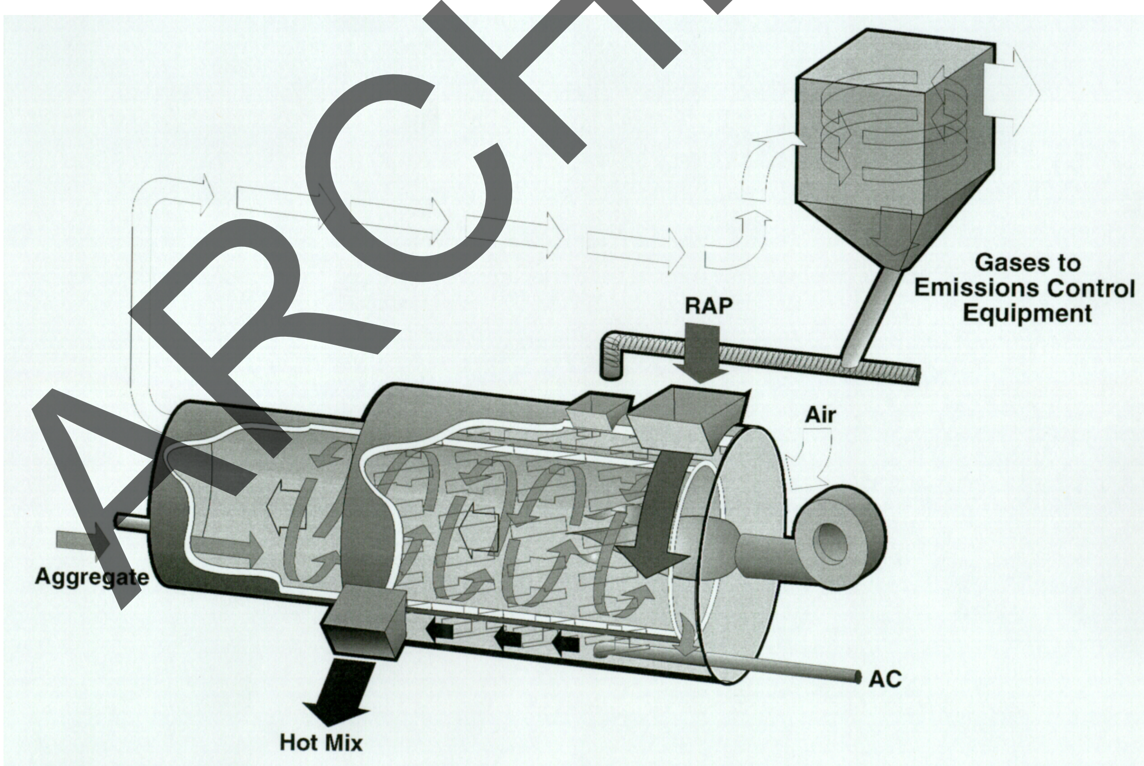

Figure 6-9. RAP added in unitized dryer/mixer.

Since the late 80s two new drum designs for more efficient heat transfer to RAP material during mixing have been developed. These are double barrel and triple drum design.

The double barrel counterflow drum mix plant, shown in figure 6-10,[3] has more mixing space than a conventional drum mixer. The shell of the drum is used as the shaft of the coater. A 3 to 3.3-m (10 to 11-ft) diameter coater is created with an extremely large insulated mixing area. The virgin aggregate material is dried in the inner drum and superheated to 315°C - 343°C (600° - 650°F) (when running 50 percent RAP). It then drops through the wall of the drum and meets with the RAP in the annular space. Approximately 1½ minutes of mixing time occurs in this outer shell. Since the outer shell does not rotate, easy access is available to add various other recycle components to the process as they become necessary and available. The heat of the inside barrel is transferred through the rotating shell to mixing in the annular space. The outer shell of the double barrel remains at approximately 49°C (120°F) at all times, leading to a very efficient plant. In this method the virgin and the RAP material are not exposed to the hot gases or to the steam of the drying process and thus the light oils are not removed from the mix. In the outer section of the double barrel, due to the moisture removed from the RAP, a steam or inert atmosphere occurs resulting in a much lower oxidation or short-term aging of the recycled HMA mix in the mixing chamber. Another benefit derived from this type of plant is the much longer life occurring with the bags in the baghouse due to relatively lower temperature of the exhaust gases. As dust is discharged from the baghouse through a rotary airlock on the double barrel plant a screw conveyor is used to transfer the mix back into the outer shell. The holes through which the virgin aggregates are directed into the outer shell are also responsible for channelizing any

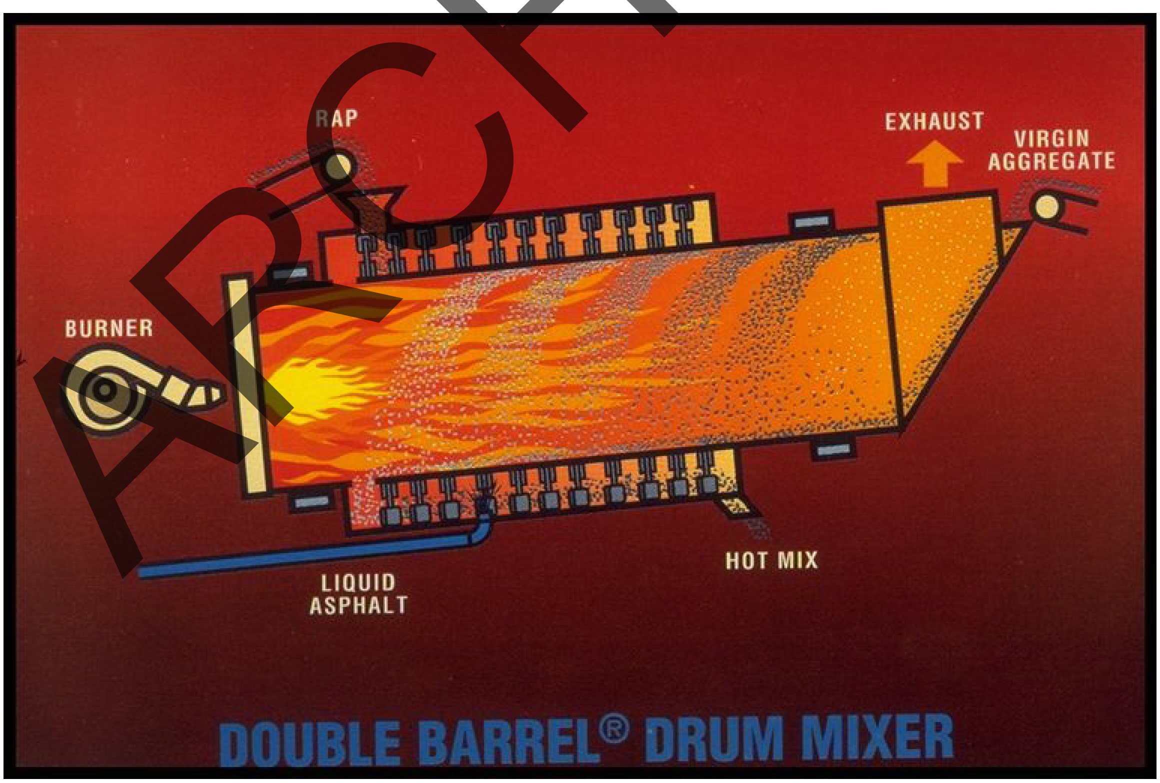

Figure 6-10. Double barrel drum mixer.

smoke from the inner mixing section to the outer space. The pollutants go directly to the flame where they are burnt. This results in reduced emission and blue smoke. The counterflow dryer design also leads to higher production rates with much lower fuel consumption.

The triple drum design also uses an outer shell, however, a stainless steel cylinder is used to enclose the combustion chamber (figure 6-11). This cylinder (without any flight or steps of a regular drum) is believed to be effective in transferring heat to the RAP material through conduction and radiation. The virgin aggregate is introduced from the opposite end of the burner flame. The RAP material is introduced in the annular space formed by the outer shell. The superheated virgin aggregates fall into the annular space and mingle with the RAP material.(8)

AMOUNT OF RAP USED

The factors controlling the production limit in a drum mix plant are the moisture content and ambient temperature of the RAP and new aggregate, the desired production rate, and the temperature and allowable moisture content in the final recycled HMA mix.(5) The maximum amount of RAP that can be used for recycling in a drum mix plant is about 70 percent, although the practical limit is about 50 percent. The use of 50 percent RAP would require extremely high gas temperature and in that case a relatively smaller amount of virgin aggregates would be available to protect the RAP from the flame. This may lead to "blue smoke" problem in some drum mix plants. Most drum mix plants recycle 30 to 50 percent of RAP.

Figures 6-12 through 6-14 show plots constructed from results of a survey of allowable RAP percentages for different states.(10) Figure 6-12 shows maximum allowable percentage of RAP for drum-mix plant in base course. The most common percentage is 50, allowed by 32 percent of states, whereas 22 percent of the states have no limit on the amount of RAP that can be used. Figure 6-13 shows the maximum allowable percentage of RAP for drum-mix plant in binder course. The limits range from none to unlimited percentage of RAP. A large number of states (30 percent) allow 50 percent RAP. About 20 percent of the states have open or no limit provision for use of RAP. The maximum allowable percentages of RAP for drum-mix plant in surface are shown in figure 6-14. About 18 percent of the states do not allow any RAP, and about 16 percent have no limit on the amount of RAP.

FEEDER SYSTEMS

A conventional cold feed system can be used to supply crushed RAP to the drum mix plant. However, to allow easy discharge and avoid stacking problems, the bin should have relatively low capacity, with steep sides and long and wide bottom. The RAP material should not be supplied to the bin as a unit drop as it can cause compaction of the RAP with resultant bridging, sticking and discharge problems. Instead, the material should be dribbled as much as possible.(4) Also, the bin should not be vibrated as this may lead to compaction of the RAP. Both belt and slat type feeders have been used successfully. On warm days RAP should not be left in the bin for more than two hours in case of plant shutdown. It is better to keep the bin half full and feed frequently. Feeders should be fairly wide and should have sufficient horsepower to be used in a start-stop operation as necessary.(4) Vibratory type feeders are not recommended to avoid consolidation and sticking problems.(9)

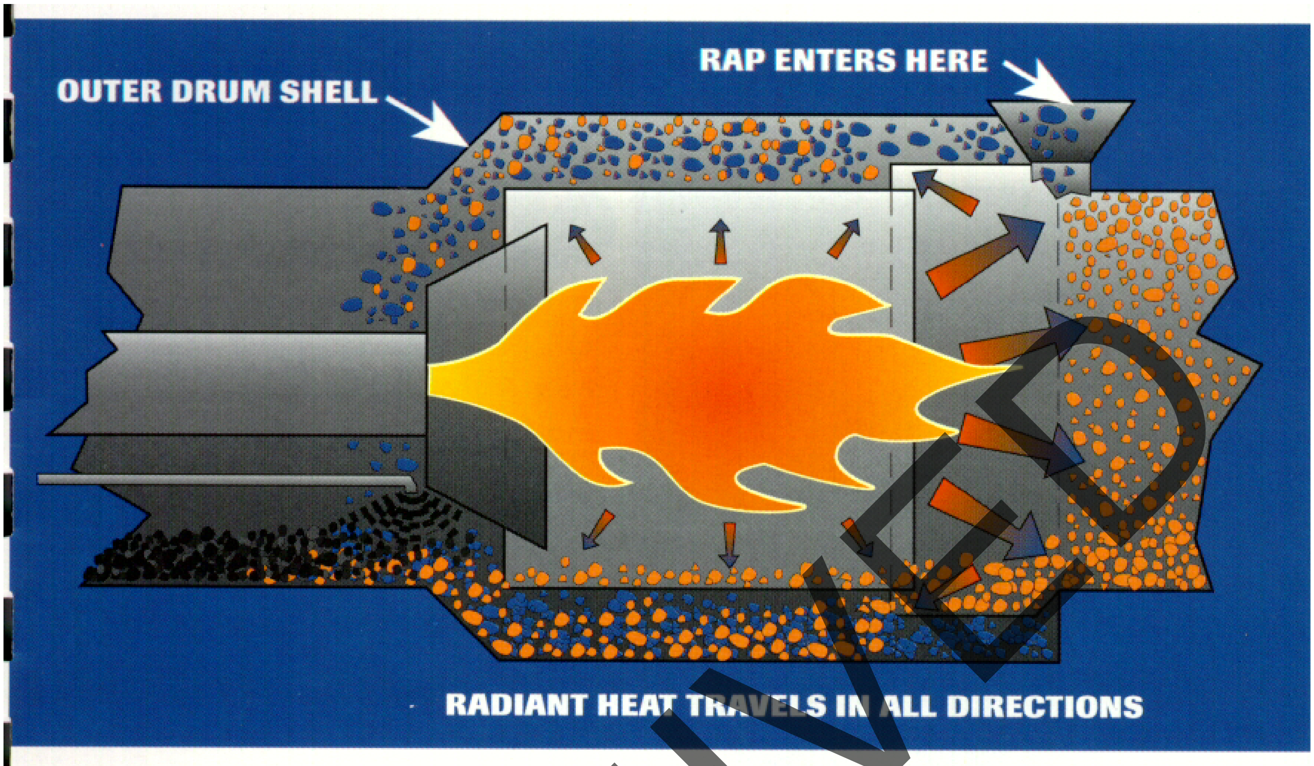

Figure 6-11. Schematic of triple drum mixer.

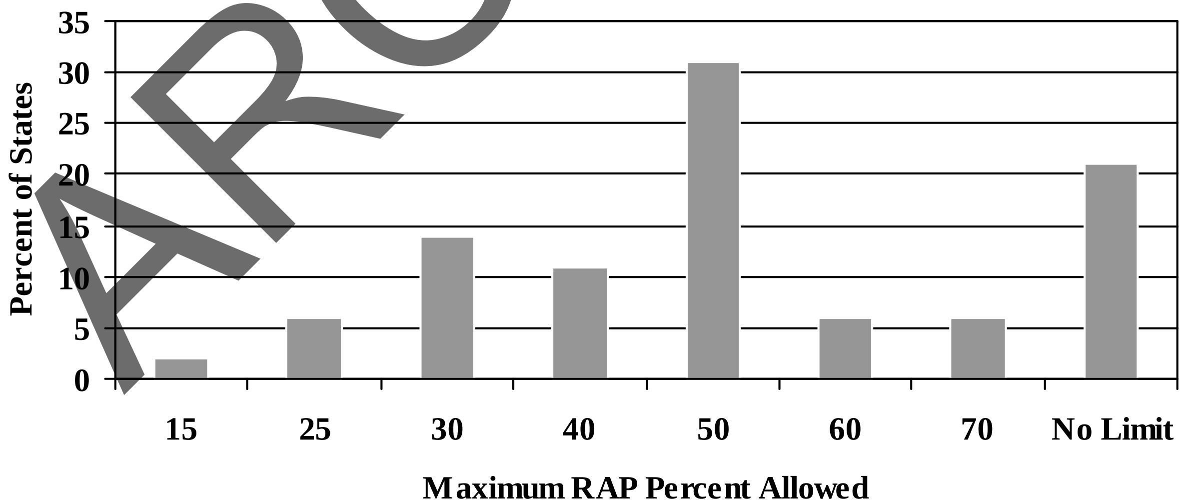

Figure 6-12. Maximum RAP percent allowed for drum-mix plant in base course.

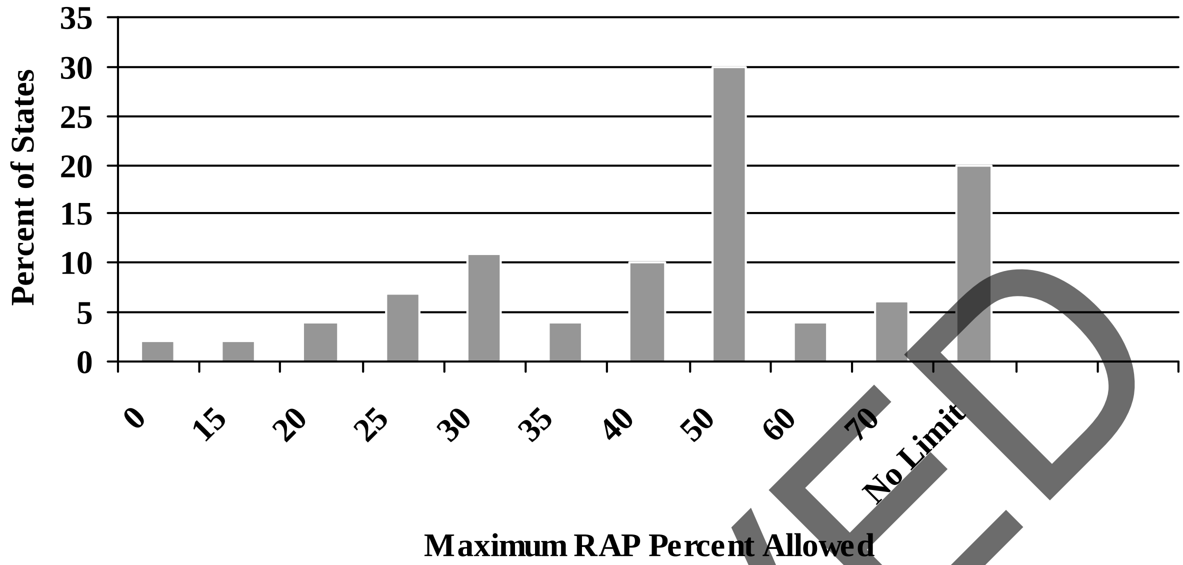

Figure 6-13. Maximum RAP percent allowed for drum-mix plant in binder course.

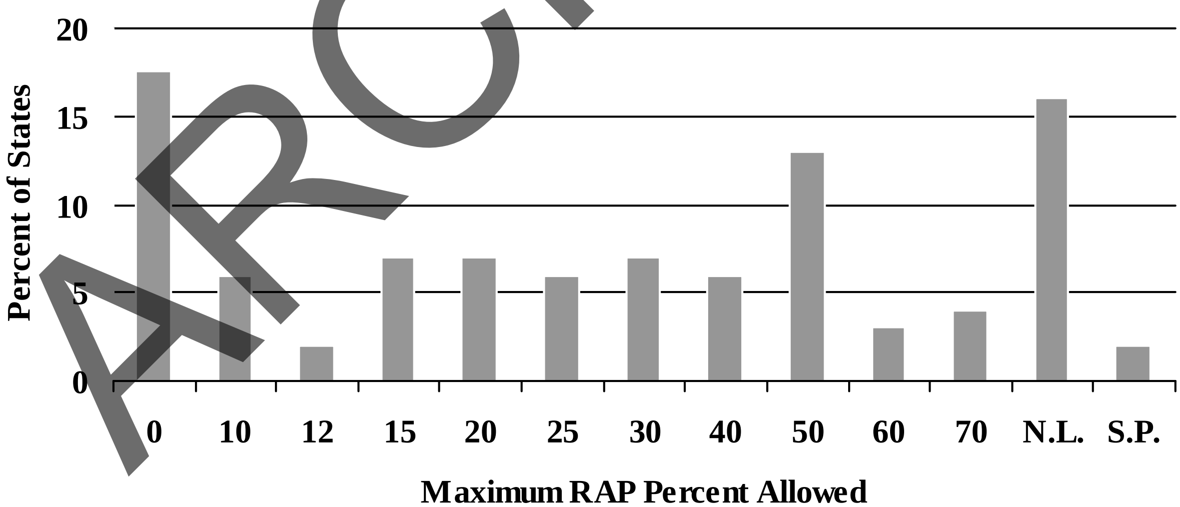

Figure 6-14. Maximum RAP percent allowed for drum-mix plant in surface course.

With computerized controls, it is now possible to achieve automatic process control of mixing operations. Mix designs can be effectively controlled by controlling belt speeds, liquid asphalt flow, and blending.

SUMMARY

When properly designed and constructed, hot recycled mixed can be used to correct pavement defects, and transform old, deficient pavements into good serviceable pavements. Hot mix recycling offers many advantages over conventional HMA construction. It eliminates the disposal problems and can be done repeatedly using the same materials. Besides these usual advantages, drum mix recycling, in particular, offers many advantages including portability and versatility. Drum mix recycling needs minor modification to existing plants, and since retrofit kits are easily available at present, it is rapidly becoming one of the most popular recycling processes. The most widely used method is that with the center entry type drum mix plant. The RAP is introduced into the drum downstream of the burner flame to mix with the superheated new aggregates. Special fixtures such as flights or rings are provided to force the RAP to mix with the virgin aggregates before being subjected to the high gas temperature, thus avoiding generation of smoke. Different modifications have been devised to control emission problems during mixing, caused by high moisture content of aggregates and the relatively long time of exposure of the asphalt binder to high temperature. Double and triple drum mix plants have also been used to prevent the virgin and RAP materials from being exposed to hot gases or steam of the drying process. The factors controlling the production limit in a drum mix plant are the moisture content and ambient temperature of the RAP and new aggregate. A practical limit of 30:70 (30 percent RAP and 70 percent new aggregate) has been recommended in the available literature.

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CHAPTER 7. HOT MIX ASPHALT RECYCLING (MATERIALS AND MIX DESIGN)

INTRODUCTION

Hot mix recycling is the process in which reclaimed asphalt pavement materials are combined with new materials, sometimes along with a recycling agent, to produce hot mix asphalt mixtures. Just as in the case of conventional HMA, recycled mixtures must be designed properly to ensure proper performance. When properly designed, recycled mixtures can have properties similar to those of new conventional hot mix asphalt mixtures.[(1)]

There are four components in hot mix recycling: the reclaimed asphalt pavement (RAP), the virgin aggregate, the virgin asphalt binder and in some cases, a recycling agent. The two steps in the mix design procedure are material evaluation and mix design. The objective of the material evaluation process is to determine the important properties of the component materials to come up with an optimum blend of materials to meet the mix requirements. The objective of the mix design step is to determine the type and percentage of asphalt binder with the help of results from compacted test mixes. The specific steps of the material evaluation and mix design process are as follows.[(2)]

1. Obtain representative field samples of the reclaimed material.
2. Perform laboratory analysis:
   1) determine composition and properties of the RAP
   2) determine the proper amounts of virgin aggregates to be added
   3) select the type and amount of the virgin asphalt binder
   4) mix, compact and test trial mixes.
3. Select the optimum combination of mix components that meet the mix design criteria.

MATERIAL EVALUATION

The material evaluation process consists of sampling and evaluation of the RAP, and the recycling agent, if any, to be used in the recycled mix. The RAP to be used in the recycled mix may come from different layers of HMA with different compositions or stockpiles built with materials from different sources. Hence, representative samples must be obtained from existing pavements, RAP conveying trucks or RAP stockpiles, to evaluate any variation in the different important properties, such as gradation and asphalt content.

Sampling of RAP

Sampling from Existing Pavements: Some highway agencies like to conduct a preliminary sampling and evaluation program for including some important properties such as gradation, asphalt content, penetration and viscosity, of the in-place mix in the Plans, Specification and Estimates package.[(3)] Historical data such as construction plans, past condition surveys and maintenance record may be utilized to delineate substantial differences in pavement section, surface distresses, or increased structural capacity. These differences can be used to separate the project into units of different construction materials or different depths of milling. A random sampling plan should be used to obtain preliminary samples from each of the units in the pavement. The following procedure for preliminary sampling is recommended. The pavement is to be separated into construction units of similar composition by using historical records. Each construction unit should be divided into six to eight sections of equal length. One sample should be selected randomly from each section. Each sample should be of sufficient size (6.8 kg, 15 lb, minimum) for extraction, recovery and testing of asphalt binder. Each of the samples should be tested individually. Table 7-1[3] shows sampling frequency and sample size for those state highway agencies that perform evaluations during the project development stage. A minimum of one sample (consisting of 3 cores) per 1.6 lane-km (1 lane-mile) is recommended. Although most of the agencies core to the full depth of the pavements, after visual examinations, the cores are trimmed off to the proposed depth of removal. For detailed sampling plan the flow chart shown in figure 7-1[2] can be used for evaluating any significant difference in properties of the RAP material. Emphasis should be placed on the random sampling method since this procedure is based on statistical principles and both cost and work may be reduced by this method of sampling.[4] AASHTO T168 Sampling Bituminous Paving Mixtures (pertaining to samples from roadway) can be used as a guidance to obtain HMA pavement cores. After running tests on these samples (as discussed later), the results should be analyzed to determine the mean and standard deviation, and outliers, if any, should be detected. Pavement sections corresponding to the outlier results should be treated separately.

Sampling from RAP Hauling Trucks: RAP samples can be obtained from the trucks hauling RAP from the milling site to the HMA plant for stockpiling. Random sampling is done as shown in the flow chart (figure 7-1). AASHTO T2, sampling aggregates, (pertaining to the samples from a hauling vehicle) can be used as a guidance for sampling RAP from trucks.

Sampling from RAP Stockpiles: To obtain representative samples from RAP stockpiles, 10 samples from different locations in the stockpile should be obtained, and to minimize the effect of segregation, at least 150 mm (6 in) of the material from the surface of the stockpile should be removed before sampling.[5] Samples are scalped off and the material retained on the 50 mm (2 in) sieve is discarded. It is recommended that the sample size should be at least 5 kg (11 lb) after sampling, of which one half should be used for mix composition testing and the other half used for mix design. Individual samples should be used for extraction for aggregate gradation and asphalt content.[6] Five samples are recommended for conducting Abson recovery and determining asphalt binder properties. AASHTO T2 Sampling Aggregates (pertaining to the samples from a stockpile) can be used as a guidance for sampling RAP from the RAP stockpiles. Since the crushing or milling of reclaimed asphalt pavement may alter the gradation of the aggregate portion, Samples from RAP cold feed stockpiles at the plant site should be tested.[4] In addition to the guidelines available in several references, engineering judgement should always be used to develop an effective sampling plan. Once a RAP stockpile is built at a HMA plant, some highway agencies assign it a number such as 96-3 (Stockpile No. 3 of year 1996) which is then referenced in the recycled mix design for that stockpile. No further RAP material is allowed to be added to that stockpile once the final sampling is made for the mix design. As in the case of sampling from existing roadway, test results from RAP stockpiles should be analyzed to identify any outlier. Material from stockpiles corresponding to the outliers should not be included in mix design.

Table 7-1. Pavement evaluation sampling frequency and size.(3)

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/750 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/800 m	Surface area minimum of 230 cm^2
Wyoming	2 cores/km	150 mm diameter for the full depth of structure

Evaluation of RAP

The RAP material needs to be evaluated before the actual mix design. This is because with aging and oxidation certain significant changes occur in the HMA. For the binder, this includes loss of the lighter fractions and a corresponding increase in the proportions of the asphaltenes, hardening (increase in viscosity), and loss of ductility. The gradation of the aggregate may change due to degradation caused by traffic loads and the environment. Hence the composition of the RAP must be determined at the beginning. Most agencies determine aggregate gradation, asphalt content, and asphalt viscosity at 60°C for the reclaimed asphalt pavement. The aged asphalt binder must be extracted from a representative sample of the RAP to determine these properties. The following guidelines are suggested for aggregate and binder evaluation.(4)

Aggregate Evaluation: AASHTO T30, Mechanical Analysis of Extracted Aggregate, or AASHTO T27, Sieve Analysis of Fine and Coarse Aggregates, should be used to perform a sieve analysis of the aggregate extracted from the RAP. Any deficiency can be corrected by blending appropriate sieve fractions of virgin and/or reclaimed aggregate with reclaimed asphalt pavement aggregate. It is also recommended to examine the angularity of both coarse and fine aggregates. <u>Extraction</u>: AASHTO T 164, Quantitative Extraction of Bitumen from Bituminous Paving Mixtures should be used to quantitatively extract the asphalt binder from RAP if the extracted binder is to be recovered and tested for further evaluation. The National Center for Asphalt Technology's (NCAT's) ignition test can be used to determine the RAP composition (asphalt content and aggregate gradation) if the asphalt binder is not intended to be recovered.

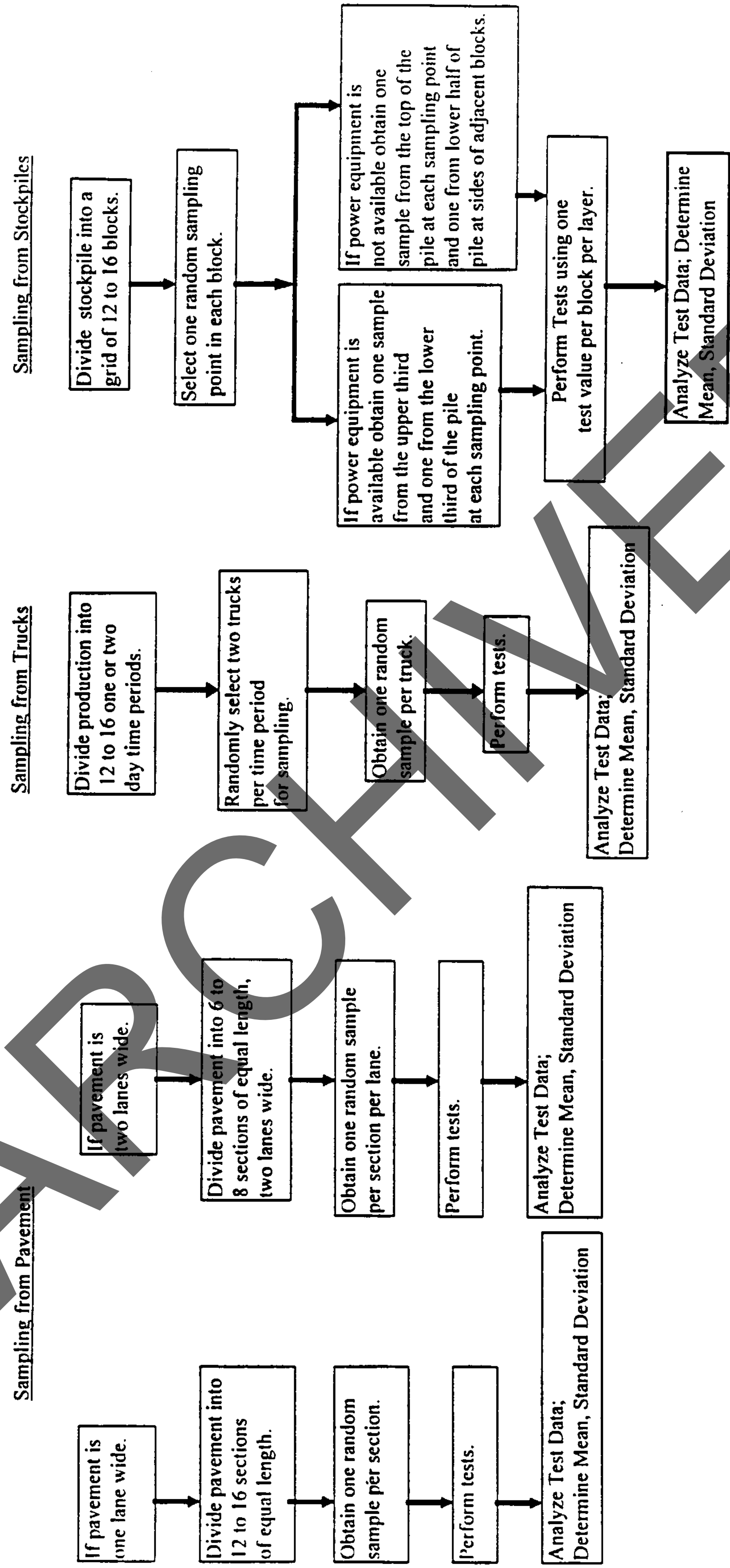


Figure 7-1. Flow chart of sampling plans.(modified from 2)

Asphalt Binder Evaluation: The extracted asphalt is recovered from the solution by AASHTO T 170. Recovery of Asphalt from Solution by Abson Method. SHRP has developed an improved method of recovering asphalt binder from solution: SHRP Designation B-006 Extraction and Recovery of Asphalt Cement for Rheological Testing. This method is preferable to AASHTO T170. AASHTO T 202 should then be used to check the consistency of the recovered asphalt binder by measuring its viscosity at 60°C, to estimate the amount and grade of virgin asphalt binder required in the recycled mix. Some agencies also test the penetration at 25°C of the recovered asphalt binder.

If no more than 15-20 percent RAP is used in the recycled mix, testing of the extracted asphalt is not required by many highway agencies and the grade of the virgin asphalt binder is kept the same as that of the conventional mix.

Recycling Agents

There are four basic purposes for using recycling agents.(7) These are: (1) to restore the aged asphalt binder characteristics to a consistency level appropriate for construction purposes and end use of the mix; (2) restore the recycled HMA mix to its optimum characteristics for durability; (3) provide sufficient additional binder to coat any virgin aggregate added to the recycled mix; and (4) provide sufficient additional binder to satisfy mix design requirements.

Recycling agents have been defined as organic materials with chemical and physical characteristics selected to restore aged asphalt to desired specifications.(4) In selecting the recycling agent, the viscosity characteristics of the combined aged asphalt binder and the recycling agent are the determining factors. These agents are also known as softening agents, reclaiming agents, modifiers, fluxing oils, extender oils, and aromatic oils.(7) The Pacific Coast User-Producer Group has defined recycling agent as a hydrocarbon product with physical characteristics selected to restore aged asphalt binder to requirements of current asphalt binder specifications. Under this definition, softer asphalt and specialty products can be classified as recycling agents.(7) Asphalt cements can be used when an increase in total binder content of the recycled mix is required and the specific grade can be blended with the aged asphalt binder in the RAP to yield an asphalt binder meeting the desired specifications. Generally, AC-10, AC-5 or AC 2.5 (85-100, 120-150 or 200-300 pen; AR-4000, AR-2000 or AR-1000) asphalt cements are used for this purpose.(4) Use of such soft grades of asphalt binder in hot mix recycling is more prevalent in the U.S. compared to the use of commercial recycling agents. If the aged asphalt binder has a very high viscosity (or low penetration) or the percentage of RAP in the recycled HMA is much greater than 50 percent, a relatively small amount of a commercial recycling agent can be used to modify the aged asphalt binder without altering the desired binder content. Then, if additional binder is required, the normal grade of asphalt for a virgin mix can be added, though this necessitates that the plant be capable of adding two binder materials.(8) Recycling agents in emulsion form have the potential advantages of improved fluxing, mixing and temperature control to prevent localized overheating in drum mixers. Furthermore, the formulation of the emulsion can be adjusted to provide the design end result viscosity of the binder in the recycled HMA mix. A disadvantage is that additional heat is required to remove the 30 to 35 percent water contained in the emulsion.(9) To ensure the proper function of the modifiers, the following properties are suggested for specification purposes:(7)

1. Be easy to disperse in recycled mixture.

2. Capable of altering the viscosity of aged asphalt binder in the RAP to the desired level.
3. Be compatible with the aged asphalt binder to ensure that syneresis (exudation of paraffins from asphalts) will not occur.
4. Have the ability to redisperse the asphaltenes in the aged asphalt binder.
5. Improve the life expectancy of the recycled HMA mix.
6. Be uniform in properties from batch to batch.
7. Be resistant to smoking and flashing.

Several tests have been investigated by various agencies for evaluation of recycling agents. Table 7-2 shows the physical properties of hot mix recycling agents contained in ASTM Standard Practice D4552 Classifying Hot-Mix Recycling Agents.[10] The important properties mentioned are as follows:

1. Viscosity at 60°C is used to measure asphalt binder consistency to grade materials and ensure uniformity.
2. Flash point is an important guide for evaluating the presence of volatile organic compounds or contaminants in the recycling agent. This is important for safety during shipping, handling, and storage of the recycling agent.
3. Weight percentage of saturates is specified to ensure compatibility.
4. Weight loss must be evaluated to minimize smoke generation and volatile loss during hot mix production.
5. Aging tests are needed to minimize excessive hardening of the agent during hot mixing and to ensure durability.

The choice of Recycling Agent (RA) grade will depend on the amount and hardness of the asphalt in the aged pavement. In general, the lower viscosity RA types can be used to restore aged asphalts of high viscosity and vice versa.

Additionally, grades RA 1, RA 5, RA 25 and RA 75[10] will generally be most appropriate for hot mix recycling of salvaged asphalt concrete when no more than 30 percent virgin aggregate is added, while grades RA 250 and RA 500 will generally be most appropriate when more than 30 percent virgin aggregate is incorporated into the mix.[10] Specifications for emulsified recycling agents are normally based on the specifications for recycling agents with additional tests that are identical or similar to those for asphalt emulsions (table 7-3). ASTM D5505 Standard Practice for Classifying Emulsified Recycling Agents can be used to select an appropriate emulsified recycling agent. The choice of emulsified recycling agent will be determined by the consistency of the binder in the aged pavement, the methods of recycling planned, the amount, if any, of new aggregates, and other design needs.[10]

MIX DESIGN PROCEDURES

Figure 7-2 shows the flow chart recommended for the different steps in mix design of recycled mixes.[4] Conventional recycled mix design will be presented first followed by the Superpave recycled mix design.

(1) Combined Aggregates in the Recycled Mixture - Using the gradation of the aggregate from the reclaimed asphalt pavement and new aggregate, a combined gradation meeting the desired

Table 7-2. ASTM specification for hot mix recycling agents.[10]

TEST	ASTM Test Method	RA 1		RA 5		RA 25		RA 75		RA 250		RA 500	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Viscosity at 140°F, cSt	D 2170 or D 2171	50	175	176	900	901	4500	4501	12500	12501	37500	37501	60000
Flash point, COC, °F	D92	425	...	425	...	425	...	425	...	425	...	425	...
Saturates, wt%	D 2007	...	30	...	30	...	30	...	30	...	30	...	30
Tests on residue from RTFO or TFO oven 325°F	D 2872 or D 1754												
Viscosity ratio[A]	-	...	3	...	3	...	3	...	3	...	3	...	3
Wt change ± %	-	...	4	...	4	...	3	...	3	...	3	...	3
Specific gravity	D 70 or D 1298	Report		Report		Report		Report		Report		Report	

Table 7-3. Specification for emulsifying recycling agents.[10]

TESTS	Test Method	ER-1		ER-2		ER-35	
		Min	Max	Min	Max	Min	Max
On emulsion							
Viscosity, 50°C, SSF	D 244		100	20	450	20	450
Sieve, %	D 244		0.1		0.1		0.1
Storage stability, 24 h, %	D 244		1.5		1.5		1.5
Residue, by distillation, %	D 244	65		65		65	
Dilution			report[A]				
Specific gravity	D 70		report		report		report
Compactibility [B]	varies		report		report		report
On residue from distillation							
Viscosity, 60°C, cSt	D 2170	50	200		30		30
Saturates, %	D 2007		30				
Solubility in trichloroethylene	D 2042	97.5		97.5		97.5	
On residue from distillation after RTFO[C]							
Penetration, 4°C, 50 g 5 s	D 5			75	200	5	75
RTFO, weight change, %	D 2872		4		4		4

Notes:

[A] ER-1 shall be certified for dilution with potable water.

[B] This specification allows a variety of emulsions, including high-float and cationic emulsions. The engineer should take the steps necessary to keep incompatible materials from co-mingling in tanks or other vessels. It would be prudent to have the chemical nature (flat test for high float emulsions, particle charge test for cationic emulsions, or other tests as necessary) certified by the supplier.

[C] RTFO shall be the standard. When approved by the engineer the Thin Film Oven Test (Test Method D 1754) may be substituted for compliance testing.

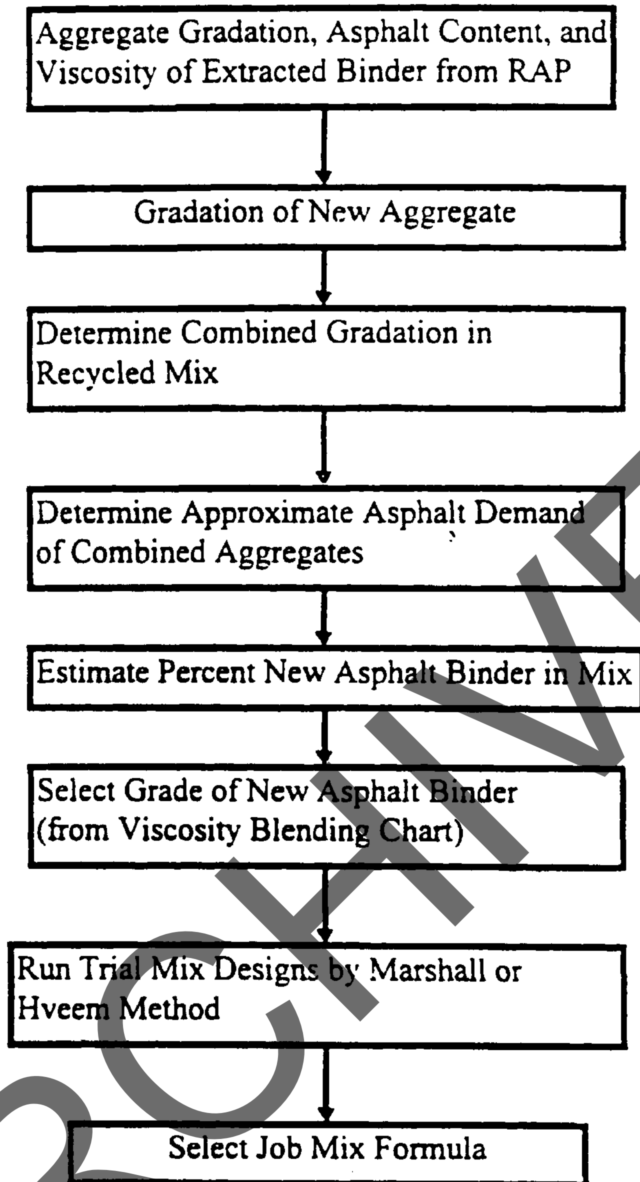
specification requirements is calculated. After the blend of aggregate (aggregate in the RAP and new aggregates) have been established, the amount of new aggregate is expressed as r, in percent. For example, suppose the following blend was established for a recycled mix:

75 percent new aggregate
25 percent RAP aggregate
100 percent total

The amount of new aggregate is 75 percent. Hence, r = 75. Table 7-4[4] contains formulas for proportioning materials for recycled HMA mixes where the blend of aggregates in the mix is kept constant.

(2) Approximate Asphalt Binder Demand of the Combined Aggregates - The most practical approach is to assume the asphalt demand of the combined aggregates in the proposed recycled HMA to be equal to the optimum asphalt content of 100 percent virgin HMA (without any RAP). Therefore, the following procedure of determining the approximate asphalt demand may not be necessary unless no mix design is available for 100 percent virgin mix.

The approximate asphalt demand of the combined aggregates may be determined by the Centrifuge Kerosene Equivalent (CKE) test included in the Asphalt Institute Hveem Method of



Note: Instead of New Asphalt, Recycling Agent may be used

Figure 7-2. Flow chart for mix design procedure.

Mix Design, or calculated by the following empirical formula:

$$P = 0.035a + 0.045b + Kc + F$$

where:

- P = approximate total asphalt demand of recycled mix, percent by weight of mix
- a = percent of mineral aggregate retained on 2.36 mm sieve, expressed as a whole number
- b = percent of mineral aggregate passing the 2.36 mm sieve and retained on the 75 µm sieve, expressed as a whole number

Table 7-4. Formulas for proportioning materials for hot recycled mixtures.[4]

	For Asphalt Content	
	by weight of total mix	by weight of aggregate
% New Asphalt, P_{nb}	$\frac{(100^2 - rP_{sb})P_b}{100(100 - P_{sb})} - \frac{(100 - r)P_{sb}}{100 - P_{sb}}$	$P_b - \frac{(100 - r)P_{sb}}{100}$
% RAP, P_{sm}	$\frac{100(100 - r)}{100 - P_{sb}} - \frac{(100 - r)P_b}{100 - P_{sb}}$	$\frac{(100 + P_{sb})(100 - r)}{100}$
% New Aggregate, P_{ns}	$r - \frac{rP_b}{100}$	r
TOTAL	100	100 + P_b
% New Asphalt to Total Asphalt Content, R	$\frac{100P_{nb}}{P_b}$	$\frac{100P_{nb}}{P_b}$

Notes:

P_{sm} = Percent salvaged mix (RAP) in recycled mix
P_b = Asphalt content of recycled mix, %
P_{sb} = Asphalt content of salvaged mix (RAP), %
P_{nb} = Additional asphalt and/or recycled agent in recycled mix, %
P_{ns} = Percent additional aggregate (new aggregate material)
r = Percent new aggregate material to total aggregate in recycled mix
R = Percent new asphalt and/or recycling agent to total asphalt in recycled mix

c = percent of mineral aggregate passing the 75µm sieve
K = 0.15 for 11-15 percent passing 75 µm sieve, 0.18 for 6-10 percent passing 75µm sieve, and 0.20 for 5 percent or less passing 75 µm sieve
F = 0 to 2.0 percent. Based on absorption of light or heavy aggregate. In the absence of other data, a value of 0.7 is suggested

With an approximate asphalt demand established, this will provide a basis for a series of trial mixes for a mix design. Trial mixes will vary in asphalt contents in 0.5 increments on either side of the calculated approximate asphalt demand.

For example, suppose that the approximate asphalt demand was calculated to be 6.2 percent. A series of trial mixes then range from 5.0 to 7.0 percent or from 5.5 to 7.5 percent.

(3) Estimated Percent of New Binder Asphalt in HMA Mixture - The quantity of new asphalt binder to be added to the trial mixes of the recycled HMA mixture, expressed as percent by weight of total mix is calculated by the following formula:

$$P_{nb} = \frac{(100^2 - rP_{sb})P_b}{100(100 - P_{sb})} - \frac{(100 - r)P_{sb}}{100 - P_{sb}}$$

where:

Pnb = Percent of new asphalt binder in recycled mix (plus recycling agent, if used), expressed as whole number

r = new aggregate expressed as a percent of the total aggregate in the recycled mix expressed as a whole number

P_b = percent, estimated asphalt content of recycled mix (assumed to be the same as that of 100 percent virgin HMA mix or determined as an approximate asphalt demand of combined aggregates in the preceding step)

P_{sb} = percent, asphalt content of reclaimed asphalt pavement (RAP) (plus recycling agent, if used)

For example, suppose the asphalt content, P_{sb} of the RAP is 4.7 percent and r = 75 percent, then

$$P_{nb} = \frac{(100^2 - 75 X 4.7) P_b}{100(100 - 4.7)} - \frac{(100 - 75) 4.7}{100 - 4.7} = 1.01 \ P_b - 1.23$$

The percentages of new asphalt binder for any asphalt content may now be readily determined. The formula above is for asphalt content expressed as percent by weight of total mix. If asphalt contents are expressed as percent by weight of aggregate the formula for calculating quantity of new asphalt binder is:

$$P_{nb} = P_b - \frac{(100 - r) P_{sb}}{100}$$

(4) Select Grade of New Asphalt Binder - Using figure 7-3,[4] a target viscosity of the asphalt blend is selected. A commonly selected target point is the viscosity at the mid-range of the specified viscosity-graded asphalt binder. For example, the target for an AC-20 asphalt binder would be 2,000 poises.

The percent of the new asphalt, P_{nb}, to the total asphalt content, P_b, is expressed by the following formula:

$$R = \frac{100 \ P_{nb}}{P_b}$$

For example, suppose the mix described in Step (3) is to have an estimated total asphalt content of 6.2 percent. The amount of new asphalt to be added (from Step 3) is:

P_{nb} = 1.01 X 6.2 - 1.23 = 5.0 percent

Then:

$$R = \frac{100(5.0)}{6.2} = 81$$

The grade of new asphalt binder (and/or recycling agent) is determined using a log-log viscosity versus percent new asphalt binder blending chart such as figure 7-3.[4] A target viscosity for the blend of recovered asphalt and the new asphalt (and/or recycling agent) is selected. As mentioned earlier, the target viscosity is usually the viscosity of the mid range of the grade of asphalt binder normally used depending on type of construction, climatic conditions, amount and nature of traffic.

Plot the viscosity of the aged asphalt in the RAP on the left hand vertical scale, Point A, as illustrated in figure 7-3. Draw a vertical line representing the percentage of new asphalt binder, R, calculated above and determine its intersection with the horizontal line representing the target viscosity (2,000 poises in this example), Point B. Then draw a straight line from Point A, through Point B and extend it to intersect the right hand scale, Point C. Point C is the viscosity at 60°C (140°F) of the new asphalt binder (and/or recycling agent) required to blend with the asphalt binder in the reclaimed asphalt pavement (RAP) to obtain the target viscosity in the blend. Select the grade of new asphalt binder that has a viscosity range that includes or is closest to the viscosity at Point C. To plot a point using the vertical scale, consider expressing the viscosity using 10 raised to some power. For example, 75,000 poises would be 7.5×10^4. To plot the point on the vertical scale, 7.5 would be interpolated on the scale between 10^4 and 10^5. It is suggested that when selecting a grade of asphalt cement for recycling that the following guide be used:

Up to 15 percent RAP =	No change in asphalt binder grade (some highway agencies use 20 percent in lieu of 15 percent)
16 percent RAP or more =	Use asphalt binder one grade softer than that normally specified for 100 percent virgin HMA mix. For example, use AC-10 in lieu of AC-20. Do not change more than one viscosity grade unless the recycled HMA mix is checked for resistance to rutting.

(5) Trial Mix Design - Trial mix designs are then made using the Marshall or Hveem method. The formulas shown in table 7-4 are used for proportioning the ingredients: new asphalt binder, P_{nb}, percent reclaimed asphalt pavement (RAP), P_{sm} and new aggregate, P_{ns}.

(6) Select Job-Mix Formula. - The optimum asphalt content is selected based on the test data obtained in the preceding step. If the Marshall mix design procedure is used, the optimum asphalt content is selected to give 4.0 percent air void content. Two mix design examples follow.

Design Example 1: The reclaimed asphalt pavement has an asphalt content of 5.4 percent by weight of total mix. The viscosity of the asphalt binder recovered from the reclaimed asphalt pavement (RAP) is 46,000 poises at 60°C (140°F). The grade of asphalt cement normally used is AC-20, and the target viscosity at a temperature of 60°C (140°F) is 2,000 poises. Gradation of RAP and new aggregate is:

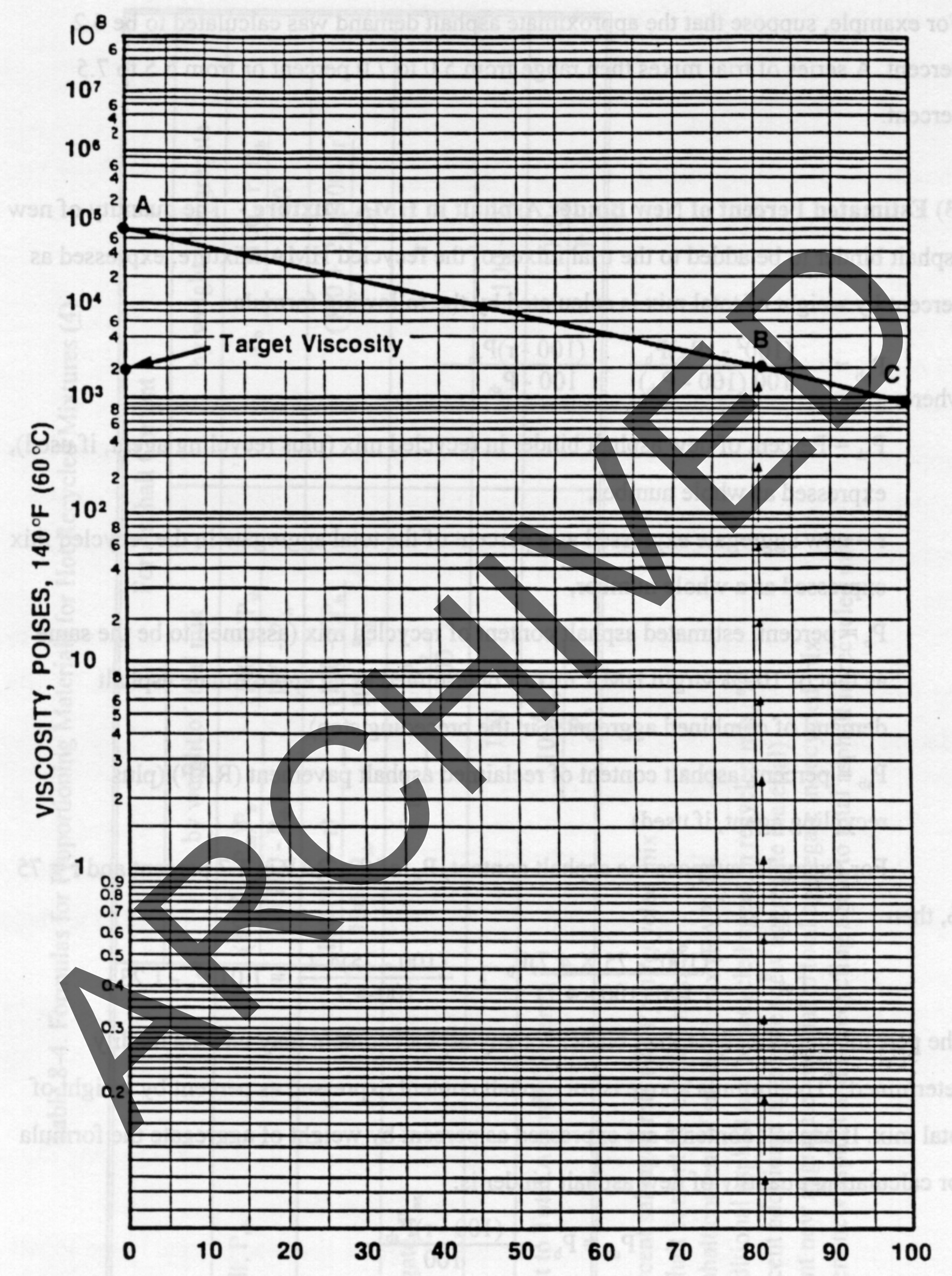


Figure 7-3. Asphalt viscosity blending chart.[4]

Sieve Size	Percent Passing	
	RAP Agg.	New Agg.
25.0 mm (1 in)	100	100
19.0 mm (3/4 in)	98	93
9.5 mm (3/8 in)	85	53
4.75 mm (No. 4)	65	30
2.36 mm (No. 8)	52	16
300 µm (No. 50)	22	5
75 µm (No. 200)	8	1

Approximately 30 percent of RAP was selected because (1) a batch plant was to be used for recycling, (2) moisture content of the RAP was 5 percent and (3) this is a practical range for maintaining mix productions based on percent of RAP and moisture.

Step 1 - Combined aggregates in recycling mixture

Sieve Size	Percent Passing		
	30% RAP Agg.	70% New Agg.	Combination Agg.
25.0 mm (1 in)	[100 × 0.3 = 30.0]	[100 X 0.7 = 70.0]	100.0
19.0 mm (3/4 in)	[98 × 0.3 = 29.4]	[93 X 0.7 = 65.1]	94.5
9.5 mm (3/8 in)	[85 × 0.3 = 25.5]	[53 X 0.7 = 37.1]	62.6
4.75 mm (No. 4)	[65 × 0.3 = 19.5]	[30 X 0.7 = 21.0]	40.5
2.36 mm (No. 8)	[52 × 0.3 = 15.6]	[16 X 0.7 = 11.2]	26.8
300 µm (No. 50)	[22 × 0.3 = 6.6]	[5 X 0.7 = 3.5]	10.1
75 µm (No. 200)	[8 × 0.3 = 2.4]	[1 X 0.7 = 0.7]	3.1

Then: r = 70

The job specification for aggregate gradation (for 19 mm nominal size) is:

Sieve Size	Percent Passing	
	Max. Size % Pass	Combined Agg. % Pass
25.0 mm (1 in)	100	100.0
19.0 mm (3/4 in)	90-100	94.5
9.5 mm (3/8 in)	56-80	62.6
4.75 mm (No. 4)	35-65	40.5
2.36 mm (No. 8)	23-49	26.8
300 µm (No. 50)	5-19	10.1
75 µm (No. 200)	2-8	3.1

Step 2 - Approximate asphalt demand of combined aggregates

$$\begin{aligned} P &= 0.035a + 0.045b + Kc + F \\ &= 0.035 \times 73.2 + 0.045 \times 23.7 + 0.20 \text{ x } 3.1 + 1.0 \\ &= 5.2 \text{ percent} \end{aligned}$$

Step 3 - Estimated percent of new asphalt binder in mix

$$\begin{aligned} P_{nb} &= \frac{(100^2 - rP_{sb})P_b}{100(100 - P_{sb})} - \frac{(100 - r)P_{sb}}{100 - P_{sb}} \\ &= \frac{(100^2 - 5.4X70)P_b}{100(100 - 5.4)} - \frac{(100 - 70)5.4}{100 - 5.4} \\ &= 1.02 \; P_b - 1.71 \end{aligned}$$

For an approximate asphalt binder demand of 5.2 percent:

$P_{nb} = 1.02\ (5.2) - 1.71 = 3.6$ percent

The percent of new asphalt binder, P_{nb}, to total asphalt, P_b, will then be

$$R = \frac{100(3.6)}{5.2} = 69 \;\; percent$$

Step 4 - Select grade of new asphalt binder

On figure 7-4, Point A is the viscosity of the aged asphalt binder at 46,000 poises (4.6×10^4). Point B is located from a target viscosity of 2,000 poises (2.0×10^3) and R = 69. The projected line from Point A through Point B to Point C indicated that the viscosity of the new asphalt binder is 7.0×10^2 (700).

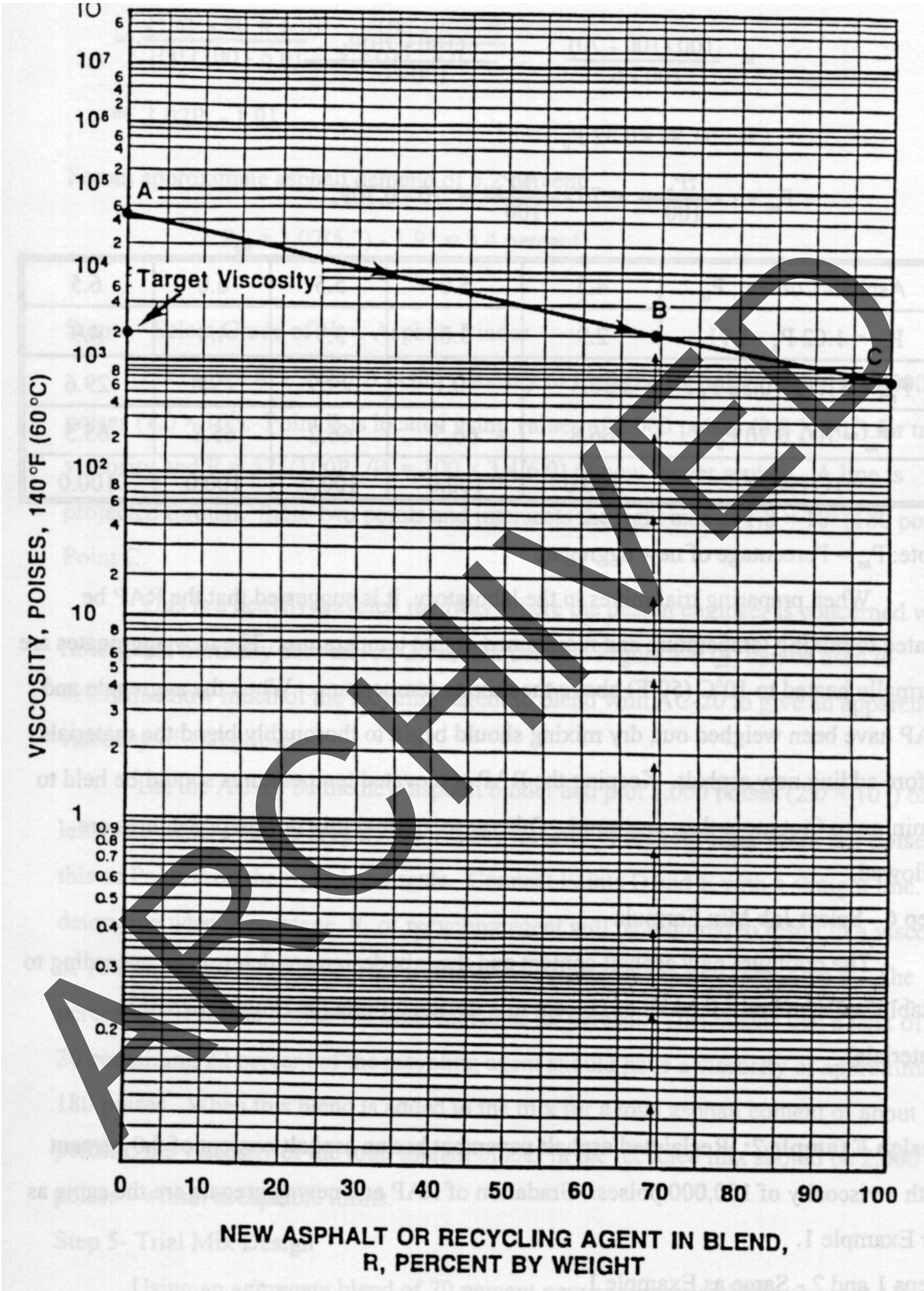


Figure 7-4. Asphalt viscosity blending chart (design example 1).

Since AC-20 is the normal grade of asphalt cement used in the area of construction, climate and traffic, an AC-10 will be chosen for this project. The AC-10 when blended with the aged asphalt binder in the RAP should result in an AC-20 within acceptable tolerances.

Step 5 - Trial mix design

Using an aggregate blend of 70 percent new aggregate and 30 percent RAP aggregate, trial mixes of different asphalt contents (varying in 0.5 percent increments on either side of the estimated asphalt demand) are prepared according to standard Marshall or Hveem mix design procedures.

The formulas in table 7-4 may be used to calculate the percentages of each ingredient in the trial mixes. Since the formula for P_{nb} was calculated in Step 3, the formulas for proportioning P_{sm} and P_{ns} are:

$$\begin{aligned} P_{sm} &= \frac{100(100-r)}{(100-P_{sb})} - \frac{(100-r)P_b}{(100-P_{sb})} \\ &= \frac{100(100-70)}{100-6} - \frac{(100-70)P_b}{100-6} \\ &= 31.91 - 0.32P_b \end{aligned}$$

$$P_{ns} = r - \frac{rP_b}{100} = 70 - \frac{70P_b}{100} = 70 - 0.70P_b$$

Asphalt Content, P_b	4.5	5.0	5.5	6.0	6.5
P_{nb} = 1.02 P_b - 1.71	2.9	3.0	3.9	4.4	4.9
P_{sm} = 31.71 - 0.32 P_b	30.3	30.1	29.9	29.8	29.6
P_{ns} = 70 - 0.70 P_b	66.8	66.5	66.2	65.8	65.5
TOTAL	100.0	100.0	100.0	100.0	100.0

Note:
P_{ns} = Percentage of new aggregate

When preparing trial mixes in the laboratory, it is suggested that the RAP be heated to mixing temperature and maintained at that temperature. The new aggregates are normally heated to 10°C (50°F) above the mixing temperature. When the aggregate and RAP have been weighed out, dry mixing should begin to thoroughly blend the materials before adding new asphalt. Keeping the RAP at elevated temperatures should be held to a minimum (not more than one hour). Otherwise, normal mix design procedures are followed.

Step 6 - Select job mix formula

The optimum new asphalt content and the mix design are determined according to established standard Marshall or Hveem mix design criteria (as is used for virgin materials).

Design Example 2: Reclaimed asphalt pavement has an asphalt content of 6.0 percent with a viscosity of 100,000 poises. Gradation of RAP and new aggregate are the same as for Example 1.

Steps 1 and 2 - Same as Example 1

Step 3 - Estimate percent of new asphalt in mix

$$\begin{aligned} P_{nb} &= \frac{(100^2 - rP_{sb})Pb}{100(100 - P_{sb})} - \frac{(100 - r)P_{sb}}{100 - P_{sb}} \\ &= \frac{(100^2 - 70X6.0)}{100(100 - 6.0)} - \frac{(100 - 70)6.0}{100 - 6.0} \\ &= 1.02P_b - 1.91 \end{aligned}$$

For an approximate asphalt demand of 5.2 percent:

P_{nb} = 1.02(5.2) - 1.91 = 3.4 percent

Step 4 - Select grade of new asphalt binder

On figure 7-5, Point A is the viscosity of the aged asphalt binder at 100,000 poises (1.0×10^5). Point B is located using values of 2,000 poises ($2.0 \text{ X } 10^3$) for target viscosity and R = 57, ($100P_{nb}/P_b$ = 100 × 3.4/6.0) of new binder asphalt. A line is projected through these two points and intersects the right axis at 1.8×10^2 (180 poises), Point C.

This is a heavily-traveled roadway where the design engineer is concerned with rutting and normally uses an AC-20 in mix design. Figure 7-6[(4)] can be used to determine how much of the recycling agent to blend with AC-20 to give an apparent viscosity of 180 poises.

Let the AC-20 be the new asphalt binder and plot 2,000 poises (2.0×10^3) on the left-hand scale, Point D (figure 7-5). The viscosity of the recycling agent is 1 poise. Plot this as Point E on the right-hand scale. Connect Points D and E with a straight line. Now determine what percentage, R, of recycling agent will be required to result in a viscosity of 180 poises for the blend. This is plotted as Point F on the line from D to E. The percentage R on the horizontal scale indicates 22 percent. This means that a tank of AC-20 containing 22 percent of the recycling agent should have a viscosity of approximately 180 poises. When this blend is added to the mix for a total asphalt content of about 5.2 percent, the viscosity of the total asphalt binder in the recycled mix should be 2,000 poises—within acceptable limits.

Step 5- Trial mix design

Using an aggregate blend of 70 percent new aggregate and 30 percent RAP aggregate, trial mixes of different asphalt contents (varying in 0.5 percent increments on either side of the estimated asphalt demand) are prepared according to standard Marshall or Hveem mix design procedures. The formulas in table 7-4 may be used to calculate the percentages of each ingredient in the trial mixes. Since the formula for P_{nb} was calculated in Step 3, the formulas for proportioning P_{sm} and P_{ns} are:

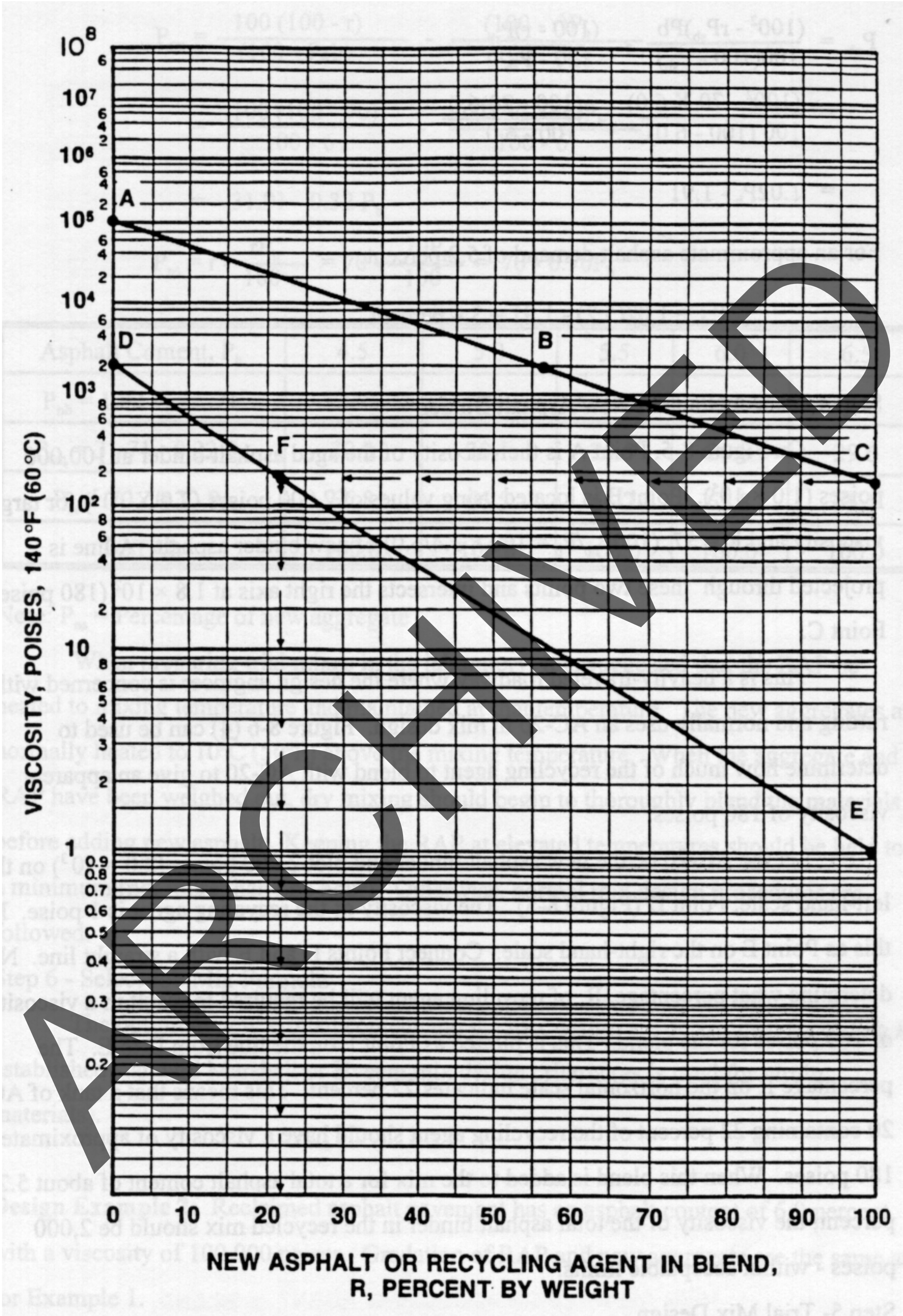


Figure 7-5. Asphalt viscosity blending chart (design example 2).

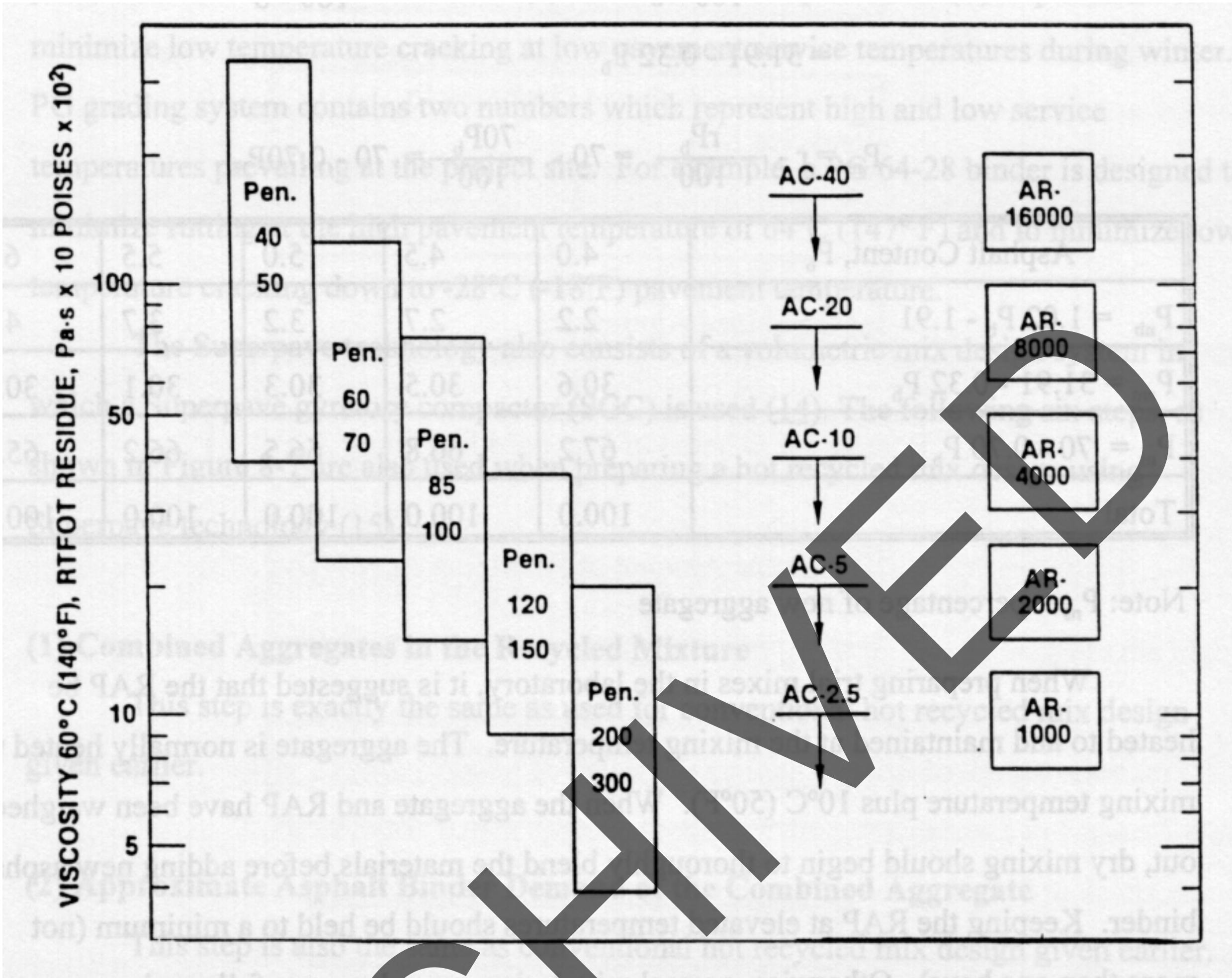


Figure 7-6. Comparison of penetration grades and viscosity grades of asphalt cement (based on RTFOT residue for AR-grades and penetration grades; TFOT residue for AC- grades).

$$P_{sm} = \frac{100\,(100 - r)}{(100 - P_{sb})} - \frac{(100 - r)\,P_b}{(100 - P_{sb})}$$

$$= \frac{100\,(100 - 70)}{100 - 6} - \frac{(100 - 70)\,P_b}{100 - 6}$$

$$= 31.91 - 0.32\,P_b$$

$$P_{ns} = r - \frac{rP_b}{100} = 70 - \frac{70\,P_b}{100} = 70 - 0.70\,P_b$$

Asphalt Content, P_b	4.0	4.5	5.0	5.5	6.0
P_{nb} = 1.02 P_b - 1.91	2.2	2.7	3.2	3.7	4.2
P_{sm} = 31.91 - 0.32 P_b	30.6	30.5	30.3	30.1	30.0
P_{ns} = 70 - 0.70 P_b	67.2	66.8	66.5	66.2	65.8
Total	100.0	100.0	100.0	100.0	100.0

Note: P_{ns} = percentage of new aggregate

When preparing trial mixes in the laboratory, it is suggested that the RAP be heated to and maintained at the mixing temperature. The aggregate is normally heated to mixing temperature plus 10ºC (50ºF). When the aggregate and RAP have been weighed out, dry mixing should begin to thoroughly blend the materials before adding new asphalt binder. Keeping the RAP at elevated temperatures should be held to a minimum (not more than one hour). Otherwise, normal mix design procedures are followed.

Step 6 - Select job-mix formula

The optimum new asphalt content and the mix design are determined according to established standard Marshall or Hveem mix-design criteria (as is used for virgin materials). If the Marshall mix design is used, select the optimum asphalt content which gives 4.0 percent air void content.

Hot Recycled Mix Design with Superpave Technology

Superpave technology, a part of the Strategic Highway Research Program (SHRP), developed a performance-based specification for asphalt binders.[11,12,13] The performance grade (PG) of asphalt binder is designed to improve the performance of HMA pavements at three service temperatures. The PG binder specifications consist of (a) a rutting factor ($G^*/\sin\delta$) to minimize rutting at high pavement temperatures during summer, (b) a fatigue factor ($G^*\sin\delta$) to minimize fatigue cracking at intermediate pavement service temperatures, and (c) a maximum creep stiffness (S) requirement to minimize low temperature cracking at low pavement service temperatures during winter. PG grading system contains two numbers which represent high and low service temperatures prevailing at the project site. For example, a PG 64-28 binder is designed to minimize rutting at the high pavement temperature of 64ºC (147ºF) and to minimize low temperature cracking down to -28ºC (-18ºF) pavement temperature.

The Superpave technology also consists of a volumetric mix design system in which a Superpave gyratory compactor (SGC) is used.[14] The following six steps, as shown in figure 7-7 are also used when preparing a hot recycled mix design using Superpave technology.[15]

(1) Combined Aggregates in the Recycled Mixture

This step is exactly the same as used for conventional hot recycled mix design given earlier.

(2) Approximate Asphalt Binder Demand of the Combined Aggregate

This step is also the same as conventional hot recycled mix design given earlier. An alternate method is given in the Superpave volumetric mix design method[16] which calculates estimated asphalt content based on the combined aggregate gradation. However, the procedure is very tedious. It is recommended to assume the estimated asphalt content of the recycled HMA mixture equal to that of 100 percent virgin HMA mixture.

(3) Estimate Percent of New Asphalt Binder in HMA Mixture

This step is also the same as conventional hot recycled mix design given earlier.

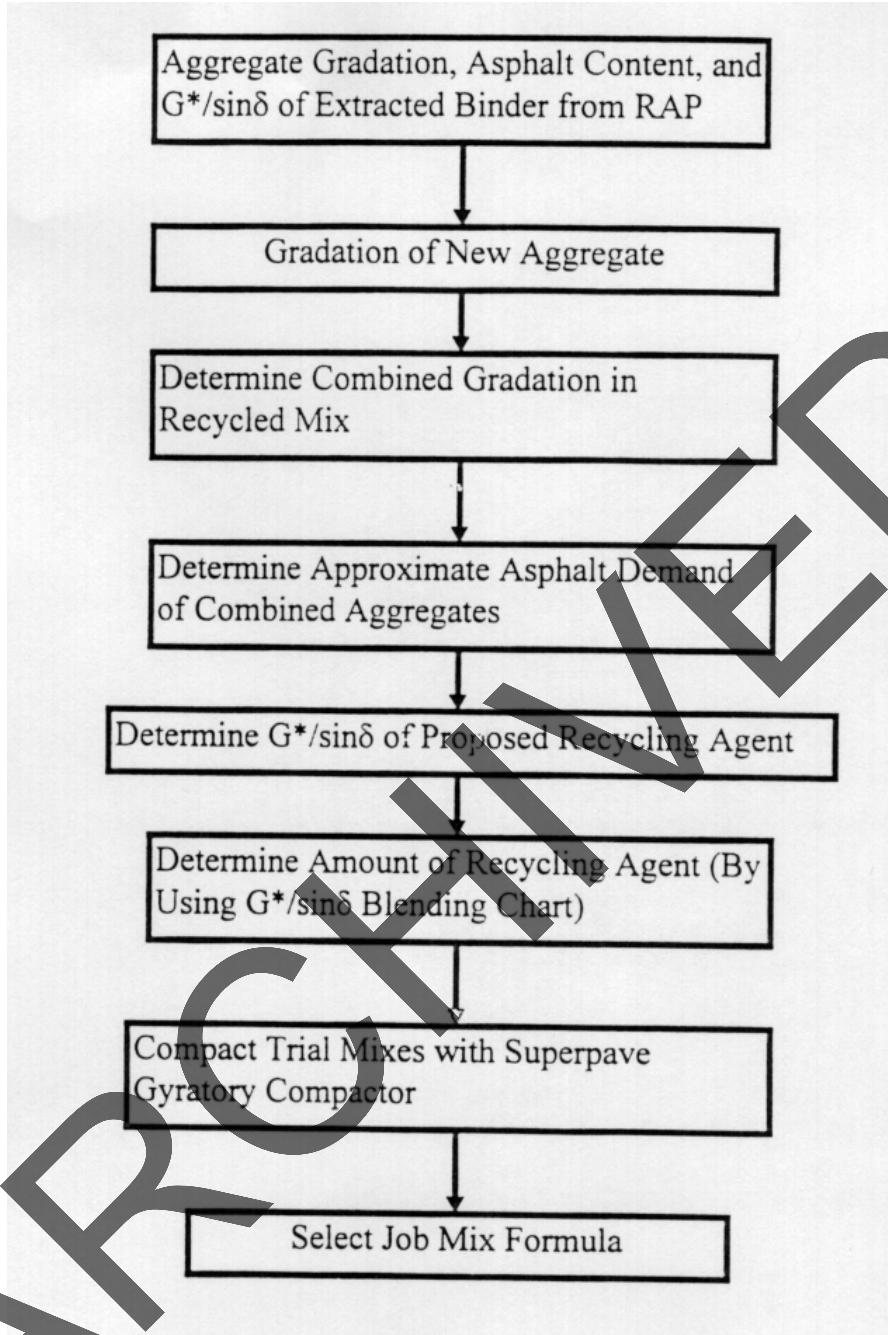


Figure 7-7. Steps in preparing hot recycled mix using Superpave technology.

(4) Select Grade of New Asphalt Binder

Based on the research conducted at the National Center for Asphalt Technology,[15] the following three tier procedure is recommended to select the Superpave PG grade of the new asphalt binder:

(a) Tier 1 (up to 15 percent RAP): If the minimum amount of the RAP in the recycled mix is 15 percent or less, use the same PG grade as that used in 100 percent virgin HMA mixture. For example, if the highway agency specifies a PG 64-28 asphalt binder for 100 percent virgin mixtures, the same grade can be used in recycled mixtures containing up to 15 percent RAP.

(b) Tier 2 (16 to 25 percent RAP): If the amount of RAP in the recycled mix is more than 15 percent but equal to or less than 25 percent, the selected PG grade of the virgin asphalt binder should be one grade below (both high and low temperature grade) the Superpave specified PG grade. For example, if the Superpave specified PG grade is PG 64-22 then a PG 58-28 asphalt binder should be selected. The use of blending chart (as given in Tier 3) to select the high temperature grade of the virgin asphalt binder is optional.

(c) Tier 3 (26 percent or more RAP): If the amount of RAP in the recycled mix is 26 percent or more, then a specific grade blending chart shown in figure 7-8 is recommended to be used. This blending chart can be used to determine the minimum and maximum amounts of the percentages of virgin asphalt binder (and conversely the maximum and minimum amounts of RAP in the recycled mix) so that the recycled asphalt binder conforms to a specific PG grade. The X-axis in this blending chart has percen virgin asphalt binder (determined in Step 3) and Y-axis has the rutting factor $G^*/\sin\delta$ obtained at the high pavement service temperature for the specific PG grade. For example, if a highway agency uses a PG 64-28 binder for 100t percent virgin mixtures, $G^*/\sin\delta$ of the aged asphalt binder (recovered from RAP) and the proposed virgin (new) asphalt binder should be determined at 64ºC (147ºF) . If the highway agency uses a PG 58-28 binder, then $G^*/\sin\delta$ of both aged and proposed virgin binder should be determined at 58ºC (136ºF). The minimum and maximum amounts of of virgin asphalt binder to obtain the specific PG grades are obtained from two horizontal lines corresponding to 1 kPa and 2 kPa stiffness (figure 7-8). Figure 7-9 shows an example of using the specific grade blending chart.

Suppose PG 64-28 was specified for a paving project. The $G^*/\sin\delta$ measured at 64ºC of the aged and virgin asphalt binder (PG 64-28) were 100 kPa and 1.13 kPa, respectively. These values were plotted as Point A and Point B as shown in figure 7-9. The line AB intersected the 2.0 kPa stiffness line at 85 percent. Therefore, the amount of the virgin asphalt binder PG 64-28 that can be added in the recycled mix was 85 to 100 percent (or about 0 to 15 percent RAP). Suppose an asphalt binder PG 58-34 was selected as the virgin asphalt binder. The $G^*/\sin\delta$ as measured at 64ºC for the PG 58-34 was 0.65 kPa and plotted as point C in figure 7-9. The line AC intersected the 1.0 kPa and 2.0 kPa stiffness lines at 72 percent and 89 percent, respectively. Therefore, the amount of the virgin asphalt binder PG 58-34 that can be used in the recycled mix is 72 to 89 percent (or about 11 to 28 percent RAP).

It should be noted that the low temperature grade of the selected virgin asphalt binder should always be at least one grade below the specified PG grade. For example, if the specified low temperature grade for 100 percent virgin mixtures is -28ºC, then the low temperature grade of the virgin binder should be -34ºC.

Note: Research is continuing at the present time (1996) to develop Superpave blending charts based on $G^*\sin\delta$ (fatigue factor) and low temperature properties of asphalt binder in addition to $G^*\sin\delta$ (rutting factor) used here.

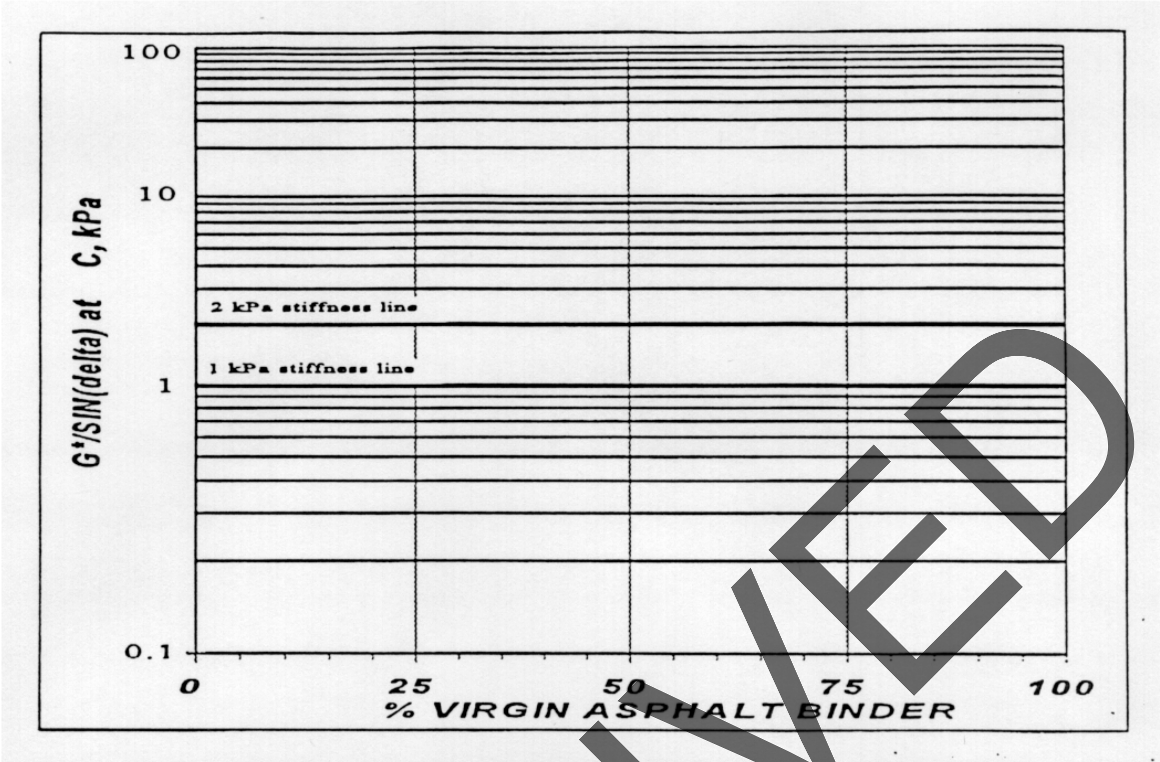


Figure 7-8. Recommended specific grade blending chart with 1.0 and 2.0 kPa stiffness lines.

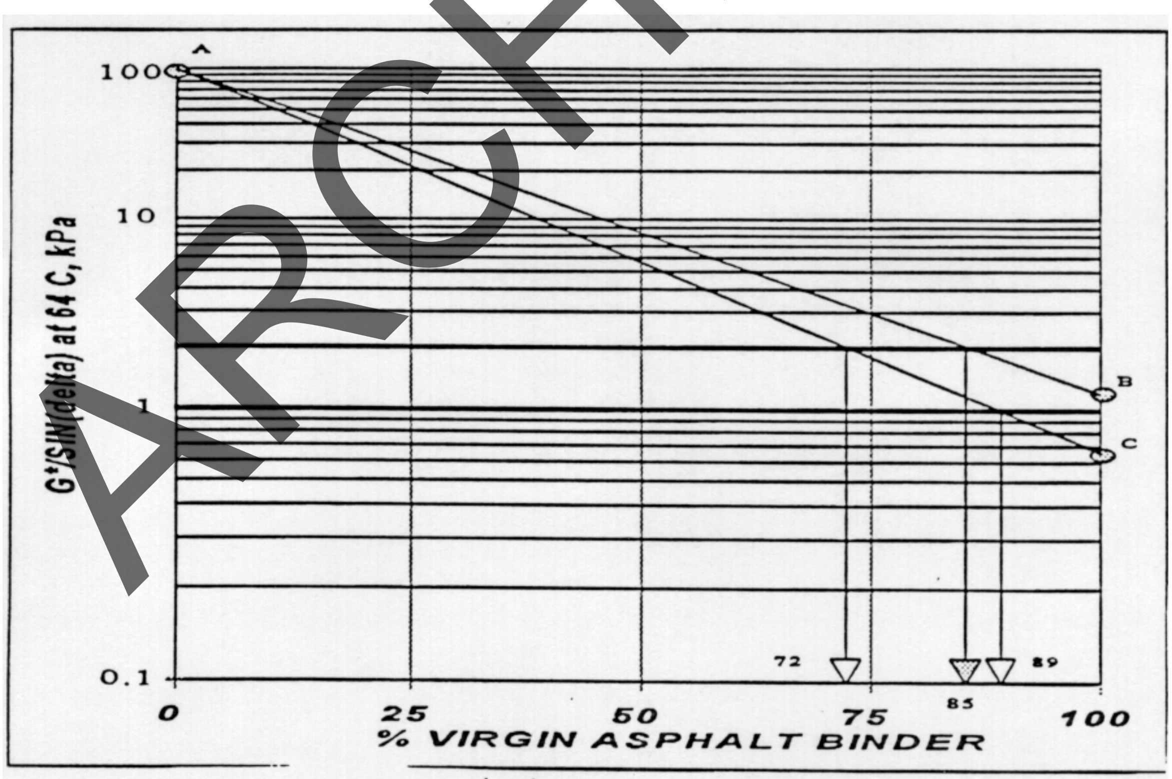


Figure 7-9. Graphical method to determine minimum and maximum amount of virgin asphalt binder in the recycled asphalt binder.(15)

(5) Trial Mix Design

Trial mix designs are made using the Superpave gyratory compactor (SGC) following the Superpave volumetric mix design procedures.[15] It may be necessary to evaluate different aggregate gradations to obtain an acceptable aggregate structure meeting the Superpave criteria. The preparation of recycled mixtures such as heating of RAP, new aggregate, and asphalt binder and mixing procedures are similar to those used in conventional recycled mix design given earlier.

(6) Select Job Mix Formula

The optimum asphalt content is selected based on the test data obtained in the Superpave volumetric mix design procedure (Step 5). The recycled mix must meet all criteria applicable to 100 percent virgin mixtures.

SUMMARY

The two main steps in design of hot mix recycling are material evaluation and mix design. The materials evaluated include the RAP and the recycling agent. A random sampling plan should be devised to obtain representative samples of the RAP. The sampling plan and frequency should be decided based on historical, construction, and material data, and if needed, the pavement may be divided into different sub sections before sampling. To evaluate the RAP material, which undergoes changes with time and traffic, its gradation, asphalt content, and rheological properties of aged asphalt binder must be determined. The recycling agent should conform to the applicable AASHTO or ASTM standards. Hot recycled mix design involves the determination of the combined gradation of the aggregates and the required amount of new aggregate to meet the target gradation. Next, the amount of new (virgin) asphalt binder required in the recycled mix is estimated. Blending charts (based on viscosity or Superpave rutting factor $G^*/\sin\delta$) are then used to select the grade of virgin asphalt binder. A series of trial mixes are then made with different asphalt contents. The optimum asphalt content for the recycled mix is selected based on Marshall, Hveem, or Superpave volumetric mix design procedures.

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CHAPTER 8. HOT MIX ASPHALT RECYCLING (CASE HISTORY AND QC/QA)

INTRODUCTION

The purpose of this chapter is to present a selected case history of hot mix asphalt recycling, and a summary of Quality Control/Quality Assurance (QC/QA) practices. The first part of the chapter presents a case history and the second part presents the specifications, and QC/QA practices.

CASE HISTORY

A summary of performance results from several states was presented in chapter 2 “Performance Data of Recycled Mixes.” Hot mix asphalt recycling is no longer considered an experimental process. It is routinely used by most states in the U.S. The following is a selected typical case history which gives development of recycled mix design, mix production, and construction.

A hot mix recycling job was done on Traffic Route 72 (Lebanon County, Pennsylvania) in 1982. This stretch of the pavement had an average daily traffic (ADT) count of about 5,000, with approximately 10 percent truck traffic. A control section was also constructed with conventional rehabilitation technique. The recycled project consisted of using recycled hot mix asphalt in the base course. The recycled asphalt pavement (RAP) material was obtained from Traffic Route 22 by milling to a depth of 40 mm (1½ in). The RAP was taken to a hot mix plant for recycling as a base course. The RAP stockpile was sampled at ten locations. The ten samples were subjected to extraction test to determine the average asphalt content and gradation of the RAP. The average asphalt content was determined to be 5.4 percent. The average gradation of the RAP, virgin coarse aggregate (AASHTO 57), and virgin fine aggregate (F.A.) are given in table 8-1. It was decided to use 20 percent RAP in the recycled mix. The proportions of coarse and fine aggregate were determined so that the total blend met the Pennsylvania DOT specification for bituminous concrete base course (BCBC) as shown in table 8-1. It was assumed that the total asphalt content in the recycled mix was equal to that used in 100 percent virgin base course mix, which was 4.0 percent. The percentage of new asphalt binder was, therefore, calculated as follows:[1]

Table 8-1. Average gradation of RAP and Pennsylvania DOT specification for bituminous concrete base course. (BCBC).

Sieve	RAP 20.0%	AASHTO 57 63.3%	F.A. 16.7%	Total Blend	Spec.
38 mm (1-1½")	100	100	100	100	100
12.5 mm (½")	100	50	100	68	40-75
4.75 mm (No. 4)	84	4	100	36	20-47
2.36 mm (No. 8)	65	2	76	27	15-37
75 mm (No. 200)	18	0.3	6.5	4.9	2-6

$$P_{nb} = \frac{(100^2 - rP_{sb})\,P_b}{100\,(100 - P_{sb})} - \frac{(100 - r)\,P_{sb}}{100 - P_{sb}}$$

where:

- P_{nb} = Percent of new asphalt binder in recycled mix (plus recycling agent, if used), expressed as whole number
- r = New aggregate expressed as a percent of the total aggregate in the recycled mix expressed as a whole number
- P_b = Percent, estimated asphalt content of recycled mix assumed to be the same as that of 100 percent virgin HMA mix or determined as an approximate asphalt demand of combined aggregates
- P_{sb} = Percent, asphalt content of reclaimed asphalt pavement (RAP)

The percentage of new asphalt binder, P_{nb}, was determined as follows:

$$P_{nb} = \frac{(100^2 - 80 \times 5.4)\,4}{100\,(100 - 5.4)} - \frac{(100 - 80)\,5.4}{100 - 5.4} = 2.9\%$$

Therefore, percent virgin or new binder in the total binder = $\frac{2.9}{4.0} \times 100 = 72.5\%$

Asphalt cement was recovered from the RAP by the Abson method and its viscosity was measured at 60ºC. The viscosity was 60,000 poise. The blending chart in figure 8-1 was used to determine the grade of the virgin asphalt cement to be used in the recycled mix. According to the blending chart, the virgin asphalt cement should have a viscosity of about 800 poise. Therefore, an AC-10 asphalt cement with a viscosity of 1,000 ± 200 poise was selected.

HMA mixture containing 20 percent RAP and 2.8 percent AC-10 asphalt cement was prepared in the laboratory and tested for volumetric properties (such as air voids and VMA) and Marshall stability and flow. The mix met the Pennsylvania DOT specifications and, therefore, approved for use.

A batch plant was used for producing the recycled base course mix containing 20 percent RAP. The RAP was directly introduced to the weigh hopper of the batch plant. The RAP was fed into the RAP bin with a front end loader. A RAP feeding bin of small size, with steep sides, wide and long bottom opening was used to facilitate easy discharge of material and reduce sticking of RAP at the sides. No vibrator was used in the bin. A grizzly screen was used to scalp off + 50 mm (+ 2 in) material. The operation of the conveyor belt was interlocked with the operation of the RAP bin feeder. This enabled the simultaneous stop/start operation of conveyor and the RAP bin feeder. The mix was transported to the Traffic Route 72 site with trucks and laid with conventional paver. The compaction was done with a vibratory roller. Quality control tests on the recycled HMA mixture (such as asphalt content, gradation and volumetric properties) showed that the recycled mix met all the Pennsylvania DOT specification requirements for 100 percent virgin mix. Table 8-2 shows average test data (31 samples) on the percentage of material passing 2.36 mm (No. 8) and 0.075 mm (No. 200), percent asphalt content, and percent air voids in compacted Marshall specimens. The test data is quite consistent and is equal to or better than that of a 100 percent virgin mix. Control charts depicting the mix composition and volumetric properties of the HMA were also maintained during the production of the recycled mix.

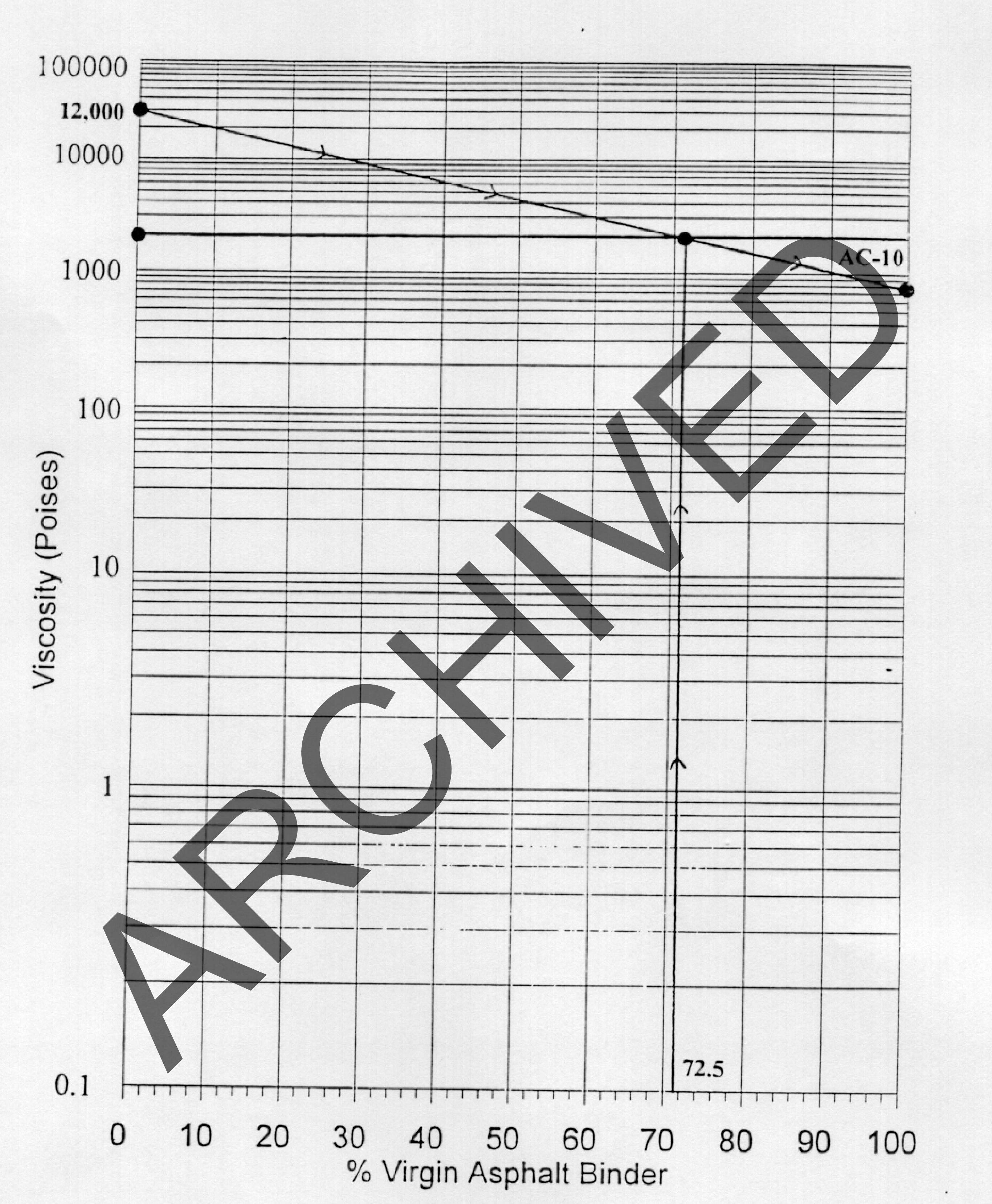

Figure 8-1. Blending chart for selection of virgin asphalt cement grade.

Table 8-2. Recycled mix production test data.

	Percent Passing		Asphalt Content (%)	Air Voids (%)
	2.36 mm (No. 8)	0.075 mm (No. 200)		
Design	27.0	4.9	4.0	5.5
Average (N = 31)	26.5	5.6	4.0	4.5
Standard Deviation	1.3	0.6	0.17	0.5
95% Confidence Limits	± 2.6	± 1.2	± 0.34	± 1.0

Distress surveys conducted after 10 years of recycling indicated no difference between the recycled and control sections in terms of rutting and cracking.

QUALITY CONTROL/QUALITY ASSURANCE (QC/QA)

Good QC/QA practices are essential to obtain a satisfactory HMA. QC normally refers to those tests necessary to control the HMA production and to determine the quality of the HMA being produced. These QC tests are usually performed by the contractor. QA refers to those tests necessary to make a decision on acceptance of a HMA and hence to ensure that the product being evaluated is indeed what the owner specified. These QA tests are normally performed by the owner. QC/QA of recycled HMA is not significantly different than those of conventional HMA except that some additional tests need to be performed when producing recycled HMA. For example, the asphalt binder need to be recovered from the recycled mix and tested for consistency (penetration, viscosity or $G^*/\sin\delta$). The following QC/QA procedures apply to both conventional and recycled HMA mixes except those specifically mentioned for recycled mixes.

Testing of the asphalt mixture during production is essential to ensure that a satisfactory product is obtained. The tests that should be performed during manufacture and placement of HMA may include aggregate gradation, asphalt content, temperature, mixture properties of laboratory samples, theoretical maximum density, and in-place density.[2]

Aggregate Gradation

For QC/QA testing, aggregate samples are typically taken from the stockpile, cold feeder belt, hot bins (if applicable), and extracted asphalt mixture. The gradation of the aggregate from the asphalt mixture is of most importance since this is the end product; however, the aggregate gradation must be controlled at the other points to ensure that the gradation of the final product is satisfactory. Since the RAP may have a significant amount of material passing 0.075 mm (No. 200) (generally referred to as the P200 fraction) sieve, the P200 in the total gradation must be monitored closely.

The aggregate and RAP stockpiles should be sampled and tested during the mix design process and approved for use. Once production begins, it is only necessary to sample new aggregate material that is added to the aggregate stockpile since the overall stockpile gradation has already been determined. The new material added to the stockpile must have the same gradation as the original stockpile, within reasonable tolerances, otherwise the gradation of the final mixture is affected. Causes in gradation variations at the stockpile include changes at source, segregation during hauling or stockpiling, and sampling and testing errors. No new RAP should be added to the RAP stockpile which was used for developing the mix design.

The second typical location for taking aggregate samples is the cold feeder belt. This belt contains the combined aggregate being fed into the HMA facility. Variability of gradation that results at this point is caused by variations in stockpile gradations, segregation of aggregate, improper loading of cold feed bins, improper setting of individual cold feed bins, and sampling and testing errors.

The third location for sampling aggregate is in the HMA batch plant hot bins (drum mix plants do not have aggregate hot bins). Causes for variability here include improper gradation fed from cold feeder, erratic feed from dust collector system, changing production rate (screening efficiency changes with production rate), blinding screens, holes in screens or bin walls, and sampling and testing errors. The hot bins, if operated correctly, will partially correct for gradation fluctuations coming into the plant.[2]

The fourth location for determining gradation is from the produced HMA. The sample is normally taken from loaded trucks but can be taken behind the asphalt paver. This test, which is performed on the finished product, must be controlled because it is the one on which acceptance of the mixture is normally based. Variability of gradation at this point (for a batch plant) could involve incorrect hot bin gradations, incorrect percentage of material from each hot bin, change in RAP composition, segregation of aggregate traveling through the plant or in the storage silo, and sampling and testing errors. For a drum mix plant, the causes of variability at this point include improper cold feed gradation, erratic feed from the dust collector, change in RAP composition, segregation of aggregate traveling through the plant or in the storage silo, and sampling and testing errors.

Evaluation of the gradation at several locations allows the engineer to troubleshoot the gradation problem and quickly identify the location where it is occurring. For instance, if the stockpile gradation is satisfactory but the cold feed gradation changes, then the problem areas are likely to be segregation of mixture, improper loading of cold feed bins, or sampling and testing errors. These items can be quickly checked and modifications made to correct the problem.[2]

Asphalt Content

Another mixture property that must be evaluated is asphalt content. The asphalt content of HMA is very important to ensure satisfactory performance. A HMA mixture with low asphalt content is not durable, and one with high asphalt content is not stable. The actual asphalt content directly affects mixture properties, such as asphalt film thickness, voids, stability (Hveem or Marshall), and Marshall flow. Therefore, it is important to monitor asphalt content, but it is really these mixture properties that need to be controlled.

The asphalt content of a mixture is measured by extraction test (AASHTO T 164) or with a nuclear gauge (ASTM D 4125). The extraction test involves adding a solvent to the asphalt mixture to dissolve the asphalt cement. The asphalt cement and solvent are then passed through a piece of filter paper, but the aggregate is now allowed to pass. This is not a highly accurate test but it is widely used for measuring asphalt content. One advantage of the extraction test when compared to nuclear asphalt content gauge is that it allows determination of the aggregate gradation of the mixture. A disadvantage of the extraction test is that the solvent used is hazardous and is difficult to dispose.[(2)]

The National Center for Asphalt Technology (NCAT) has developed a test method to determine the asphalt content of HMA mixtures by ignition. The test method is based on research started in 1990 at NCAT.[(3)] In the NCAT ignition method, a sample of HMA mixture is subjected to an elevated temperature of 538ºC (1000ºF) in a furnace to ignite and burn the asphalt cement from the aggregate. NCAT's work has resulted in a test procedure and equipment that automatically measures the asphalt content in 30-40 minutes. The grading of the aggregate can then be determined using standard sieve analysis. Based on round robin studies conducted by NCAT in which 12 laboratories participated, the accuracy and precision of the NCAT ignition test was found to be better than those of the solvent extraction method. Therefore, this test method (AASHTO TP 53-95) is increasingly replacing solvent extraction methods, which are being eliminated due to growing health and environmental concerns associated with the use of chlorinated solvents.

Improper asphalt content can be caused by several factors in a batch plant. These causes include inaccurate aggregate scales, inaccurate asphalt cement scales, leaking valve in asphalt cement pot, segregation, and sampling and testing errors. Causes of incorrect asphalt content in a drum mix plant include inaccurate aggregate belt scales, improperly calibrated asphalt cement meter, incorrect moisture content correction for aggregates, segregation, and sampling and testing error.[(2)]

Field Management of Volumetric Properties

The Federal Highway Administration (FHWA) Demonstration Project No. 74 has clearly shown that significant differences exist between the volumetric properties of the laboratory designed and plant produced HMA mixtures. The volumetric properties include voids in the mineral aggregate (VMA) and voids in the total mix (VTM). The FHWA project concluded that a field mix verification of the material produced at the HMA facility should be included as a second phase in the mix design process. This also applies to recycled HMA mixtures. Mix verification is defined as the validation of a mix design within the first several hundred tons of HMA production. Field management of HMA provides a viable tool to identify the differences between plant produced and laboratory designed HMA mixes and effectively reconcile these differences.[(4)] The National Center for Asphalt Technology (NCAT) conducted a statistical analysis of field data from 24 FHWA demonstration projects to develop practical guidelines for the HMA contractors to reconcile the differences, thereby assisting them to consistently produce high quality HMA mixes.[(5)] Recycled HMA mixtures were used on some projects. The field data was analyzed first to identify and, if possible, quantify the independent variables (such as asphalt content and the percentages of material passing 0.075 mm (No. 200) and other sieves) significantly affecting the dependent variables such as VMA and VTM. The following conclusions were drawn from the

NCAT study:

1. Significant differences exist between the volumetric properties of the laboratory designed and plant produced hot mix asphalt.
2. VMA is most affected by the amount of material passing 0.075 mm (No. 200) sieve and the relative proportions of coarse and fine aggregates.
3. VMA can be increased by reducing the amount of material passing 0.075 mm (No. 200) sieve or natural sand in the HMA mixes. VMA can also be increased by moving the aggregate gradation away from the maximum density line (MDL) especially for HMA mixes with no natural sand.
4. VTM is most affected by asphalt content, material passing 0.075 mm (No. 200) sieve, and the relative proportions of coarse and fine aggregates.
5. VTM can be increased by reducing asphalt content and material passing 0.075 mm (No. 200) sieve.

Flow charts were developed as general guidelines for reconciling the VMA and VTM difference between the laboratory designed and plant produced HMA mixes. These flow charts are given in figures 8-2 and 8-3.

Construction

The temperature of the mixture during production should be closely monitored. The temperature must be just high enough to provide good coating on the aggregate and to allow for satisfactory compaction. The temperature of the recycled mix need to be monitored more closely when the recycling is done in a batch plant rather than a drum plant.

The TMD (Theoretical Maximum Density) should be measured on a daily basis, since this is needed to calculate voids in the mixture and is used in some cases to specify density. A change in TMD indicates a change in asphalt content, aggregate gradation, specific gravity and absorption of the aggregate, RAP composition, or sampling and testing errors.

Compacting the asphalt mixture to a satisfactory in-place density is required for satisfactory performance. Two methods that are used for checking in-place density are nuclear gauges and cores. The nuclear gauge is generally preferred for QC testing while cores are desirable for QA testing. When the nuclear gauge is used for QA testing, some cores must be taken routinely for verifying the accuracy of the nuclear gauge. Low density can be caused by inaccurate reference density, improper gradation or asphalt content, a mixture temperature which is too low, a layer thickness which is too thin (cools quickly and bridges under rollers) or too thick, improper rolling techniques, inadequate rollers sampling and testing errors.

Testing and Quality Control Charts

Testing Frequency. It is impossible to establish one desired testing frequency for all projects. Factors that may affect testing frequency include the size of project, importance of project, and variability of materials. However, the suggested number of tests in Table 8-3 is provided as a rough guide to the actual minimum number that should be conducted on a project. Obviously, the specifying agency’s guidelines should be followed, if available.

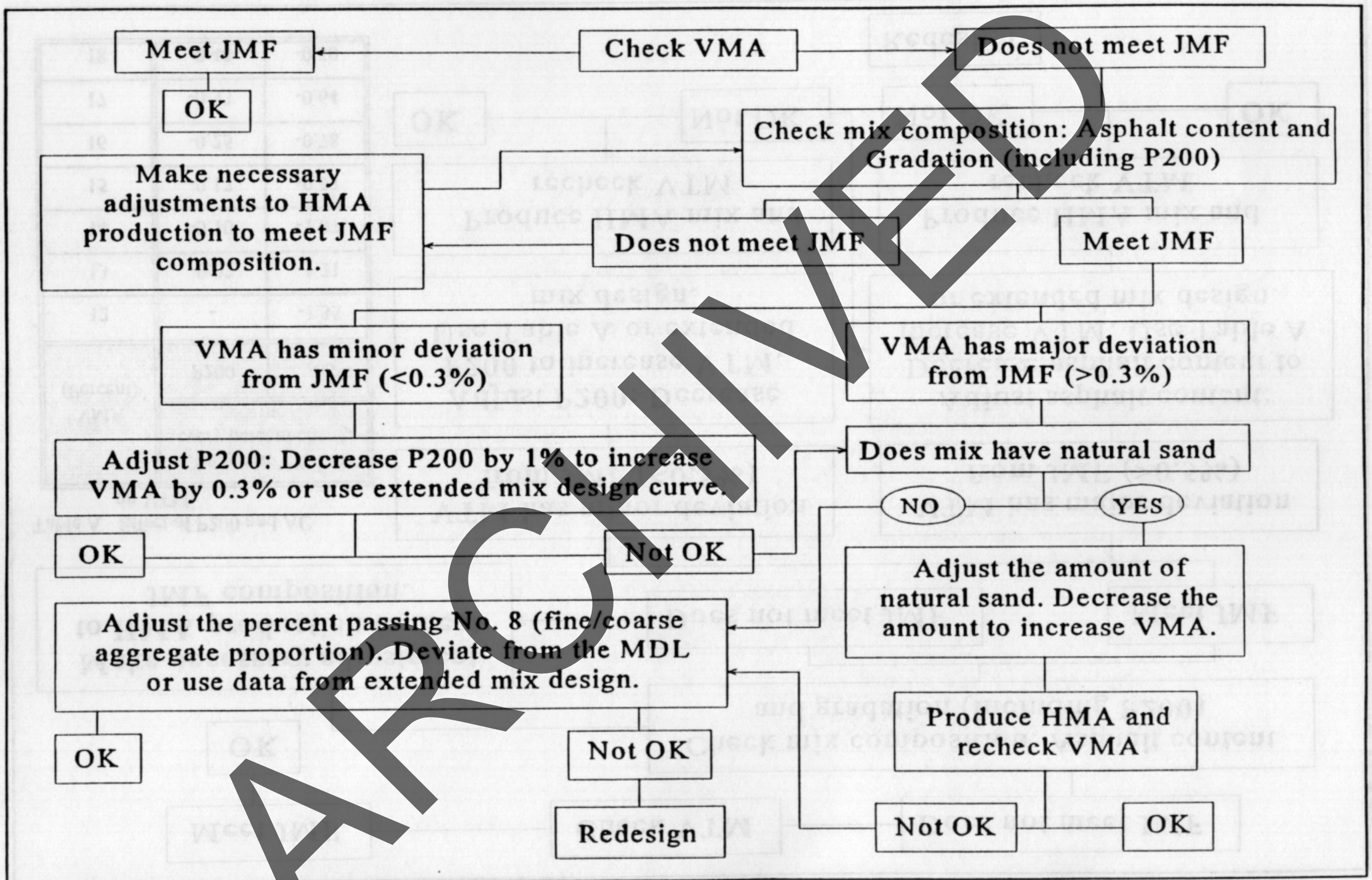

Figure 8-2. Guidelines for reconciling the VMA difference between the laboratory designed and plant produced HMA mixes.

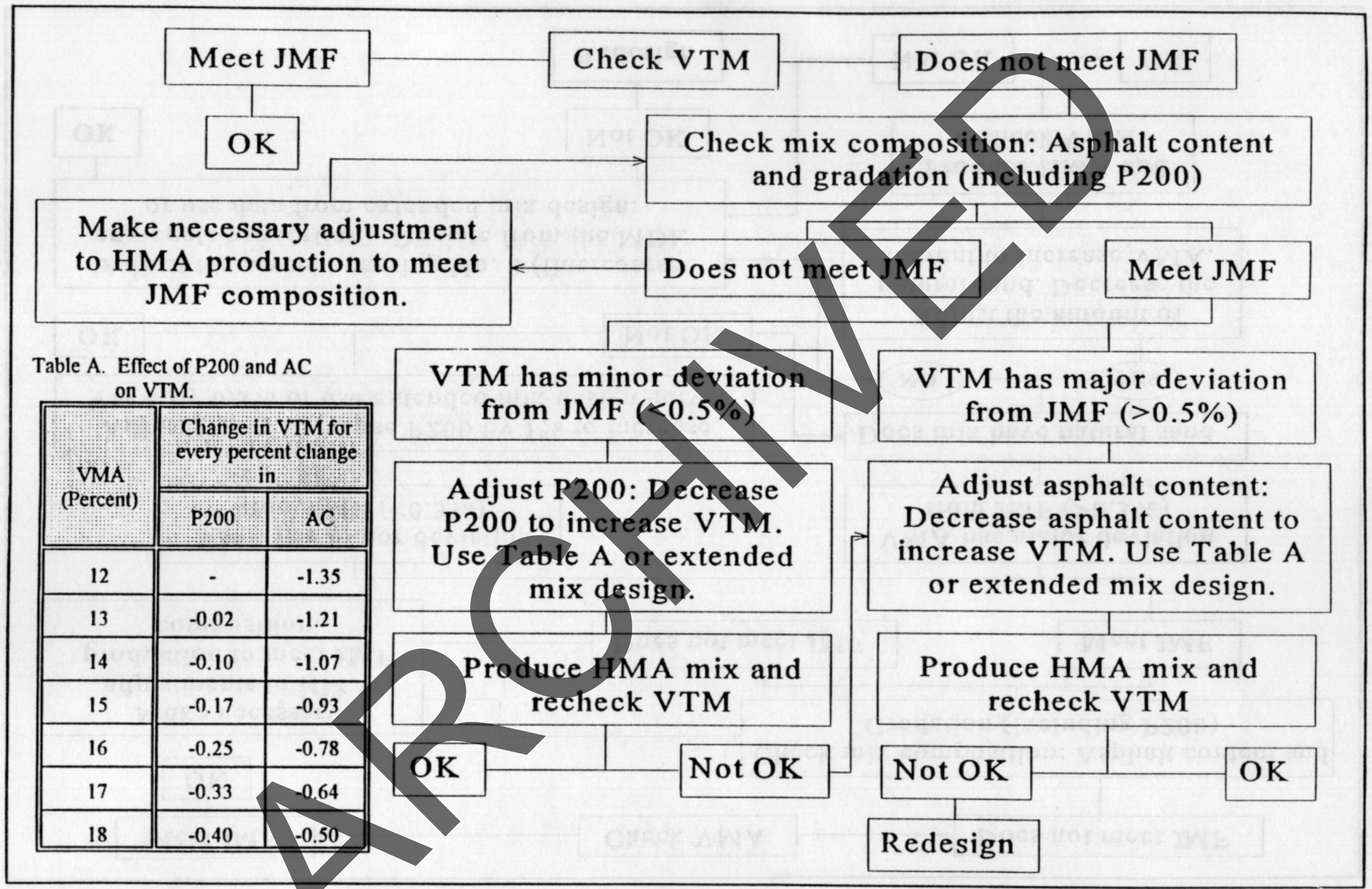

Table A. Effect of P200 and AC on VTM.

VMA (Percent)	Change in VTM for every percent change in	
	P200	AC
12	-	-1.35
13	-0.02	-1.21
14	-0.10	-1.07
15	-0.17	-0.93
16	-0.25	-0.78
17	-0.33	-0.64
18	-0.40	-0.50

Figure 8-3. Guidelines for reconciling the VTM difference between the laboratory designed and plant produced HMA mixes.

Technician Qualifications. Sampling and testing errors can be a high percentage of the overall variations in test results. For this reason it is essential that testing technicians be highly qualified to ensure that sampling and testing errors (for some tests this is over 50 percent of variability) are minimized. Many states have begun to require certification of technicians (state and contractor) that work on state or federally funded projects. More emphasis needs to be placed on this technician certification program to ensure that all projects have qualified personnel performing QC and QA tests.

Quality Control Charts. Analysis and evaluation of test results must be performed during the progress of work for adequate control of the project. The best way to monitor the quality of work during construction is with control charts. Control charts are simple methods of graphically displaying the QC data as it is developed. Control charts are helpful in detecting trends which may lead to HMA production out of specified tolerance limits.

QC/QA procedures are also applicable to recycled HMA mixtures used in the Superpave system.

Table 8-3. Suggested number of tests per project.

Test	Frequency
Stockpile gradation	1 per day
Cold feed gradation	1 per day
Hot bin gradation (if applicable)	1 per day
Extracted asphalt content and gradation	2 per day
Laboratory compacted samples voids, stability, flow	2 sets per day
Theoretical maximum density	2 per day
Temperature	Regularly throughout day
In-place density	6-10 per day
RAP composition (asphalt content and gradation)	1 per week (more if RAP is very variable)
Consistency of asphalt binder recovered from recycled mix	1 per 1000 tons of HMA (more at the beginning of the project)

SUMMARY

The use of hot mix asphalt recycling is no longer considered an experimental process. A selected case history of hot mix asphalt recycling shows that the recycled mix met all DOT specification requirements for 100 percent virgin mix. The test data on the recycled mix was found to be quite consistent and equal to or better than that of a 100 percent virgin mix. However, it must be noted that good quality control and quality assurance (QC/QA) practices are essential to obtain satisfactory results with recycled mix. Testing required for proper QC/QA control include testing of asphalt mixture during production, gradation testing of aggregates from stockpile, feeder belt, bins and extracted aggregates from asphalt mixtures. The asphalt content of the recycled mix and the RAP material should be determined. After design, during field production, the mix should be verified for proper VMA and VTM. If any significant difference is found between designed and produced mixes, the VTM or the VMA can be adjusted by changing the percent passing 0.075 mm sieve. During placement of the mix, proper temperature required for coating and compaction of the mix must be obtained. For satisfactory compaction, the density of the in-place mix should be checked in terms of the theoretical maximum density, which should be determined before compaction. Finally, quality control charts should be maintained so as to identify any trend which may lead to HMA production out of specified tolerance limits.

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CHAPTER 9. HOT IN-PLACE RECYCLING (CONSTRUCTION METHODS AND EQUIPMENT)

INTRODUCTION

Hot in-place recycling (HIR) has been described as an on-site, in-place method that rehabilitates deteriorated asphalt pavements and thereby minimizes the use of new materials.[1] Basically, this process consists of four steps: (1) softening of the asphalt pavement surface with heat; (2) scarification and/or mechanical removal of the surface material; (3) mixing of the material with recycling agent, asphalt binder, or new mix; and (4) laydown and paving of the recycled mix on the pavement surface. The primary purpose of hot in-place recycling is to correct surface distresses not caused by structural inadequacy, such as raveling, cracks, ruts and holes, and shoves and bumps. It may be performed as a single-pass operation or a multiple-pass operation. In a single-pass operation the virgin materials are mixed with the restored reclaimed asphalt pavement (RAP) material in a single-pass, whereas in the multi-step process, a new wearing course is added after recompacting the RAP materials. The advantages of hot in-place recycling are that elevations and overhead clearances are preserved, it is comparatively economical, and needs less traffic control than the other rehabilitation techniques. This process can also be used to recoat stripped aggregates, re-establish crown and drainage, modify aggregate gradation and asphalt content, and improve surface frictional resistance. Hot in-place recycling is usually performed to a depth of 20 mm to 50 mm (3/4 to 2 in), with 25 mm (1 in) being a typical depth.

The Asphalt Recycling and Reclamation Association (ARRA) recognizes three basic types of hot in-place recycling processes: (1) surface recycling, (2) repaving, and (3) remixing. Recycling agents for rejuvenating the aged asphalt binder may be added in all the three methods, but virgin aggregate is used only in repaving and remixing operations. The three processes are described below.

Surface Recycling Method and Equipment

The Asphalt Recycling and Reclamation Association (ARRA) defines surface recycling as a rehabilitation process that restores cracked, brittle, and irregular pavement in preparation for a final thin wearing course.[2] Ideal candidates for this process are pavements with stable and adequate base. Although a scarification depth of 50 mm (2 in) can be achieved, depths of 20 mm to 25 mm (3/4 in to 1 in) are common.[3,4] If a hot mix asphalt overlay is placed as a separate operation after surface recycling, the process is referred to as a two-pass method. Otherwise, it is called a single-pass method.

The primary purpose of the surface recycling process is to eliminate surface irregularities and cracks. It is also used to restore the pavement surface to the desirable line, grade, and cross section to ensure proper drainage.[5] Limited and short term surface frictional resistance improvement may also be achieved.[5] Surface recycling has been reported to be successful in removing reflective cracks when used prior to hot mix overlay.[5] This may be more effective if a heater scarifier is used immediately before the overlay to improve the bond between old and new layers.[5]

Figure 9-1[6] shows a schematic of one of the surface recycling process. The equipment consists of a preheating unit, a heating and recycling unit, and a rubber-tired roller. The preheating unit heats up the old HMA pavement surface, the heating and recycling unit applies more heat and scarifies the HMA pavement with a set of non-rotating teeth, and sprays the recycling agent. Then the old pavement and recycling materials are mixed with a standard auger, and leveled off with a screed. A rubber-tired roller is used for compacting the recycled mix. No new aggregate is generally added in the surface recycling process. Figure 9-2 shows a surface recycling process.

Although direct contact with the flame was used initially to heat the HMA pavement surface, at present radiant or infrared heating is used to avoid damage to the asphalt cement binder and prevent undesirable emissions.[7,8,9] Propane is the most commonly used fuel for the indirect heating process.[10] Heating may be carried out with one heating unit with two sets of heaters or two units traveling in tandem, each with a single set of heater. At least two sets of heaters are normally used for heating. The temperature of the HMA pavement is raised to 110°C to 150°C (230°F to 302°F).[11,12] Multiple rows of spring loaded scarifiers are used to scarify the heated pavement. The spring-loaded mounting allows the scarifier to pass over road obstacles such as manhole covers and concrete patches.[10] To eliminate the effect of oxidative hardening due to long term aging, and heating during the recycling process, recycling agents are added to the pavement during the scarifying operation.[5]

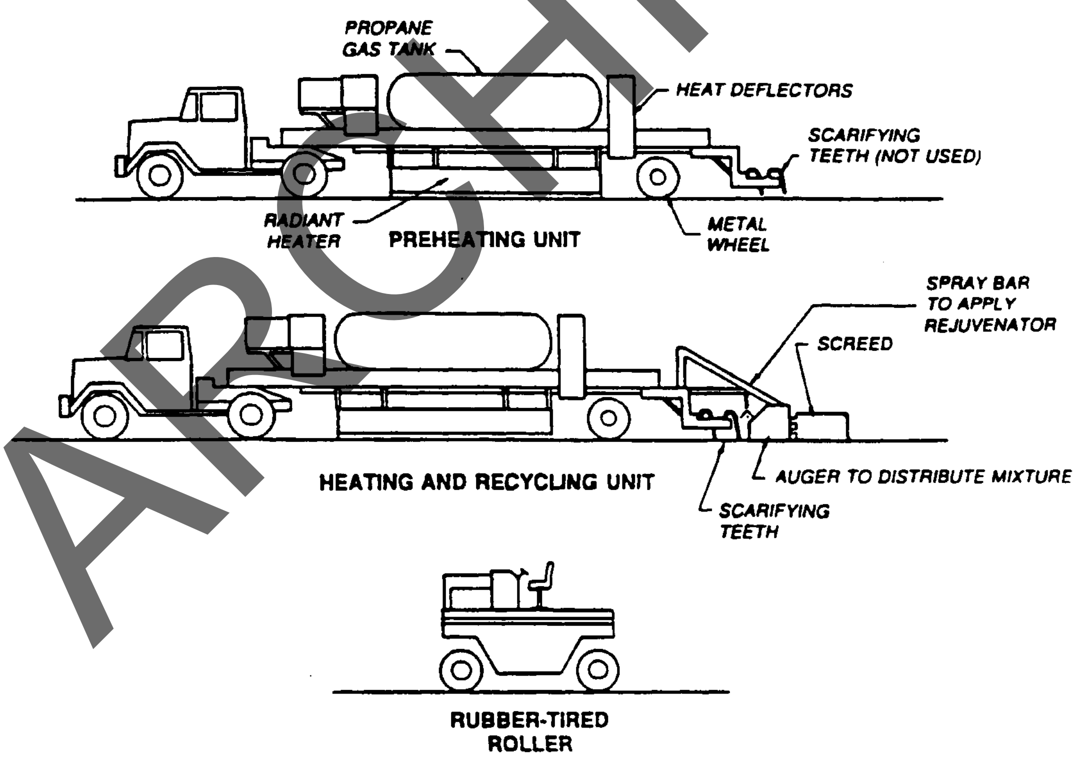

Figure 9-1. A basic surface recycling process.

Figure 9-2. Surface recycling.

Repaving Method and Equipment

Repaving is defined as surface recycling method combined with simultaneous overlay of new hot mix asphalt (HMA) to form a thermal bond between the new and recycled layers.[2] It is basically the surface recycling process followed by an overlay paving process. This process is used to correct the pavement deficiencies in the upper 25 to 50 mm (one or two in) of an existing asphalt pavement.[2] Pavement problems such as minor rutting, shrinkage cracking, and raveling can be eliminated by this method.[2] The repaving process is useful when the surface recycling process is not sufficient to restore the pavement's desirable surface requirements, or when a conventional HMA overlay is impractical or not needed.[5] Very thin overlays (12 mm or 0.5 in) may be used in conjunction with the repaving process to yield good, skid resistant pavements[5] at a much less cost when compared to a conventional HMA overlay process which uses more than 25 mm (1 in) thick overlays.

Figures 9-3 and 9-4[5,6] show schematics of multiple and single-pass repaving process, respectively. The process consist of preheating, heating and scarifying and/or rotary milling, applying and mixing a recycling agent, placing the recycled mix as a leveling course, and finally, placing a new hot mix wearing course.[13] In the single-pass repaving process, two screeds are used—one used to level the scarified HMA mix and the other used to level off the new HMA layer. The steps up to the placement of the recycled mix are similar to those in the surface recycling process. Figure 9-5[6] shows a repaving process. With the first and the second heating units, the pavement is first heated up through forced air or radiant heaters to a temperature of approximately 190°C (374°F) to a depth of 22 mm to 30 mm (0.9 in to 1.2 in).[5] Scarifier teeth

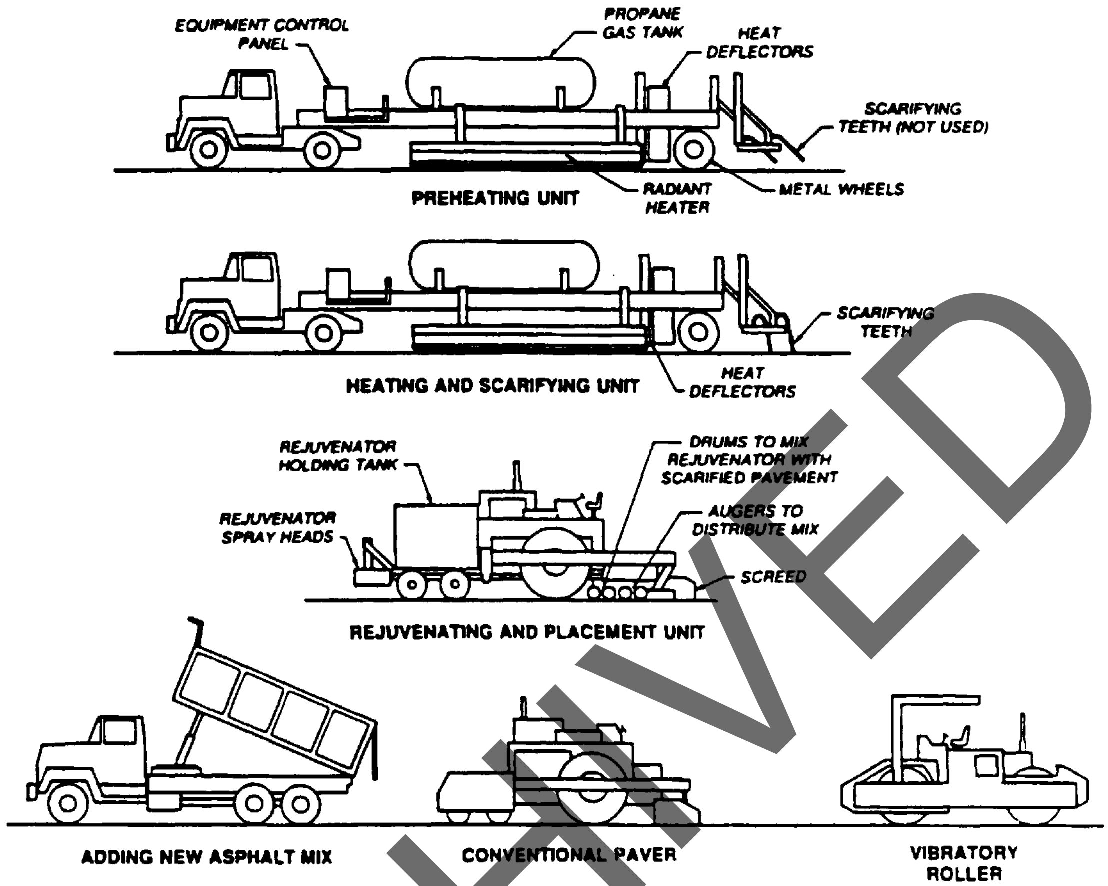

Figure 9-3. Multiple pass repaving process.

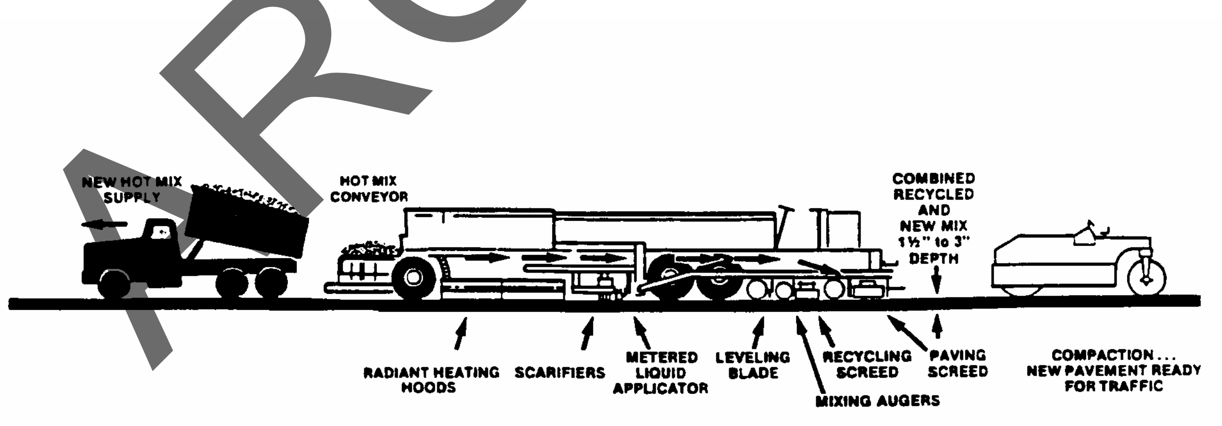

Figure 9-4. Single pass repaving process.

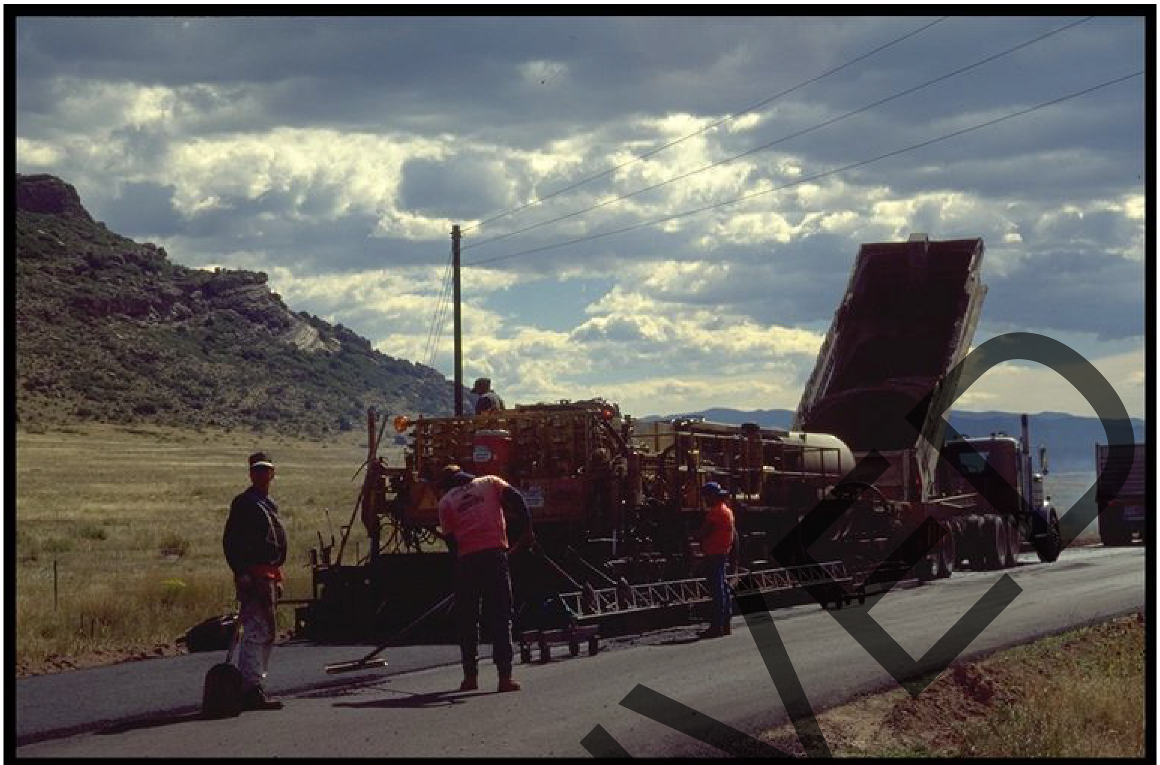

Figure 9-5. Repaving process.

in the second heating unit are then used to scarify the softened HMA pavement to a depth of 20 mm to 25 mm (0.75 in to 1 in).[5] In some systems, individual scarifier tooth or sections of scarifier teeth, mounted in a staggered formation, can be controlled separately to allow scarification to a desired depth and to work around pavement obstacles such as manhole covers.[5] A recycling agent is then added to the scarified material at a predetermined rate. The RAP, along with the applied recycling agent, is then gathered by a blade and then moved transversely into a center windrow with an auger type cross conveyor, which mixes and coats the RAP particles with the recycling agent. Next, the recycled mix is spread in front of the first screed with transverse augers, and partially compacted as a leveling course. Finally, new hot mix asphalt from the hopper is placed on the recycled mix with a second screed. The new mix is placed when the temperature of the recycled mix is approximately 104°C (219°F).[5] Conventional methods immediately after the screed are used to compact the new mix, to ensure monolithic bond between the new and the recycled layer.[14] The screeds used in this method may be with manual or automatic control. In manually controlled screeds, depth measurements are taken with hand and the screeds are adjusted manually, whereas automatic screeds may be completely automated for grade, slope, or depth control. Multiple lifts may be placed in a single-pass machine with two screeds, one trailing the other.[8] Automatic screeds should be equipped with vibrators to achieve some initial compaction.[5]

Remixing Method and Equipment

The Asphalt Recycling and Reclamation Association (ARRA) defines remixing as a process which consists of the following steps: heating of the roadway to a depth of 40 to 50 mm (1½ in to 2 in), scarification and collection of the softened material into a windrow, mixing of the material with virgin aggregates and recycling agents (and new HMA, if required) in a pugmill, and laying of the recycled mix as a single, homogeneous mix.(2) This procedure is used when repaving method is not sufficient to restore the pavement to its desirable properties and additional aggregates and/or new HMA mix are required to provide strength and stability to the existing pavement.(5) The process can effectively eliminate rutting, cracking, and oxidation (hardening) in the upper 50 mm (2 in) of the pavement surface. Asphalt pavements with one seal coat are remixable, and the seal coat may help in softening the recycled binder. However, pavements with multiple seal coats can create smoke and fire at the surface and act as an insulator against the heating of the underlying pavement.(5)

A schematic concept of the remixing method is shown in figure 9-6.(5) The existing pavement is first heated and softened with a series of infrared heaters in preheating units. The temperature of the asphalt pavement is raised to 85°C to 104°C (185°F to 219°F). The softened material is scarified or milled, and then collected in a windrow. Scarification may be done by stationary tines (or milling heads), and may be followed by an additional set of rotating milling heads. The pavement is generally scarified to a depth of 25 to 40 mm (1 to 1½ in), although more than 50 mm (2 in) can be achieved.(5) A scarification depth of 75 mm (3 in) was achieved in a recycling process in Canada, because of the softer grade of asphalt binder used in the existing pavement.(15) The material from the windrow is carried into a pugmill, where it is combined with a recycling agent and predetermined amount of virgin aggregates or hot mix asphalt, which is dumped from a truck at the front end of the remixing process and stored in a hopper. In some cases the recycling agent is added prior to mixing in the pugmill to allow sufficient time for good dispersion and mixing. The recycled mix is placed in a windrow, from where the material is spread with a set of augers. A vibrating, tamping screed is then used to place and partially compact the material.(5) The exposed surface on which the recycled mix is placed is typically at about 66°C (150°F).(16,17) Finally, the recycled mix is placed with a compacting screed, and

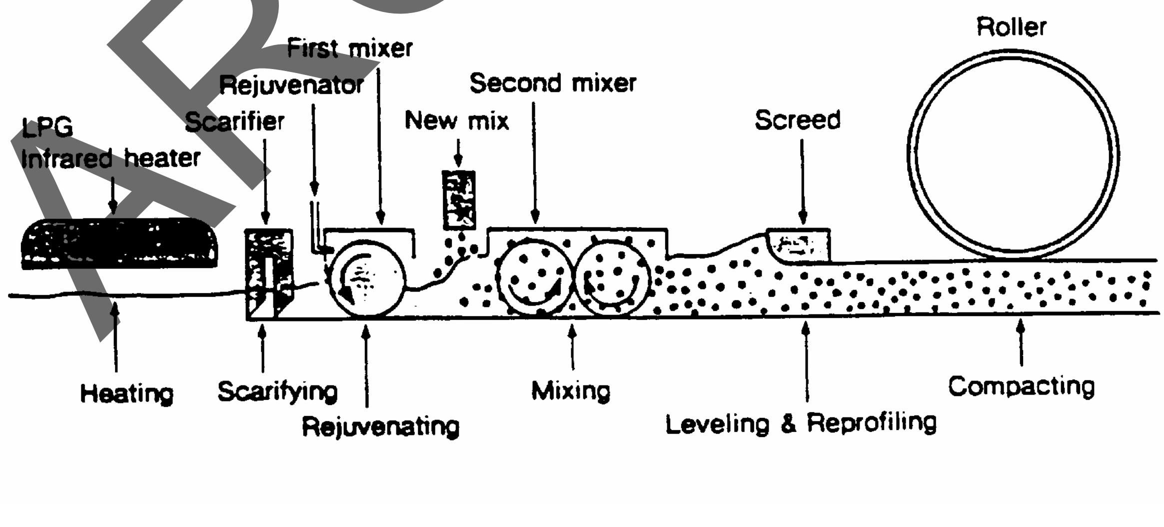

Figure 9-6. Schematic concept of the remixing method.

compacted in the usual method.[15,18,19,20] Figure 9-7 shows a single-pass remixing process. Since remixing uses only 16 to 30 kg/m^2 (42 to 80 lb/yd^2)[5] of new material, fewer haul trucks are required than for conventional HMA overlay operations, and hence results in shorter lane closure time and less disruption to the motoring public.

The use of high intensity infrared heaters tend to overheat and damage the asphalt binder, causing smoke and other undesirable emissions. However, if a less intense heat is applied, aggregate fracturing can occur during milling. To solve this problem, one manufacturer has developed a preheating equipment which uses a combination of hot air and infrared heating system. The application of high velocity hot air in combination with low-level infrared heat is supposed to produce uniform heating of the pavement surface. The recycling train consists of six equipment: two preheaters, one heater miller, one heater miller with paver, rubber tired roller and vibratory roller. A view of the equipment train is shown in figure 9-8.[28]

Emission Control System

A new emission control system has been developed recently, which greatly reduces gaseous hydrocarbon and particulate emissions from the hot in-place recycling equipment.[5] It has been successfully used in the U.S. (Idaho, Montana, and Oregon) and Canada (Alberta, British Columbia, Ontario, and Saskatchewan). The system basically works by collecting the vapor and smoke through a vacuum duct and treating the effluent in an after burner to eliminate undesirable properties.[5] Particulate emissions have generally not been an issue with HIR. However, during HIR operation, joint and crack filling materials can cause flare-ups under preheater. A strip of sand or hydrated lime, 1 mm to 2 mm thick, spread over the filled cracks, has been shown to reduce flare-ups.[21] If there is an excessive amount of crack filling material present on the roadway then the filler may have to be removed prior to recycling.

SUMMARY

Hot in-place recycling has proved to be a very economical pavement rehabilitation strategy which can be used to maintain existing pavements by reusing existing material. However, this process is not suitable for existing asphalt pavements which have too much variation in HMA mix composition within the project limits. The three different types of hot in-place recycling techniques: surface recycling, repaving, and remixing, can be used to achieve different recycling objectives. Surface recycling is used as a process to correct minor surface cracks or irregularities; repaving is used to eliminate rutting, shrinkage cracking, and raveling; and remixing is used to restore the pavement to a greater depth with the addition of virgin aggregate or hot mix asphalt. Whatever the procedure might be, when done in a proper way, hot in-place recycling generally results in savings, and eliminates nonstructural pavement problems with minimum disturbance to traffic, and at the same time maintains the pavement at the existing elevation.

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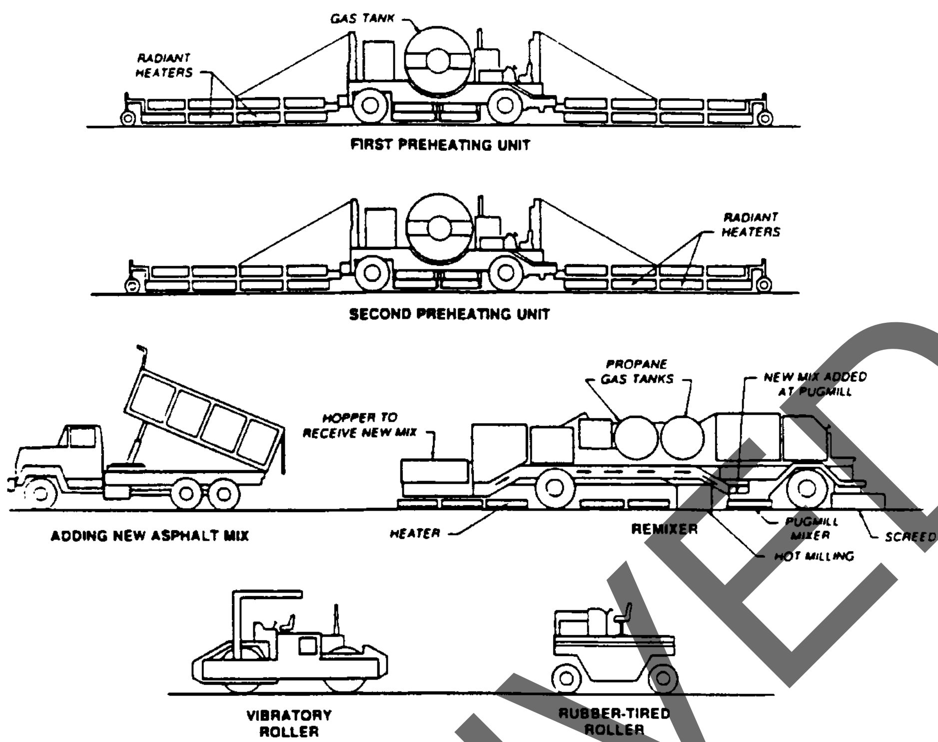

Figure 9-7. Single-pass remixing process showing equipment used.

Figure 9-8. Recycling train with remixer.

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CHAPTER 10. HOT IN-PLACE RECYCLING (MATERIALS AND MIX DESIGN)

INTRODUCTION

Hot in-place recycling (HIR) has proven to be a viable technique for rehabilitation of pavements at low cost by using existing in-place materials. The Asphalt Recycling and Reclaiming Association (ARRA) describes hot in-place recycling as an on-site, in-place method that rehabilitates deteriorated asphalt pavements and thereby minimizes the use of new materials.(1) The primary purpose of this process is to correct surface distresses not caused by structural inadequacy, such as cracks, ruts and holes, and shoves and bumps. Basically, this process consists of four steps: (1) softening of the pavement surface with heat, (2) mechanical removal of the surface material, (3) mixing of the material with recycling agent and/or virgin aggregate and asphalt binder, and (4) laydown and paving of the recycled mix on the pavement surface. The advantages of hot in-place recycling are that elevations and overhead clearances are preserved, it is comparatively cheap, and needs less traffic control than the other rehabilitation methods. This process can also be used to recoat stripped aggregates, re-establish crown and drainage and modify aggregate gradation and asphalt content, and improve surface frictional resistance. According to the ARRA guidelines,(2) hot in-place recycling is performed typically to a depth of 20 mm to 40 mm (¾ to 1½ in). Just as in the case of conventional hot mix asphalt (HMA), recycled mixtures must be designed properly to ensure proper performance. When properly designed, recycled mixtures can have properties similar to those of new conventional hot mix asphalt mixtures.(3)

MATERIAL EVALUATION

The objective of the material evaluation process is to sample, test and determine the important properties of the component materials to come up with an optimum blend of materials to meet the final mix requirements. The process consists of sampling and evaluation of the aged mix (Reclaimed Asphalt Pavement, RAP), the proposed recycling agent, and the proposed virgin aggregate material. For a detailed discussion on different steps of material evaluation, the reader should refer to material evaluation section in chapter 7. In the case of hot in-place recycling the sampling from haul trucks or stockpiles are however, not relevant. The reader should refer to the sampling from pavement sections only.

MIX DESIGN PROCEDURES

Several mix design procedures for HIR are available in the literature. However, these procedures are very similar. The following general steps are recommended for the mix design of hot in-place recycling:(4)

1. Evaluation of salvaged materials.
2. Selection of type and amount of recycling agent.
3. Determination of the need for additional aggregates and/or asphalt binder and/or virgin HMA.
4. Preparation and testing of paving mixtures.

5. Selection of optimum combination of new aggregates, asphalt binder, and recycling agent or virgin HMA.

The following are the most important steps in mix design.[5] The detailed steps are given in table 10-1.[5, modified by 4]

Step A. Determine material properties and proportions
Step B. Prepare materials for mix design
Step C. Complete mixture design
Step D. Carry out quality control/quality assurance (QC/QA) tests

Figure 10-1 shows a flow chart recommended for the different steps in mix design of hot in-place recycled mixes.[6] For a detailed discussion on mix design steps the reader should refer to section on mix design procedures in chapter 7. However, the reader should note the following exceptions which are to be dealt in hot in-place recycling:

1. Amount of RAP is generally very high in hot in-place recycling. Whereas 15-20 percent RAP is common in hot mix recycling, in the case of hot in-place recycling 80-100 percent RAP is common. If 100 percent RAP is used, it is not necessary to determine any combined gradation of RAP and virgin aggregates.
2. Air voids in hot in-place recycled mix can be higher than 4 percent. Higher design air voids (as much as 6 percent) have been used successfully in hot in-place recycling in Canada.

An example of in-place recycling with 100% RAP is given below.

Design Example: It was decided to use 100% RAP in a hot in-place recycling operation. The viscosity of the aged binder was determined to be 50,000 poises, the target viscosity is 2,000 poises, and the available recycling agent has a viscosity of 100 poises. Determine the percentage of recycling agent required.

In figure 10-2, plot Point A as the viscosity of aged binder (50,000 poises) and Point C as viscosity of the recycling agent (100 poises). Draw a horizontal line corresponding to the target viscosity (2,000 poises). Join A and C. The abscissa of the point where the line AC cuts the target viscosity line gives the required percentage of the recycling agent (42 percent) in the binder.

HIR Mix Design with Superpave Technology

The reader should refer to section on hot recycled mix design with Superpave technology in chapter 7 for general guidelines. It is not certain at this time (1997) whether the experience of hot mix recycling with Superpave technology is completely applicable to HIR.

SUMMARY

The two main steps in design of hot in-place recycling are material evaluation and mix design. The materials evaluated include the RAP and the recycling agent. A random sampling plan should be devised to obtain representative samples of the RAP. The sampling plan and frequency should be decided based on historical, construction, and material data, and if needed, the

Table 10-1. Recycled hot mix design procedure.[5, modified by 4]

A.	DETERMINE MATERIAL PROPERTIES AND PROPORTIONS
1.	Obtain representative samples of RAP[a], new aggregates[a], and new asphalt cement selected[b].
2.	Determine asphalt cement content of RAP (including penetration/viscosity of the recovered binder).[b]
3.	Determine gradation of RAP aggregate, including bulk specific gravity.
4.	Determine gradation, percent crushed, bulk specific gravity, and absorption of new aggregates.[c]
5.	Determine if adjustments in aggregate gradation are necessary to develop voids in mineral aggregate (VMA) and select as necessary, ensuring adequate stability is maintained.[d]
6.	Determine the total aggregate grading, check specification compliance and modify as necessary.
B.	PREPARE MATERIALS FOR MIXTURE DESIGN
1.	Determine increments (range) of total asphalt content required to develop specified parameter plots.
2.	Select recommended grade or preferred penetration/viscosity of new (additional) binder.
3.	Determine mass of RAP, new aggregates, and new binder for each increment.
C.	COMPLETE MIXTURE DESIGN
1.	Prepare compacted briquettes incorporating RAP,[e] new aggregates, and new binder.
2.	Test briquettes - bulk specific gravity, maximum specific gravity, stability, flow, air voids, VMA, and appearance.
3.	Report recommended recycled mixture design.
D.	QUALITY CONTROL/QUALITY ASSURANCE (QC/QA)
1.	Similar to conventional hot mixture with addition of monitoring RAP (moisture content, gradation, and asphalt-cement content) and more emphasis on absolute viscosity and penetration of recovered binder.

Notes:

[a] All samples must be representative. Process control data should be used.
[b] The new asphalt cement selected must provide properties in the recycled mixture meeting specifications.
[c] For new aggregates that have not been used before, factors such as petrography and stripping resistance must be considered. This also applies to RAP aggregate, if aggregate-related pavement distress is involved.
[d] In order to develop VMA, it is often necessary to incorporate a clean, fine aggregate.
[e] The RAP must be carefully dried during testing to avoid excessive asphalt cement hardening, and then combined with suitably heated new aggregates to give an overall mixing temperature meeting the appropriate combined RAP asphalt cement and new asphalt cement mixing temperature viscosity.

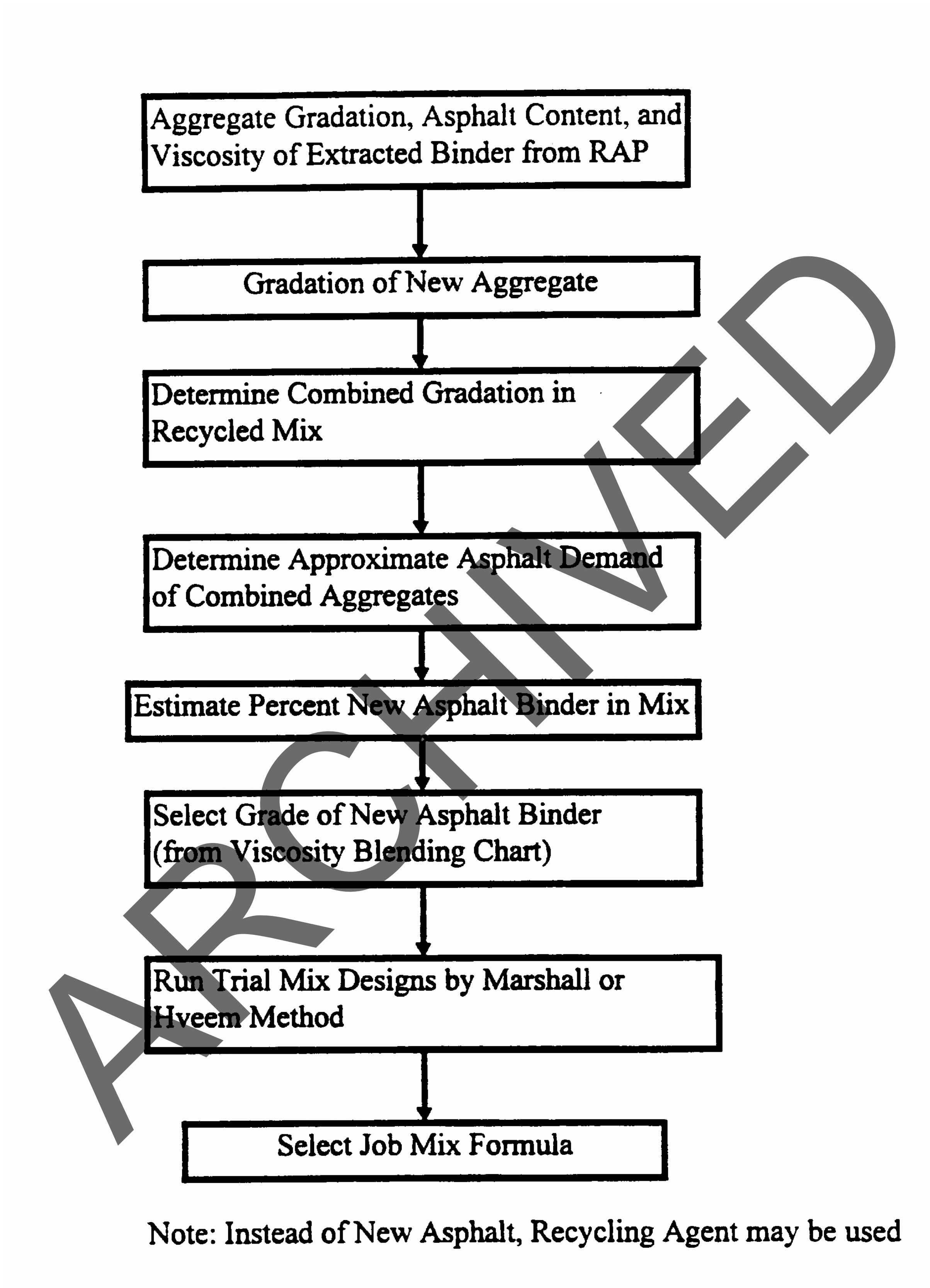

Figure 10-1. Flow chart of mix design procedure.

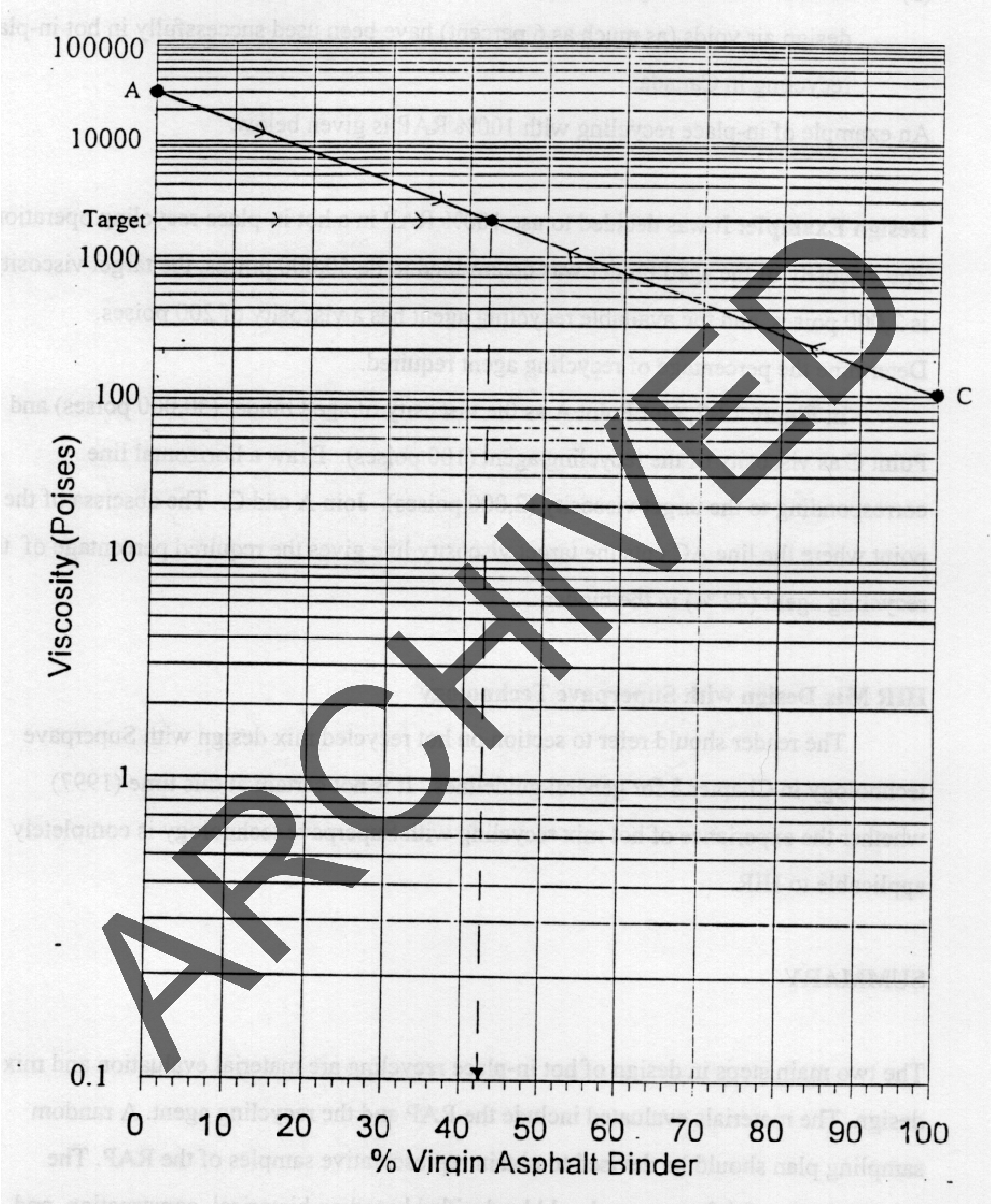

Figure 10-2. Use of asphalt viscosity blending chart (design example).

pavement may be divided into different sub sections before sampling. To evaluate the RAP material, which undergoes changes with time and traffic, its gradation, asphalt content, and rheological properties of aged asphalt binder must be determined. The recycling agent should conform to the applicable AASHTO or ASTM standards. Hot in-place recycled mix design involves the determination of the combined gradation of the aggregates and the required amount of new aggregate, if required, to meet the target gradation. Next, the amount of new (virgin) asphalt binder or recycling agent required in the recycled mix is estimated. Blending charts (based on viscosity or Superpave rutting factor $G^*/\sin\delta$) are then used to select the grade or amount of virgin asphalt binder or recycling agent. A series of trial mixes are then made with different asphalt contents. The optimum asphalt content for the recycled mix is selected based on Marshall, Hveem, or Superpave volumetric mix design procedures.

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CHAPTER 11. HOT IN-PLACE RECYCLING (CASE HISTORIES AND QC/QA)

INTRODUCTION

Hot in-place recycling (HIR) is a hot process in which the existing asphalt pavement material is recycled in place. Typically, the pavement is processed to a depth of 20 to 40 mm (¾ to 1½ in).[1] The deteriorated asphalt pavement is heated and the softened material is scarified and mixed with virgin aggregate and/or recycling agent and/or virgin asphalt mix. In the single-pass method, the restored existing pavement material is combined with virgin materials and compacted in a single pass. In the case of multiple pass hot in-place recycling, the restored and treated pavement material is recompacted in one-pass and a new overlay is applied after a prescribed interval in the next pass.

Different types of hot in-place recycling procedures have been discussed in chapter 9. The objectives of this chapter are to present selected case histories and discuss specifications and quality control/quality assurance (QC/QA) procedures required for successful hot in-place recycling. Case histories of projects using repaving and remixing processes only are available.

CASE HISTORIES

Hot In-Place Recycling in Orange County, Florida[2] (1995)

Only the construction case history is available for this project in Florida, which used the repaving process. It was decided to use hot in-place recycling process to treat cracks in the existing pavement (figure 11-1). The pavement section had a traffic count of 33,000 ADT with 10 percent trucks. First the existing surface was milled to reveal the curb (figure 11-2). The remaining surface was preheated by a preheater moving immediately in front of the single pass repaving equipment (figure 11-3). Heating was accomplished by using a forced air system. A flat flame was produced that was turned 90 degrees at combustion rather than blasting the pavement surface directly. The flame heated a ceramic wool insulation at the top of the heating hood. The insulation transferred heat to the pavement surface. The pavement surface between the preheater and the repaving equipment was generally above 107°C (225°F). The repaving unit was also equipped with a heating unit, about 5.4 m by 3.9 m (18 ft by 13 ft) (figure 11-4). Rows of air-pressured, carbide tipped scarifiers were then used to cut the heated pavement in a level plane to a depth of 25 mm (1 in) (figure 11-5). Presence of nine teeth per foot section enabled the lifting and lowering to avoid manholes and other obstacles. The scarifiers cut through the pavement and produced loose materials. The next step was the application of an emulsified recycling agent to modify the properties of the existing aged binder. In this repaving equipment, six spinning cups delivered the recycling agent to the hot scarified material (figure 11-6). The application rate was geared to the forward speed of the machine, ensuring a constant rate of application. A heavy duty carbide mold board in the repaving equipment gathered the scarified material and an auger-type conveyor distributed the material transversely across the width being processed as the recycling agent was applied. Next, the scarified material and the recycling agent were mixed. A four section, vibratory screed (figure 11-7) was used to distribute and lay the recycled material as a leveling course prior to placement of the final asphalt wearing surface. The temperature of the

Figure 11-1. Cracks in existing pavement.

Figure 11-2. Milling.

Figure 11-3. Preheater.

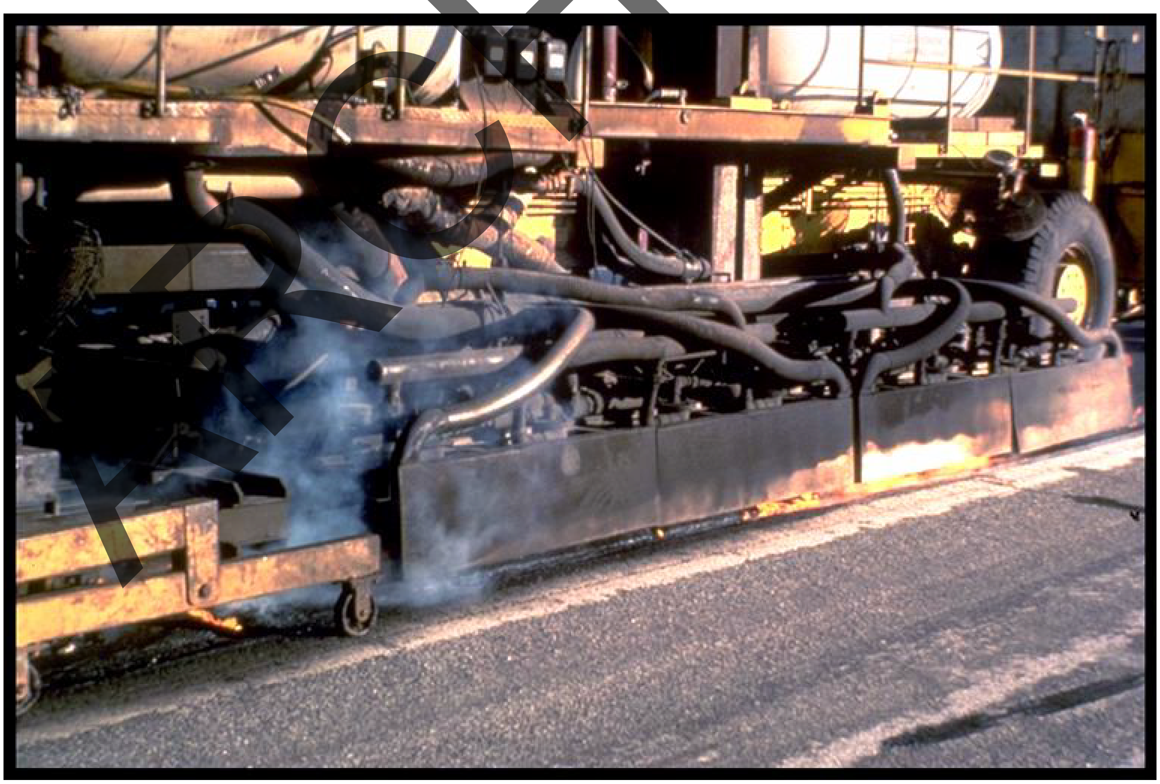

Figure 11-4. Heating unit of repaving machine.

Figure 11-5. Scarifiers.

Figure 11-6. Spinning cups to spray recycling agent.

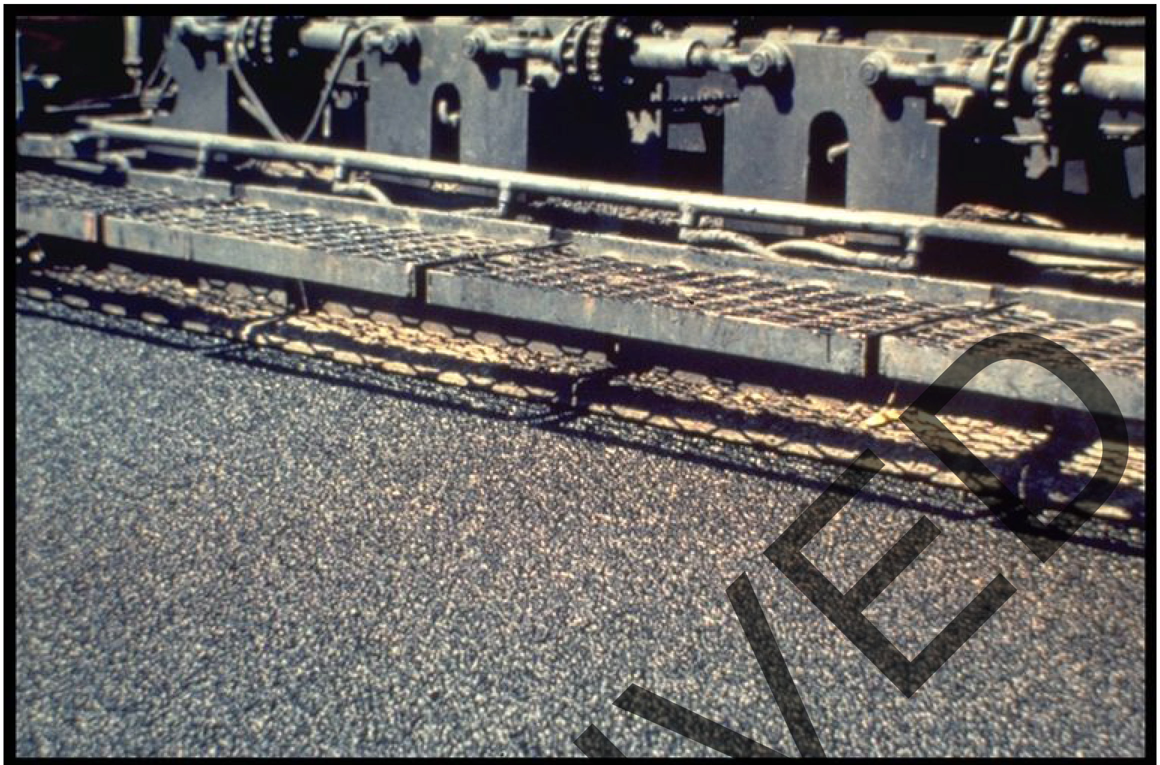

Figure 11-7. Four section vibratory screed.

recycled material was 93°C (200°F) at the time of placement. Such a high temperature was felt necessary to ensure a monolithic bond between the leveling and final course. A dump truck was then used to transfer new hot mix to the repaving equipment. The mix was carried across the length of the machine via a reverse flow chain link conveyor. The vibratory screed, equipped with electronic grade and slope controls, laid the new overlay. Conventional method was then used to compact the new mix. The work was done in a single lane and traffic flow was not blocked in the other lanes (figure 11-8). The cost of recycling was estimated to be \$3.44 per m^2 for this project constructed in 1995.

Hot In-Place Recycling Project Highway 3:14 and 3:16, Alberta, Canada[3] (1993)

This project was constructed on Highway 3:14 and :16 in May and June of 1993. The project involved the use of a hot in-place recycling equipment called "Pyropaver." Highway 3:14 and :16 is a two lane facility in the southeastern part of Alberta. The project limits were from east of Whitla to Medicine Hat. The existing pavement was last overlaid in 1975 with a subsequent seal coat application in 1977. In 1993, the average annual daily traffic (AADT) count on this highway was 3,040 with a design lane daily ESAL count of 188. Rehabilitation was required primarily due to poor ride quality caused by a relatively high incidence (50 to 70 cracks/km, 81 to 113 cracks/mile) of rough, distorted transverse cracks and minor to moderate amount of rutting (2 to 14 mm, 0.1 to 0.6 in). The existing shoulder material was extremely coarse and weathered with areas containing small cold mix patches and raveling pavement. It was decided to use hot in-place recycling to a depth of 40 mm (1.6 in), followed by a 60-mm (2.4-in) thick hot mix asphalt overlay. To obtain samples of the existing material, the project was divided into two sections. Core samples were obtained at a frequency of three cores per kilometers for a total of 18 cores in

Figure 11-8. Recycling operation in one lane.

Section 1 and six cores in Section 2. Preliminary testing involved density measurement on each core and penetration and viscosity testing of the recovered asphalt binder from one lane from each site. Test results from Section 1 (in Highway 3:14) showed average asphalt content of 5.88 percent, in-place air voids of 4.9 percent and average binder penetration of 65 mm. During construction, clean fine blend sand (the gradation of the blend sand was as follows: 100, 99, 97, 70, 26.0, 9.2 percent passing the 4.75 mm, 1.18 mm, 0.60 mm, 0.30 mm, 0.15 mm, and 0.075 mm sieves, respectively) was used with the existing dense graded mix to increase the voids. No recycling agent was used since the binder was found to be borderline acceptable (penetration of 65 dmm). Section 2 (on Highway 3:16) results showed an average asphalt content of 4.55 percent, in-place air voids of 7.7 percent and average penetration of 93 dmm. Results from laboratory tests indicated that an addition of 0.3 percent (by weight of total mix) “Cyclogen L” and 10 percent blend sand was required to change the air voids to an acceptable level of 3.4 percent. The process selected for hot in-place recycling operation was a “two-stage” process. Heating of the pavement was done with both infrared heaters and open flame burners using liquid propane gas. The equipment train consisted of three units; a preheater with a simple row of 20 open flame burners, towed by a 3-ton truck, a self propelled unit containing improved heaters and milling heads, and the final unit propelled by a standard paver containing milling head. The milling heads in the second unit removed all but the center meters of the driving lane to one half of the final treatment depth. A recycling agent, when required, was pumped through two nozzles; one located near each of the two milling heads. The flow rate was positively interlocked to the speed of that unit and was monitored with an in-line flow meter. The third unit milled
the center portion of the mat and picked up all of the millings from the first stage and transported them through a drag-slot conveyor over top of the final series of heaters. The second stage milling

was completed by a full lane width milling head that was located at the rear of the unit.

The first stage millings were then deposited on top of the final milled windrow directly behind the milling head. A material transfer unit used a transversely mounted single shaft pugmill to mix and pick up the windrowed material for placement with the paver hopper. A removable hopper was mounted on the front of the third unit to receive an aggregate additive. The blend sand additive was fed through a gate at the back of the hopper and dropped into the first windrow prior to being picked and conveyed over the third set of heaters. A typical production rate for a full day operation was approximately 2.5 lane km. A schematic of the equipment used is shown in figure 11-9. Figure 11-10 shows the condition of the pavement before recycling, figure 11-11 shows the recycling operation, and figure 11-12 show the condition of the pavement after recycling.

Various nominal addition rates of "Cyclogen L" were used in the material recycled in Section 2.

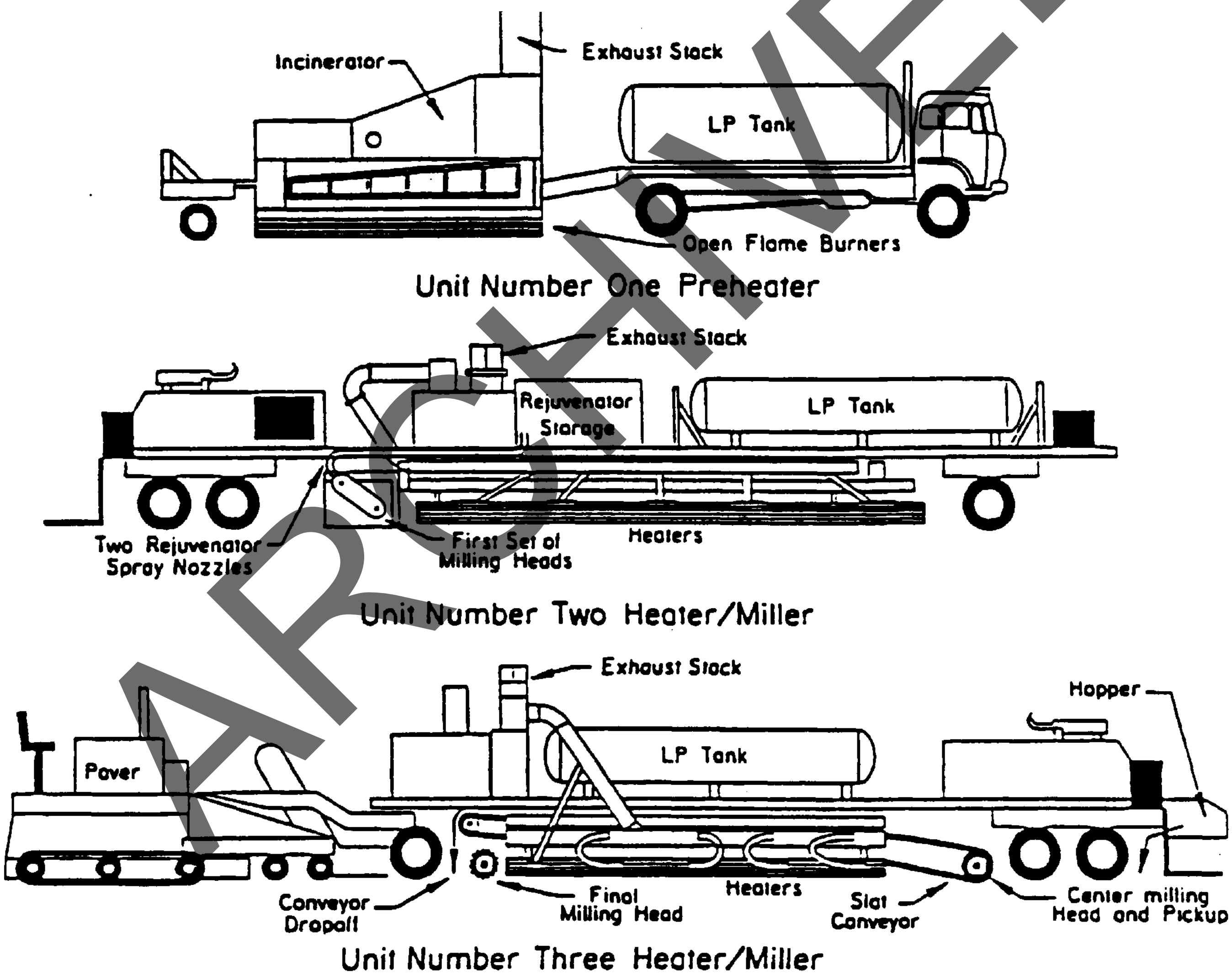

Figure 11-9. Schematic of equipment used in HIR on Highway 3:14 and 3:16 in Canada.

Figure 11-10. Condition of pavement before recycling.

Figure 11-11. Recycling operation.

Figure 11-12. Condition of pavement after recycling.

Checks on the quality of Cyclogen was done by field staff monitoring an in-line flow meter. The finished hot in-place recycled surface was smooth with an average Profilograph Index of 7.3 mm/0.1 km (1.8 in/mile). The existing pavement had a Profilograph Index of 24.1 mm/0.1 km (5.9 in/mile). Emission levels varied widely throughout the project. The higher levels of emissions were generally attributed to higher production rates, stronger winds, and the presence of a seal coat treatment. For evaluation purposes, a 200-m (656-ft) part of the hot in-place recycled section was not overlaid. To date (January 1995) the surface remained in good condition, except for some spot patching on shoulders.

Material evaluation tests included density, air voids, extracted binder content and gradation. The following cost comparisons were made on the basis of equal life cycle costs:

	HIR	HMA Overlay
Cost per square meter	$2.00	$3.21
Cost per Mg	$23.97	$25.67
Cost per kilometer (2-lane)	$14,600.00	$41,400.00

Hot In-Place Recycling in the City of Edmonton, Canada[4] (1993)

Three sections of roadway were selected for hot in-place recycling in the City of Edmonton. These three sections included Victoria Park Road from the Goat Bridge Interchange I-115 Street, 137 Avenue eastbound from 113A Street to 97 Street and Learning Drive southbound from 167 Avenue to 144 Avenue and 50 Street to 137 Avenue. Each of the roadways had distress features consistent with surface disintegration (figure 11-13). On Learning Drive, some slight rutting was noted. Cores from each project were tested for density, asphalt content, and gradation.

Penetration and viscosity tests on recovered asphalt binder were also conducted. Preliminary mix design consisted of the following steps:

1. Cores from the project were taken and the top 50 mm (2 in) was obtained and used for mix design. In-situ density and theoretical maximum density (TMD) measurements were conducted on the top portion of the cores.
2. The top portion of the cores were heated to 135ºC (275ºF) and then some of the material was used to compact Marshall briquettes using 75 blows per face. Marshall density, stability, and flow were measured on these compacted samples.
3. Based on the information supplied by the city and design nomographs, 0.2 percent "Cyclogen L" was added to the mix to soften the aged asphalt cement.
4. Four Marshall briquettes were made using the asphalt mix with "Cyclogen L" using 75 blows per face.
5. The TMD was determined on the mix with "Cyclogen L" added.
6. One of the four briquettes containing "Cyclogen L" was used to conduct extraction and Abson tests. Viscosity and penetration was measured on the recovered asphalt binder.
7. Marshall stability and flow were measured on the other briquettes.
8. After examining the air void information for the mixes, the gradation was examined and a blend sand consisting of fine concrete aggregate was added at the rate of 7 percent (for some of the projects).

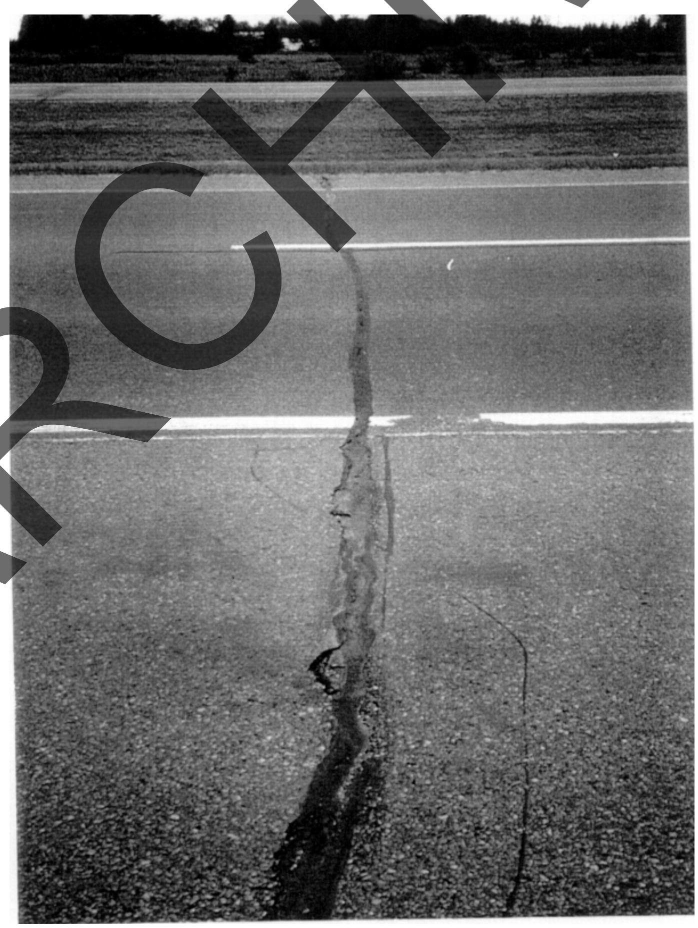

Figure 11-13. Condition of pavement before recycling.

9. The material was reheated, mixed and compacted using 75 blows per face. Marshall properties were then measured.

The mix design results indicated several trends in the material properties. In-situ field air voids for the projects before recycling ranged from 2.1 percent to 3.2 percent. After the addition of “Cyclogen L,” the void content ranged from 1.2 percent to 2.2 percent. The air voids after the addition of “Cyclogen L” was too low for two of the projects so the addition of blend sand was considered. The addition of 7 percent blend sand resulted in the voids for 137 Avenue and Victoria Park Road increasing to 2.0 to 3.2 percent, respectively. This level of air voids, although slightly lower than desirable, was considered acceptable.

The field control parameters were as follows:

1. “Cyclogen L” addition rate varied from 0.15 to 0.2 percent by total weight.
2. The quantity of blend sand added was kept constant at 7 percent by total weight.
3. Coated blend sand was used. The amount of asphalt binder in the blend sand varied from 2.5 to 3.0 percent.

Hot in-place recycling operations began on September 19, 1993, at the west end of Victoria Park Road and proceeded east. The initial admixture settings were as follows:

1. “Cyclogen” at the rate of 0.2 percent by weight of mix.
2. 7 percent sand hot mix at 2.0 percent asphalt cement content.

As recycling operations progressed, the recycled mix (after the addition of 0.2 percent cyclogen) appeared quite “wet.” The mix also had a slight tendency to “flush” upon completion of the compaction operations. Based on these visual observations, a decision to reduce the amount of “Cyclogen” to a 0.15 percent addition rate was implemented. The mix was continually monitored on a visual basis. After compaction on the initial stretch of the road was completed, the finished pavement surface was inspected and some “stripping” of the larger aggregate particles was evident. Some uncoated particles (crushed during milling operations) were also observed to exist as the recycled mix was fed into the paver. At this time a decision was made to increase the amount of virgin asphalt cement content in the sand mix to aid, and ensure effective coating of the aggregates. The asphalt cement content was increased incrementally to 3.0 percent. After this, the recycled mix appeared satisfactory with respect to consistency, coating, and workability— both before and after placement. These settings/addition rates were maintained for the duration of the Victoria Park Road project.

Hot in-place recycling operations on Victoria Park Road were completed on September 20, 1993 and HIR operations on 137 Avenue began on September 21, 1993, at the west end of the project on the east bound lanes. The start-up admixture (“cyclogen” and virgin sand mix) addition rates for 137 Avenue Project were kept the same as that used on the Victoria Park Road Project.

With these settings in place, the recycling mix produced appeared to be relatively “drier” than that achieved on the previous project. Therefore, the “Cyclogen” addition rate was increased to 0.2 percent. After this, the recycled mixture exhibited a satisfactory appearance and paving operation progressed without any problems.

Field construction monitoring was conducted by the City for Manning Drive. Hot in-place recycling operations on Manning Drive began September 23, 1993, at the north end of the project in the west southbound lane.

The initial admixture settings for the Manning Drive were as follows:

1. Cyclogen at the rate of 0.15 percent.
2. 7 percent sand hot mix at the rate of 3.0 percent asphalt cement content.

Sand hot mix for Manning Drive was supplied by the City of Edmonton Asphalt Plant to attain additional flexibility in adjusting the asphalt content and gradation of the sand mix. As the recycling operation progressed, the recycled mix appeared “wet” and test results were indicating low voids. Based on this observation and test results, the asphalt cement content in the sand mix was reduced from 3.0 percent to 2.5 percent.

On September 24, 1993, existing asphalt material conditions changed and the recycled product appeared dry. In an attempt to increase the voids in the recycled product, “Cyclogen” and/or asphalt content in the sand mix were not increased but the gradation of the sand mix was altered by reducing the amount of sand and increasing the amount of 6 mm (¼ in) material. This alteration resulted in the mixture exhibiting a satisfactory appearance.

Hot in-place recycling was attempted on September 25, 1993, but was discontinued due to low ambient temperature (7ºC, 45ºF) and high winds. As a result of these conditions, temperatures behind the screed of higher than 85-90ºC (185-194ºF) could not be attained. The 90 linear meters (295 ft) of roadway that was completed under these conditions was redone the following day. Hot in-place recycling was completed on Manning Drive on September 27, 1993.

Examination of the results of testing indicated the following:

1. Aggregate gradation was relatively consistent within each project. All mixes appeared to be a 12.5 mm (½ in) top size aggregate with some variation on percent passing the 5 mm (¼ in) sieve; however, the variation was not considered extreme. The gradations for the field samples agreed very closely with the gradation considered for design.
2. The asphalt content was variable on each project with the following variations noted:

Victoria Park Road	5.4 - 6.2 percent
137 Avenue	5.2 - 6.4 percent
Manning Drive	5.2 - 6.0 percent

3. Air voids were generally low with the maximum range of 0.7 to 3.7 percent. However, the majority of the air voids fell between 1.0 and 2.5 percent.
4. Stability and flow values were generally good with stability ranging from 10,936 kN (2.46×10^6 lbf) to 20,923 kN (4.70×10^6 lbf) and flow ranging from 9.1 to 13.3.
5. Density of the recycled hot mix asphalt was generally higher than 97 percent of Marshall density. Because of the latent heat involved in in-place recycling, density was obtained relatively easily.

The recycling train (figure 11-14) consisted of four pieces of equipment: a preheater (figure 11-15), a heater miller (figure 11-16), a second heater miller with conveyor (figure 11-17), and a paver. The preheater was used to raise the surface temperature. The first heater miller was also used to raise the surface temperature. However, it also milled the in-place material up to a depth

Figure 11-14. Recycling train.

Figure 11-15. Preheater.

Figure 11-16. Heater miller (primary).

Figure 11-17. Heater miller (secondary) with paver.

of 25 mm (1 in). The milled material was left as windrow in the center of the roadway. Recycling agent was added during the milling operation. The second heater miller heated up the exposed surface, milled an additional 25 mm, and also reworked the windrow of material. New mix and sand blend were added at this point. This heater miller contained a pugmill which completely reblended all milled and new material along with the recycling agent. The final unit was the paver, which was equipped with a windrow elevator. It picked up the windrow of the remixed material and laid down as a conventional paver. All equipment used to heat the pavement were equipped with environmental controls to reduce the amount of emissions. Figure 11-18 shows the condition of the road before and after recycling.

The total cost of the hot in-place recycling project was \$262,701. This cost amounted to \$5.01/m^2 (\$4.00/yd^2). Compared to this, the cost of conventional remove and replacing was estimated to be \$6.60 - \$7.70/m^2 (\$5.28 - \$6.16/yd^2).

Figure 11-18. Condition before and after recycling.

HIR has also been used in Canada for treating rutting at intersections. Figures 11-19 through 11-22 show recycling operations in the city of Edmonton. Figure 11-19 shows a rutted intersection. Figure 11-20 shows the recycling train. Figure 11-21 shows a closeup of the rutting intersection, and figure 11-22 shows a view of the pavement after recycling.

SPECIFICATIONS AND QC/QA

Guidelines and Specifications

The two necessary steps required for ensuring satisfactory construction of a hot in-place recycling (HIR) project are the development of an adequate specification, and ensuring that the

Figure 11-19. A rutted intersection.

Figure 11-20. Recycling train.

Figure 11-21. Closeup view of the rutting intersection.

Figure 11-22. A view of the pavement after recycling.

specification requirements are met during mix design and construction. As in the case of conventional asphalt overlay, a set of guidelines or specifications is required in hot in-place recycling to describe the materials, workmanship, and other general requirements for the project. Where appropriate, agencies should consider the hot in-place recycling process along with other alternatives.[5] This process can help the user agency to evaluate the two or more methods and determine the most cost effective approach.

A set of general specification guidelines for effective completion of hot in-place recycling process is presented in table 11-1.[6, modified by 5] The major steps involved are preliminary pavement evaluation to determine structural adequacy, determination of applicability of hot in-place recycling, a detailed pavement evaluation, and selection of the particular hot in-place recycling technique.

Table 11-1. General steps in a hot in-place recycling project.[6, modified by 5]

Step	Further Details	Comments
1. Preliminary Pavement Evaluation	Table 11-2	Mainly to determine if pavement structure is adequate.
2. Applicability of HIR	Table 11-2	If HIR not applicable, develop alternative rehabilitation or reconstruction method(s).
3. Detailed Pavement Evaluation	Table 11-3	Mainly quality and properties of existing pavement surface course.
4. Selection of HIR Option	Table 11-4	Surface recycling, remix, repave or remix-repave.
5. a. Remix - Select Rejuvenator (Type and Application Rate), and/or Design New Hot Mix. b. Repave - Specify New Hot-Mix Overlay	Method for determining optimum amount of recycling agent, from ASTM D 4887	
6. Completion of HIR Project	Table 11-5	Quality control important.

Note:

It is assumed that the appropriate specification preparation, bidding and payment, and quality control have been incorporated in the steps, as required.

Before any rehabilitation process is specified, the most suitable rehabilitation process should be determined on the basis of the source and cause of any surface defects such as rutting, cracking and/or deficient surface frictional resistance. If the cause of the defect remains unknown, then the proper rehabilitation technique cannot be applied, and the defect would most likely reappear in future. Use of hot in-place recycling can remedy the existing problem if it is caused by mix problems, such as excess asphalt, inadequate aggregate interlock, or too hard/too soft asphalt.[5] Table 11-2 presents the information required for evaluation of the existing pavement so that a proper recycling process can be specified. The different information required include an inventory information, details about the pavement structure, knowledge of the prior treatments, geometry and profile of the pavement, and the presence of miscellaneous structures such as

Table 11-2. Information required from preliminary pavement structure evaluation.(6, modified by 5)

Item	Details	Reason
Pavement Inventory Information	•class of pavement •pavement structure[a] •pavement history •traffic volume	•work schedule •applicability of HIR •supplement detailed •evaluation •work schedule
Pavement Structure	•structural defects (types and extent)[a] •non-structural defects (types and extent) •localized structural defects	•applicability of HIR •selection of HIR option •need for preliminary localized repairs
Prior Treatments (See Pavement Inventory Also)	•any special treatments or materials (surface treatment, rubberized asphalt, road markings fabrics, epoxy patching, etc.)	•need for removal (cold milling for instance), if possible, before HIR process
Geometry and Profile	•width, alignment and gradient •surface profile (rutting and wear)[b]	•applicability of HIR •need for preliminary treatment (cold milling for instance) before HIR process
Miscellaneous	•manholes, catch-basins, utility covers, etc. •adjacent (close plants, trees, flammables, etc.	•work schedule, protection, and potential flammable gas counter-measures •work schedule and protective action as necessary

Notes:

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

[b] Pavement width, alignment and/or gradient improvement requirements, or excessive rutting and wear (greater than about 50 mm), may preclude HIR.

manholes or utility covers on the pavement. These information help the user agency to evaluate the applicability of the hot in-place recycling process, determine the need for any prior treatment (such as cold milling), and specify the particular hot in-place recycling technique applicable (such as remixing or repaving). Table 11-3[6, modified by 5] shows the importance of information from detailed evaluation of existing pavement surface. The most important surface features which must be evaluated, include cracks, wear, and rutting. The important existing HMA features include thickness, binder content, grading, density, and penetration and viscosity of the binder. Finally, the particular hot in-place recycling technique can be identified by the guidelines presented in table 11-4.[6, modified from 5] Surface recycling is employed to improve the profile of a surface course deformed by rutting or wearing, but in comparatively unaged condition with minor cracking. Repaving is used to improve the profile of a surface course severely deformed by rutting or wearing, with new hot-mix overlay placed in one pass. This method improves frictional characteristics, and provides some pavement strengthening. Remixing can be used to improve the quality of old, cracked, aged surface course by the addition of recycling agent and/or new hot mix

Table 11-3. Importance of information from detailed evaluation of existing pavement surface.[6, modified by 5]

Pavement Evaluation Item	Pavement Evaluation Parameter	Surface Defect			
		Wear	Rutting	Cracking	Friction
Surface Condition[a]	•cracks (types and extent)	N	N	M	N
	•transverse profile	M	M	N	R
	•longitudinal profile	R	R	N	N
Existing Asphalt Concrete[b] (usually surface course, but must be at least to proposed scarification depth)	•thickness	M	M	M	M
	•asphalt-cement content (for scarification depth)	M	M	M	M
	•grading (for scarification depth)	M	M	M	M
	•density	M	M	M	M
	•air voids	M	M	M	M
	•penetration, viscosity and softening point of recovered asphalt cement (for scarification depth)	M	R	M	N

Notes:

M = Mandatory

R = Recommended

N = Not Necessary

[a] Information should be representative of the pavement section involved, with special areas (extensive patching for example) and localized structural distress areas noted.

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

Table 11-4. Hot in-place recycling process options.(6, modified by 5)

Purpose[a]	Option	Process
To improve the profile of a surface course deformed by rutting or wearing, but in comparatively unaged condition with minor cracking.[b]	Surface recycle	Heating, Scarification, Rejuvenator (if needed), Leveling, Reprofiling[c], Compaction[d]
To improve the profile of surface course severely deformed by rutting or wearing, with new hot-mix overlay placed in one pass. To improve frictional characteristics. To provide some pavement strengthening.	Repave	Heating, Scarification, Rejuvenation, Leveling, Laying New Hot Mix[f], Reprofiling, Compaction[d]
To improve the quality of old, cracked aged surface course by the addition of rejuvenator and/or new hot mix[e].	Remix	Heating, Scarification, Rejuvenator, Mixing and/or New Hot Mix, Mixing, Leveling, Reprofiling, Compaction[d]

Notes:

- [a] Primary purpose given in each case.
- [b] Often used prior to hot-mix resurfacing (surface recycling).
- [c] Standard screed and screed controls.
- [d] Standard compaction equipment and procedures.
- [e] The composition, grading, and/or asphalt-cement content of the new hot mix can be adjusted to improve the quality of the old mixture.
- [f] Standard augers and auger controls.

asphalt. The existing HMA mixture should be evaluated to help specify the particular hot in-place recycling technique required and to determine the type and amount of any recycling agent required. The process basically consists of extraction and recovery of the asphalt binder from the mix, up to the scarification depth. The type and amount of recycling agent chosen should be such as to restore the binder to the as-placed rheological condition. Adjustments of amount of recycling agent may be required in the field, since laboratory evaluations often indicate more recycling agent than is actually needed.(5)

For construction guidelines in specifications for recycling, the average recycled mixture temperature required for satisfactory compaction is in the 105°C to 115°C (221°F to 239°F) range at the breakdown rolling,(6) depending on specific site and ambient condition, and for scarification of the existing old HMA to be effective and efficient, the minimum temperature at the depth of the scarification should be the softening point for the project's recovered asphalt cement before rejuvenation.(5)

The two common types of specifications used for HMA construction are the method and the end-result specifications. The method specification describes in detail the equipment and procedures used to obtain the desired quality of asphalt mixture.This type specification requires sufficient detail to describe all the variables required to obtain a satisfactory asphalt mixture. On the other hand, an end-result specification sets the limits on certain properties of the HMA, and the method of construction is left at the discretion of the contractor. There are advantages and disadvantages for both types of specifications. For example, if a user agency has sufficient experience with the construction method, a method specifications may be easier to write. However, method specification requires that an inspector be on the job at all times to ensure proper compliance with the procedure. The end-result specification may be easier to write, since it is shorter and less detailed than the method specification. However, it may be very difficult to determine what properties to specify and what limits to set for these properties. This becomes more of a problem when dealing with material with high amount of variability, such as recycled asphalt pavement (RAP) material. Hence, in the case of recycling it is best to adopt a specification which is a combination of method and end-result specification. In this way, the experience of the user agency, contractors, material suppliers and equipment manufacturers can be utilized to obtain a recycled HMA with desirable quality.(6) Generally, the specifications for recycling projects are more of end-result nature than of method specification. This allows, and also encourages, the contractor to develop and use new construction methods and equipment for HMA recycling. However, in some cases it may be required to specify the type of equipment that will produce an acceptable pavement.(5) It is advisable to specify that the application rate of the recycling agent and any virgin HMA must be related directly to the forward movement of the equipment to minimize variation during speed changes and stoppages.(5)

Quality Control/Quality Assurance (QC/QA)

Quality control (QC) refers to those tests necessary to control a product and to determine the quality of the product being produced. These QC tests are usually performed by the contractor. Because of greater variation expected in the case of recycled HMA, the frequency of testing should be more, even though the same tests that are used in the case of conventional HMA may be used. Before starting construction, it is very important to know the quality of the existing pavement, in terms of aggregate gradation and asphalt content of the mix. The pavement should first be delineated into subprojects, on the basis of differences in design, maintenance and rehabilitation actions. Once the subprojects are identified, samples should be taken from each of the subprojects to obtain representative materials. In this way the variation in the existing material can be identified and evaluated.(7)

In general, the quality control and quality assurance (QC/QA) measures for hot in-place recycled mixes should be similar to those for the hot mix recycled mixtures. The reader is referred to chapter 8 for this. However, unlike recycled mixtures produced in a HMA plant, the hot in-place recycled mixes are produced and modified in the field. Therefore, some features involving sampling and testing of HIR mixes need to be discussed.

In hot in-place recycling, the softened material from the existing pavement is scarified and recompacted after mixing with recycling agent. Samples of in-place mix can be obtained from the laydown machine for checking the mix components such as gradation and asphalt content. The scarified existing material can also be sampled behind the scarifiers. The National Center for Asphalt Technology (NCAT) ignition oven can be used to determine the amount of asphalt binder (or recycling agent) being incorporated in the recycled mix by checking the asphalt content of the existing, scarified mix and the asphalt content of the recycled mix.

Items of interest in hot in-place recycling to be checked or observed are recycled mix temperature, compacted mat density, surface smoothness, cross slope, handwork, mat depth, and general mat appearance. Proper care should be taken to avoid excessive smoke or flames on the

Table 11-5. Quality Control for Hot In-Place Recycling Process[a].[(6, modified by 5)]

Item	Recommended Method[b]
Width	As usual
Depth of Scarification	Measure depth from existing surface adjacent to second mixer or Use circular ring method[c]
Rejuvenator Application Rate (if any)	ASTM D 4887 Calculate from quantity used
Rejuvenator Quality (if any)	As usual (specifications and ASTM D 4552)
New Mixture Addition Rate (if any)	Calculate from quantity used (tons) and in-place density
Thickness of New Hot-Mix Overlay (if any)	Calculate from quantity used (tons) and in-place density
Temperature at Breakdown Rolling	Monitor at mid-point of re-profiled depth
Temperature of New Hot-Mix (if any)	As usual
Asphalt Cement Content, Gradation, and Stability Requirements	As usual
Compaction	As usual. Important to compare to relevant re-compacted density
Surface Tolerance	As usual
Penetration/Viscosity and Softening Point of Asphalt Extracted from Recycled Mixture	As usual

Notes:

[a] As the HIR processes are largely based on conventional hot-mix paving technology, it is only necessary to supplement the usual quality control requirements. The quality control items and frequency of testing should be established at the level necessary to ensure specification compliance.

[b] All testing should be done on random, representative samples, by qualified technicians in a certified laboratory.

[c] A ring of known internal diameter (typically, 355 mm = 0.1 m^2 area) is pushed into the scarified old pavement as deeply as possible, the scarified old mixture within the ring is removed and its mass determined, and from the bulk density of the old pavement the depth of scarification is calculated.

pavement. Some recommended guidelines for quality control are presented in table 11-5.[6, modified by 5] Some of the tests mentioned in table 11-5 can also be used for quality assurance (QA) by the user agency. However, the frequency of QA tests is usually significantly lower than the frequency of QC tests. Many of the features are same as those of conventional hot mix construction. The important features are the applicability of ASTM D 4887 for recycling application, the new mixture (if any) addition rate, the thickness of the new hot mix overlay (if any), and the temperature at breakdown rolling. Some states require construction of a test strip to evaluate the recycling process, before starting actual operations. The New York DOT remixing specification requires that the contractor sample, test, and supply test results of the recycled loose mixture.[8]

SUMMARY

In hot in-place recycling, the existing pavement is heated and the softened material is scarified and mixed with virgin aggregate and/or recycling agent and/or virgin asphalt mix. Different types of hot in-place recycling methods can be selected, based on the type of distress in the existing pavement. The three primary types of hot in-place recycling processes are surface recycling, repaving, and remixing. Case histories for these three kinds of recycling show that hot in-place recycling can effectively treat pavement distress at a much lower cost, compared to conventional rehabilitation treatments. However, to ensure proper performance, hot in-place recycling operation must be accompanied by strict quality control and quality assurance measures. The cause of distress in the existing pavement must be ascertained and the applicability of hot in-place recycling must be evaluated. Based on the type of distress and objective of rehabilitation the proper hot in-place recycling procedure should be selected. Testing of the existing asphalt binder is required to evaluate the effectiveness of the chosen recycling agent. For construction guidelines, recommendations regarding mat temperature during rolling should be followed. In general, QC/QA measures for hot in-place recycling are similar to those for hot mix recycling. However, softened and scarified material should be evaluated for gradation and asphalt binder properties in hot in-place recycling. Items of interest to be checked include depth of scarification, recycled mix temperature, compacted mat density, surface smoothness, cross slope, handwork, mat depth, and mat appearance.

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CHAPTER 12. COLD-MIX ASPHALT RECYCLING - CENTRAL PLANT (CONSTRUCTION METHODS AND EQUIPMENT)

INTRODUCTION

Cold-mix asphalt recycling is defined as a process in which reclaimed asphalt pavement (RAP) materials are combined with new asphalt and/or recycling agents to produce cold base mixtures.[1] The term “cold-mix recycling” generally refers to central plant mixing and is done without application of heat. Central plant recycling is used for asphalt cold- mix recycling projects that require high rates of production or close control of the mix design.[1] Central plant recycling is used when stockpiles of RAP are available or when the existing pavement has to be removed off site for some reason and in-place recycling is not an option.

Cold-mix recycling has been used to correct pavement distress that involves both surface and base courses, although the method has been used mostly for base courses. One of the most popular methods is stabilization of cold recycled mixtures with emulsified asphalt. In addition to asphalt materials such as foamed asphalt cement, emulsion and cutbacks, the other types of additives include fly ash and portland cement.[2] Emulsified asphalts have also been used in combination with hydrated lime and portland cement. The important surface deficiencies that could be restored by cold mix recycling are reflection cracking and ride quality. The advantage of this process is that significant structural improvements can be made without altering the horizontal or vertical geometry of the pavement.[3] Roadway geometrics and structure can be improved and all crack types are fixed. Although acceptable performance has been achieved with cold central plant recycled mixes as surface courses, it is normally required that a surface treatment or a hot mix asphalt overlay be placed as a surface course. The surface course protects the recycled mix from moisture damage and abrasion by traffic. The different steps in cold-mix recycling in a central plant are shown in figure 12-1. The four main steps are: (1) removal of the existing pavement, (2) crushing and stockpiling, (3) mixing, and (4) laydown, aeration, and compaction. A wearing surface should be applied after the completion of the cold mix recycling process.

REMOVAL OF THE EXISTING PAVEMENT

The first step is to rip, scarify, pulverize or mill the existing pavement to a specified depth. The material is then hauled to a central plant, where it is crushed further, if required, stockpiled, and mixed with virgin asphalt binder and aggregate, if required, in a batch or drum-mix plant or a continuous (stabilization) plant. Removal of the existing pavement can be done in different ways.[2] However, it should be noted that recycled cold mix produced at a central plant from an existing RAP stockpile can be used for overlaying an existing pavement which does not have to be removed.

The first method is to rip the existing pavement material and load on grade. The material is then crushed and sized at the central plant. If the material is crushed entirely in the central plant, a better control can be achieved over the sizing of the RAP and reclaimed aggregates and hence oversizing can be avoided.

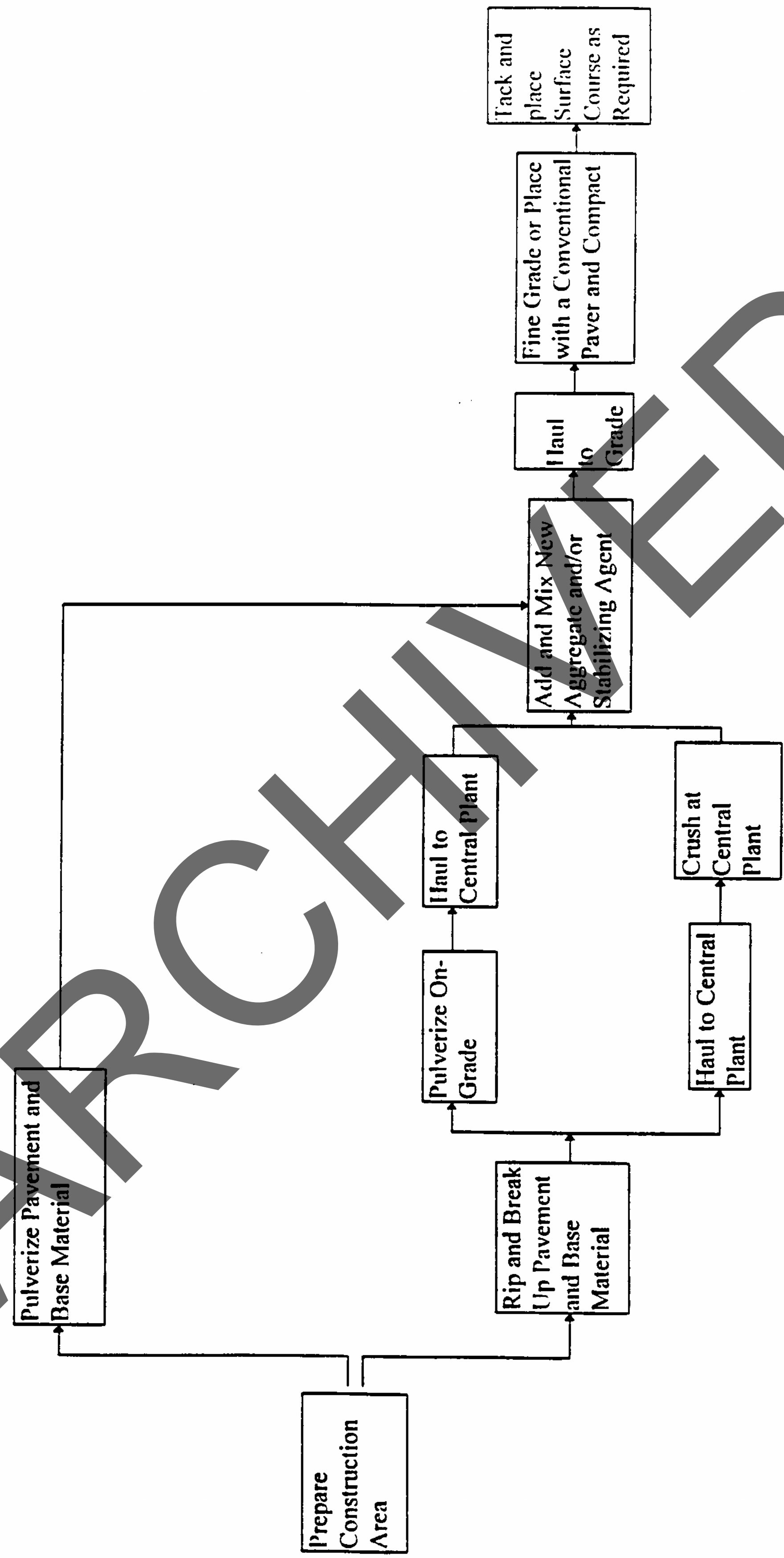

Figure 12-1. Different steps in cold mix recycling.

The second method consists of ripping, breaking, and pulverizing the in-place material before being hauled to a central plant for mixing. The important aspects of this method are that the method requires specialized equipment, considerable amount of traffic control and construction coordination efforts are needed, and since the sizing of the material is performed in-place, over sizing of RAP or reclaimed aggregate can occur.

The third option, which is very common, is to cold mill the pavement and haul the material to a central plant. This method provides a good control over the depth of pavement removal, and can achieve high production rate. However, the method may result in some aggregate oversizing.(2)

CRUSHING AND STOCKPILING

Crushing and screening plants are used to reduce the pieces of broken pavements to acceptable limits. The material is then stockpiled for immediate or future use. The height of the RAP stockpiles should be limited to prevent the crushed material from sticking together because of dead load and high temperature.(1) Construction equipments should not be permitted on the RAP stockpiles. To minimize sticking and excessive moisture in the stockpiles, the height of the stockpiles can be kept at a minimum by coordinating crushing and mixing operations.(1)

MIXING

Mixing may be done at a batch, drum, or continuous (stabilization) type of plant. A continuous type of plant is most often used for mixing.(1) Figure 12-2(1) shows the continuous type of mixing plant.

Figure 12-2. Continuous type cold-mix recycling plant.

The feed rates of the cold bins control the proportioning of the RAP and the new materials, since the screens are usually removed for cold-recycling operations in a batch plant.[3] Oversized material can be removed from individual bins by scalping screen or grizzly, and gradation of the combined materials should be checked periodically by taking samples from the belt. The plant should have the capability of accurately adding water (if needed) as well as the asphalt modifier to the recycled mix.

A twin-shaft pugmill is usually employed for mixing in a batch plant. Sized reclaimed asphalt pavement material, virgin aggregate, asphalt binder, and water, if needed, are proportioned by weight and fed into the pugmill. The batch is mixed and discharged into the haul truck before mixing another batch.[1]

Correct proportions of materials are maintained automatically by interlocked devices in a continuous mixing plant.[1] A positive displacement asphalt metering pump controls the automatic feeders, which in turn, measure and govern the flow of materials. Temperature corrections are needed to compensate for the volumetric changes in the materials. Some of these plants are now equipped with a belt scale to add asphalt emulsion and mixing water by weight. Also, sometimes the plant has a screening/crushing unit between the cold feed bins and pugmill to reduce oversized material from the stockpile. The plant may also have a storage silo or bin for the recycled mix which allows for a more continuous plant operation and facilitates truck loading. Emulsified asphalt mixes require shorter mixing time than HMA. There is a tendency to overmix emulsified asphalt base mixtures, resulting in scrubbing the emulsified asphalt from the coarse aggregate particles, and premature breaking of the emulsified asphalt, causing overly-stiff mixtures.[1] Undermixing can cause insufficient coating of the aggregates. The mixing time can be controlled in a continuous pugmill plant by changing the arrangement of the paddles, by varying the height of the end gate, or by changing the location of the asphalt spray bar. With a drum mix plant, mixing time is varied by varying the slope of the drum or by changing the location of the asphalt inlet pipe within the drum.

One hundred percent of coating of the coarse aggregate is not always achieved in the mixing plant, and it is not necessary to have 100 percent coating at the time of mixing.[1] Further coating takes place during spreading and rolling of the mix. Difficulty in coating particular types of aggregates should be evident in the mix design stage, and the mixing procedure should be adjusted to produce uniform dispersion of the emulsified asphalt with a complete coating of the finer aggregate fractions.[1]

LAYDOWN, AERATION AND COMPACTION

Aeration of the recycled mix is required to reduce the water and volatile content of the mix. The laydown and spreading equipment used for cold recycled materials is generally the same as for conventional hot mix asphalt.[2] The material can be placed in a windrow after mixing, after which it can be leveled to proper cross slope with a motor grader. The motor grader can also be used to aerate the mix by blading the mix back and forth across the roadway. This aeration process helps in reducing the fluid content of the mix so that it becomes stable enough to support the weight of the compaction roller. The rate of volatile loss is controlled primarily by the type of asphalt modifier, mix water content, gradation of the aggregate, wind velocity, ambient temperature, and humidity.

If the process of aeration can be avoided by accurately controlling the mixing moisture or due to climatic conditions the water evaporates without further manipulation of the mix, then conventional self-propelled pavers can be used to place the recycled asphalt cold-mix.[1] Towed types and Jersey spreaders attached to the front end of crawlers or rubber-tired tractors can also be used. Sufficient amount of fluid must be present in the mix to avoid tearing beneath the screed or strike-off bar. The screed should not be heated to avoid such a problem, as it makes the mix less workable by accelerating the drying process.[1] If the mix is too dry, the moisture content should be increased. The mixture should be placed uniformly over the pavement, beginning at the point farthest from the mixing plant. Hauling over freshly placed material should not be allowed except when required for completion of the work.

Dense-graded cold mixes should be placed in compacted thickness of 75 mm (3 in) or less, if practical, and with multiple lifts, some curing time should be allowed between successive lifts (two to five days under good curing conditions).[1] Open-graded cold recycled mixes can be placed up to thickness of about 100 mm (4 in). Construction should not continue during rainfall, or begin when rain is expected. The emulsified asphalt base should not be placed if the ambient temperature is below 10°C (50°F).[1]

Compaction can be done with static steel-wheel, pneumatic-tired and vibratory rollers, and combination of two or all three. Figure 12-3[2] shows a steel-wheel and a pneumatic-tired roller in combination for compacting cold recycled mixes. Very heavy pneumatic-tired rollers of 23 metric tons (25 short tons) or more are preferred for initial compaction (breakdown rolling) especially for thick lifts of 75 mm or more. Vibratory rollers are regularly used with the vibration normally at high frequency and a low amplitude. The factors controlling the number of passes required for compaction are properties of the mix, lift thickness, type and weight of roller, and environmental conditions.[4] Cold recycled mixes tend to be “fluffy” and therefore uncompacted thicknesses should be increased to achieve desired compacted thickness.[5,6] The moisture content is very critical to compaction of the mix. Sufficient moisture lubricates the particles and helps in compaction, whereas excess moisture causes low density and moisture retention in the sealed layers. After laydown, if it is found that additional curing is needed due to excessive moisture, then compaction should be postponed unless traffic disruption is a major problem.[2]

Usually a wearing course, in the form of HMA overlay or a double surface treatment is applied over the cold recycled asphalt base. The application of the overlay should be delayed for sufficient time if the mix needs additional curing to avoid moisture retention and loss of stability. During this delay, ideally, traffic should not be allowed on the surface. However, it is not always practical to delay the opening of traffic. Fog seal should be used if raveling becomes a problem.

SUMMARY

Cold-mix recycling is performed by combining reclaimed asphalt pavement (RAP) materials with virgin asphalt and aggregate (if required) in a central mixing plant without the application of heat. Usually, this process is done for base course, and the asphalt cement is in emulsified form. This process can be used to rectify all types of cracks except fatigue cracks and those caused by base failures.

Figure 12-3. Steel and pneumatic - tired roller for compaction.

It can improve ride quality without altering the geometry of the pavement. It can be used to lower pavement profile by milling or removing a greater depth of pavement than that required for recycling. This allows pavement widening. The steps involved in the process consist of removal of the pavement to a specified depth, ripping in-place if desired, hauling the material to a central plant and further reduction in size by crushing, mixing with virgin materials, laydown, spreading, and compaction. Conventional pavers can be used for spreading cold recycled mix. However, the mix may require aeration before compaction to reduce the excess fluid content by evaporation. The moisture content of the mix must be carefully monitored during production to prevent excessive moisture which can cause stability problem, or insufficient moisture which can reduce workability. Although cold central plant recycled mixes can produce stable surfaces, a wearing surface over the recycled mix is normally required.

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CHAPTER 13. COLD IN-PLACE RECYCLING (CONSTRUCTION METHODS AND EQUIPMENT)

INTRODUCTION

Cold In-place Recycling (CIR) is defined as a rehabilitation technique in which the existing pavement materials are reused in place.(1) The materials are mixed in-place without the application of heat. The reclaimed asphalt pavement (RAP) material is obtained by milling, planing, or crushing the existing pavement. Virgin aggregate or recycling agent or both are added to the RAP material which is then laid and compacted.(2) The use of cold in-place recycling can restore old pavement to the desired profile, eliminate existing wheel ruts, restore the crown and cross slope, and eliminate pothole, irregularities and rough areas. It can also eliminate transverse, reflective, and longitudinal cracks.(3) Some of the major reasons for the increased use of cold in-place recycling are the increased scarcity of materials, particularly gravel and crushed rock, the method's high production rate and potential of cost savings, minimum traffic disruption, ability to retain original profile, reduction of environmental concerns, and a growing concern for depleting petroleum reserves.(2) Cold in-place recycling is more suitable than cold central plant recycling particularly for secondary low-volume roads that are located at a considerable distance from a central plant.(4) CIR does not involve hauling RAP to the central plant and then hauling the cold recycled mix back to the job site.

Cold in-place recycling can be performed in two ways: full depth and partial depth. In full depth recycling (reclamation or stabilization), both bound (asphalt) and portions of unbound (subbase, base) layers are crushed, mixed with binder, and placed as a stabilized base course. In partial depth recycling, a portion of the bound layer (asphalt), normally between 50 and 100 mm (2 and 4 in) is used to produce a base course for generally low-to-medium traffic volume highways.(5) With the improvement in cold milling techniques, full depth recycling can now be used to include a substantial portion of underlying unbound materials. As a result, the Asphalt Recycling and Reclaiming Association (ARRA) defines cold in-place recycling as a partial depth recycling (process involving 75 to 100 mm (3 to 4 in)) of the existing pavement and defines full depth recycling as full depth reclamation which is considered a separate procedure.(1) To follow the ARRA guidelines, this chapter presents cold in-place recycling as a partial depth recycling method only. The full depth recycling method is described in chapter 16 under Full Depth Reclamation.

The steps in cold in-place recycling consist of preparation of construction area, milling the existing pavement, addition of recycling agent and virgin materials, laydown, compaction, and placement of surface course. A flow chart for the method is shown in figure 13-1.(5) The addition of new aggregates may not be necessary in some projects. At present two different methods are used for cold in-place recycling. The methods are: single machine and the single-pass equipment train. These two methods are discussed below.

Single Machine

The single machine or single-pass equipment is capable of breaking, pulverizing, and adding

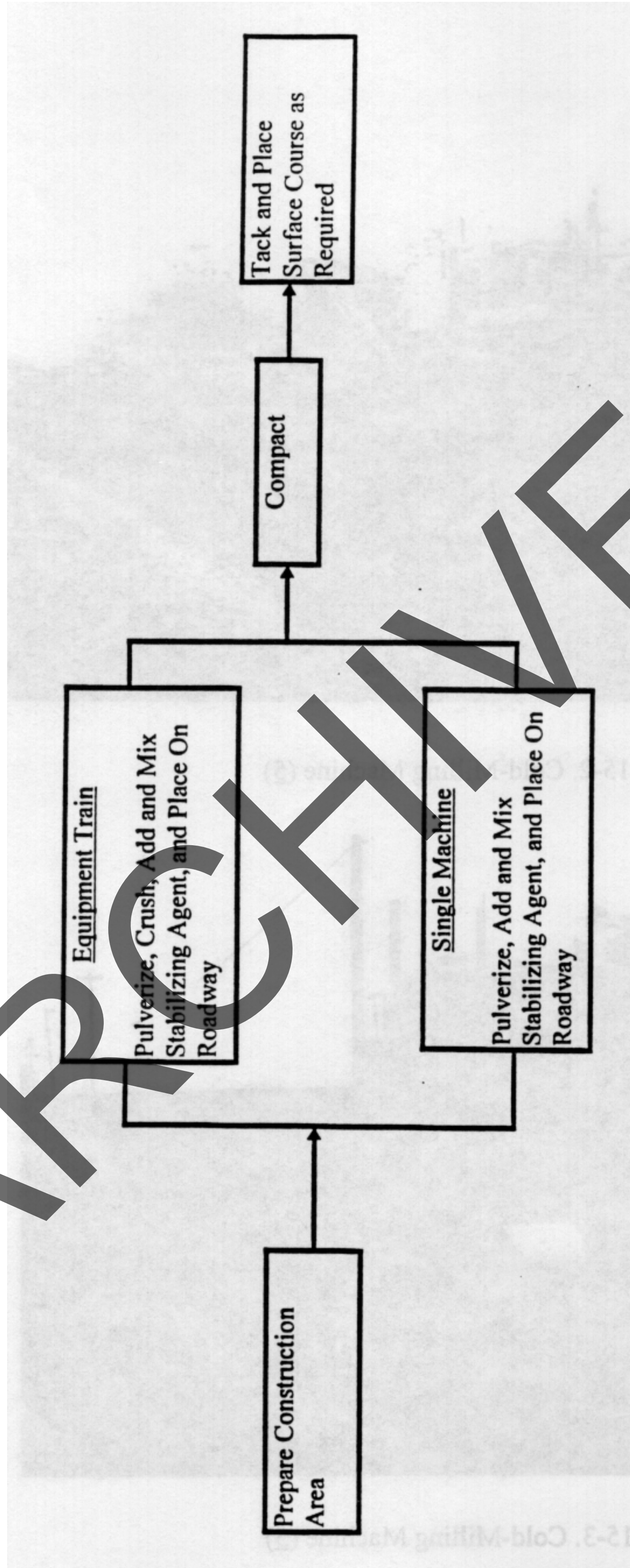

Figure 13-1. Steps in partial depth cold in-place recycling.

recycling agents in a single pass. Some examples of single machine are shown in figures 13-2, 13-3, 13-4, and 13-5.[5] Figure 13-2 shows a single machine which basically consists of a paver mixer. RAP is added to the machine either by cold milling (by a milling machine) or by a dump truck. Virgin material, if required, is spread on existing surface ahead of the recycling equipment. One pass of this machine is sufficient to mill, pulverize, add recycling agent and lay down. The recycling agent is added in the milling chamber of the paver mixer.

Figure 13-3 shows a single machine which mills, injects emulsion, mixes, and lays down with screed. This type of machine is used together with a tanker which supplies the recycling agent to the single machine. In this machine, the recycling agent or emulsion is added on the milled material and the milled material is mixed, and finally precompacted with screed.

In another type of single machine (figure 13-4), the existing material is milled, mixed with recycling agent, and deposited in a windrow. The recycled material is picked up by a paver which lays it down and precompacts it with a screed. An emulsion tanker is used with this type of machine.

Figure 13-5 shows a schematic of the equipment which is used if virgin aggregate is needed to modify the existing material. A truck with virgin aggregate is positioned in between the cold milling machine and the single machine. In this case the emulsion tanker generally follows the single machine. The single machine injects recycling agent on the mixed virgin aggregate and existing material, spreads the recycled mix, and precompacts with a screed.

The advantages of a single machine are high production capacity and simplicity of operation. It is also suitable for urban areas due to its short length. However, depth limitation and RAP aggregate oversize are the main disadvantages of this method.

Single-Pass Equipment Train

The single-pass equipment train consist of a series of equipment, each capable of a particular operation. The usual components are a cold milling machine, portable crusher, travel-plant mixer, and laydown machine. A schematic of the train is shown in figure 13-6. The different machines are shown in figures 13-7 through 13-10.[5] The crushing and screening unit crushes and screens the oversized material from the milling machine, and deposits the processed material into a pugmill, where the recycling agent is added. After mixing, the material is either deposited onto the hopper of a self-propelled laydown machine, or deposited in windrow. If the mix is placed on a windrow, it is then picked up by a paver for laydown. Figure 13-11 shows a recycling train in action, along with condition of the road before and after recycling.

Field Adjustments to Mix Design

The optimum moisture and emulsion contents from the laboratory-mix design are recommended as a starting point in the field, subject to necessary adjustments by persons experienced in cold recycling. First, the coating of the recycled mix is examined after the surface dries. If the coating is not satisfactory (less than 75 percent), the moisture content is adjusted before the emulsion content. If the mix lacks cohesion in spite of an adequate coating, the emulsion content is increased. A crude test for evaluating cohesion has been used. A ball of the recycled mix is made

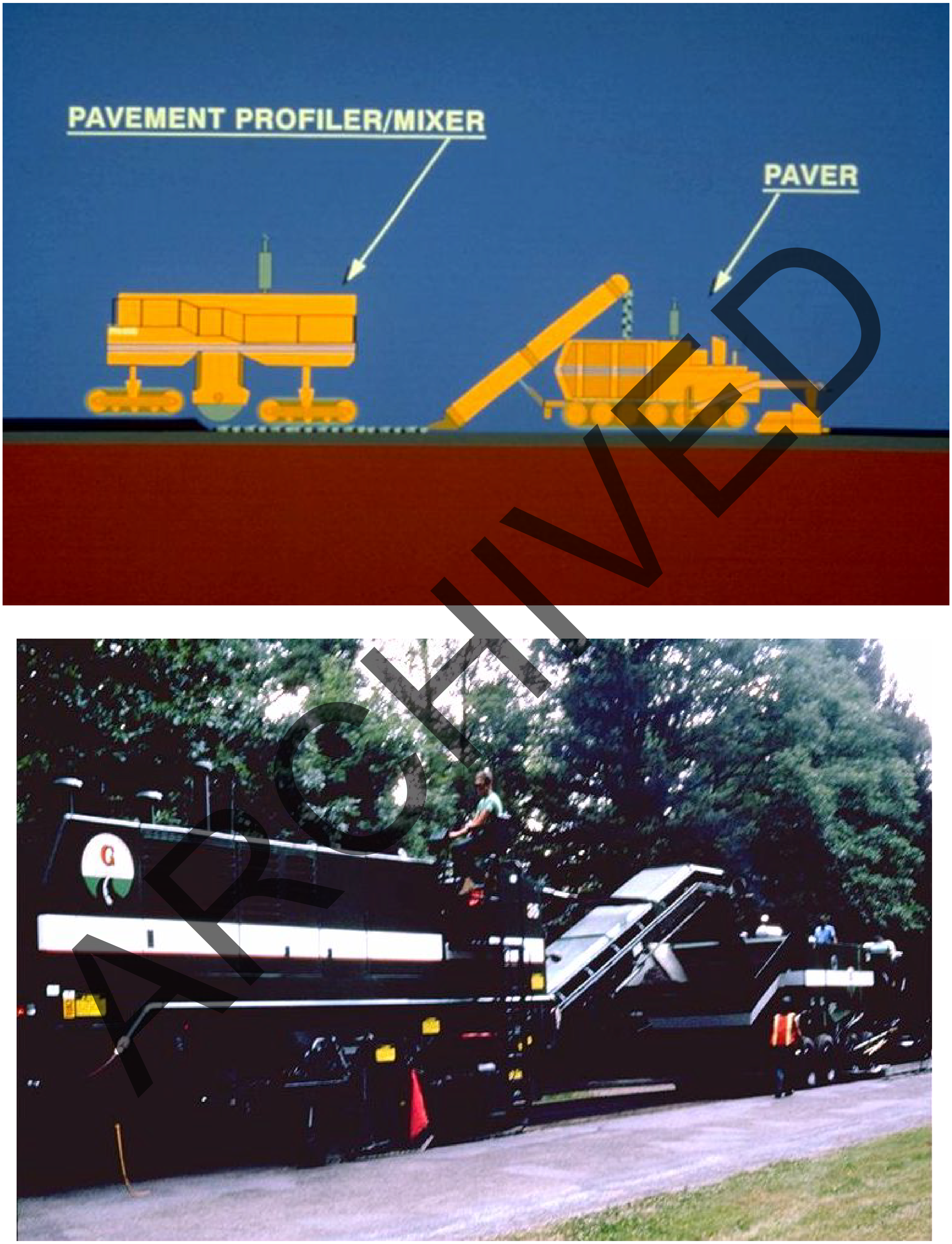

Figure 13-2. Single machine.

Figure 13-3. Single machine.

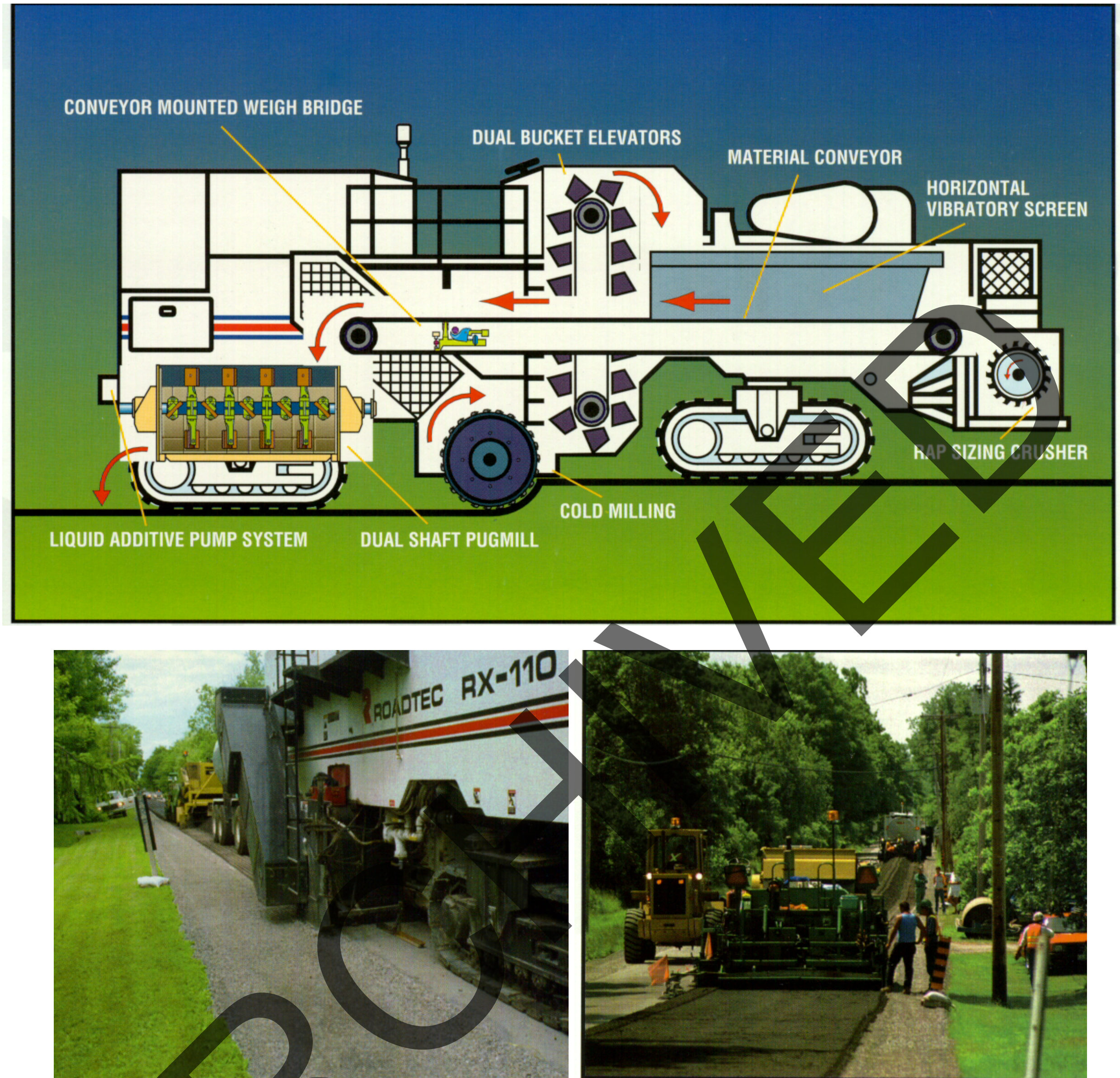

Figure 13-4. Single machine.

by squeezing it in the palm of one’s hand. If the ball falls apart (friable) after the pressure is released, the mix lacks cohesion. The palm of one’s hand should also be examined for stains. If specks of asphalt are present, the emulsion content is generally adequate. A palm that is almost completely stained by asphalt indicates an excessive emulsion content. Rational field test methods for QC/QA are being developed.

Curing and Application of Wearing Surface

For a detailed discussion on this, the reader should refer to section on this topic in chapter 12.

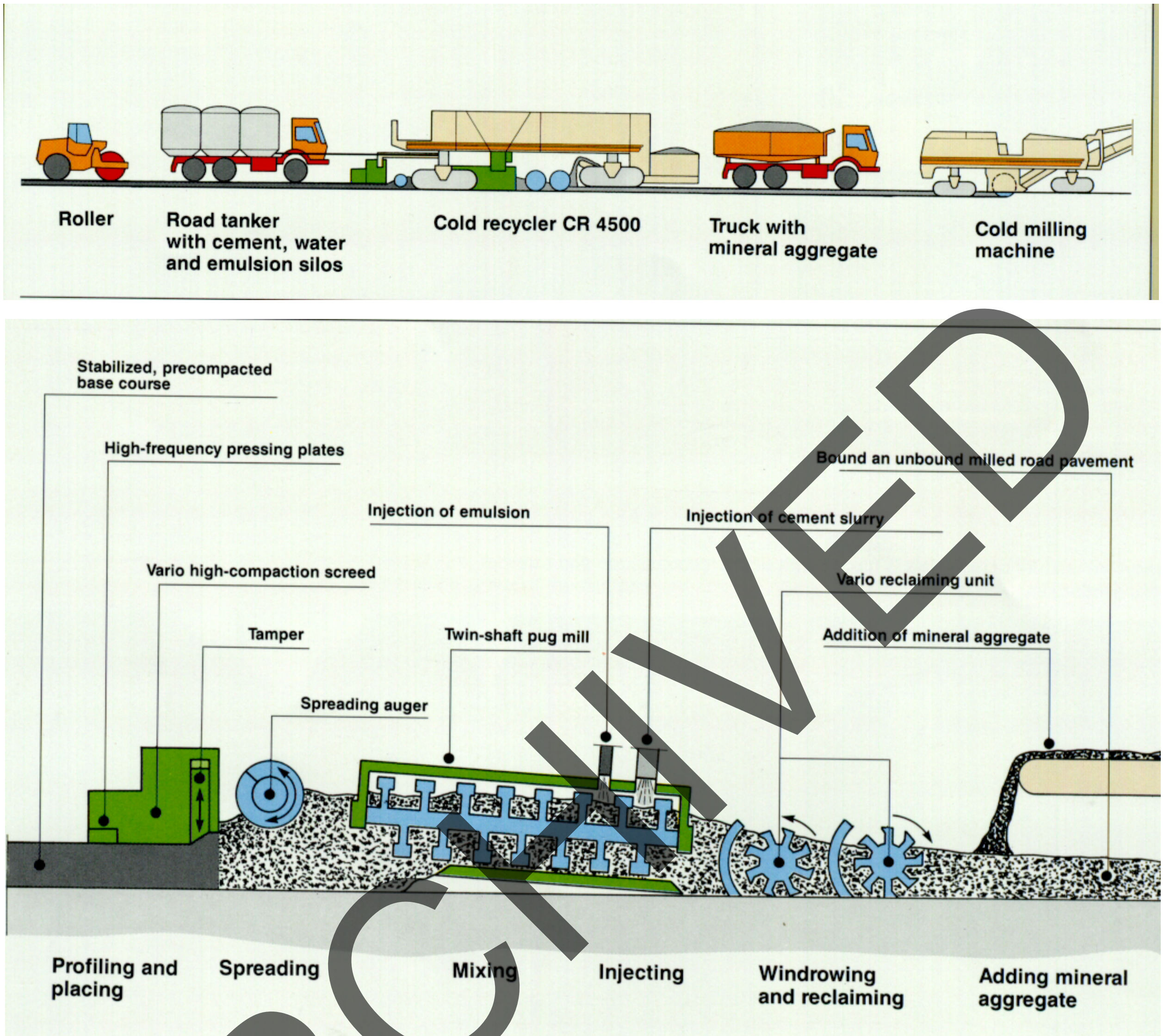

Figure 13-5. Single machine.

SUMMARY

In the cold mix in-place recycling process, existing in-place materials are mixed with recycling agents and/or new or reclaimed materials without the application of heat. The method can be used to eliminate a variety of distresses such as rutting, cracks, and irregularities while maintaining the original profile and with a minimum traffic disruption.

The process can be carried out by using a single machine for milling, mixing, and laydown, or by a train of specialized machines for different steps including milling, crushing, screening of the RAP, and mixing. The moisture content of the recycled mix must be carefully monitored to prevent excessive moisture which can cause stability problem, or insufficient moisture which can affect mixing and reduce workability. The mix may require aeration before compaction to reduce the excess fluid content by evaporation. Although cold in-place recycled mix produces a stable

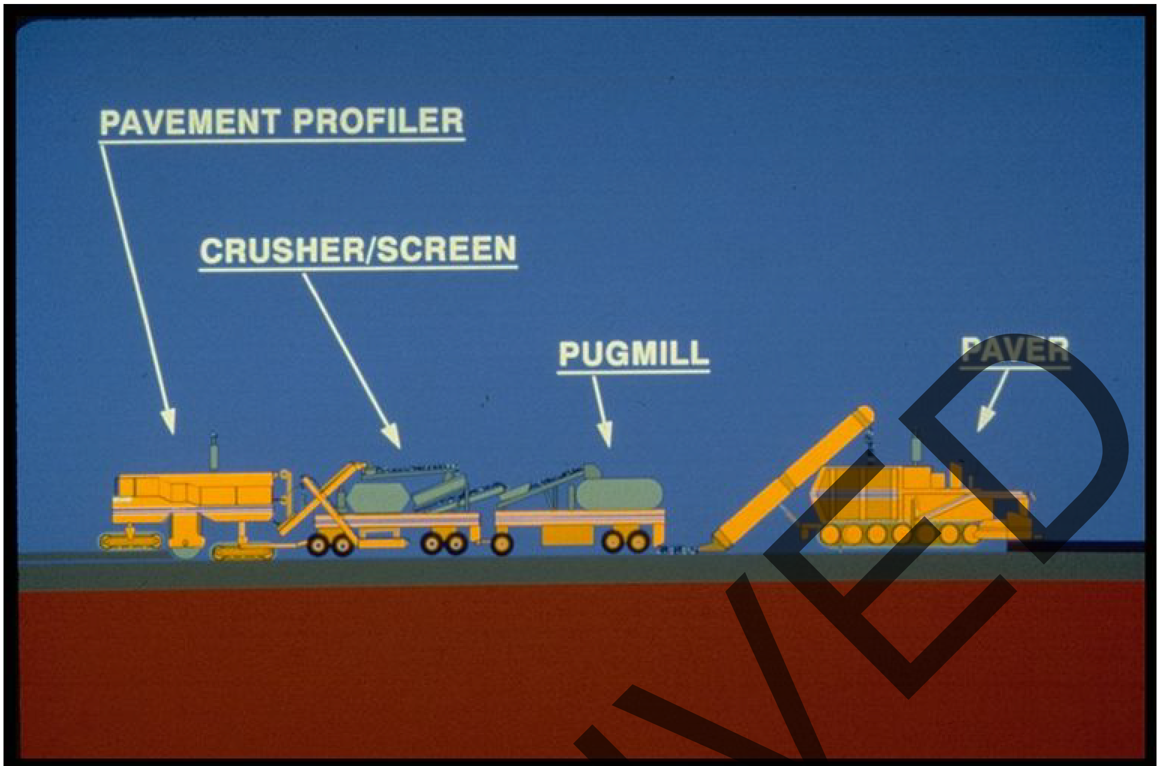

Figure 13-6. Schematic of recycling train.

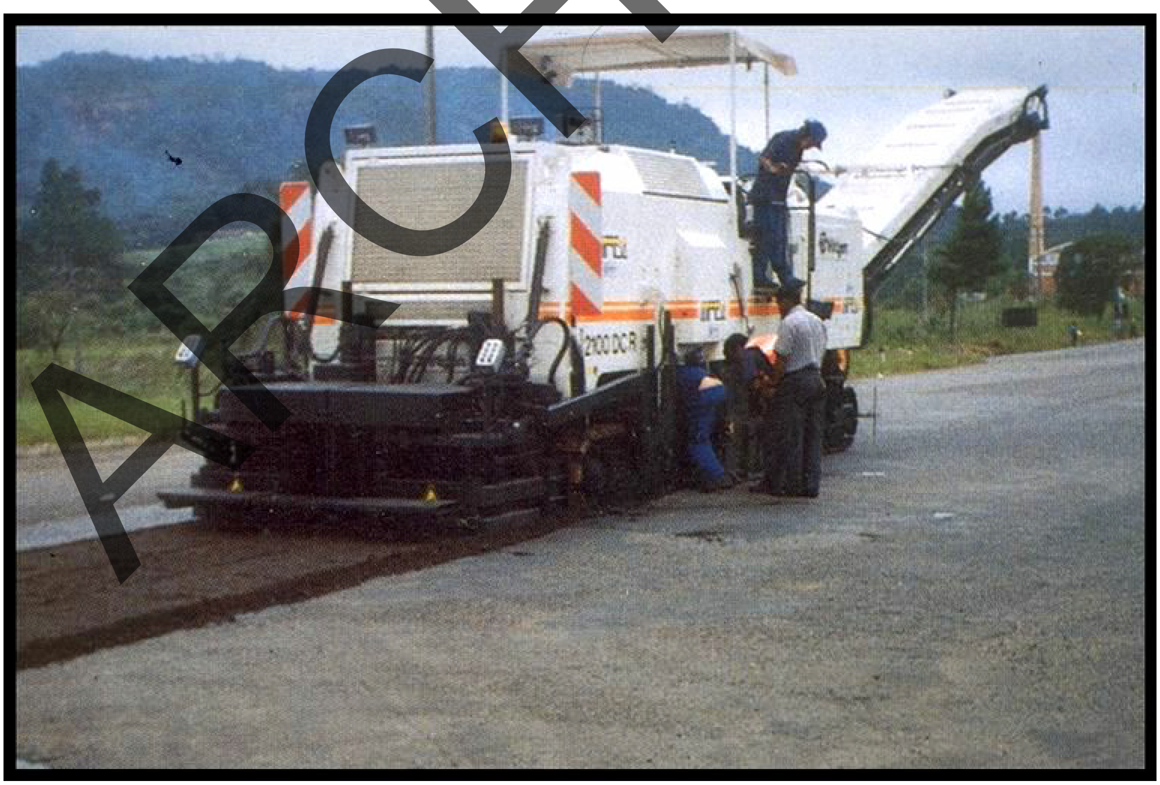

Figure 13-7 Cold-milling machine.

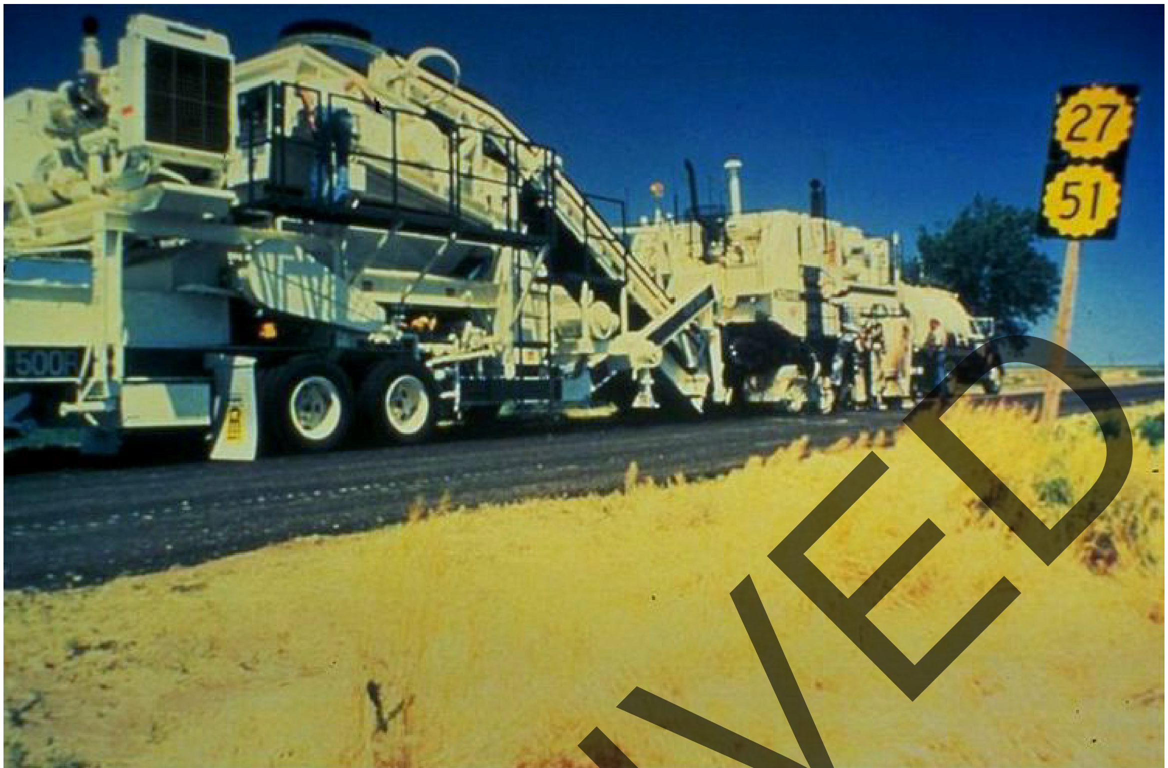

Figure 13-8. Portable crusher attached to cold-milling machine.

Figure 13-9. Travel-plant mixer.

Figure 13-10. Laydown machine.

Figure 13-11. Single-pass equipment train CIR.

surface, a wearing surface consisting of hot mix asphalt or seal coat is normally required because the recycled surface is not adequately resistant to abrasion by traffic and moisture intrusion.

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CHAPTER 14. COLD-MIX ASPHALT RECYCLING (MATERIAL AND MIX DESIGN)

INTRODUCTION

The main purpose of recycling is to reuse existing pavement material for rehabilitation of pavements. The most important advantages of recycling are conservation of resources and money. Cold-mix recycling is one of the various recycling methods available today. Cold-mix recycling can result in a stable pavement at a total expenditure of 40 to 50 percent less than that required by conventional construction methods.[(1)] However, like conventional hot mix asphalt, cold-mix asphalt used for recycling must be designed properly to ensure reliable performance. The unique features of cold recycled mixes are time temperature effects (curing) due to the presence of the water and/or volatiles and the slower binder softening rate.[(2)] Hence, proper considerations should be given to changes in mixture properties with time and target reduction of aged binder consistency in the mix design.[(3)]

A standard national method for designing cold recycled mixes is not available. However, certain basic steps, as shown in the flow chart in figure 14-1,[(4)] are included in most mix design procedures used by highway agencies. The first step in mix design is material evaluation. The material evaluation step includes field sampling, determination of aged mix composition, and properties of aged asphalt binder and aggregates. One of the important purposes for this step is to identify the deficiencies of the aged mix and determine the need for virgin material(s). The mix design procedure consists of selection of the recycling agent and the determination of the optimum binder content. These steps are discussed in the following paragraphs.

MATERIAL EVALUATION

The material evaluation phase basically consists of sampling and testing of materials. Material from the existing pavement must be sampled in a systematic way to obtain representative samples. The important properties of the reclaimed asphalt pavement (RAP), which could affect performance of the recycled mix should be determined to ensure proper selection of new asphalt binder and virgin aggregates, if required.

Field Sampling

To obtain representative samples from each of the different sections of the existing pavement, sections of pavements with differences in pavement cross section and material composition should be delineated and treated as different units. A visual inspection and a review of construction and maintenance records can be used for this purpose. The locations for sampling from each of the unit should then be determined by the random sampling technique.[(4)]

At least five or six locations for sampling have been suggested by some researchers,[(5)] whereas others[(4)] suggest a minimum of five samples per kilometer or one per block in city work. One sample per lane mile for larger jobs (length greater than 6.4 km, 4 mile) with a minimum of six per project has been recommenced.[(6)] Generally, core samples are obtained. The thickness of

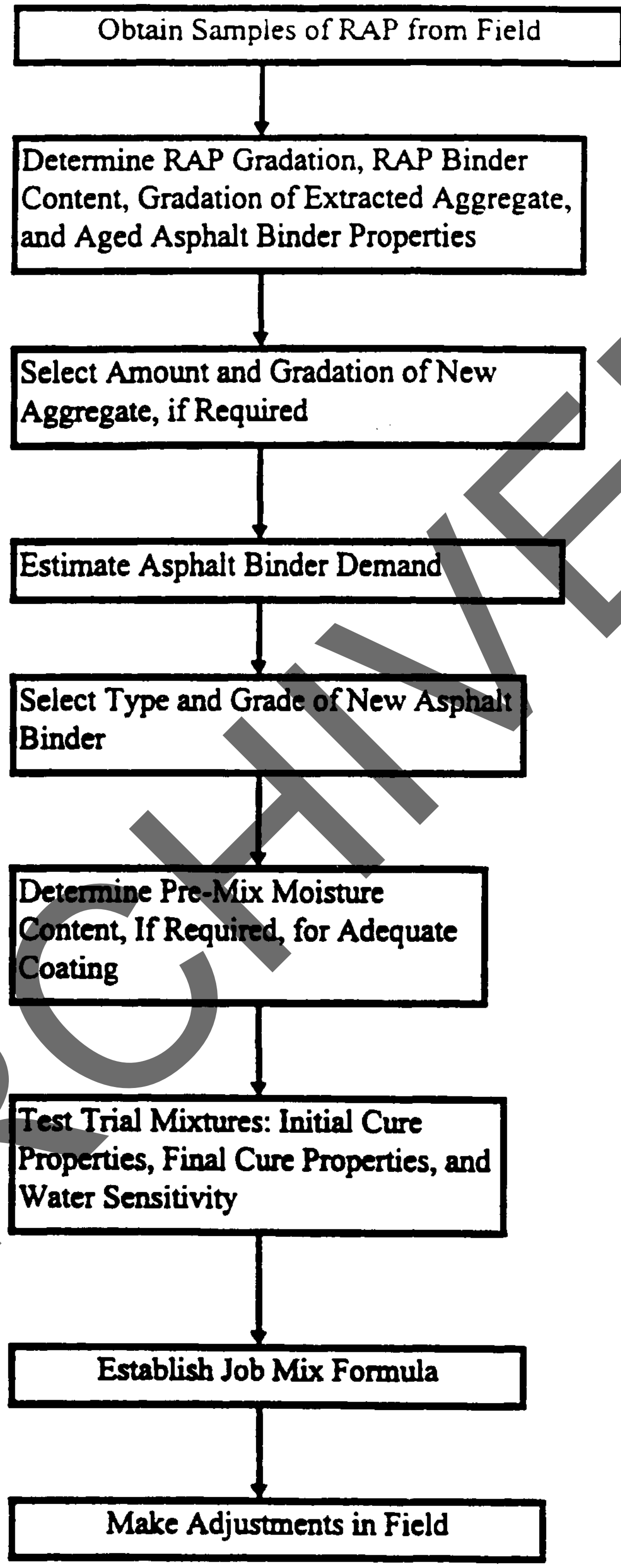

Figure 14-1. Flow chart for mix design of cold recycled mixes.

all layers in the cores should be recorded. Since the process of milling can produce more fines than the process of coring and also gives realistic samples, it is desirable to obtain field samples by the equipment proposed to be used to remove and size the reclaimed material. In this way a more representative sampling can be obtained.(2) However, this is not always possible since the use of full lane milling can generate a substantial amount of milling. This requires a substantial amount of patching material also. Hence, sampling by core or a small milling machine (30 to 45.7 cm, 12-18 in) is normally used. Quite often, cores are obtained, which are sawed-off at the desired depth of cold recycling and crushed in a laboratory jaw crusher to produce RAP for evaluation and mix design. In some states, cone penetration test is conducted at the bottom of core hole to determine the strength of the subgrade. If the subgrade is found to be weak and unstable, cold recycling may not be performed. In such a situation it is very difficult to operate the cold milling machine, which can cut through the subgrade and get stuck. Again, the importance of obtaining realistic field samples by milling cannot be overemphasized.

RAP Mix Composition

The milled RAP material must be subjected to sieve analysis using AASHTO T 27 Sieve Analysis of Fine and Coarse Aggregates. Generally, the RAP particles are treated like "black rock" or aggregates in cold-recycled mix design. AASHTO T 164-93, Quantitative Extraction of Bitumen From Bituminous Paving Mixtures, is used to determine the asphalt binder content of the RAP. For mixes that were originally made from cutback asphalts or emulsified asphalts containing solvents, a determination of "residual asphalt" can be obtained, if required, by heating the samples before extraction for about 3 hours at 120°C (248°F).(4) The aggregate extracted by AASHTO T 164-93 is subjected to sieve analysis to determine its gradation using AASHTO T 27-93, Sieve Analysis of Extracted Aggregate. The National Center for Asphalt Technology (NCAT)'s ignition test method (AASHTO TP 53-95) can also be used to determine RAP's binder content and gradation if the aged asphalt binder is not recovered for further testing, and the RAP does not contain cutback asphalt.

Properties of Aged Asphalt Binder

Aged asphalt binder should be recovered from the RAP using AASHTO T 170, Recovery of Asphalt from Solution Using Abson Method. However, the recently developed Rotovap procedure (AASHTO TP 2-94) of asphalt binder recovery (recommended by SHRP) is preferred to Abson Recovery. The recovered asphalt binder should be tested at least for penetration at 25°C (77°F) (AASHTO T 49), and absolute viscosity at 60°C (140°F) (AASHTO T 202). The evaluation of these consistency test data is helpful in selecting a proper recycling agent for cold recycled mixes. It is anticipated that Superpave binder test properties such as $G^*/\sin\delta$ (rutting factor) will be measured in the future.

New Aggregate

New aggregates may be required to satisfy the gradation requirement or structural improvement of the recycled mix.(7) Gradation of the RAP (as received from milling or crushed from cores) may not meet the specification requirements for the intended recycled course such as base course and binder course. The RAP gradation is affected by the fines generated due to milling and pulverization, or contamination from the underlying layers or due to degradation by traffic. In some cases, RAP may consist of sand-asphalt mix. In such cases, the recycled mix gradation can be made coarse by adding new aggregate.

Additional aggregate may also be needed to increase the structural capacity of the pavement by increasing its thickness. This may be required by increased traffic loading. New aggregate may also be needed to improve recycled mix properties such as stability, durability, or workability.

The gradation of the selected new aggregates should be determined by sieve analysis AASHTO T 27-93). The new aggregate and the RAP material must be combined in proportions to meet the specified gradation.

MIX DESIGN PROCEDURES

Although no universally accepted mix design procedure for cold-mix recycling is available at present, guidelines have been developed by several agencies, based on laboratory tests, empirical formulas or past experience with identical projects. The following is a general discussion of various steps involved in cold-recycled mix design. This will be followed by specific mix design procedures used by some highway agencies.

Selection of Recycling Agent

The types of recycling agents used include emulsified recycling agents, softer grade of asphalt cements (such as grades AC-2.5, and AC-5 asphalt cement), and cutback asphalts.(2) The relevant specifications for asphalt cement for cold-mix recycling are AASHTO M226 (ASTM D 3381), and AASHTO M20 (ASTM D 946). The most commonly used recycling agent for completely cold recycling processes are emulsified asphalt cements (AASHTO T 59-93) or emulsified recycling agents (ASTM D 5505). This is because the emulsions are liquid at ambient temperatures, have the capacity for being dispersed throughout the mix, and does not cause major air pollution problems.(2) Cement, fly ash, lime or other chemical stabilizers have been used in combination with asphalt emulsions. Softer grades of asphalt cement and cutback asphalts are used very rarely. Foamed asphalt cements have been used and are more effective in terms of dispersion than asphalt cements.

The choice of recycling agent depends on the time and temperature dependent interaction between the recycling agent and the aged asphalt. At ambient temperature, the softening effect of the recycling agent is a time and temperature dependent physico-chemical process.(2) The rate at which the reaction between the recycling agent and the aged asphalt occurs is a function of the properties of the recycling agent and the aged asphalt cement, and the mechanical effects of the physical processes such as mixing, compaction, traffic and climatic conditions. When using viscosity or penetration based nomograph for determining the amount of asphalt binder needed to achieve target viscosity, consideration should be give to the fact that the reaction between the recycling agent and the asphalt cement does not take place throughout the mix at the same time, but rather starts at the interface of the recycling agent and the aged asphalt cement media. Another important consideration is that the properties of the mix, such as stability, change with the loss in moisture or volatile content. Hence, it is more important to determine the mechanical properties of the recycled mix with the emulsion before and after curing than to simply determine the consistency of the blend.(8)

The selection of recycling agent primarily depends on the asphalt demand and the reduction in viscosity of the aged asphalt cement. The relative contributions of the recycling agent and the aged asphalt binder are not fully understood at this time. One theory is that, instead of acting as an binder, the aged asphalt may largely act as part of the aggregate. In such a case there will be an effective asphalt content, consisting part of the aged asphalt and the new asphalt binder or recycling agent. This effective asphalt content will then govern the ultimate performance of the mix, rather than the total asphalt content.[9] Therefore, the testing of recycled mix for mechanical properties appears a better approach for selecting the type and amount of recycling agent.

Field coating test, as given in AASHTO T 59 (Standard Methods of Testing Emulsified Asphalts) has also been suggested for determining whether anionic or cationic emulsified asphalt is more compatible with the RAP and new aggregate. It has been recommended[4] that for determining the type and amount of recycling agent, first consideration should be given to the type and grade performing satisfactorily on local projects with aggregate gradations and traffic conditions similar to those on the project under study. Proper judgement should be used in selecting the type and grade of the recycling agent, and the decision should consider the usage of the completed pavement, environmental conditions at the pavement location, type of equipment available, and construction operations. The major consideration should be the properties of the new asphalt binder including its consistency, and curing or setting rate.

Asphalt Cements

The viscosity of various asphalts cements at the ambient temperature should be considered to ensure workability of the recycled mix. A higher viscosity can be used if the recycled mix contains a relatively low percentage of material passing the 75 µm (No. 200) sieve, but if the mix contains a high proportion of fines, it is better to use an asphalt cement of low to medium viscosity (such as AC-2.5) to ensure effective mixing. As mentioned earlier, asphalt cements are rarely used in cold recycling because of inadequate coating problems. Foamed asphalt cements have been used successfully.

Emulsified Asphalts

Laboratory evaluation of the RAP (plus aggregate if used) and emulsified asphalt is the best way to determine its suitability as a recycling agent. Different types and quantities of emulsified asphalt should be tried with the RAP to find the best combination for the intended use. The type and grade of the emulsified asphalt is selected after the material gradation (RAP + new aggregate) is determined. A guideline for choosing type and grade of emulsified asphalt is shown in table 14-1.[4] The medium-setting (MS) emulsions are designed for mixing with open- or coarse-graded aggregate. Mixes using these emulsions remain workable for an extended period of time since these grades do not break immediately upon contact with aggregate. High float medium-setting asphalt emulsions may give better aggregate coating and asphalt retention under extreme temperature conditions. They may be used with coarse- or dense-graded aggregates.

The slow-setting (SS) emulsions are designed for maximum mixing stability. They are used with dense-graded aggregate or aggregate with high fines content. All slow-setting grades have low viscosities that can be further reduced by adding water.

Table 14-1. Guideline for choosing emulsified asphalt.[4]

Type of Cold-Mix Recycling	Gradings (See Table 14-2)	AASHTO M140 ASTM D 977 (Anionic)					AASHTO M208 ASTM D 2397 (Cationic)			
		MS-2, HFMS-2	MS-2h, HFMS-2h	HFMS-2s	SS-1	SS-1h	CMS-2	CMS-2h	CSS-1	CSS-1h
Plant Mix:										
Open-graded aggregate	A,B,C	X	X				X	X		
Dense-graded aggregate	D			X	X	X			X	X
Sand	E,F			X	X	X			X	X
Mixed-in-place:										
Open-graded aggregate	A,B,C	X	X				X	X		
Dense-graded aggregate	D			X	X	X			X	X
Sand	E,F			X	X	X			X	X
Sandy soil	G			X	X	X			X	X

Note:

Only standard grades of emulsified asphalt have been listed. For certain aggregate or climatic conditions other types might be appropriate. In such cases the emulsion supplier should be consulted.

It has been suggested that a medium-setting emulsion with solvent (cationic or anionic) should be used if the penetration of the recovered asphalt binder in the RAP is less than 30, while a slow-setting emulsion should be used if the penetration of the recovered asphalt binder is greater than 30. Similarly, some agencies (such as Pennsylvania DOT) use hard residue emulsified asphalts (such as CMS-2h, HFMS-2h, and CSS-1h) when the recovered asphalt binder is soft (penetration more than 30).

Proprietary emulsified recycling agents, which are derived from the hot mix recycling agents, may be more effective in softening aged asphalt if adequately dispersed and mixed, since they contain recycling agents binders specifically designed to restore aged asphalt binders to their original properties.[2] A low quantity of recycling agent can be used to soften the aged binder without increasing the binder content, if 100 percent RAP is used. However, it may be very difficult to disperse the recycling agent if too small a quantity is used. Depending upon the amount and characteristics of the RAP in the recycled mix, a combination of recycling agent and emulsified asphalt can also be used.[2]

Some agencies (such as New Mexico State Highway Department) have used high float, polymer-modified emulsified asphalts to reduce thermal cracking, resist rutting, and provide improved early strength.

Table 14-2. Gradation guidelines for cold-mix recycling for combination of aggregate from RAP and virgin aggregate.[4]

Sieve Size	Percent Passing by Weight						
	Open-Graded			Dense-Graded			
	A	B	C	D	E	F	G
38.1 mm (1½ in.)	100			100			
25.0 mm (1 in.)	95-100	100		80-100			
19.0 mm (¾ in.)		90-100					
12.5 mm (½ in.)	25-60		100		100	100	100
9.5 mm (⅜ in.)		20-55	85-100				
4.75 mm (No. 4)	0-10	0-10		25-85	75-100	75-	75-100
2.36 mm (No. 8)	0-5	0-5				100	
1.18 mm (No. 16)			0-5				
300 µm (No. 50)							
150 µm (No. 100)						15-	15-65
75 µm (No. 200)	0-2	0-2	0-2	3-15	0-12	30	12-20
						5-12	

The ideal recycling agent should possess the following characteristics: (a) facilitate good mixing and coating, (b) should be free of solvent so that atmospheric curing is not needed, and (c) should set fast so that the roadway can be opened to traffic soon.

In the cold-mix recycling process, water may be required to facilitate coating and compaction. The water may be present as natural moisture in the RAP or aggregate, or may be added before addition of the recycling agent, or as a component of the recycling agent (such as diluted slow-setting emulsified asphalt). For mixing with an asphalt cement, it is essential that the moisture content of the material to be recycled should be 4-6 percent to cause the hot asphalt cement to foam and thereby serve as an aid to coating.[4] For asphalt emulsion, the compatibility of water with the emulsion should be checked, since water from all sources may not be compatible to the emulsion. If any adverse effect (such as premature breaking) on the emulsified asphalt is noted, a new source of water should be found. Generally, the slow-setting emulsified asphalts and the anionic grades of medium setting emulsified asphalts require moisture for mixing.[4] The HFMS grades (particularly the HFMS-2s) and the CMS-2 and 2h emulsions, along with other available modifications, contain a quantity of petroleum distillates. These products perform much better with dry aggregates (mixing, laying, etc), than with wet aggregates.[4]

In any case, it is recommended to perform a coating test in the laboratory to determine if premix moisture content is needed to disperse the selected emulsified asphalt and if so, the amount of moisture content needed.

Asphalt Demand of the Recycled Mix

The amount of new inder required for cold in-place recycling generally ranges from 0.5 to 3 percent for emulsified asphalts. This is equated to 0.3 to 2 percent residual asphalt cement for emulsified asphalts. Most highway agencies prepare trial recycled mixtures containing 1, 1.5, 2, 2.5, and 3 percent emulsified asphalt. Higher amounts are needed if new aggregate is incorporated in the RAP.

Very few agencies use empirical formulas, such as suggested by the Asphalt Institute,[4] to estimate the total asphalt demand of the recycled mix based on the surface area of the extracted gradation of the RAP or the RAP/aggregate blend. Such formulas have not been thoroughly validated in the field and, therefore, are not given here.

For in-place cold recycling construction it is often better to proportion asphalt binder based on the weight of the aggregate. This conversion is as follows:

Percent of new asphalt by weight of aggregate, $$P_d = \frac{100\,P_r}{100 - P_r}$$

where:

P_r = Percent of new asphalt in the recycled mix

Some agencies[10] use an optimum liquid content (consisting of emulsion content and water) of 4.5 percent in all trial mixtures. For example, water contents of 4.0 percent, 3.5 percent, 3.0 percent and 2.5 percent would be used with emulsion contents of 0.5 percent, 1.0 percent, 1.5 percent, and 2.0 percent, respectively.

As mentioned earlier, there is no standard national procedure for designing cold-recycled asphalt mixtures. However, some agencies and groups appear to have the most developed mix design procedures.[10] Methods proposed by the Asphalt Recycling and Reclaiming Association (ARRA), California, Chevron, Oregon, Pennsylvania, and the Asphalt Institute are reviewed below.

Asphalt Recycling and Reclaiming Association (ARRA)[11]

The ARRA guidelines indicate three different methods for cold-mix asphalt mix design. Two of these methods consist of modified Marshall and Hveem methods intended for designing cold recycled mixtures with asphalt emulsion or emulsified recycling agent (ERA). The third procedure has been developed by Oregon State University for determination of required asphalt emulsion content. These three methods are discussed briefly in the following paragraphs.

1. **Modified Marshall, Method A.** The design mixtures are prepared in such a way so as to achieve a 3 percent total water content (percent emulsion water + percent water remaining in RAP + percent mixture water added). Emulsions are incorporated into the mixtures at desired content in 0.5 percent increments. Mixtures are then compacted with 50 blow (per face) of the Marshall compacting hammer. The compacted specimens are cured for 6 hours at 60°C (140°F). Next, the specimens are tested for bulk specific gravity, stability (60°C), and flow (60°C). The maximum specific gravity is then determined. Finally, at the optimum additive content, specimens are prepared at additional total water content at 0.5 percent increment (such as 2.0

percent, 2.5 percent, 3.5 percent and 4.0 percent). The average void content for each moisture content is then determined. The recommended mix design parameters include minimum and maximum design air voids of 9 and 14 percent, respectively.

2. **Modified Hveem, Method B.** In this method, the method of specimen preparation is same as in Method A. However, instead of using the Marshall compactor, specimens are compacted with the kneading compactor. Approximately 20 tamping blows are applied at 1.725 MPa (250 psi) pressure to accomplish a semi-compacted condition. Next, the compaction pressure is raised to 3.45 MPa and 150 tamping blows are applied to complete the compaction. The specimen is then subjected to a leveling-off load with a testing machine at 5.6 KN (1250 lbf) at a head speed of 1 mm (0.05 in) per minute. Next, the specimens are tested for bulk specific gravity and stabilometer value (60°C). The maximum specific gravity is determined at one additive content. Finally, at the optimum additive content, specimens are prepared at additional varying total water contents, such as 2.0 percent, 2.5 percent, 3.5 percent and 4 percent. Void content of these specimens are then determined.

   The recommended mix design parameters include minimum and maximum design air voids of 9 and 14 percent, respectively.

   For both Method A and B, ARRA recommends (optional) the use of mix testing for moisture sensitivity or susceptibility in accordance with AASHTO T 283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage."

3. **Oregon Estimation, Method C.** This method has been used in Oregon for selecting an initial asphalt emulsion content to be added to the recycled mix containing 100 percent RAP and no new aggregate. The procedure consists of adjusting a base emulsion content of 1.2 percent (by weight of RAP) on the basis of properties of aggregate and asphalt binder recovered from RAP. The method is applicable only when a cationic medium setting or anionic high float medium setting type (HFE-150) emulsion is used as a recycling agent. First the gradation of RAP millings are determined for the 12.5-mm (½-in), 6.3-mm (¼-in), and 2.0-mm (No. 10) sieves. The asphalt binder recovered from the RAP is then tested for penetration at 25°C and absolute viscosity at 60°C. The estimated asphalt emulsion content is then determined from the following equation and figure 14-2.

$$EC_{EST} = 1.2 + A_G + A_{AC} + A_{P/V}$$

   where:

   EC_{EST} = Estimated added emulsion content, percent
   1.2 = Base emulsion content, percent
   A_G = Adjustment for milling gradations, percent.
   A_{AC} = Adjustment for milling residual asphalt content, percent
   $A_{P/V}$ = Adjustment for millings penetration or viscosity, percent

In this method, for the cases falling on a boundary, the adjustments resulting in a lower estimated

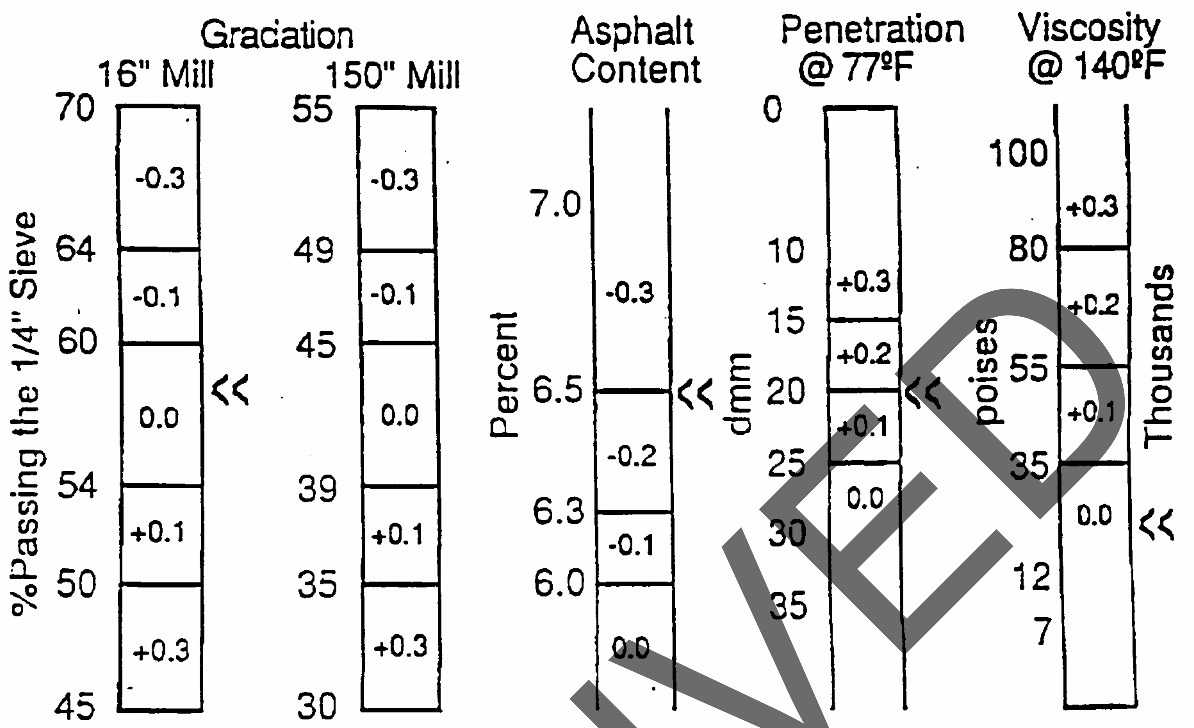

Figure 14-2. Emulsion content adjustment for determining EC_{EST} (ARRA/Oregon method).

emulsion content (EC_{EST}) should be used. If a discrepancy exists between the adjustments for penetration and absolute viscosity, the adjustments resulting in a low EC_{EST} should be used. Next, the percent of water needed is established by determining the required total liquid content. Sample of pavement RAP are prepared at estimated emulsion content with incremental water contents, such as 1.0, 1.5, and 2.0 percent. The weight of each of the samples is recorded. Next, the samples are placed and rodded in a 101.6-mm (4-in) (diameter) x 292.1-mm (11.5-in) (height) split mold in two lifts. Each of the samples is then gradually compressed in a hydraulic compaction device to a load of 172,400 kPa (25,000 psi)—one minute to achieve 137, 900 kPa (20,000 psi) plus one half minute to obtain the additional 34,500 kPa (5,000 psi). The 172,400 kPa (25,000 psi) load should be held for one minute. After compression, the specimen weights are determined, and the difference between the initial and compacted sample weight is recorded as the total liquid loss. The design total liquid content should be the total liquid content that results in a liquid loss of 1 to 4 grams. The amount of water needed is then determined by subtracting the estimated emulsion content and the existing water content of the RAP from the design total liquid content.

California Mix Design Method[10]

The California mix design guidelines specify method of sample preparation from pavement cores, gradation of material obtained by crushing of RAP, and sample preparation method for pulverized field samples. Pulverized field samples are to be checked for gradation using 38-mm (1½-in), 25-

mm (1-in), 20-mm (¾-in), 9.5-mm (⅜-in) and 4.75-mm (4-in) sieves. The specifications also require determination of viscosity of aged asphalt obtained by extraction from RAP. A method of determination of amount and grade of recycling agent is given, and curing of laboratory samples are indicated. The mix design tests specified include bulk specific gravity, air voids, and stability (with stabilometer) of the compacted recycled mix. The selected emulsion content is the highest emulsion content that provides a specimen with the desired stabilometer value, no evidence of surface flushing or bleeding, and a minimum of 4 percent voids.

Chevron Mix Design Method[10]

The Chevron mix design method for cold-mix recycling consists of the following six steps:

1. Evaluation of RAP.
2. Selection of amount and gradation of untreated aggregate.
3. Estimation of asphalt binder demand.
4. Selection of type and amount of emulsified recycling agent.
5. Testing of trial mixes.
6. Determination of job mix formula.

Methods to determine asphalt content, consistency of asphalt binder in RAP and gradation of extracted aggregate are discussed. Procedures for determination of virgin aggregate gradation and amount, and estimation of asphalt binder demand are specified. A guide for selection of type and amount of emulsified recycling agent is presented. Trial mixes, at both early cure and fully cured condition are tested for resilient modulus, stabilometer and cohesiometer values. The final job mix formula is selected based on the lowest emulsifying recycling agent content (minimum of 2 percent) that meets the design criteria for resilient modulus, stabilometer and cohesiometer values. The use of 100 percent RAP is allowed in this method. Detailed design examples are provided in this method.

Oregon Mix Design Method[10]

In this method, the steps for preparation of samples and estimation of emulsion and water content are the same as indicated in the ARRA method (Method 3 - Oregon Estimation). However, there is an additional step in which the emulsion contents producing the peak Hveem stability and resilient modulus are to be evaluated.

Pennsylvania Mix Design Method[10]

The Pennsylvania mix design method specifies RAP sample size, and procedures for determination of optimum moisture and emulsion contents. The initial evaluation consists of determination of gradation of aggregate in the RAP, asphalt content of the RAP, and penetration and viscosity of asphalt binder extracted from the RAP material.

Two series of tests are conducted in this method. A set of coating tests are run on specimens with different moisture content but constant emulsion content. Based on the results, an optimum moisture content is determined. Next, the optimum emulsion content is determined on the basis of water-conditioned and unconditioned resilient modulus tests on cured, compacted specimens.

Asphalt Institute Mix Design Method[10]

The Asphalt Institute mix design method consists of the following steps:

1. Determination of combined aggregate gradation (for virgin and RAP aggregates). The prerequisite to this step is determination of gradation of aggregate and asphalt content of the RAP material.
2. Selection of grade of new asphalt binder.
3. Determination of percent asphalt demand of the combined aggregate on the basis of suggested empirical formula.
4. Calculation of percent of new asphalt in the mix.
5. Field mix trial for adjusting asphalt content.

Detailed design examples are provided in this method.

SUMMARY

With its unique potential of conserving resource and energy, cold-mix recycling has become one of the most popular rehabilitation technique. To ensure proper performance, the design of cold-mix should be based on considerations of time and temperature effects on the recycled mix and slower binder softening rate. The first step is proper material evaluation by representative sampling and testing. The composition (asphalt content and gradation) of the reclaimed asphalt pavement (RAP) or milled material must be determined. The viscosity and penetration properties of the recovered asphalt cement from the RAP are also determined. The amount of new aggregates needed, if any, is determined on the basis of the target gradation of the recycled mix and the gradation of the RAP or milled material. Guidelines are available for selecting a proper recycling agent which is generally an emulsified asphalt. Laboratory tests (such as coating tests) must be carried out to ensure the compatibility of the recycling agent and the RAP/new aggregate mixture. The selection of the recycling agent primarily depends upon the gradation of RAP (plus new aggregate, if needed) and the consistency of the aged asphalt binder in the RAP. Proper judgement, along with knowledge about type and grade of recycling agents which have performed satisfactorily on similar local projects, are helpful. Finally, the amount of emulsified asphalt and water (if needed for dispersing the recycling agent) is determined by preparing and testing several trial mixes containing varying amounts of these components. Although no national standard test method is available for designing cold-recycled mixes, several agencies and groups have fully developed their own mix design procedures which have been presented.

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CHAPTER 15. COLD-MIX ASPHALT RECYCLING (CASE HISTORY AND QC/QA)

INTRODUCTION

Cold-mix recycling is a rehabilitation technique that reuses existing pavement material without the application of heat. Generally a recycling agent and/or asphalt binder (for example, emulsified asphalt) is added to the reclaimed asphalt pavement (RAP) material. In this technique, the existing pavement is pulverized, the RAP is sized, if necessary, recycling agent is added to the mix, and finally the mix is placed and compacted. Similar to conventional hot mix asphalt, cold recycled mix must be produced and placed according to proper guidelines and specifications. Since there are no universally acceptable guidelines on cold-mix recycling, it is always helpful to review the experience of past users and guidelines developed by different agencies. The objective of this chapter is to present some selected case histories and specifications including quality control and quality assurance (QC/QA) practice of some highway agencies.

CASE HISTORIES

Mercer County Project, Pennsylvania[1] (1985)

An in-place recycling project was completed in Mercer County, Pennsylvania on Traffic Route 208 (west of I-79 London interchange) in May 1985. The recycling train (figure 15-1) consisted of an emulsion tanker, a milling machine, a crusher, a mixer, and a paver. The milled material passed over a 38-mm (1½-in) scalping screen. The oversized material was fed into the crusher by a conveyor to reduce its size. The material was milled and recycled to a 75 mm (3 in) depth. Because no provision was made for adding water before the material was mixed with the CSS-1h emulsion, the latter was diluted with water in a 50:50 ratio to provide an acceptable dispersion of the binder.

It was noted that the gradation of the RAP on this project was significantly finer than the laboratory-generated RAP. About 3 percent (approximately 0.03 liter/kg, 7½ gal/ton) CSS-1h emulsion by weight of the RAP was used. Compaction was performed with a vibratory and a pneumatic-tired roller. Because the average daily traffic on this road was 2,000 to 3,000, the recycled base course was overlaid with 90 mm (3½ in) hot mix overlay. The recycled pavement had been performing satisfactorily when it was inspected in 1986 after one year (figure 15-2).

US 64 Project, New Mexico[2] (1984)

This cold in-place recycling operation was performed on US 64 in New Mexico in 1984. The existing pavement consisted of 75 mm (3 in) HMA over 150 mm (6 in) sand and gravel base. The existing surface exhibited extensive medium to high severity transverse, shrinkage and fatigue cracking (figure 15-3), and extensive moderate to high severity rutting. The surface also had extensive maintenance patching. Cold in-place recycling was done up to a depth of 100 mm. A polymer modified, high float emulsion was used at rate of 1-3 percent. The quantity of

Figure 15-1. Recycling train.

Figure 15-2. Condition of road after recycling.

Figure 15-3. Condition of existing road.

recycling agent was based on laboratory mix design, but was adjusted on the basis of field requirements. A 100 mm HMA overlay was used on the recycled base. The equipment train used for recycling consisted of a milling machine, crusher, mixer, and paver (figure 15-4). The milling machine milled the existing pavement and transferred the material to the crusher. The milled RAP material was screened and sized in this equipment. The maximum size of the RAP material was reduced to 32 mm (1.25 in). The screened and sized RAP material was mixed with emulsion in the mixer. A truck supplied the emulsion to the mixer. The mixer then laid down the recycled mix in a windrow. The paver picked up the recycled mix from the windrow and laid it down with a screed. Heavy pneumatic-tired rollers (27 Mg, 30 ton) were used for breakdown compaction. Steel-wheel rollers were used for final compaction (figure 15-5). Survey results reported in 1996 indicated that the pavement was performing adequately.

Baltimore County, Maryland[(3)]

Cold in-place recycling was done to rehabilitate a deteriorated road in Baltimore County in Maryland. The existing road had thermal cracking, rutting, poor profile and alligator cracking and patching (figure 15-6). Since this road is the only artery feeding a hospital, emergency and general business traffic had to be maintained. Hence the road could not be totally closed. Both sides of this road had concrete gutters. Following rehabilitation through recycling, the hot mix wearing surface needed to meet the top of the gutter. This means that the 100 mm (4 in) recycled base course had to be 37.5 mm (1.5 in) lower than the top of the gutters when compacted. With CIR, it was decided to move the recycled material into the center of the road and build a 20

Figure 15-4. Recycling train.

Figure 15-5. Pneumatic-tired breakdown roller.

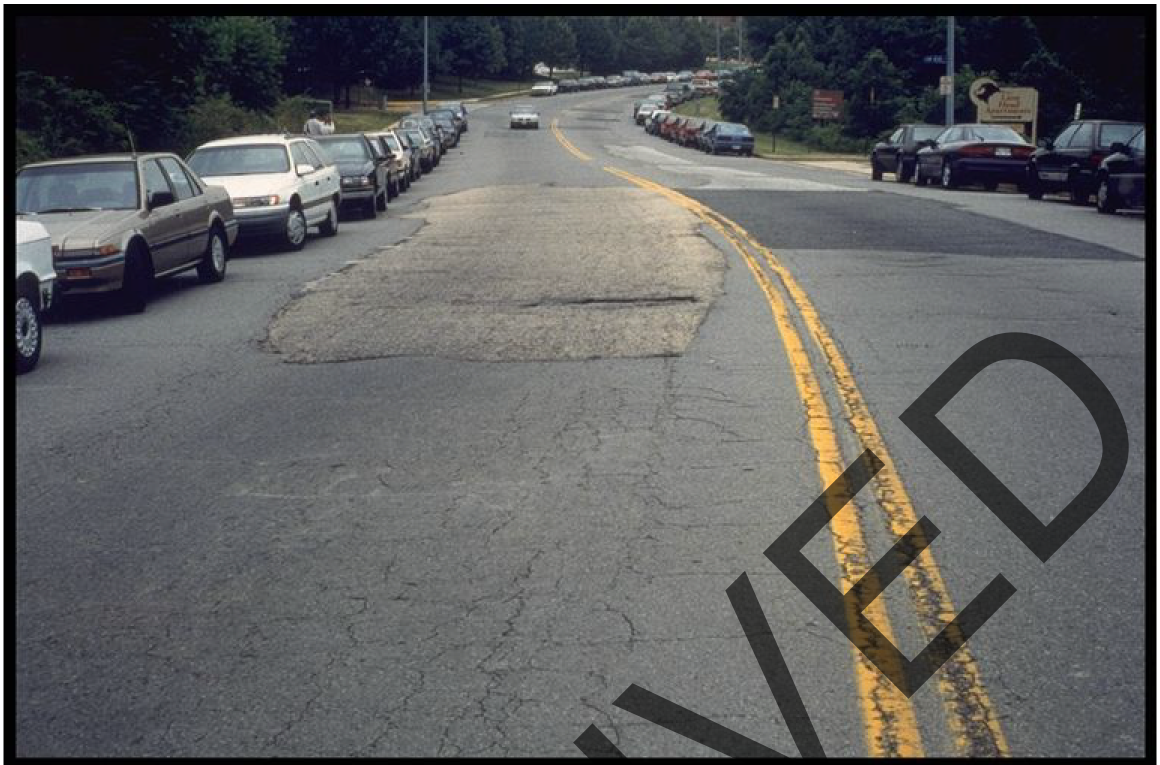

Figure 15-6. Existing road.

percent cross slope. Recycling was done with an asphalt tanker, pushed by a down-cutting full lane width (3-m wide) milling machine, with an appropriately computerized asphalt additive system. The old roadway material was milled and mixed with new asphalt in a single operation, then deposited directly into a paver and relaid to the desired depth (figure 15-7). The recycled material could be driven on without major problem. Traffic flowed around the construction equipment under restricted lanes and speed.

The recycled mix was left to cure for a period of seven days. Traffic was allowed to use the newly recycled section with no restriction. To achieve ideal compaction, a combination of a pneumatic 27 Mg (30 ton) smooth-tired roller and a steel wheel 10.8 Mg (12 ton) vibratory roller were used (figure 15-8).

Recycling Around Utilities[3]

Generally, a box is painted around the utility to first guide the operator of a small milling machine as to how much of the roadway must be milled to accommodate the larger recycling machine (figure 15-9). The 40 cm (16 in) head of a small milling machine goes around the utility to the depth of the new base course (figure 15-10). The milled material stays in-place around the utility until the larger recycling machine approaches. Then, all of the milled material is excavated out from the cut area, and placed on the old roadway where it is processed with the recycling machine. As the recycling machine pulls the paver behind it, it lays the new recycled base course around the utility, recycling 100 percent of the existing material (figure 15-11).

Figure 15-7. Recycling train.

Figure 15-8. Rollers used for compaction.

Figure 15-9. Marking utility.

Figure 15-10. Milling around utility.

Figure 15-11. Recycled material around utility.

SPECIFICATIONS AND QC/QA

There are primarily two types of specifications. The method specification specifies the equipment to be used and all construction processes. An end result specification sets control limits on some test property of the finished pavement. However, as in the case of other recycling procedures, in cold-mix recycling it is better to have a specification which is a combination of the method and end result specifications. This allows the effective use of the experience and expertise of the user agency, the contractor, and the equipment manufacturer to obtain a good pavement at a reasonable cost.[4] Since there is usually a great variation in material properties in cold-mix recycling, specifications for cold-mix recycling tend to be more end result oriented than method specification.[5] For example, the specification may allow either in-place or plant mixing, provided the recycled mix meets the specification, and any type of milling or pulverization equipment may be used if the depth of the cut and the gradation of the RAP material (for example, top size) meet the required specification tolerance.

The top size of the RAP material is usually specified by most agencies. It is realized that this requirement can slow down the recycling process, since the top size of a milled or pulverized material is a function of the condition of the existing pavement (oversized material may be produced from a pavement with alligator cracking), top size of the original aggregate, and the depth of the cut (thicker cuts may produce chunks of greater size).[6] Nonetheless, this requirement is essential for smooth and uniform laydown operations. The gradation of the existing road materials should be taken into account when writing the specification for the aggregate gradation. Due to the inherent variability of material in cold-mix recycling, it may not be practical to specify aggregate gradation for all the sieve sizes. However, the equipment used in cold-mix recycling (pulverization, for example) should be capable of cutting the pavement to the specified depth reasonably well.

The next important thing in cold-mix recycling is the specification for the asphalt recycling agent. The recycling agent should conform to the appropriate AASHTO, ASTM or state specifications for different types of asphalt binders, such as emulsified asphalt. Also, the equipment used for adding the recycling agent should be capable of an accurate application rate such that the total binder content of the recycled mix is equal to the job-mix formula amount within a specified tolerance, typically ± 0.5 percent.(5) The specification should also include clear directions regarding accurate application of any pre-mix water. Generally no limits are placed on the amount of RAP to be used, but any new material to be used should be tested for specification compliance. The responsibility for establishing the job-mix formula and the required sampling procedures, test methods and design criteria for the mix design should be clearly outlined in the specification.(5)

Adjustments to the gradation or asphalt content of the recycled mix can be made based on the results from the extraction tests conducted on recycled mix. Conventional methods of extraction (reflux, centrifuge, vacuum) which use solvents are being phased out by many highway agencies. Asphalt content and gradation of the aggregate in the recycled mix can be determined by the recently developed ignition method. The density of the compacted mat is another important test property for specification. The density can be specified either as a percentage of theoretical maximum density or laboratory density, or as a target density. The use of theoretical maximum density is recommended over the use of laboratory density, since there may be substantial differences in temperatures, fluid contents and other conditions between laboratory and field compactions. Specification of a target density (in actual kg/m^3, lb/ft^3 unit) combined with an adjustable rolling pattern has also been suggested to overcome the problem of material variability in the existing pavement.(7) When deciding on a density specification, prior experience with similar type of recycling and environmental conditions should be taken in account.

In the absence of proper performance data for developing statistically based specifications, it is suggested that the user agency remain flexible and evaluate several alternatives to encourage competition.(5) The specification should be written in such a way that it reflects the following functions of the user agency:(4)

1. Be responsible for the adequacy of design alternatives.
2. Write simple straightforward specifications which clearly state what is expected.
3. Permit the contractor to select the materials and methods which will accomplish the end result.
4. Use standard specifications familiar to the contractor.
5. Modify standard specifications only as necessary to obtain the end result.
6. Focus on end results by allowing the contractor flexibility in choosing the most economical methods and procedures to accomplish the work.

The important features of cold-mix recycling specification from the Asphalt Recycling and Reclaiming Association, and the states of New Mexico , Oregon and Pennsylvania are presented below.(8) The New Mexico DOT specification is given in Appendix B for ready reference.

Asphalt Recycling and Reclaiming Association (ARRA)

Specification regarding gradation of pulverized material, equipment, and construction requirements are provided. Specifications for equipment include description of mixes and construction operations for paver and roller. Guidelines regarding minimum allowable air temperature and tolerance for the application rate of recycling agent or additive are also provided.

New Mexico

The New Mexico cold in-place recycling specification describes material, equipment, and construction requirements. Type of emulsions and gradation of recycled material are specified. Descriptions of cutting rotor and asphalt application pump for mixers are provided. Required criteria for operations of paver and roller are also mentioned. For construction requirements, minimum air temperature and application rate of emulsified binders are specified.

Oregon

The Oregon specification describes requirements for maximum size of RAP material, construction equipment and methods. Requirements for components of recycling train, including planing machine, crusher, and mixer are described. Weather conditions required for recycling operation are specified. Requirements for temperature of emulsified asphalt cement, mixing and rolling are also specified. Method specification has been provided for initial compaction and recompaction of cold in-place recycled pavements.

Pennsylvania

The Pennsylvania DOT provides an end result specification for cold in-place recycling. General guidelines regarding type of equipment are provided. Requirements for mixing and transporting cold recycled (central plant) mix are given. Required criteria for mobile mixing plants are specified. For compaction, minimum and maximum depth of compacted layer are specified. Guidelines regarding rolling operation and use of a control strip to establish rolling pattern have been provided.

The following guidelines are recommended on cold-mix recycling:[8]

1. Cold in-place recycled mixtures should not be placed in depths greater than about 75 mm to 100 mm (3 to 4 in), because curing can be a problem, nor should depths be less than about 50 mm (2 in), because segregation may be a problem during construction. However, when portland cement or Class C fly ash has been used with asphalt emulsions, depths up to 150 mm (6 in) have been possible.
2. Softening of the recycled mix may occur within the first two to three days. Some agencies re-roll the pavement at this time to obtain additional density.
3. An excessive amount of initial compaction can cause problems. However, several states, including New Mexico and Pennsylvania, do not re-roll their pavements after construction.
4. Traffic should not be allowed on the recycled pavement for a minimum of two hours after compaction.
5. If the surface starts to ravel under the action of traffic, a fog seal should be applied as

soon as possible.
6. Rain within 24 hours of construction can create performance problems depending upon the type of emulsified asphalt used.
7. Before placing the wearing surface, curing should be allowed to reduce the moisture content to the 1 to 1.5 percent range. Summertime curing for 7 to 14 days is typically used. Late season construction can cause performance problems.
8. Problems with density control are common. Nuclear density devices provide relative numbers. Cores may not be able to be obtained without proper curing (which may be one year).

In conclusion it should be mentioned that final adjustments to mix design must be made during construction. A recent survey[9] indicates that 60 percent of the agencies surveyed based their adjustments on combinations of experience and workability.

Quality Control and Quality Assurance

Quality control (QC) refers to those tests necessary to control a product and to determine the quality of the product being produced. These QC tests are usually performed by the contractor. Because of greater variation expected in the case of cold recycled asphalt mixtures, the frequency of testing should be more, even though the same tests that are used in the case of conventional HMA may be used. Before starting construction, it is very important to know the quality of the existing pavement, in terms of aggregate gradation and asphalt content of the mix. The pavement should first be delineated into subprojects, on the basis of differences in design, maintenance, and rehabilitation actions. Once the subprojects are identified, representative samples should be taken from each of the subprojects. In this way, the variation in the existing material can be identified and evaluated.

The quality control for cold-mix recycling is primarily dependent upon the equipment used. The equipment should be such as to allow the following operations:[10]

1. Pulverization of recycled pavement material to the desired size.
2. Proper pre-mix water content (uniformly mixed).
3. Proper recycling agent content (uniformly mixed).
4. Attainment of some minimum specified mat density.

Favorable temperature and moisture conditions are necessary for strength development during the curing period. The stabilized surface should be protected from traffic to prevent abrasion and to ensure adequate time for strength development.

The following are the potential problem areas for in-place and central recycling:[5]

1. Depth of removal and pulverization.
2. Blending associated with addition of new aggregate, water, stabilizers, or modifiers.
3. Degree of pulverization.
4. Distribution of modifiers, water, or stabilizers.

Table 15-1 presents the material sampling and testing procedures for quality control, as suggested by AASHTO-AGC-ARTBA.[11] The items that should be monitored are listed below. The specific characteristics which need to be evaluated are mentioned in parentheses.

Table 15-1. Control and testing—recommended field sampling and testing.[11]

Type of Testing	Purpose of Testing	Frequency	Sample Location and Size
Recommended for Control and Testing			
RAP gradation, 50 mm, 37.5 mm, or 31.5 mm (2", 1½", or 1¼") sieves	Specification compliance with maximum RAP size determined	Each 0.8 km[1,6] (½ mile)	From conveyor belts, windrows or mat, minimum weight of 9.1 kg (20 lb)[2]
Asphalt emulsion, recycling agent, portland, fly ash, and lime	Check on specification compliance	Every load sampled, one test per day	From asphalt tank on recycling unit or transport truck, wide-mouth plastic bottle, 1 L (1 qt) sample size[3]
Moisture added to RAP[4]	Adjustment of water content for proper mixing and compaction	Each 0.8 km[1,6] (½ mile)	From belt into mixer or after spreading, minimum weight of 9.1 kg (20 lb)[2]
Mat moisture content after curing (emulsions/recycling agents only)	To determine when the new asphalt surface can be placed	Each 0.8 km (½ mile), one each lane[1,6]	Full lift depth sample, minimum weight of 1.4 kg (3 lb)[2]
Recycling additive content	Verify amount of recycling additive and also accuracy of meter readings	Minimum of one per day	By tank gauging, transport truck weighing or meter readings and RAP weight by belt scale readings
Recycled material compacted density by rolling control strips[5]	To establish rolling procedures and target density for specification compliance	Minimum of two strips and nuclear density testing each 0.8 km (½ mile)[1,6]	Strips at beginning of project and additional if major changes in recycled mixture properties occur, 120 to 150 m (400 to 500 ft) length
Or			
Recycled material compacted density by field compacted specimens[5]	To establish the target for specification compliance	Material sample and nuclear density testing each 0.8 km (½ mile)[1,6]	Material sampled from windrow or mat after spreading, minimum weight of 9.1 kg (20 lb)[2]
Depth of pulverization/milling	For specification or plan compliance	Each 0.2 km (1/8 mile) or additional as needed	Measurements across the mat, adjacent to longitudinal joints and at the outside edge
Recommended for Control and Testing			
Spreading depth of recycled material, central plant cold recycling only	Check of the lift thickness for specification or plan compliance	Each 0.2 km (1/8 mile) or additional as needed	Measurements across the mat, adjacent to longitudinal joint and at the outside edge

Table 15-1. Control and testing—recommended field sampling and testing[11] (continued).

Type of Testing	Purpose of Testing	Frequency	Sample Location and Size
Mixing equipment calibration	To assure proper content of the recycling additive and moisture	Prior to beginning of work each year and additional as needed[7]	Material being recycled from mixer into a truck and liquids into barrels, tanker or asphalt distributor for weighing by a scale
<u>For Information Only</u>			
Recycled material temperature	To determine the influence of temperature on compaction and temperatures for mix design	Minimum of four each day, two early morning and two late afternoon	Determined for the recycled material when mixing and the mat immediately prior to the beginning of compaction
Recycled mat smoothness	To develop data on spreading and for possible future specification requirements	Continuously or at selected locations of existing pavement and after cold recycling	By profilograph device (California or other)
Original pavement and recycled material asphalt contents (by solvent extraction)[8]	To determine added and total asphalt contents	Randomly[6]	From selected locations in a stockpile or pavement before recycling and in the recycled mat, minimum weight of 9.1 kg (20 lb)[2]

Notes:

1. Additional sampling and testing may be required if major changes in RAP characteristics are observed, such as a much coarser or finer gradation or noticeable differences in asphalt content, or when considerable variability is occurring in field test results.
2. It is recommended that RAP sampling generally should be in accordance with the ASTM D 979 or AASHTO T 168 procedures for Sampling Bituminous Paving Mixtures.
3. Asphalt emulsion and asphalt recycling agent sampling should be in accordance with ASTM D 140 or AASHTO T 40 for Sampling Bituminous Materials.
4. The moisture content can be determined with ASTM D 1461 or AASHTO T 110 for Moisture or Volatile Distillates in Bituminous Paving Mixtures. Also, the moisture content appears can be determined adequately by weighing and drying to a constant weight using a forced draft oven as for ASTM D 2216 or AASHTO T 265 or by microwave oven drying as for ASTM D 4643.
5. Target densities for recycled mix compaction are being established by using rolling control strips or by the field compaction of density specimens using Marshall, Proctor or gyratory compactors. The compacted density, when determined, is measured with a nuclear density/moisture gauge since it is generally not possible to obtain cores during construction. For control strips, backscatter is typically used but for density checks for specification compliance, direct transmission measurements are preferred. The procedures generally followed are in accordance with ASTM D 2950 for the Density of Bituminous Concrete in Place by Nuclear Methods. The density obtained will be a “wet density” as conversion to a true “dry density” by the gauge is not possible with these types of mixes. A reasonably accurate dry density may be obtained by sampling the recycled mix at the nuclear gauge test location, determining the moisture content by drying and correcting the gauge wet density.
6. For each length or lot size quantity specified, materials sampling may be completed on a random basis using the procedures of ASTM D 3665 for Random Sampling of Construction Materials.
7. Based on the mixer computer meter readings and other checks, additional calibration may be required. This calibration may require only checking and adjusting the best scale system using weights.
8. The asphalt content in the cold recycled mixture can be determined by one of the following asphalt extraction testing methods: ASTM D 2172, ASTM D 4125, AASHTO T 164, or AASHTO T 287.

1. RAP Gradation (maximum size).
2. Recycling agent (type and amount).
3. Moisture (amount).
4. Compacted density.
5. Depth of milling.
6. Spreading depth/cross slope.
7. Mixing Equipment (calibration).

For checking compacted density, two methods are recommended:[11] By control strips and by the field compaction of the recycled mix taken from windrow or immediately behind the paver.

The following test procedures are suggested for QC/QA operations. The depth of pulverization can be obtained by completely removing the pulverized material adjacent to an unpulverized road surface and measuring the depth. The depth of pulverization can also be calculated if the density of the existing road is known and the pulverized material is removed from a known area (a steel frame can be used) and weighed.

The amount of pre-mix water can be calculated from the amount of water actually used. If it is possible to obtain the sample of the pulverized material with water only, the water content can be determined rapidly by heating the pulverized sample to constant weight in a microwave oven.

The amount of recycling agent (such as emulsified asphalt) can be determined by extraction or ignition test on the recycled mix. However, the amount of pre-mix water, if any, must be determined first and accounted for in the extraction or ignition test. The amount of recycling agent can also be determined from the actual quantities used on the project.

Density of the compacted mat can be determined using a nuclear density gauge. However, the water content in the compacted mat must be accounted for to calculate the dry compacted density. Usually it is not possible to obtain intact cores because water is used in the coring operation and it damages the recycled mix which is not completely cured just after compaction. If a control strip is constructed to establish rolling pattern, its density can be measured by a nuclear density gauge and this density can be used as a target density for the remaining project. If the pre-mixed water content is held relatively consistent, there is no need to determine the dry density of the mat.

SUMMARY

Cold-mix recycling consists of four basic steps: (1) pulverization of existing pavement, (2) sizing of RAP, (3) addition of recycling agent, (4) placement and compaction. Similar to hot mix asphalt, cold recycled mix must be produced and placed according to proper guidelines. Experience of previous users have shown that substantial cost savings and pavement improvement can be achieved with cold mix recycling. Since there is usually a great variation in material properties in cold-mix recycling, specification for cold-mix recycling tend to be more of end result oriented than method specification. Commonly used specifications specify maximum RAP size, pre-mix water content, recycling agent content, and density measurements. Quality control measures involve checks on depth of pulverization, pre-mix water content, recycling agent content, gradation of recycled mix, and in-place density.

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CHAPTER 16. FULL DEPTH RECLAMATION (CONSTRUCTION METHODS AND EQUIPMENT)

INTRODUCTION

Full depth reclamation has been defined as a recycling method where all of the asphalt pavement section and a predetermined amount of underlying materials are treated to produce a stabilized base course.(1) Different types of additives, such as asphalt emulsions and chemical agents such as calcium chloride, portland cement, fly ash and lime, are added to obtain an improved base. The five main steps in this process are pulverization, introduction of additive, shaping of the mixed material, compaction, and application of a surface or a wearing course. If the in-place material is not sufficient to provide the desired depth of the treated base, new materials may be imported and included in the processing.(1) This method of recycling is normally performed to a depth of 100 to 300 mm (4 to 12 in)(2)

The major advantages and benefits of full depth reclamation are as follows:(2,3)

1. The structure of the pavement can be improved significantly without changing the geometry of the pavement and shoulder reconstruction.
2. It can restore old pavement to the desired profile, eliminate existing wheel ruts, restore crown and slope, and eliminate potholes, irregularities, and rough areas. Pavement widening operations can also be accommodated in the process. A uniform pavement structure is obtained by this process.
3. It can eliminate alligator, transverse, longitudinal, and reflection cracking. Ride quality can be improved.
4. Frost susceptibility may be improved.
5. The production cost is low, and only a thin overlay or chip seal surfacing is required on most projects.
6. Engineering costs are low.
7. Materials and energy are conserved, and air quality problems resulting from dust, fumes, and smoke are eliminated. The process is environmentally desirable, since disposal problem is avoided.

Full depth reclamation has been recommended for pavements with deep rutting, load-associated cracks, nonload associated thermal cracks, reflection cracks, and pavements with maintenance patches such as spray, skin, pothole, and deep hot mix. It is particularly recommended for pavements having a base or subgrade problem.

CONSTRUCTION PROCESSES AND EQUIPMENT

Figure 16-1(4) shows a flow chart for full depth reclamation. The first step is to rip, scarify or pulverize or mill the existing pavement to a specified depth. Four processes are listed in figure 16-1 for this step. The second process (from the top) involves central plant whereas the other three are in-place processes. The resulting material can be processed further for size reduction and mixed with recycling agents and new materials, if required, in-place or in a central plant. The choice between in-place and central plant depends on equipment availability, roadway condition,

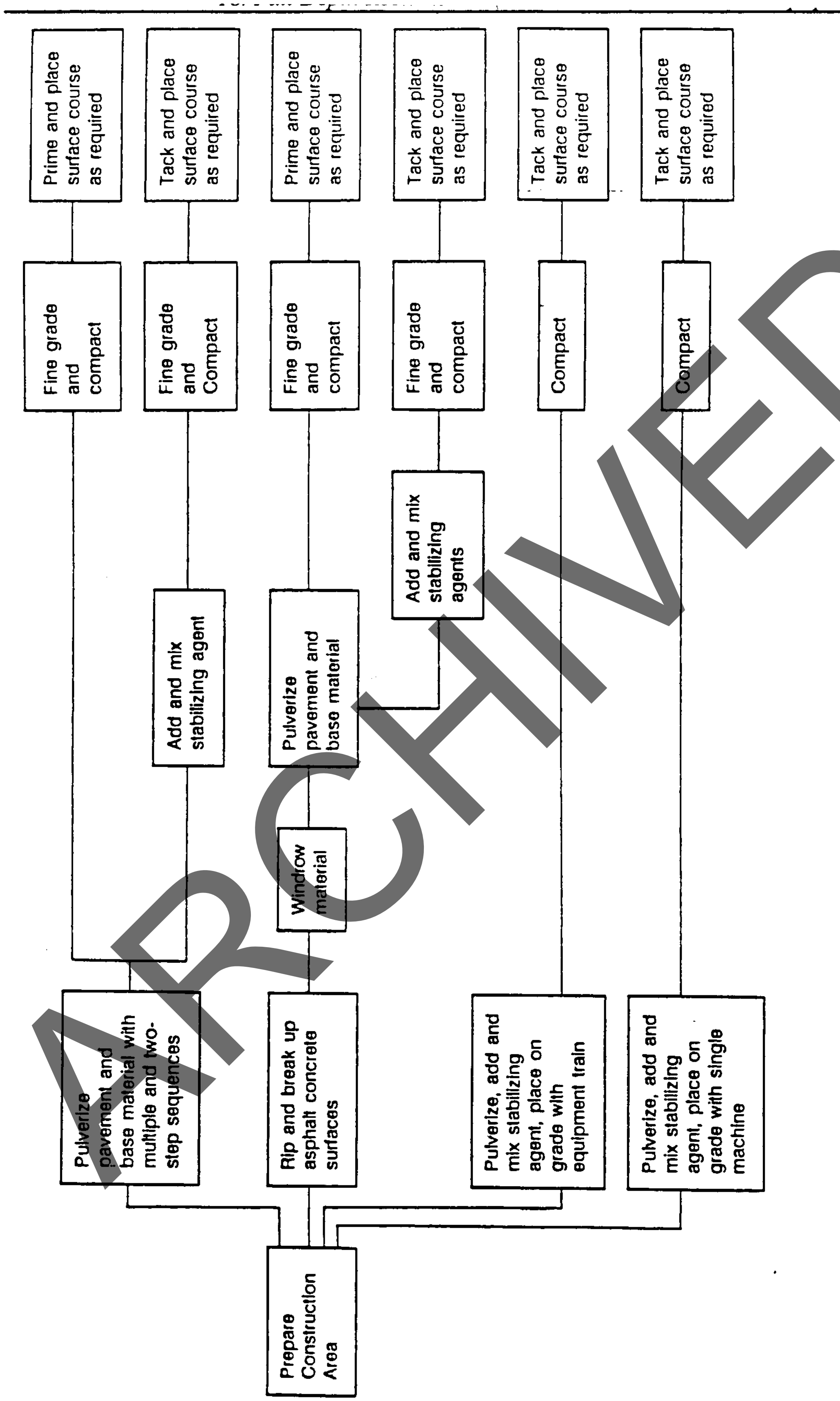

Figure 16-1. Flow chart for full depth reclamation.[4]

and economics.

The in-place method is generally more economical than the central plant method. The different mixing methods include blade, flat type, windrow type and hopper type (figure 16-2).[5]

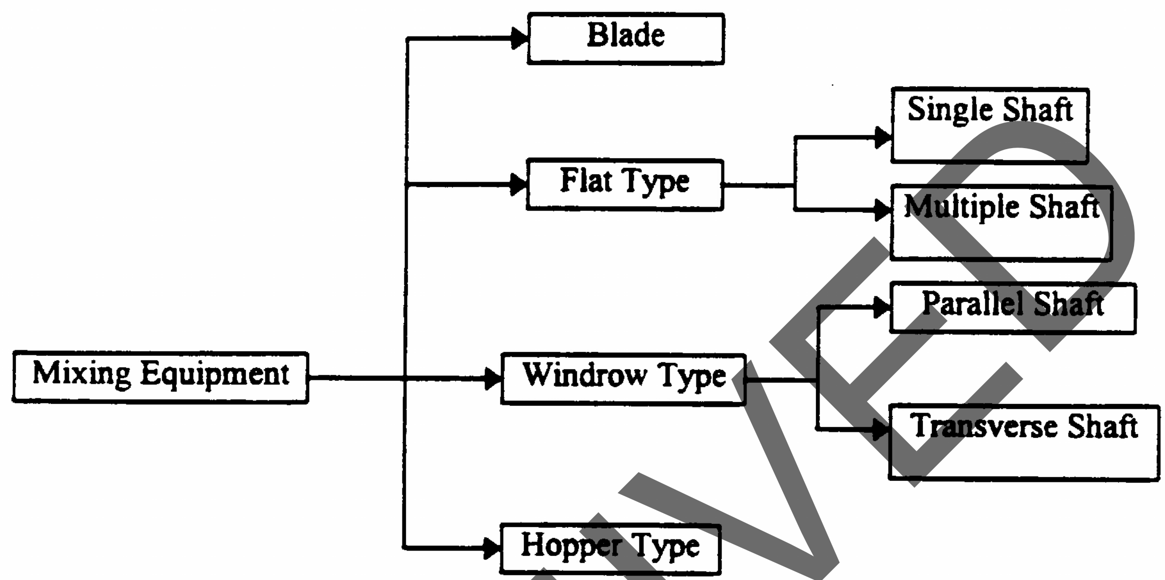

Figure 16-2. Soil and stabilization equipment used for full depth reclamation.

Four different types of in-place sizing and mixing operations are used at present. These include the multiple-step sequence, two-step sequence, single machine, and the single-pass equipment train. The different methods are discussed in the following paragraphs.

Multiple-Step Sequence

In this process, the existing pavement is broken, pulverized, and mixed with a recycling agent. The equipments available for initial ripping or scarifying include motor grader or dozer with either front- or rear-mounted ripper teeth (figure 16-3). This method is believed to be efficient with thin Hot Mix Asphalt (HMA) layers, but it may produce larger chunks of material than needed when cutting deeper.[8] Materials produced by this method may need additional size reduction.

A variety of equipment is available for size reduction or pulverization after the initial ripping. The different equipment are as follows:[4,6]

1. Sheep foot, grid, or similar type of roller. This type of roller can also be used for initial scarification or crushing of thin seal-coat roads. A vibratory padfoot type roller is shown in figure 16-4.
2. Motor grader with ripper teeth, equipped with a cutter-crusher-compactor in the rear. This equipment combines the scarifying and size reduction operations. Figure 16-5 shows a typical motor grader.

Figure 16-3. Dozer with ripper teeth.

Figure 16-4. Vibratory padfoot roller.

Figure 16-5. Motor grader.

3. Towed or self-propelled hammermill (or impact breaker or preparator). Figure 16-6 shows a traveling hammermill.
4. Rotary mixers. The self-propelled, single-pass mixer with single or multiple transverse rotary shafts, each containing multiple mixing paddles, can be used for removal, crushing, and mixing operations.

The mixing operation is generally performed with a blade mixer or a transverse-shaft mixer.

The drawbacks of using the above equipments are that they need multiple passes to achieve required size reduction, may cause lack of uniformity in depth of cut, have low production rate and have limitations on depth of cut. Construction coordination and traffic control can be major problems. The major advantage of this method is that readily available equipment can be used.

Two-Step Sequence

In this process, the breaking and pulverizing or sizing operations are combined together with a cold milling machine or a large pulverizing machine. The second step involves addition of the recycling agent with soil stabilization mixing equipment and traveling mixers. Figure 16-7 shows a cold milling machine. The main feature of a cold milling machine is a rotating drum lined with a variable number (depending on width) of replaceable, tungsten-carbide-tipped cutting teeth, which is used to grind the existing pavement. These machines can provide accurate control of depth and profile as well as pulverize and size in a single pass, resulting in less interference with traffic. They can also be equipped with a pump and metering system to serve as a mixing unit.

Figure 16-6. Traveling hammermill.

Figure 16-7. Cold milling machine.

The cold milling machine can provide a high production rate in almost any weather.[2] However, trained personnel is required for operation of the cold milling machine. Also, the entire pavement should be reduced to the proper size, and the increase in amount of fines due to milling should be considered during mix design.[9]

The drum of the cold-milling machine can be set to operate either in the up cutting or the down cutting mode. In the up cutting mode, the teeth cut from the bottom of the pavement layers upward as the machine moves forward. This method provides accurate cutting depth with lower cost, greater speed, less tooth wear, less power to operate, and less damage to the underlying surface. The only drawback is that this method can produce a significant amount of oversized material.[2] In the down cutting mode, the teeth strike the top of the pavement surface in a downward direction as the machine travels ahead. This method is appropriate for full-depth cuts, since the reclaimed materials are pinched against the underlying layers resulting in proper sizing.[2]

Material quality and depth of cut are the two main factors affecting the resistance of pavement to the penetration of the cutting teeth, which in turn control the productivity of the milling machine. The main factors related to material quality can be summarized as follows.[2]

1. **Structural soundness of the pavement**. A pavement layer with alligator or fatigue cracks is easier to cut than a pavement which is structurally sound.
2. **Hardness or toughness and gradation of aggregate.** Productivity decreases and tooth wear increases as the hardness or toughness of the aggregate increases and as the gradation becomes finer.
3. **Characteristics of binder agent**. Material with a stiffer binder is harder to mill than a material with a softer grade of binder.

The productivity of cold milling operation is also affected significantly by the depth of the cut. As the depth increases, in a single pass, more amount of material is produced, but at the cost of reduced speed and greater demand for cutting power. The net number of tons of material reclaimed increases as the depth of cut increases up to about 75 mm to 100 mm (3 to 4 in) depth, depending on the quality of the material. Beyond this depth the net productivity decreases as the traveling speed of the machine becomes the dominant factor affecting the productivity. Hence, beyond 75 mm to 100 mm (3 to 4 in) depth of cut, two passes of the cold milling machine may be more efficient than a single pass.

For a given cold milling machine, the travel speed can vary from as low as 2.4 m to 3.0 m (8 to 10 ft) per minute to 30.5 to 45.7 m (100 to 150 ft) per minute, depending on the quality of the mix. Hence, the machine can have a wide ranging production rate.

Automatic grade and slope controlled cold milling machine are very common nowadays. Both sides of the equipment can be regulated, using either dual grade references or a grade control on one side and a slope control on the other side of the machine. The type of grade reference controls the leveling performance. If a joint machine shoe is used, the machine will duplicate the profile of the surface being matched. If a mobile ski or erected string line is being used, the cold miller will do the required leveling work.[2] The machine can be used with dual-grade controls to remove a constant depth of material. It can also be operated using a combination of grade control and slope control to produce the required cross-section across the existing pavement. However, the contractor cannot operate the cold-milling machine to obtain a constant depth of cut and a constant cross slope at the same time.(2)

Material quality and depth of cut affect the life of cutting teeth, and hence the cost of operation of a cold-milling machine. The other important factors affecting the cost of operation are: operating hours per year or annual ownership costs, maintenance and repair or operating costs, labor expenses, and fuel, lubrication and auxiliary equipment charges.(10)

The important advantages of this method are that partial depth removal of asphalt layer is possible, and that it has high production capacities. The disadvantages are that the depth of cut is limited, can result in aggregate oversize, and needs specialized equipment.(2)

Single Machine

The reader should refer to section on single machine in chapter 13. An example of single machine operation used for FDR is shown in figures 16-8 through 16-11. The existing road in Quebec was cracked because of freeze-thaw cycled, and needed major increase in structural capacity because of increasing semi-tractor-trailer loadings. It was decided to conduct FDR of the existing material with asphalt emulsion and cement. Figure 16-8 shows a schematic of the machine. The single machine was attached to a slurry mixer, which was connected to an emulsion tanker (figure 16-9). The single machine received the emulsion from the tanker and cement-water slurry from the slurry mixer. The single machine milled the existing road, mixed the lime and cement-water slurry with the milled material. A grader was then used to profile the treated material. Figure 16-10 and 16-11 show the grader and the completed base course, respectively.

Single Pass Equipment Train

The reader should refer to section on single pass equipment train in chapter 13.

Recycling Additives

To improve the mechanical property of recycled base, liquid additives such as asphalt products are used as recycling agents in cold recycling. These include emulsified asphalts (either slow or medium setting), cutback asphalts, and emulsified versions of commercial recycling agents. Water is also added initially sometimes to help in the dispersion of the asphalt modifier during the mixing operations. A small percentage of portland cement may also be added to emulsified asphalts to help stabilize the recycled mix and reduce curing time.

The choice of stabilizing agent depends on several factors including the composition of the existing structure, the type of subgrade soil, and the recycling objective. If the recycled base material is mixed with untreated subgrade soil, then additives required for soil stabilization are used. Some of the commonly used recycling agents are:(11)

1. Asphalt emulsion.
2. Portland cement.
3. Lime.

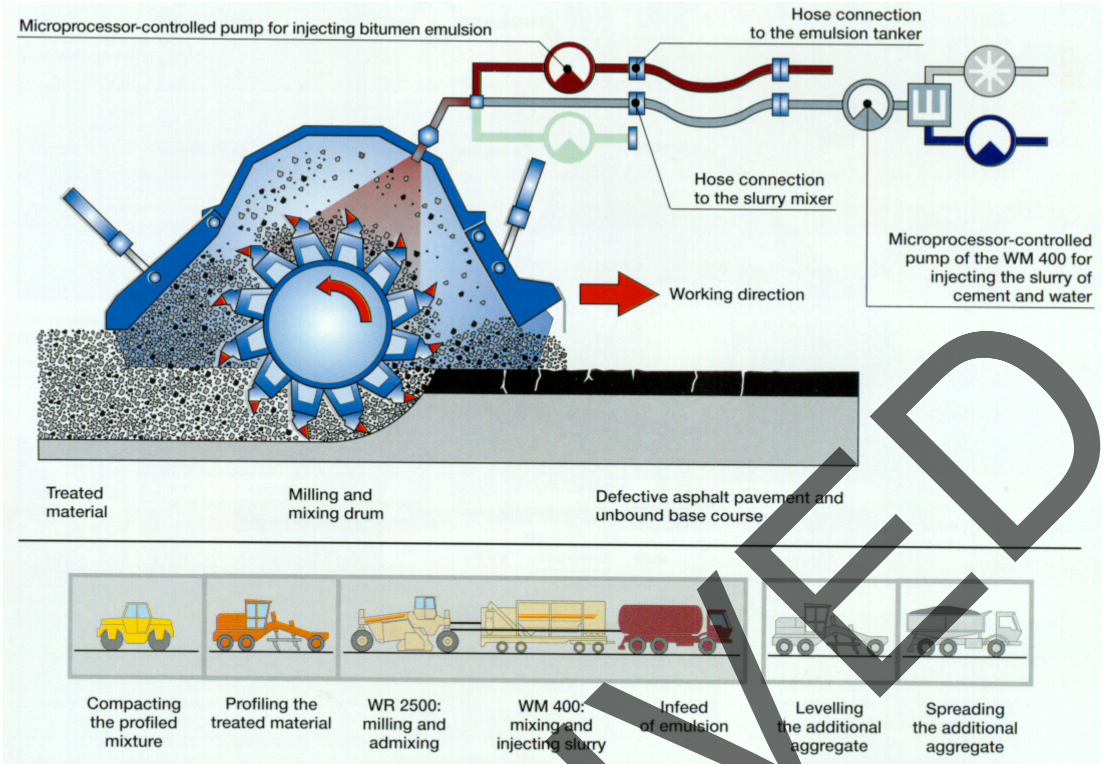

Figure 16-8. Schematic of single machine (Wirtgen America Inc.).

Figure 16-9. Single machine.

Figure 16-10. Grader.

Figure 16-11. Completed base course.

4. Fly ash.
5. Calcium chloride.
6. Foamed asphalt.

Asphalt emulsion: Asphalt emulsion helps to increase cohesion and load bearing capacity of the mix. It also helps in rejuvenating and softening the aged binder in the existing asphalt material. Emulsions are mixtures of asphalt cement, water, and an emulsifying agent. The advantage of using emulsion is that emulsions are low in viscosity and very suitable for application through an on-board liquid additive system in the recycling equipment. After the blending of the base material and emulsified asphalt, the emulsion “breaks” and water separates out from the asphalt cement. This water is forced out of the base during compaction or will evaporate out during curing period. The resulting residual asphalt cement has high viscosity and, therefore, helps in improving the cohesion of the base material.

Portland cement: This additive is used to increase compressive strengths of bases. When cement, soil and water are combined, a cementitious bond between the soil particles is formed immediately, and the mix continues to gain compressive strength over a long period of time. Addition of cement is best effective in granular and low plasticity base or subgrade.

Lime: Lime is used as an additive to mitigate the effect of reactive clay in base materials. Lime reduces the plasticity within days and brings down the swelling potential. It also helps in resisting water damage and increasing tensile and compressive strengths of the recycled mix.

Fly ash: The main reasons of using fly ash as an additive are to form cementitious bond in soil (in presence of water) and increase impermeability and strength of the recycled mix. Fly ash is generally spread by a mechanical spreader and then blended with a reclaiming machine in a second pass.

Calcium chloride: Calcium chloride is used to lower the freezing point of reclaimed base material and thus helps against freeze and thaw problems. Load-bearing capacity of base can also be improved by the addition of calcium chloride. Liquid calcium chloride can be added in three steps: primary application, blending, and secondary application to seal the shaped and compacted surface. An onboard liquid additive system or a distributor truck can be used for application of calcium chloride.

If water is required in addition to the recycling agent, the liquids may be pre-mixed before delivery to the asphalt storage tank of the travel plant. This system may cause problem if the recycled mix requires variable water contents.

Foamed asphalt: Foamed asphalt is being used increasingly in FDR. Foaming facilitates better dispersion of the asphalt into the materials to be recycled. A small amount of water is sprayed into hot asphalt as it is mixed with pulverized recycled pavement and soil. As the hot liquid and water mix, the liquid expands in a mini-explosion, creating a thin film of asphalt with about 10 times more coating potential. In another system, instead of adding water to the asphalt during mixing, foamed asphalt from a separate foaming chamber is added directly to the pulverized road material.

Curing, Compaction, and Application of Wearing Surface

Curing or aeration of the mix is required to reduce the water and volatile content of the recycled mix. The material can be placed in a windrow after mixing, after which it can be leveled to proper cross slope with a motor grader. The motor grader can also be used to aerate the mix by blading the mix back and forth across the roadway. This aeration process helps in reducing the fluid content of the mix so that it becomes stable enough to support the weight of the compaction roller. The rate of volatile loss will be controlled primarily by the type of asphalt modifier, mix water content, gradation of the aggregate, wind velocity, ambient temperature, and humidity.

Compaction can be done with static steel-wheel, pneumatic-tired, and vibratory rollers, and combination of two or all three. Figure 16-12 shows a combination of steel-wheel and pneumatic-tired rollers for compacting cold recycled mixes. The factors controlling the number of passes required for compaction are properties of the mix, lift thickness, type and weight of roller, and environmental conditions.[8] Cold-recycled mixes tend to be “fluffy” and, therefore, the uncompacted thicknesses of the mat should be increased to achieve the desired compacted thickness. The moisture content is very critical to compaction of the mix. Sufficient moisture lubricates the particles and helps in compaction, whereas excess moisture causes low density and moisture retention in the sealed layers. If it is found that the mix has an unacceptably high moisture content, then compaction should be delayed or completed after mix aeration and relaying if traffic disruption is a major problem. Usually a wearing course, in the form of an HMA overlay, or a single or double surface treatment is applied over the cold-recycled asphalt base. The application of the overlay should be delayed for sufficient time if the mix needs additional curing to avoid excessive moisture retention and loss of stability. Ideally, heavy traffic should not be allowed on the surface during this delay. A light application of an asphalt modifier or an emulsion fog seal may be necessary over cold recycled base before opening to traffic to minimize raveling.

Other Construction Considerations

The following additional guidelines are recommended specifically for full depth reclamation.[12]

1. The unbound base course must be free of 100-mm (4-in) bones and cobbles, large boulders, rocks, and tree stumps.
2. There must be limitations for gradation with the reclaiming machine. Maximum particle size typically allowed is 100 percent passing 50 mm (2 in). The percentage of material passing 75 µm (No. 200) sieve is sometimes less than three percent. If the depth of cut is 100 mm (4 in), fines must sometimes be added. It may be extremely difficult to achieve 100 percent passing through a 25-mm (1-in) screen, which is a typical specification for materials on a project using calcium chloride as an additive.

Other important elements which should be monitored in a full depth reclamation process are summarized as follows:[11]

1. Method of Cut: The existing pavement structure can be cut in either of the two ways: (a) the machine is lined up along one edge of work area. With the machine stopped, the rotor is lowered and the pavement is ground from the surface to the base until the depth of cut is reached. This method can cause accelerated tool wear and the rear of the machine can experience some bouncing when cutting through thick dense

Figure 16-12. Rollers used for compaction of cold recycled mixes.

material; (b) the machine can be positioned laterally along the work area with the rotor over an unpaved surface. The rotor is lowered to the depth of cut through softer material, and then the machine is driven across the width of the area. This way, a neat 90° joint can be achieved at the start. This method reduces tooth wearing and lowering of the machine while cutting.

2. Depth of Cut: The depth of the cut should be a minimum of 25 mm (1 in) below the full depth of the paved layer to provide relief to the rotor tools. If water is not added when pulverizing, then the cutting of some underlying material is required to have moisture for tool cooling and reduction of wear. If there is unsuitable material directly below the asphalt layer, the rotor may be kept even with the bottom of the asphalt layer.
3. Width of Cut: The width of the cut can be limited to the width of the pavement. However, an existing pavement can also be widened by reclaiming the shoulders on each side of the driving lanes. There are some important considerations if a widening is planned. The shoulder material properties must be considered when selecting a recycling agent or stabilizing agent or virgin materials for modification of engineering properties. Next, the total square meter (or square yardage) of the project (including the shoulders) should be considered for application of additives. The total width of the pavement to be reclaimed should be compared to the width of the rotor (of the cutting machine) before planning the number and location of passes required for the cut. Normally, if the pavement is less than 7.3 m (24 ft) in width, the total width can be processed by three passes. If the pavement width is greater than 7.3 m (24 ft), one half of the pavement is typically closed to traffic and processed for the length of the

project. The other half remains open to the traffic. Next, the other half is processed, and finally the full length and width of the base is paved. Care should be taken to remove the contaminants (such as vegetation) from the shoulder materials before blending them into the recycled mix.

4. Gradation: The position of the discharging door from the mixing chamber in the reclaiming machine should be so adjusted as to avoid generation of excessive amounts of fines.
5. Rotor Speed: The speed of the rotor used for pulverizing asphalt and base materials should be controlled to produce the RAP material with proper aggregate size. Higher the rotor speed, finer is the mixture.
6. Machine Speed: Generally, the slower the machine speed, the finer is the gradation. Hence the speed should be controlled so as to produce required aggregate size in the RAP material.
7. Ambient Temperature: Properties of HMA layers are greatly affected by the ambient temperatures. A high ambient temperature (> 32ºC, 90ºF) increases the chance of breaking off large chunks ("slabbing") in front of the cutting machine. The machine speed should be decreased and the discharge door opening from the mixing chamber should be reduced for effective processing of larger chunks of HMA.

SUMMARY

Full depth reclamation is a process in which all of the asphalt pavement section and a predetermined amount of underlying materials are treated with recycling agents to produce a stabilized base course. Asphalt emulsions and/or chemical agents like fly ash or portland cement are added as recycling agents. The advantages of this method include improvement of pavement structure, restoration of desired profile, and elimination of cracks. The process can be accomplished without changing the geometry of the pavement or shoulder reconstruction. The main steps include pulverization, introduction of additive, shaping of the mixed material, compaction, and application of wearing or surface course. Sizing and mixing operations can be achieved in four different ways—multi-step sequence, two-step sequence, single machine, and the single-pass equipment train. In the multiple-step sequence different machines are involved in the different phases of operation. These include motor grader for initial scarifying, sheep foot roller for size reduction, and blade mixer for mixing operations. Although readily available equipment can be used in this method, there are several disadvantages including lack of depth control, limitation of operating width, contamination of asphalt layer with base material, and traffic control problems. In the two-step sequence, the breaking and sizing operations are combined with a cold milling machine and the mixing is done with a soil stabilization mixing equipment. This method needs trained personnel and specialized equipment, but has a high production capacity. The single machine combines the breaking, sizing, and mixing operations with a single specialized equipment. The advantage is high production rate, but the drawbacks are aggregate oversize, depth limitation, and need for specialized equipment. A single pass equipment train consists of a set of equipment for breaking, sizing, mixing and laydown operations. The material from a cold milling machine is screened and sized in a portable crusher and delivered to the pugmill of a traveling mixer. The mix is then windrowed or deposited on the hopper of a laydown machine. This method has a high production rate, produces no oversize material, and allows partial removal of asphalt layer. However, the method needs specialized equipment. The recycling agents, in the form of emulsified asphalt, cutback asphalt, and/or stabilizing agents such as portland cement, lime, fly ash and calcium chloride, are added to the mix with soil stabilization equipment. Proper aeration of the mix is required before compaction to reduce the water and volatile content of the recycled mix. A motor grader can be used to level and aerate the mix by blading back and forth across the roadway. Finally, the mix can be compacted with a steel wheel, pneumatic-tired or vibratory roller, or combinations of two or all three.

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CHAPTER 17. FULL DEPTH RECLAMATION (CASE HISTORIES AND QC/QA)

INTRODUCTION

Full depth reclamation is a rehabilitation technique in which all of the asphalt pavement section and a predetermined amount of underlying materials are treated to produce a stabilized base course. The procedure consists of five steps: (1) pulverization of existing material, (2) introduction of additive, (3) shaping of the mixed material, (4) compaction, and (5) application of wearing course. In general, asphalt emulsion and stabilizing additives such as portland cement, lime, fly ash, calcium chloride, and foamed asphalt are used in this procedure.

A review of published case studies of full depth reclamation shows that when executed properly, full-depth reclamation can effectively reconstruct pavements by eliminating a variety of distresses. This method provides a very economic alternative to conventional construction methods by reusing the existing pavement material. Some examples of pavement restoration by full depth reclamation are discussed below.

CASE HISTORIES

Reclamation of Mt. Wachusett Road, Princeton, MA[1] (1991)

The candidate pavement section was 9.7 m (32 ft) wide consisting of 75 mm (3 in) of HMA over 150 mm (6 in) of macadam base. Although there was no indication of base failure, the surface had become badly potholed. It was decided to use full depth reclamation with the application of liquid calcium chloride to make the material frost resistant.

In 1991, the existing HMA pavement and part of the underlying base was cut and pulverized to an average depth of 150 mm (6 in). A road reclaimer was used for this purpose (figure 17-1). Four passes of the 2.4-m (8-ft) wide machine completed the full width of the roadway. Next, a 35 percent solution of calcium chloride was applied to the pulverized material at a rate of 3.6 l/m^2 (0.75 gal/yd^2). The calcium chloride solution was applied by a spray bar on the rear of a 14,383 liter (3,800 gal) tank mounted on a truck (figure 17-2). In the next step, the base was pulverized a second time to thoroughly mix the aggregate, asphalt and calcium chloride. A grader was then used to shape the surface and a vibratory roller was used to compact the reclaimed base (figure 17-3). Finally, calcium chloride solution was applied at the rate of 1.2 l/m^2 (0.25 gal/yd^2) to seal the base surface. The reclaimed surface appeared to be hard, smooth and dust free. It was decided to put 50 mm (2 in) of HMA binder and 32 mm (1¼ in) of HMA wearing course on the reclaimed base. The reclaimed base was found to be capable of accepting traffic before the application of HMA binder and wearing courses (figure 17-4). Throughout the reclaiming process, traffic was allowed on the pavement and there was no need for setting up detours or applying any fog seal to the reclaimed base.

Figure 17-1. Road reclaimer used in FDR.

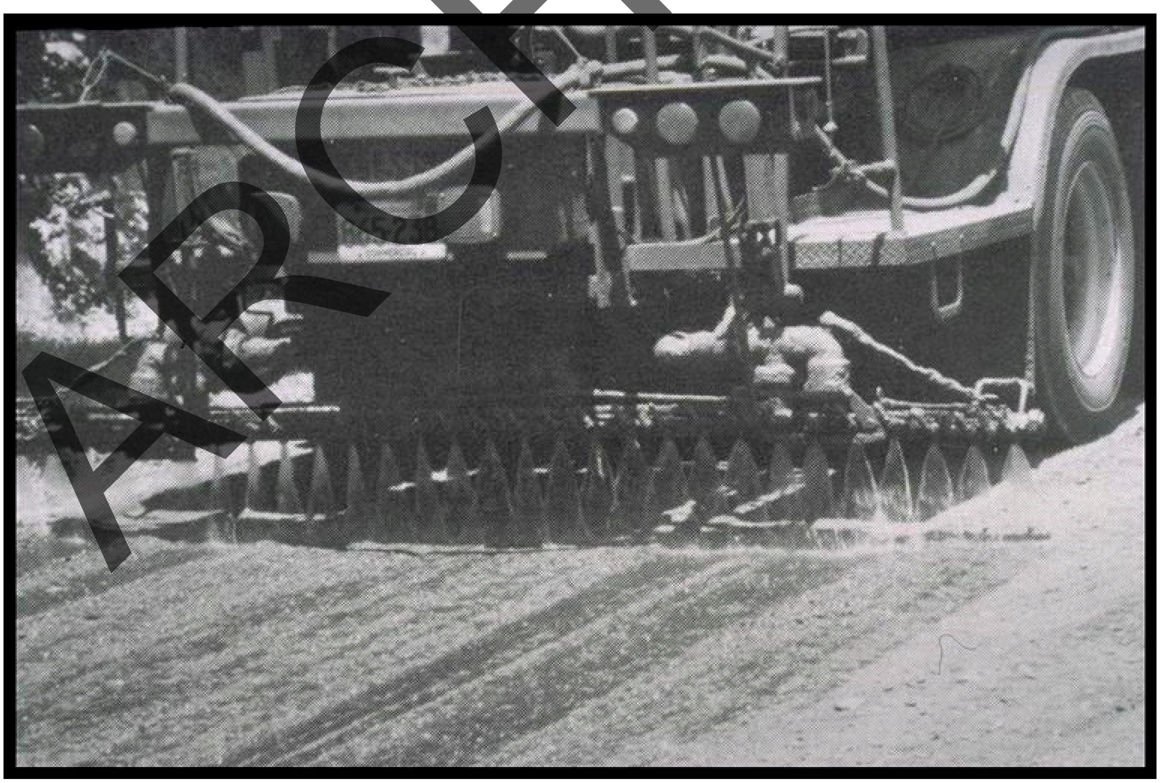

Figure 17-2. Application of calcium chloride.

Figure 17-3. Grader.

Figure 17-4. Completed surface.

Texas DOT Full Depth Reclamation Process[2] (1995)

In 1995, a project was completed on I-40, west of Amarillo, Texas. The project consisted of processing the 180 mm (7 in) of existing HMA and 76 mm (3 in) of the existing aggregate base. The existing material was milled, pulverized, screened, and treated with cement and water to produce a low strength cement treated base (CTB). The production of CTB base from recycled materials was all completed using two recycling trains. A MC-30 cutback asphalt was used to prime the finished CTB surface. Finally, HMA leveling and surface courses were placed above the CTB. Figure 17-5 shows the recycling train. Cement was applied ahead of the recycling train by a spreader (figure 17-6). The milling machine in the train milled the road material and deposited in the crusher screening unit (figure 17-7). After the material was crushed to the proper size, it was transferred to the mixer where cement, water and the existing material were mixed and deposited on a windrow (figure 17-8). A grader was then used to shape the windrow material (figure 17-9). Finally, a water tanker applied water to the surface (figure 17-10) for curing.

Full Depth Reclamation of Road in Mendota, California[3]

The existing pavement had severe alligator cracking, generally along the outer edges, and block cracking over most of the original surface. The asphalt surfacing was brittle where deflection occurred under loading. Figure 17-11 shows a view of the existing roadway. The structure of the roadway consisted of 40-mm (1.5-in) asphalt over 300-mm (12-in) silty sand of which the top 150 mm (6 in) was stabilized. It was decided to conduct full depth reclamation to a depth of 100

Figure 17-5. Recycling train used in FDR.

Figure 17-6. Application of cement.

Figure 17-7. Crusher and screening unit.

Figure 17-8. Recycled material in windrow from mixer.

Figure 17-9. Grader.

Figure 17-10. Water truck.

Figure 17-11. Condition of existing road.

mm (4 in) with foamed asphalt, cement and gravel. The amounts of additives were:

asphalt: 4 percent by mass of recycled material
cement: 2 percent by mass of recycled material
gravel: 50 mm (2 in) layer over area to be recycled.

It was decided to use cement along with the foamed asphalt to resist strength loss due to saturation. The gravel was included in the mix to facilitate good dispersion of foamed bitumen, especially with a high percentage of fine material (material passing 75 µm, No. 200 sieve). The amount of foamed asphalt was decided on the basis of laboratory mix design, and the amount of cement was determined from laboratory tests for plasticity of the recycled material. To serve as a wearing course and to prevent water ingress through the surface of the road, it was decided to apply a chip seal after about four weeks of construction of the base. The FDR process was carried out with a single machine along with a grader, spreader, asphalt tank, water tank, vibratory roller (9 Mg), and a pneumatic-tired roller (11 Mg). A schematic of the equipment is shown in figure 17-12. The virgin aggregate was spread by a spreader. Another spreader applied the cement on the existing surface. The grader spread the virgin material in front of the recycler. The recycler was connected to a water tanker and an asphalt tanker. The recycler milled and mixed the existing material with foamed asphalt. Another grader behind the recycler spread out the recycled material, which was then compacted with vibratory and pneumatic-tired roller, respectively. Figure 17-13 shows the recycler attached to the water and asphalt tank. Figure 17-14 shows the recycled material at the back of the recycler. Figure 17-15 shows a grader spreading the recycled material. Figure 17-16 shows a vibratory roller compacting the recycled material, and figure 17-17 shows the completed base course.

SPECIFICATIONS AND QC/QA

Since full depth reclamation is a type of cold recycling of asphalt pavements, specifications and quality control procedures for full depth reclamation are similar to those of cold-mix recycling. There are primarily two types of specifications. The method specification specifies the equipment to be used and all construction processes. An end result specification sets control limits on some test property of the finished pavement. However, as in the case of other recycling procedures, in full depth reclamation it is better to have a specification which is a combination of the method and end result specification. This allows the effective use of the experience and expertise of the user agency, the contractor, and the equipment manufacturer to obtain a good pavement at a reasonable cost.[4] Since there is usually a great variation in material properties in full depth reclamation, specifications for full depth reclamation tend to be more end result oriented than method specification.[5] For example, the specification may allow any type of milling or pulverization equipment, if the depth of the cut and the gradation of the RAP material (for example, top size) meet the required specification tolerance. The top size of the RAP material may be limited by the user agency. The gradation of the existing road materials should be taken into account when writing the specification for the aggregate gradation. Due to the inherent variability of material in full depth reclamation, it may not be practical to specify aggregate gradation for all the sieve sizes. However, the equipments used in full depth reclamation (pulverization, for example) should be capable of cutting the pavement to the specified depth reasonably well. The specification may state that the construction method shall be such as to pulverize the existing asphalt surface to the full depth, and the material shall be 97 percent passing a 50 mm sieve.[6]

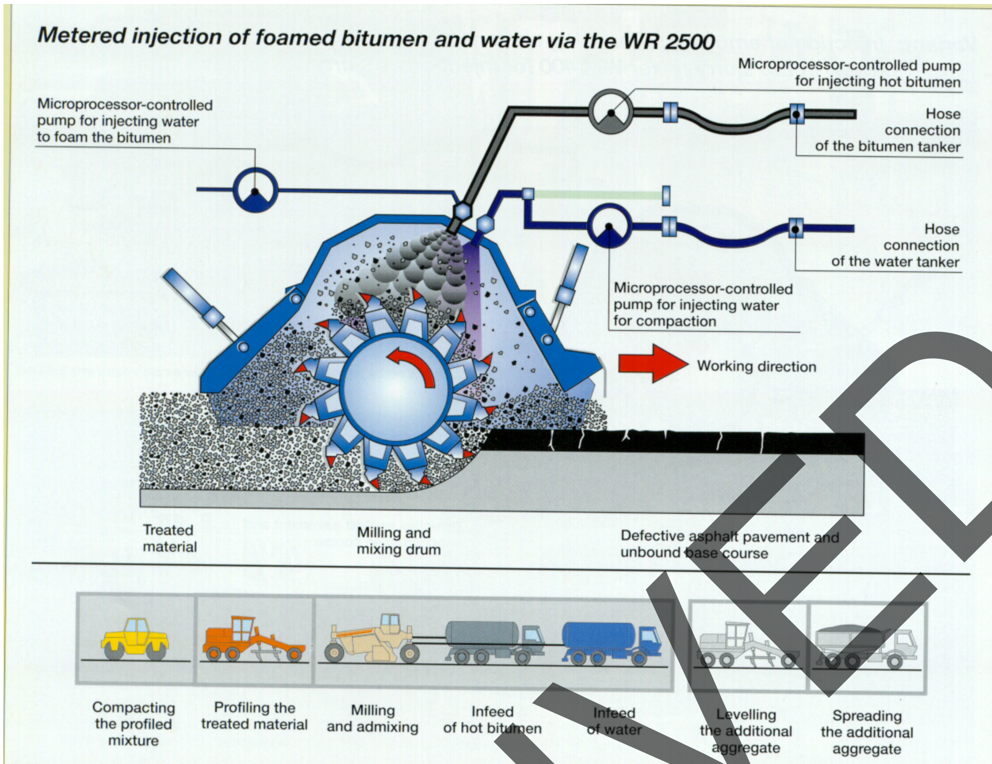

Figure 17-12. Schematic of recycler.

Figure 17-13. Recycler with water and asphalt tanker.

Figure 17-14. Recycled material at the back of recycler.

Figure 17-15. Grader spreading recycled material.

Figure 17-16. Vibratory roller compacting recycled material.

Figure 17-17. Recycled base course.

The next important thing in full depth reclamation is the specification for the asphalt recycling agent. The recycling agent should conform to the appropriate AASHTO, ASTM or state specifications for different types of asphalt binders, such as emulsified asphalt. Also, the equipment used for adding the recycling agent should be capable of an accurate application rate such that the total binder content of the recycled mix is equal to the job-mix formula amount within a specified tolerance, typically ± 0.5 percent.[5] The specification should also include clear directions regarding accurate application of any pre-mix water, if needed. The responsibility for establishing the job-mix formula and the required sampling procedures, test methods and design criteria for the mix design should be clearly outlined in the specification.[5]

Adjustments to the gradation or asphalt content of the recycled mix can be made based on the results from the extraction tests conducted on recycled mix. Conventional methods of extraction (reflux, centrifuge, vacuum) which solvents are being phased out by many highway agencies. The National Center for Asphalt Technology (NCAT) has developed a test method to determine the asphalt content of HMA mixtures by ignition. The gradation of the aggregate can then be determined using the standard sieve analysis. Larger samples (2,400 grams, 5.28 lb) can also be tested.

The density of the compacted mat is another important test property for specification. The density can be specified either as a percentage of theoretical maximum density or laboratory density, or as a target density. The use of theoretical maximum density is recommended over the use of laboratory density, since there may be substantial differences in temperatures, fluid contents and other conditions between laboratory and field compactions. Specification of a target density (in actual kg/m^3, lb/ft^3 unit) combined with an adjustable rolling pattern has also been suggested to overcome the problem of material variability in the existing pavement.[7] When deciding on a density specification, prior experience with similar type of recycling and environmental conditions should be taken in account. Typical cold-mix recycling specifications require air voids content in the 12 to15 percent range.[8] This may also be applicable to mixes from full depth reclamation. To obtain desired density, an agency may specify the roller sequence for compaction. For example, for a compacted depth of 150-200 mm, a minimum 22.7 Mg rubber tired roller with 620 kPa tire pressure followed by a minimum 7.2 Mg vibrating steel roller may be specified.[6]

In the absence of proper performance data for developing statistically based specifications, it is suggested that the user agency remains flexible and evaluate several alternatives to encourage competition.[5] The specification should be written in such a way that it reflects the following functions of the user agency:[4]

1. Be responsible for the adequacy of design alternatives.
2. Write simple straightforward specifications which clearly state what is expected.
3. Permit the contractor to select the materials and methods which will accomplish the end result.
4. Use standard specifications familiar to the contractor.
5. Modify standard specification only as necessary to obtain the end result
6. Focus on end results by allowing the contractor flexibility in choosing the most economical methods and procedures to accomplish the work.

The Wisconsin DOT specification for full depth reclamation is provided in Appendix C.

Quality Control and Quality Assurance

Quality control (QC) refers to those tests necessary to control a product and to determine the quality of the product being produced. These QC tests are usually performed by the contractor. Because of greater variation expected in the case of full depth reclamation asphalt mixtures, the frequency of testing should be more, even though the same tests that are used in the case of conventional HMA may be used. Before starting construction, it is very important to know the quality of the existing pavement, in terms of aggregate gradation and asphalt content of the mix. The pavement should first be delineated into subprojects, on the basis of differences in design, maintenance and rehabilitation actions. Once the subprojects are identified, representative samples should be taken from each of the subprojects. In this way, the variation in the existing material can be identified and evaluated.

The quality control for full depth reclamation is primarily dependent upon the equipment used. The equipment should be such as to allow the following operations.[9]

1. Pulverization of recycled pavement material to the desired size.
2. Proper pre-mix water content (uniformly mixed), if needed.
3. Proper recycling agent content (uniformly mixed).
4. Attainment of some minimum specified mat density.

Favorable temperature and moisture conditions are necessary for strength development during the curing period. The stabilized surface should be protected from traffic to prevent abrasion and to ensure adequate time for strength development.

SUMMARY

In full depth reclamation technique, all of the asphalt pavement section and a predetermined amount of underlying materials are treated to produce a stabilized base course. The treatment additive can be emulsified asphalt binder, portland cement, lime, fly ash, and calcium chloride. The procedure consists of pulverization of existing material, introduction of additive, shaping of existing material, compaction, and application of wearing course. A review of some case histories show that full depth reclamation can be used successfully and without major traffic flow interruption with the types of equipment available at present. Typical specification and quality control/quality assurance factors include aggregate gradation, stabilizer content, water content, roller weight and sequence, and density measurements.

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CHAPTER 18. STRUCTURAL DESIGN OF RECYCLED PAVEMENTS

INTRODUCTION

Structural design of pavements takes into consideration those aspects of design which provide required strength or stiffness to the pavement structure. The method has evolved from the application of engineering judgement to predominantly mechanistic or semi-mechanistic procedures. Pavement materials can now be characterized by resilient modulus and fatigue characteristics, and pavement materials with different strength and structure can be denoted by appropriate "structural numbers." Recycled asphalt materials can provide pavements similar or even better than pavements constructed with conventional hot mix asphalt. However, the wide range of properties of recycled mixes, resulting from variation in material and construction methods must be considered during structural design of recycled pavements.[1] On an average, the coefficients for both recycled surface and recycled base courses are found to be greater than the coefficients for respective conventional mixes determined in the AASHTO Road Test. The AASHTO guide indicates that in essence there is no difference between hot recycled and virgin HMA material, and recommends the structural rehabilitation analysis method (for conventional mix) for design of recycled pavements as well.[1] However, it also cautions that since long-term performance data is not available for recycled mixes, engineering judgement should always be applied for design of such mixes. In this chapter design guidelines recommended by AASHTO and the Asphalt Institute are discussed.

STRUCTURAL DESIGN OF RECYCLED HOT MIX ASPHALT PAVEMENT AASHTO

Method

The AASHTO guide[1] presents a method of overlay design based primarily on structural number, thickness of underlying layers, and drainage coefficients. Design of recycled pavements can be based on the same methodology.[1] Basically, a nomograph is used to calculate a combined total structural number for the whole pavement section, based on performance period, traffic, and change in Present Serviceability Index (PSI). The structural number can be represented by a combination of product of depth, structural number, and drainage coefficients for each of the pavement layers. The structural number of the recycled layer required is calculated by subtracting the effective structural number of the existing pavement from the structural number required by the "new pavement," which includes the recycled layer. The effective structural number of the existing pavement is modified by a remaining life factor for the existing pavement. The equation is as follows:

$$SN_{OL} = SN_{Y} - (F_{RL} \text{ X } SN_{xeff})$$

where:

- SN_{OL} = structural number of the required overlay
- SN_{Y} = structural number required for a "new" pavement to carry the estimated future traffic for the prevailing roadbed soil support conditions
- F_{RL} = remaining life factor

Sn_{xeff} = effective structural number of the existing pavement at the time the overlay is placed

Structural number (SN) is defined as follows:

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3$$

where:

a_1, a_2, a_3 = layer coefficients representative of surface, base, and subbase courses, respectively

D_1, D_2, D_3 = actual thickness (in mm, inch) of surface, base and subbase courses, respectively

m_2, m_3 = drainage coefficients for untreated base and subbase layers, respectively

One important feature of the design method is the inclusion of reliability factor in traffic and performance prediction. The reliability design factor considers chance variations in both traffic predictions (the actual number of load applications during the analysis period in terms of equivalent 18-kip single-axle loads, ESAL) and performance prediction (the number of ESALs that will result in the pavement reaching a specified terminal serviceability level). A reliability level, R, and an overall standard deviation, S_o, are the required input parameters for calculating reliability. A higher value of R means a greater assurance of pavement serviceability for the design period, and hence a greater thickness and a higher cost. Values of S_o are based on pavement types and are available for flexible and rigid pavements.[1] The details of the design method are presented in the AASHTO guide.(1) A simplified flow chart is shown in figure 18-1.

Asphalt Institute Method

For hot-mix recycling, the Asphalt Institute[2] recommends the same design procedure as for conventional mixes. It has been recommended to use the method outlined in the Asphalt Institute's publication "Thickness Design - Asphalt Pavements For Highways and Streets."[3,4] The parameters required for designing the pavement thickness include the following:

1. Equivalent 18-kip single-axle load (ESAL) applications. A simple traffic estimation procedure[4] is presented in table 18-1. This can be utilized on the basis of roadway type. A detailed analysis can also be performed based on type of vehicle, truck factor for each vehicle, and single or multiple growth factors. The design ESAL is calculated by the summation of the products of number of vehicles and the corresponding truck and growth factors.
2. Resilient Modulus, M_R of the subgrade. This can be determined by testing or through correlations with CBR or R-value, as presented in table 18-2.
3. Type of surface and base. The total required pavement thickness can be calculated by entering the design traffic and M_R values in the design charts. In the comparison of properties of recycled materials to those of new materials, the recycled materials are to be considered equivalent to conventional mix in the design procedure.

The overlay design procedure, as outlined in the Asphalt Institute Manual, Asphalt Overlays for Highways and Street Rehabilitation,[5] can also be used for thickness design. The overlay thickness is calculated as the difference between the thickness required by a new pavement to the

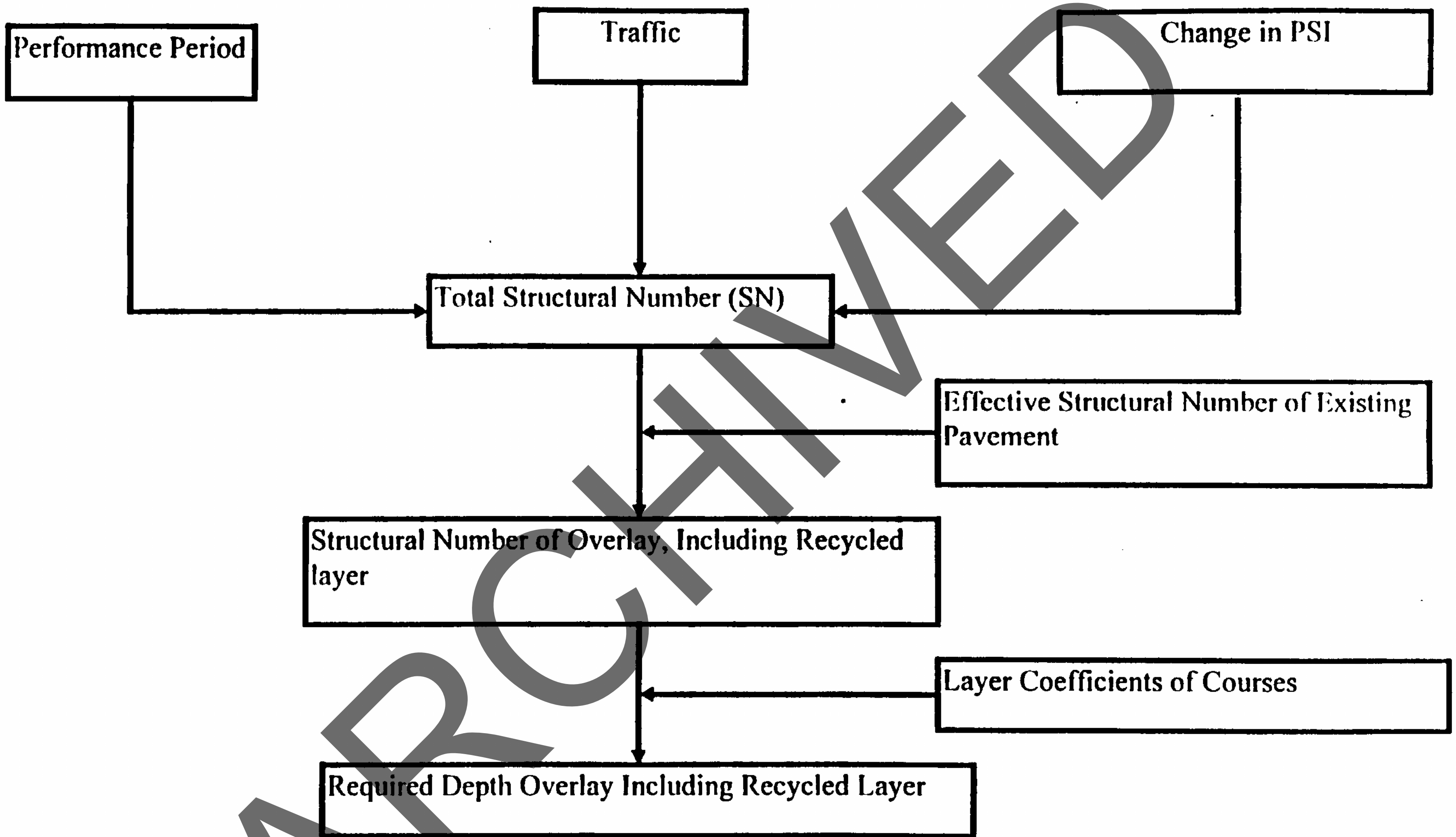

Figure 18-1. Flow chart for AASHTO design method.

Table 18-1. Traffic analysis.[4]

Whenever possible the traffic analysis and design procedures given in The Asphalt Institute manual, Thickness Design - Asphalt Pavements for Highways and Streets (MS-1) should be used. However, in many cases it is necessary to estimate traffic using only limited information. In such cases, the following table may be used.

Definitions

The following definitions apply to the traffic analysis procedure:

ESAL is defined as equivalent 80 kN (18,000 lb) single-axle load applications. It is the effect on pavement performance of any combination of axle loads of varying magnitude equated to the number of 80 kN (18,000 lb) single-axle loads required to produce an equivalent effect.

Heavy trucks are described as two-axle, six-tire trucks or larger. Pickup, panel and light four-tire trucks are not included. Trucks with heavy-duty, wide-base tires are included.

Traffic Classifications

Traffic Class	ESAL	Type of Street or Highway	Approximate Range - Number of Heavy Trucks Expected During Design Period
I	5×10^3	Parking lots, driveways Light traffic residential streets Light traffic farm roads	5,000-7,000
II	10^4	Residential streets Rural farm and residential roads	7,000-15,000
III	10^5	Urban minor collector streets Rural minor collector roads	70,000-150,000
IV	10^5	Urban minor arterial and light industrial streets Rural major collector and minor arterial highways	700,000-1,500,000
V	3×10^6	Urban freeways, expressways and other principal arterial highways Rural Interstate and other principal arterial highways	2,000,000-4,500,000
VI	10^7	Urban Interstate highways Some industrial roads	7,000,000-15,000,000

Table 18-2. Subgrade soil.[4]

It is desirable to use laboratory tests to evaluate the load-supporting characteristics of subgrade soils. However, if laboratory test equipment is not available, designs may be made on the basis of a careful field evaluation by an engineer who can assign the subgrade soils to one of the following categories:

Poor Subgrade Soils

These soils become quite soft and plastic when wet. Included are those soils having appreciable amounts of clay and fine silt. The coarser silts and sandy loams may also exhibit poor bearing properties in areas where frost penetration into the subgrade is a factor. Typical properties: Resilient modulus = 30 Mpa (4,500 psi) CBR = 3, R-value = 20.

Good to Excellent Subgrade Soils

Good subgrade soils retain a substantial amount of their load-support capacity when wet. Included are the clean sands and sand-gravels and soils free of detrimental amounts of plastic materials. Excellent subgrade soils are unaffected by moisture or frost. They include clean and sharp sands and gravels, particularly those that are well graded. Typical properties: Resilient modulus - 170 Mpa (25,000 psi), CBR = 17, R-value = 43.

The Asphalt Institute's Soils Manual (MS-10) describes in detail the commonly used soil evaluation systems and test procedures listed below. Field evaluation of the soil involves visual inspection and simple field tests.

Resilient Modulus (Mr)

A test used for evaluating the stress-strain properties of materials for pavement thickness design.

California Bearing Ratio (CBR)

A test used for evaluating bases, subbases, and subgrades for pavement thickness design.

Resistance Value (R-value)

A test used for evaluating bases, subbases, and subgrades for pavement thickness design.

design traffic ESAL and the effective thickness of the existing pavement. The effective thickness of the existing pavement can be determined by either of two methods. In one method a condition rating, the Present Serviceability Index, and equivalency factors for converting various pavement materials to equivalent thicknesses of asphalt concrete (figure 18-2 and table 18-3) are used. The second method uses the conversion factors for each pavement layer (based on the condition of each layer prior to overlay) to directly convert each layer to an equivalent thickness of asphalt concrete (table 18-4). Figure 18-3 shows the recommended chart for determining the thickness of a full depth HMA pavement for new construction. The effective thickness of the existing pavement should be subtracted from the thickness of the recycled layer. A simplified flow chart for the Asphalt Institute Design method is shown in figure 18-4. Three examples for determining the thickness of recycled layers are shown in figure 18-5.[5]

Other Design Methods

The National Stone Association method can also be used for design of hot recycled mix. The method is based on the Corps of Engineers method and mechanistic design procedures. The

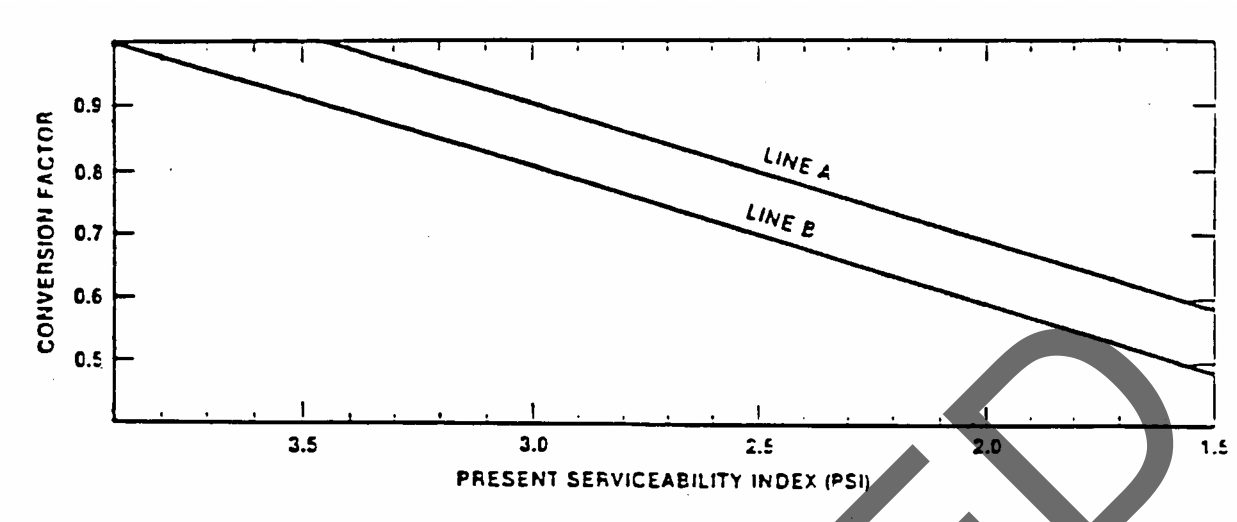

Figure 18-2. Conversion factors.[5]

Table 18-3. Equivalency factors for converting layers of material types to equivalent thickness of asphalt concrete.[5]

Material Type	Equivalency Factor (E)
Asphalt Concrete	1.00
Type I Emulsified asphalt base	0.95
Type II Emulsified asphalt base	0.83
Type III Emulsified asphalt base	0.57
Type I - Emulsified asphalt mixes plant-mixed with processed, dense-graded aggregates, and having properties similar to asphalt concrete.	
Type II - Emulsified asphalt mixes made with semi-processed crusher-run, pit-run, or bank-run aggregates.	
Type III - Emulsified asphalt mixes with sands or silty sands.	

mechanistic design process assumes that the pavement can be modeled as a multilayered elastic or viscoelastic structure on an elastic or viscoelastic foundation, and stress, strain and deformations are calculated accordingly. A number of computer programs are available which can determine pavement responses (stress, strain) at different locations with the help of wheel load data, material properties, such as Elastic Modulus and the Poisson's ratio and the thickness of layers. Such computer programs include CHEV5L (Chevron Research Co.), BISTRO and BISAR (Shell Oil Co.), ELSYM5 (University of California at Berkeley), PDMAP (NCHRP 1-10B), and DAMA (The Asphalt Institute). The VESYS program developed by the Federal Highway Administration uses the visco-elastic approach for calculation of pavement responses.

Table 18-4. Conversion factors for converting thickness of existing pavement components to effective thickness (T_c).[5]

Classification of Material	Description of Material	Conversion Factors*
I	a) Native subgrade in all cases b) Improved Subgrade** - predominantly granular materials - may contain some silt and clay but have P.I. of 10 or less c) Lime modified subgrade constructed from high plasticity soils - P.I. greater than 10.	0.0
II	Granular subbase or base - reasonably well-graded, hard aggregates with some plastic fines and CBR not less than 20. Use upper part of range if P.I. is 6 or less; lower part of range if P.I. is more than 6.	0.1-0.2
III	Cement or lime-fly ash stabilized subbases and bases** constructed from low plasticity soils - P.I. of 10 or less.	0.2-0.3
IV	a) Emulsified or cutback asphalt surfaces and bases that show extensive cracking, considerable raveling or aggregate degradation, appreciable deformation in the wheel paths, and lack of stability. b) Portland cement concrete pavements (including those under asphalt surfaces) that have been broken into small pieces 0.6 meter (2 ft) or less in maximum dimension, prior to overlay construction. Use upper part of range when slab is on subgrade. c) Cement or lime-fly ash stabilized bases** that have developed pattern cracking, as shown by reflected surface cracks. Use upper part of range when cracks are narrow and tight; lower part of range with wide cracks, pumping or evidence of instability.	0.3-0.5
V	a) Asphalt concrete surface and base that exhibit appreciable cracking and crack patterns. b) Emulsified or cutback asphalt surface and bases that exhibit some fine cracking, some raveling or aggregate degradation, and slight deformation in the wheel paths but remain stable. c) Appreciably cracked and faulted portland cement concrete pavement (including such under asphalt surfaces) that cannot be effectively undersealed. Slab fragments, ranging in size from approximately one to four square meters (yards), and have been well-seated on the subgrade by heavy pneumatic-tired rolling.	0.5-0.7

Table 18-4. Conversion factors for converting thickness of existing pavement components to effective thickness (T_c) (continued).[5]

Classification of Material	Description of Material	Conversion Factors*
VI	a) Asphalt concrete surfaces and bases that exhibit some fine cracking, have small intermittent racking patterns and slight deformation in the wheel paths but remain stable. b) Emulsified or cutback asphalt surface and bases that are stable, generally uncracked, show no bleeding, and exhibit little deformation in the wheel paths. c) Portland cement concrete pavements (including such under asphalt surfaces) that are stable and undersealed, have some cracking but contain no pieces smaller than about one square meter (year).	0.7-0.9
VII	a) Asphalt concrete, including asphalt concrete base, generally uncracked, and with little deformation in the wheel pahts. b) Portland cement concrete that is stable, undersealed and generally uncracked. c) Portland cement concrete base, under asphalt surface, that is stable, non-pumping and exhibits little reflected surface cracking.	0.9-1.0

Notes:

* Values and ranges of Conversion Factors are multiplying factors for conversion of thickness of existing structural layers to equivalent thickness of asphalt concrete.

** Originally meeting minimum strengths and compaction requirements specified by most state highway departments.

Different state DOTs have also developed their own pavement design methods of which very few employ the direct use of the mechanistic design procedures.

STRUCTURAL DESIGN OF RECYCLED COLD-MIX ASPHALT PAVEMENTS

Two main types of design methods are available for design of cold-mix recycled layers. One method uses the pavement layer coefficients and the other involves the characterization of pavement as a multi-layered elastic system. The AASHTO method, which uses the layer coefficient method, and the Asphalt Institute method, which is an example of multi-layered elastic structure approach, are discussed below.

AASHTO Method

The 1986 AASHTO Design Guide[1] presents the method of using a structural number, SN, which is a combination of layer coefficients and layer thicknesses for the various layers in the pavement. The required SN for a particular reliability level, R, and overall standard deviation, S_o,

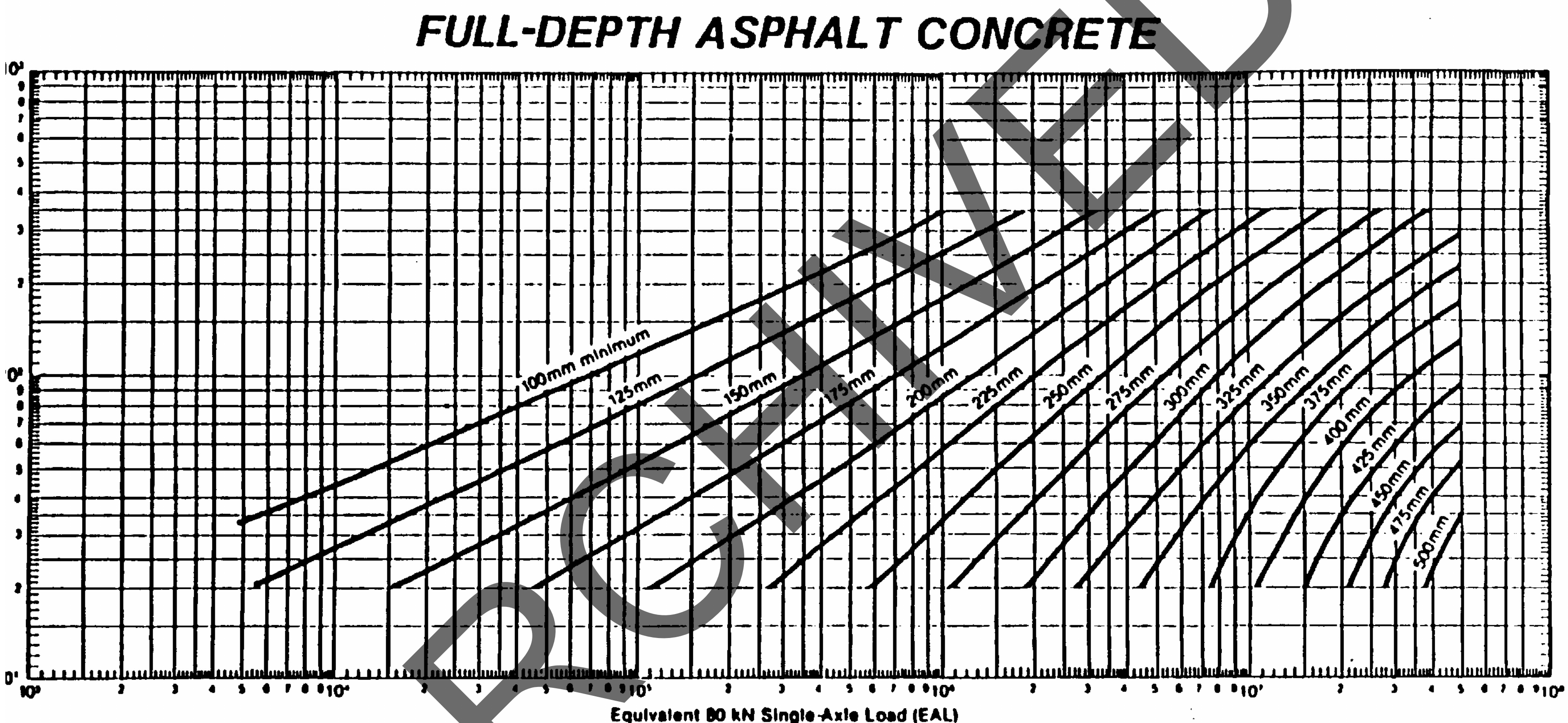

Figure 18-3. Design chart for full-depth asphalt concrete.[5]

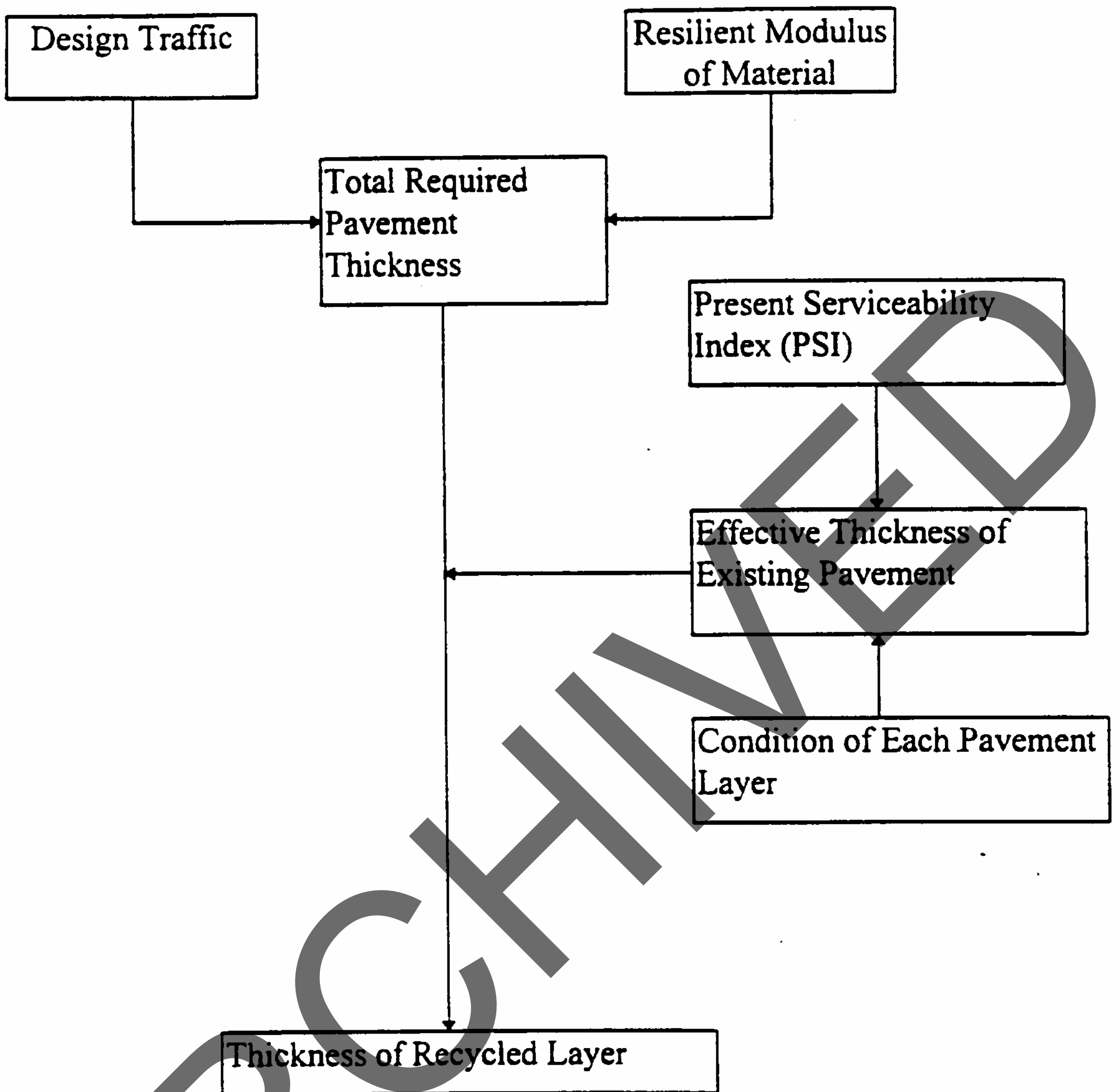

Figure 18-4. Flow chart for Asphalt Institute design method.

the estimated traffic level (ESAL) for the design period, the effective resilient modulus of the roadbed soil or the subgrade and the serviceability loss in terms of the Present Serviceability Index (PSI) can be determined from nomographs. A factor for including the effect of drainage conditions is also included for each of the unbound layers. The SN equation is as follows:

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3$$

where:

a_1, a_2, a_3, = layer coefficients representative of surface, base, and subbase courses, respectively

D_1, D_2, D_3 = actual thickness (in mm, inch of surface, base and subbase courses, respectively

m_2, m_3 = drainage coefficients for untreated base and subbase layers, respectively

<u>Example</u> (Method 1):

Determine the effective thickness of a two-layer full-depth asphalt pavement, PSI = 2.3. Even though cracked, the cracks are not open and the pavement appears to be stable. It consists of a 50-mm (2-in) asphalt surface course and a 150-mm (6-in) Type 11 emulsified asphalt base course. A conversion factor C = 0.70 is selected from figure 18-2. An equivalency factor E = 0.83 for the Type 11 emulsified asphalt base is determined from table 18-3.

T_e (AC) = 50 (2) x 0.70 x 1.00 = 35 mm (1.4 in)
T_e (Type II) = 150 (6) x 0.70 x 0.83 = 87 mm (3.5 in)
T_e (All Layers) = 122 mm (4.9 in)

<u>Example</u> (Method 2):

Determine the effective thickness of a three-layer pavement consisting of a 100-mm (4-in) asphalt concrete surface, a 150-mm (6-in) cement stabilized base and a 100-mm (4-in) untreated crushed gravel base. The surface shows numerous transverse cracks and considerable alligator cracking in the wheel paths. The cement-stabilized base shows signs of pumping and loss of stability along the pavement edges. The conversion factors, C = 0.5 for the surface, C = 0.3 for the cement-stabilized base and C = 0.2 for the crushed gravel base, are determined from table 18-4.

T_e (AC Surface) = 100 (4) x 0.5 = 50 mm (2.0 in.)
T_e (Cement-Stabilized base) = 150 (6) x 0.3 = 45.7 mm (1.8 in.)
T_e (Gravel Base) = 100 (4) x 0.2 = 20 mm (0.8 in)
T_e (All Layers) = 116 mm (4.6 in) (use 4.5 in)

Figure 18-3 is used to determine the thickness of a full-depth asphalt concrete pavement of new construction from which is subtracted the effective thickness of the existing pavement to establish the thickness of the recycled layer.

<u>Example:</u>

Given - subgrade M_R = 82,800 kPa (12,000 psi)

$ESAL_d = 2 \times 10^6$

from figure 18-3, T_n (thickness of new pavement) = 241 mm (9.5 in)
T_e (effective thickness of new pavement) = 144 mm (4.5 in)
T_o (overlay thickness) $= T_n - T_e$
= (241 - 114)
= 127 mm (5.0 in)

Figure 18-5. Design examples for hot recycled mix.

If the recycled layer is treated as an overlay (above part of the original pavement) the equation for the structural number of the overlay is as follows:

$$SN_{OL} = SN_Y - (F_{RL} X\ SN_{xeff})$$

where:

SN_{OL} = structural number of the required overlay
SN_Y = structural number required for a "new" pavement to carry the estimated future traffic for the prevailing roadbed soil support conditions
F_{RL} = remaining life factor
Sn_{xeff} = effective structural number of the existing pavement at the time the overlay is placed

The resulting overlay thickness would include the thickness of the cold recycled layer plus the thickness of the asphalt concrete surface layer, if used. Table 18-5 shows the typical AASHTO structural layer coefficients obtained from a variety of recycled test sections using several types of recycled material (a refers to layer coefficient). These values were derived from the results of AASHTO Road Test and layered elastic programs. Layer coefficients for cold-recycled mixes can be derived from these values. Coefficients of foamed-asphalt recycled layers were found to range from 0.20 to 0.42 with a midpoint value of 0.31 according to a study reported in 1984.[(6)] The range for emulsion recycled layer ranged from 0.17 to 0.41 with a midpoint value of 0.29. A value between 0.30 and 0.35 can be considered appropriate for cold recycled mixes, as compared to a value of 0.44 for hot mix asphalt concrete.[(3)] However, the structural coefficient of cold recycled mixes is dependent on several other factors such as cure rate, and must be evaluated on the basis of sound engineering judgement.

Asphalt Institute Method

The thickness design method presented in The Asphalt Institute Manual for Cold-Mix Recycling[(7)] is based on the use of emulsified asphalt mixes but is considered applicable for cold-recycled mixtures made with other types of asphalt binders such as asphalt cement. The required input parameters include estimated design traffic level and subgrade strength. Design charts, shown in figures 18-6 and 18-7[(1)] can be used to determine the thickness of the recycled layers.

Traffic is classified by ESAL, type of street or highway, or by volume of heavy trucks (table 18-2, mentioned before). The subgrade support is classified by type of subgrade or obtained from Resilient Modulus, CBR, or R-value test data (table 18-3, mentioned before). The mix can be classified into two types—Type A and B. Type A is the mix which consists of semi processed, crusher run, pit ran or bank run aggregates, mixed in central plants or by travel plants (figure 18-6). Type B includes mixes which use sands or silty sands, mixed in central plants, or by travel plants, rotary mixers or motor graders. This type of mix also includes Type A aggregate (as explained in table 18-6) when mixed by rotary mixer or motor grader (figure 18-7). The output from the design chart gives the combined thickness of a recycled cold-mix base and an asphalt surface course. Table 18-7[(7)] shows the recommended thicknesses of asphalt surfaces over cold-mix recycled bases. A surface course of asphalt concrete or emulsified asphalt mix Type I (plant-mixed, laboratory designed, emulsified asphalt mixes made with dense graded aggregate and having properties similar to asphalt concrete) may be substituted for a portion of the thickness of

Table 18.5. Typical AASHTO structural layer coefficients.[1]

Type of Recycled Material Used	Layer Used As	Range of a_i Computed	Average a_i	Number of Test Sections	a_i for Corresponding Layer and Material at AASHTO Road Test
Central plant Recycled asphalt Concrete surface	Surface	0.37-0.59	0.48	14	0.44
Central plant Recycled asphalt Concrete surface	Base	0.37-0.49	0.42	3	0.35
In-place recycled asphalt concrete stabilized with asphalt and/or an asphalt modifier	Base	0.23-0.42	0.31	4	0.15-0.23
In-place recycled asphalt concrete and existing base material stabilized with cement	Base	0.40	0.40	1	0.15-0.30
In-place recycled asphalt road mix stabilized with asphalt	Surface	0.42	0.42	1	

Note:
a_i - Layer Coefficient.

emulsified asphalt Type A or B mix obtained from the design chart. When Type I emulsified asphalt mix is used, a single or double surface treatment should be used as a wearing course, but this should not be substituted for any of the thickness obtained from a design chart. For light traffic conditions, ESAL less than 10^4, a surface treatment may be placed directly on, but should not be substituted for. any portion of the thickness of Type A or B emulsified asphalt mix obtained from a design chart. Two design examples are shown in figure 18-8[1]

STRUCTURAL DESIGN FOR ASPHALT SURFACE RECYCLING

The load carrying capacity of an existing pavement cannot be improved by asphalt surface recycling, since this method is used for only 50 mm (2 in) or less depth of the pavement. The improvement can be effected only by improving the existing HMA mix. Surface distress can be removed but structural or subgrade problems which cause the distresses cannot be eliminated by this method.[3] The thickness of the overlay will depend on the purpose of recycling. If the objective is to rejuvenate the upper layer of the existing material and improve the ride quality of a structurally adequate pavement, then a minimum thickness should be considered on the basis of the maximum size of the aggregate used for the overlay mix. In general, the thickness of the overlay should not be less than 1½ times the maximum particle size in the new mix.[3] On the other hand, if the primary purpose is to increase the load carrying capacity of the mix, then the overlay should be designed according to conventional methods to yield the required strength. Depending on the specific need of the overlay, the thickness can range from 25 mm to 100 mm

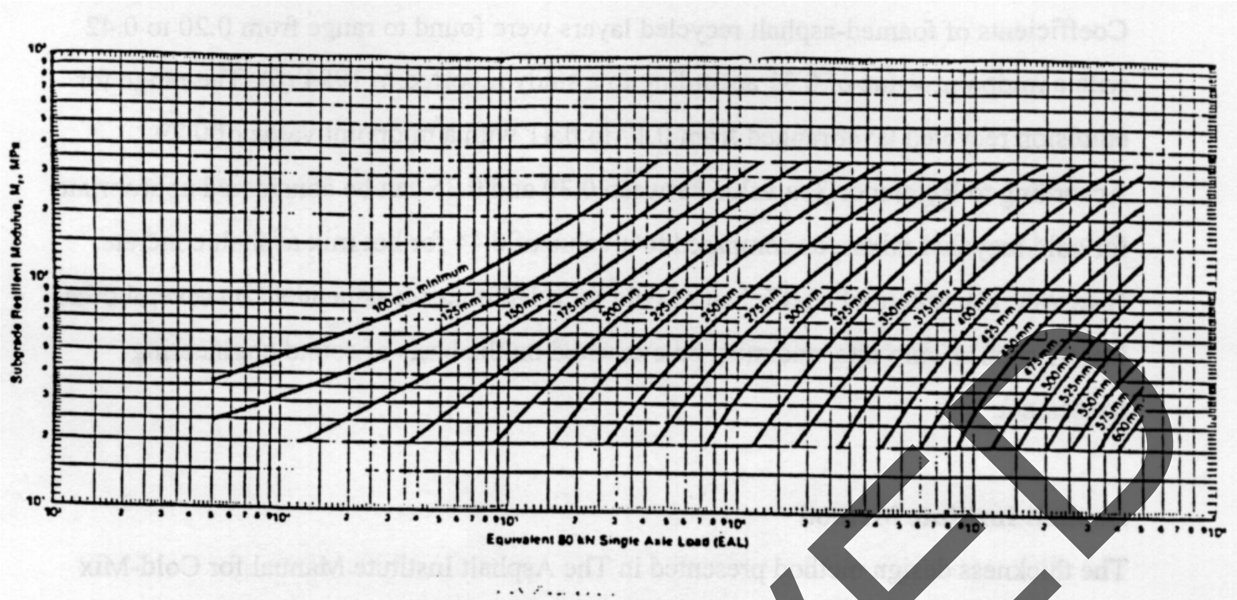

Figure 18.6. Design charts (metric units) for recycled cold mixed Type A.(7)

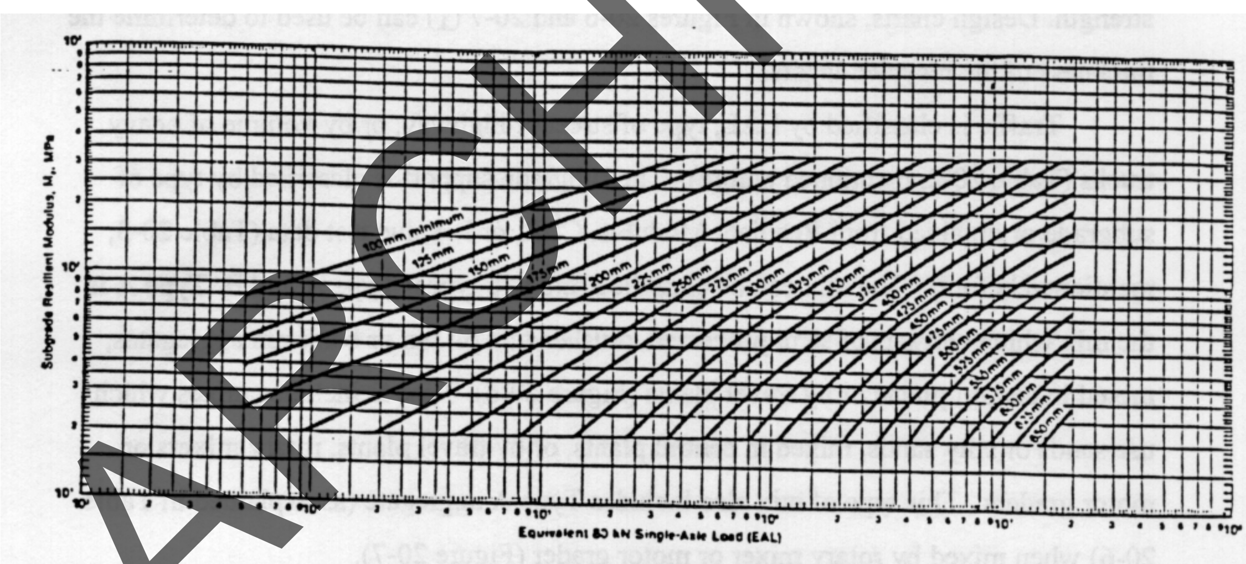

Figure 18.7. Design charts (metric units) for recycled cold mixed Type B.(7)

Table 18.6. Gradation guidelines for cold mix recycling.(7)

Sieve Size	Percent Passing by Weight						
	Open-Graded			Dense-Graded			
	A	B	C	D	E	F	G
38.1 mm (1½ in)	100			100			
25.0 mm (1 in)	95-100	100		80-100			
19.0 mm (3/4 in)		90-100					
12.5 mm (½ in)	25-60		100		100	100	100
9.5mm (3/8 in)		20-55	85-100				
4.75 mm (No. 4)	0-10	0-10		25-85	75-100	75-100	75-100
2.36 mm (No. 8)	0-5	0-5					
1.18 mm (No. 16)			0-5				
300 µm (No. 50)						15-30	
150 µm (No. 100)							15-65
75 µm (No. 200)	0-2	0-2	0-2	3-15	0-12	5-12	12-20

Table 18.7. Minimum thickness of surface course over cold-mix recycled base.(7)

Traffic Level (ESAL)[a]	Minimum Surface Course Thickness	
	mm	(in)
$<10^4$	x[b]	x[b]
10^4	50[c]	(2)[c]
10^5	50[c]	(2)[c]
10^6	75[c]	(3)[c]
10^7	100[c]	(4)[c]
$>10^7$	130[c]	(5)[c]

Notes:

[a] Equivalent 80 kN (18,000 lb) single-axle load applications.

[b] Single or double surface treatment.

[c] Asphalt concrete or Type 1 emulsified asphalt mix with a surface treatment.

Example 1:

Assume the following conditions:

Subgrade: Resilient Modulus = M_r = 30 Mpa (4,500 psi)
CBR = 3, R = Value = 6
Design Traffic: ESAL = 10^5
Combined aggregate gradation: Within Type A limits (semi-processed, crusher, pit or bank run)
From Design Chart, obtain the combined thickness of surface and base: 190 mm (7.5 in)
From table 18-7, the minimum thickness of the surface course is found to be 50 mm (2 in) for ESAL = 10^5.

The difference between the combined thickness and the minimum surface course is the thickness of the cold-mix recycled base:

190 mm (7.5 in) - 50 mm (2 in) = 140 mm (5.5 in)

If a portion of an old granular base is to remain below a recycled base the properties of the granular base materials should be evaluated, and appropriate layer equivalencies assigned for use in the thickness design. Conversion factors are listed in the following table. The remaining aggregate base and/or subgrade should be recompacted and primed if left as an aggregate base. Also, any drainage deficiencies in the old pavement structure should be corrected before reconstruction proceeds.(7)

Classification of Material	Description of Material	Conversion Factors*
A	Native subgrade in all case	0.0
B	Improved subgrade-predominantly granular materials - may contain some silt and clay but have a P.I. of 10 or less (improved subgrade = any course or courses of improved material between the native subgrade soil and the pavement structure).	0.00
C	Granular subbase or base - reasonably well graded, hard aggregates with some plastic fines and CBR not less than 20. Use upper part of range if P.I. is 6 or less; lower part of range if P. I. is more than 6.	0.1-0.2

These conversion factors apply only to pavement evaluation for cold-mix recycling. In no case are they applicable to original thickness design.

*Values and ranges of conversion factors are multiplying factors for conversion of thickness of existing structural layers to equivalent thickness of cold-mix recycled base.

Example 2:

A cold-mix recycling design requires 150 mm (6 in) of recycled base. 100 mm (4 in) of well graded, hard aggregates with a plasticity index (P. I.) Of 5 are left to remain below the recycled base. A conversion factor of 0.2 is obtained for the aggregate layer. The effective thickness of the remaining granular base is 100 mm (4 in) X 0.2 = 20 mm (0.8 in). Therefore, the recycled base thickness is reduced from 150 mm (6 in) to 130 mm (5 in).

Figure 18-8. Design examples for cold-recycled mix.(7)

(1 to 4 in).[8]

The thickness of the overlay will also depend on the construction method, since extra structural capacity can be added (a) through an overlay after heating, scarifying, rejuvenating, and compacting the recycled mixture, (b) by blending virgin mix with scarified old mix prior to compaction (re-mixer process), or (c) by overlaying the loose, scarified, and rejuvenated old mix with loose, virgin mix and compacting both at the same time (re-paving process). Either of the three methods can produce an acceptable surface. When the two mixes are not mixed together, some extra structural advantage can be obtained, but only the new mix is considered to comprise the overlay. An allowance can be made for the rejuvenating effect of the recycling process in determining the effective thickness or remaining life of the existing pavement. The material that has been recycled with a modifier will provide a soft layer that can act as a stress-relieving layer. This layer acts as a barrier in crack propagation through the new surface, especially when thin overlays are used. It is possible that a 25-mm (1-in) overlay over 25 mm (1 in) of recycled material can provide better performance than 65 mm (2½ in) of new overlay over the original surface.[9] If the recycled material is mixed with new aggregate or asphalt concrete mix, then the resulting additional thickness is considered as an overlay. Both mix design and structural design would be the same as for hot mix recycling.

SUMMARY

The method of structural design, which provides the required strength to a pavement structure, has evolved from an empirical to a semi-mechanistic procedure. Since hot recycled asphalt material can provide similar or even superior performance compared to conventional hot mix asphalt, the AASHTO design guide indicates that there is essentially no difference between the recycled and virgin materials, and recommends the structural rehabilitation analysis method for conventional mix for design of recycled pavements as well.

The AASHTO method for design of hot mix recycled asphalt is based on the derivation of the structural number required for the pavement with the help of design traffic, reliability level of prediction of traffic and performance, performance period, and the pavement condition rating. The structural number can be expressed as the sum of the product of the depth, layer coefficient, and drainage coefficient of each of the layers. The structural number for the recycled layer, which can be treated as an overlay, can be calculated as the difference between the structural number required by the finished pavement and the structural number of the existing pavement. Values of layer coefficients are also presented in the AASHTO design guide. The Asphalt Institute method uses the traffic level, the subgrade resilient modulus, and the type of surface and base to calculate the design thickness. In this method also, the hot recycled material can be considered to be similar in performance to conventional hot mix. In another Asphalt Institute procedure, the recycled layer can be considered as an overlay and its thickness can be calculated as the difference between the total thickness required by the pavement and the thickness of the existing pavement. The total thickness required can be determined on the basis of condition rating of the pavement and a method of converting and expressing each type of material or pavement layer as equivalent thickness of asphalt concrete layer. Other methods include design procedures based on load-deformation response calculation by computer methods with the help of loading and material properties of the pavement layers. In such methods the pavement is assumed to behave as an elastic or viscoelastic layer on an elastic or viscoelastic layer.

The AASHTO design method for cold recycled mixes is similar to the design method for the hot-mix asphalt. However, layer coefficients for cold-recycled mixes are dependent on construction methods, and should be determined on the basis of engineering judgement. The Asphalt Institute method assumes the pavement as a multilayered elastic structure, and determines the required thickness on the basis of design traffic and subgrade strength. The combined thickness of cold-recycled base and surface course is obtained from charts. The thickness of cold-recycled bases can be obtained by taking into consideration the recommended thickness of hot mix asphalt overlay on the cold-recycled base.

Since asphalt surface recycling does not normally improve the structural capacity of an existing pavement, there is no method for thickness design of surface recycling. However, the thickness of any overlay should be based on conventional overlay design method. If the overlay is meant to improve the ride qualities only, then the minimum thickness should be based on the maximum aggregate size used in the mix.

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GLOSSARY

Asphalt Surface Recycling - Reworking and/or removal of the surface of a pavement by planing or scarifying devices.

Cold Milling - An automatic removal method of asphalt pavement by machines having rotating drum lined with variable number of tungsten-carbide tipped teeth.

Cold-Mix Recycling - A method in which the existing pavement material is reused without the application of heat. The process can be carried out in-place (cold in-place recycling) or at a central plant.

Cold Planing - An automatic removal method of asphalt pavement by shearing off the surface.

Full Depth Reclamation - A recycling method in which all of the asphalt pavement section and a predetermined amount of underlying material is treated to produce a stabilized base course.

Heater Planing - A process in which a device heats the pavement surface and a stationary or vibratory flat steel blade or plate is used to shear off up to 25 mm of the heated surface.

Heater Scarification - A process in which a device heats the pavement surface and stationary steel tines or teeth are used to rake off up to 25 mm of the hot surface.

Hot In-Place Recycling - A method in which the existing pavement is heated and softened, and then scarified or hot rotary mixed to a specified depth.

Hot Mix Asphalt Recycling - A process in which reclaimed asphalt pavement material are combined with new material, sometimes along with a recycling agent, to produce hot mix asphalt (HMA) mixtures.

Recycling - Reuse of existing materials to produce new materials.

Recycling Agent - Organic materials with chemical and physical characteristics selected to restore aged asphalt to desired specifications.

Rehabilitation - Work undertaken to extend the service life of an existing facility. This includes placement of additional surfacing material and/or other work necessary to return an existing roadway including shoulders, to a condition of structural or functional adequacy.

Rejuvenator - A liquid petroleum product, usually containing maltenes, added to asphalt paving material to restore proper viscosity, plasticity, and flexibility to the asphalt cement.

Remixing - A process consisting of the following steps: (1) heating of the roadway to a depth of 37.5 to 50 mm, (2) scarification and collection of the softened material into a windrow, (3) mixing of the material with virgin aggregates and recycling agents in a pugmill, and (4) laying of the recycled mix as a single, homogeneous mix.

Repaving - A heater scarification method combined with simultaneous overlay of new hot mix asphalt (HMA).

APPENDIX A

Present Value (or worth): An economic concept that represents the translation of specified amounts of costs or benefits occurring in different time periods into a single amount at a single instant (usually the present). Two related considerations underlie the need for computing present values: (1) the fact that money has an intrinsic capacity to earn interest over time (known as the time value of money) due to its productiveness and scarcity, and (2) the need in an economic study for comparing or summing incremental outlays or savings of money in different time periods.(1)

Equivalent Uniform Annual Cost (or Benefit): A uniform annual cost (or benefit) that is the equivalent, spread over the entire period of analysis, of all incremental disbursements or costs incurred on (or benefits received from) a project. The present value of the uniform series of equivalent annual costs equals the present value of all project disbursements.(1)

Discount Rate (Interest rate, Time Value of Money): A percentage figure—usually expressed as an annual rate- representing the rate of interest money can be assumed to earn over the period of time under analysis. A governmental unit that decides to spend money improving a highway, for example, loses the opportunity to "invest" this money elsewhere. That rate at which money could be invested elsewhere is sometimes known as the "Opportunity Cost of Capital" and is the appropriate discount rate for use in economic studies. Discount factors derived as a function of the discount rate and time period relative to the present can be used to convert periodic benefits and costs for a project into present value or into equivalent uniform annual cost. However, calculating benefits in constant dollars and using market rates of interest is an error because the market rate of return includes an allowance for expected inflation. Hence, if future benefits and costs are calculated in constant dollars, only the real cost of capital should be represented in the discount rate used. The discount rate assumes annual end-of-year compounding, unless otherwise specified. The sum of $100 in cash today is equivalent, at a 10 percent discount rate, to $110 a year from now, $121 at the end of the second year, and $259.37 at the end of the tenth year. Correspondingly, a commitment to spend $259.37 in the tenth year discounted at 10 percent has a present value of $100.(1)

Residual or Salvage Value: The value of an investment or capital outlay remaining at the end of the study or analysis period.

The equation for determining the present worth or rehabilitation and maintenance costs for a given facility is as follows:

$$PW = C + Mi\left(\frac{1}{1+r}\right)^{ni} + \text{.........}\ Mj\left(\frac{1}{1+r}\right)^{ni} - S\left(\frac{1}{1+r}\right)^{N}$$

where:

PW = Present worth or present value of all costs
C = Present cost of initial rehabilitation activity

Mi = Cost of the ith maintenance & rehabilitation (M&R) alternative in terms of constant dollars
r = Discount rate
ni = Number of years from the present to the ith M & R activity
S = Salvage value at the end of the analysis period
N = Length of the analysis period in years

The term $\left(\frac{1}{1+r}\right)^{n}$ is commonly called the single payment present worth factor.

The present worth or present value of all costs over the analysis period can be stated in terms of EUAC by multiplying PW by the uniform series capital recovery factor:

$$
\begin{aligned}
EUAC &= PWX\ crf(r,N) \\
&= PWX\ \frac{r(1+r)^N}{(1+r)^N-1}
\end{aligned}
$$

where:

PW = Present Worth as before
crf (r, N) = The uniform series capital recovery factor for discount rate r and analysis period N

The major initial and recurring costs that should be considered in the economic evaluation of alternative techniques include the following:[2]

1. Agency Costs:
   a) Initial construction costs.
   b) Future construction or rehabilitation costs (overlays, seal coats, reconstruction, etc.)
   c) Maintenance costs, recurring throughout the design period.
   d) Salvage return or residual value at the end of the design period (which may be a “negative” cost).
   e) Engineering and administration costs.
   f) Traffic control costs if any are involved.
2. User Costs:
   a) Travel time.
   b) Vehicle operation.
   c) Accidents.
   d) Discomfort.
   e) Time delay and extra vehicle operating costs during resurfacing or major maintenance.

For a simplified analysis, the following costs are usually considered for life cycle analysis:

1. Initial capital costs of rehabilitation.
2. Future capital costs of reconstruction or rehabilitation.
3. Maintenance costs.
4. Salvage value.

However, certain user costs such as time delay costs during rehabilitation must be considered on certain facilities.[(3)] Factors that must be considered when determining these costs include:

1. Will the roadway be closed over a lengthy period of time?
2. Are alternate roadways available?
3. Can operations be moved to a different facility?
4. What are the costs of traffic delays associated with closing the facility?

For present worth calculation, a discount rate of four percent is suggested.[(4)] It is recommended that because the results of present worth analyses are sensitive to the discount rate, economic calculations at two or three discount rates of 4, 7, and 10 percent be made for a sensitivity analysis (3). Alternatives with large initial costs and low maintenance or user costs are favored by low rates of return. On the other hand, high discount rates favor strategies that combine low initial costs and higher maintenance and user costs.

The 4 percent discount rate must be used with constant dollar costs at the time the analysis is conducted and must remain fixed for the analysis period. For example, if an asphalt concrete pavement is to be constructed, the cost of asphalt concrete at the time of an overlay 20 years after construction should be the same as at the time of initial construction.

The following reasons against inclusion of inflation rates in economic studies have been advanced:[(3)]

1. Difficulties in predicting future inflation rates.
2. The acceptance of inflation as a norm may be counter to the government's responsibility for price stabilization.
3. Federal programs, if justified in part by inflating benefits, may contribute to inflation.
4. Debtor's gains through repaying outstanding debts with inflated dollars are offset by creditors' losses.
5. Future dollars to pay for future expenses will likewise be inflated and therefore there is no net change.

Life Cycles

An important factor in identifying and performing economic analyses of alternatives in the design of new pavement construction and/or the repair and rehabilitation of existing pavement is the life cycle of the alternative under consideration. The life cycle is the period of time of actual use before replacement, reconstruction, or extensive rehabilitation is required. Obviously, there is a time variation of specific service lives between project sites for a given pavement alternative. Therefore, the life cycle is an overall average of service lives of the specific service lives for identical pavement alternatives experienced at various project sites. The designer may use the generally accepted life cycle for a particular alternative, such as 40 years with maintenance for new PCC pavement, or he/she may elect to use a different life cycle for the same alternative, such as 30 years with little or no maintenance. Table A-1[(3)] shows typical life cycles for new pavement construction and pavement overlays.

Table A-1. Estimated life cycles of new pavements and overlays.[3]

Pavement Type	Representative Ranges*
New PCC	15 - 25
PCC Overlay	7 - 14
New AC	12 - 20
AC Overlay	8 - 12

Note:
* Varies depending on location, traffic, thickness, existing pavement condition, etc.
PCC - Portland Cement Concrete, AC - Asphalt Concrete.

Table A-2. Maintenance activity life cycles.[4]

Maintenance Activity	Life Cycle (Years)
Crack Sealing (flexible)	4
Chip Seal (flexible)	5
Shallow Patch (flexible)	3
Deep Patch (flexible)	6
Slurry Seal (flexible)	6
Cold Milling (flexible)	10
Heater Planing (flexible)	6
Crack Sealing (rigid)	5
Joint Sealing (rigid)	7
Shallow Patch (rigid)	5
Deep Patch (rigid)	8
Slab Replacement (rigid)	19
Grinding (rigid)	11
Mud Jacking (rigid)	16

Pavement repair, maintenance, and rehabilitation life cycles were derived from responses to a questionnaire in 1985 from more than 40 Air Force bases.[3] Respective maintenance activity lives were averaged for all locations in the survey and rounded to the nearest year to arrive at the life cycle for the particular alternative, and are listed in table A-2.[4]

Analysis Life

In performing economic studies of projects under consideration an economic life, service life and analysis life must be established. The service life is the time period of actual use. The economic life is the time period over which a project is economically profitable, or until the service by the project can be provided by another facility at lower costs. The economic life may be less than the service life. Lack of capital may extend a project service life beyond the end of its economic life. Economic life usually ends when the physical deterioration of a pavement proceeds to the point where reduced service and increased maintenance costs justify replacement with an alternative having expected lower life-cycle costs.

Analysis life may not be the same as the service life or economic life of a project, but it is a realistic estimate for use in an economic analysis. The analysis life period selected should be long enough to include the time between major rehabilitation actions for the various alternatives under study, but not so long as to make the analysis uncertain. Suggested values to use for analysis life are shown in table A-3.[3]

Salvage Value

The salvage value of a pavement structure is the residual value at the end of the analysis period. If at the end of this analysis period, it is expected that the facility will be abandoned, the salvage value is any value that the materials may have if removed and reused. In general, it is practical to assume that the salvage value is zero unless specific data are available to calculate otherwise. However, the facility may possess useful life after the analysis period, and if so, the salvage value should be included in the life-cycle cost analysis. The residual value of the last rehabilitation action based on its anticipated remaining life appears to be the best method for determining salvage value. A simplified, but adequate, method for estimating the salvage value can be calculated with the following equation:

$$SV = 1 - \left(\frac{L_A}{L_E}\right) C$$

where:

SV = salvage value (or residual value) of rehabilitation alternative
L_A = analysis life of rehabilitation alternative in years, i.e., difference between the year of construction and the year of termination of the life cycle analysis
L_E = expected life of the rehabilitation alternative
C = cost of the rehabilitation alternative

Use of this simplified approach in estimating salvage value is justified by the fact that there are several uncertainties associated with the service lives and costs for the different pavement component layers, and the relatively small impact that salvage value actually has on life cycle comparisons.

Table A-3. Recommended analysis life for comparing alternatives.[3]

Activity	Pavement Surface Type	Recommended Analysis Life, Years
New construction, reconstruction or thick overlays	PCC and AC PCC Only AC Only	45 45 30
Rehabilitation	PCC Only AC Only	20 20
Maintenance	PCC Only AC Only	20 10

Note:
PCC - portland cement concrete.
AC - asphalt concrete.

The following is an example situation[3] in which the above equation can be used to calculate the estimated salvage value: If an analysis period of 20 years is used on a project where a rehabilitation alternative has a life cycle of nine years, the residual or salvage value of the second rehabilitation action is equal to the straight-line depreciated value of the alternative at the end of the analysis period as follows:

$$SV = \left(1 - \frac{2}{9}\right) \ \$3.12 \ (\$2.50) = \$2.43 \ (\$1.94)$$

(Assuming cost of the rehabilitation alternative is 3.12 per square meter, $2.50 per square yard). A more detailed discussion of salvage value and other terms used in this section is contained in Reference 2.

Price Data

Price data are needed for construction, rehabilitation and maintenance operations. Sources of these data include:

1. Local records.
2. State records.
3. Experience.
4. Bid summaries.

Price data for recycling and other rehabilitation operations are discussed further in chapter 6: Summary and Cost Data.

Example of Life Cycle Cost Analysis

A simplified example of a life cycle cost analysis is shown in tables A-4 to A-7.[3] Table A-4 shows cost data for rehabilitation alternatives considered for a project in the southwestern United States. A typical calculation sheet for determining present worth and equal uniform annual cost is

Table A-4. Representative costs of rehabilitation alternatives.[3]

Rehabilitation Alternative	Costs \$/m² (\$/yd²)
Asphalt cement chip seal	1.08 (0.86)
Asphalt-rubber chip seal or interlayer	1.56 (1.25)
Fabric interlayer	1.50 (1.20)
Heater scarification	1.12 (0.90)
Asphalt concrete - 25 mm (one in)	2.06 (1.65)
Asphalt rubber interlayer with 36 mm (1.4 in) asphalt concrete	4.66 (3.73)
Fabric interlayer with 38 mm (1.5 in) asphalt concrete	4.60 (3.68)
Heater scarification with 38 mm (1.5 in) asphalt concrete	2.79 (2.23)
Cold recycle 152 mm + 50 mm (6 in + 2 in) asphalt concrete	8.25 (6.60)
Hot recycle 177.8 mm (7 in)	10.12 (8.10)

shown in table A-5. Table A-6 shows costs associated with seven rehabilitation alternatives. A summary of first costs and life cycle costs is shown in table A-7.

Table A-5. Calculation form for present worth life cycle costing.[3]

Year	Cost, Dollars per sq m (sq yd)	Present Worth Factor, 4%	Present Worth, Dollars
Initial Cost	1.56 (1.25) A-R Chip Seal	1.0000	1.56 (1.25)
1		0.9615	
2		0.9246	
3	0.31 (0.25) maintenance	0.8890	0.27 (0.22)
4	6.19 (4.9) 76 mm AC (3") AC	0.8548	5.29 (4.23)
5		0.8219	
6		0.7903	
7		0.7599	
8		0.7307	
9		0.7026	
10	0.12 (0.10) maintenance	0.6756	0.08 (0.07)
11	0.12 (0.10) maintenance	0.6496	0.08 (0.06)
12	0.12 (0.10) maintenance	0.6246	0.07 (0.06)
13	0.19 (0.15) maintenance	0.6006	0.11 (0.09)
14	0.31 (0.25) maintenance	0.5775	0.18 (0.14)
15	3.12 (2.50) 38 mm AC (1-1/2") AC	0.5553	1.73 (1.39)
16		0.5339	
17		0.5134	
18		0.4936	
19	0.12 (0.10) maintenance	0.4746	0.06 (0.05)
20	0.19 (0.15) maintenance	0.4564	0.09 (0.07)
Salvage Value	0.89 (0.71)	0.4564	-0.41 (-0.32)
Total	11.49 (9.19)	Total	9.14 (7.31)

Notes:

Uniform Annual Cost = Present Worth x Capital Recovery Factor
= 9.14 x (7.31) x 0.07358
= 0.672 (0.538)

Table A-6. Life cycle costs associated with rehabilitation alternatives dollars per square meter (dollars per square yard).[3]

Year	Rehabilitation Alternatives						
	1 AR Chip Seal	2 76 mm (3" AC)	3 HS + 50 mm (2" AC)	4 A-R + 50 mm (2" AC)	5 Fabric: + 50 mm (2" AC)	6 Cold Recycle	7 Hot Recycle
Initial	1.56 (1.25)	6.19 (4.95)	5.25 (4.20)	3.64 (4.55)	5.62 (4.50)	6.60	8.10
1							
2		0.12 (0.10)					
3	0.31 (0.25)	0.19 (0.15)					
4	6.19 (4.95)	0.25 (0.20)					
5		0.25 (0.20)	0.12 (0.10)		0.12 (0.10)		
6		0.31 (0.25)	0.12 (0.10)		0.12 (0.10)		
7		3.12 (2.50)	0.12 (0.10)		0.12 (0.10)		
8			0.19 (0.15)	0.12 (0.10)	0.19 (0.15)		
9		0.12 (0.10)	0.31 (0.25)	0.12 (0.10)	0.31 (0.25)		
10	0.12 (0.10)	0.19 (0.15)	3.12 (2.50)	0.12 (0.10)	3.12 (2.50)	0.05	
11	0.12 (0.10)	0.25 (0.20)		0.19 (0.15)			
12	0.12 (0.10)	0.25(0.20)		0.31 (0.25)		0.05	0.05
13	0.19 (0.15)	0.31 (0.25)		3.12 (2.50)			
14	0.31 (0.25)	3.12 (2.50)	0.12 (0.10)		0.12 (0.10)	0.10	0.05
15	3.12 (2.50)		0.19 (0.15)		0.19 (0.15)	0.15	
16		0.12 (0.10)	0.31 (0.25)		0.31 (0.25)	0.25	0.10
17		0.19 (0.15)	3.12 (2.50)	0.12 (0.10)	2.50	2.50	
18		0.25 (0.20)		0.19 (0.15)			0.10
19	0.12 (0.10)	0.25 (0.20)		0.31 (0.25)			0.20
20	0.19 (0.15)	0.31 (0.25)		3.12 (2.50)			0.25
Salvage Value	0.89 (0.71)	0.45 (0.36)	1.79 (1.43)	3.12 (2.50)	1.43	1.43	0

Notes:

A-R - Asphalt Rubber
H-S - Heater Scarification
AC - Asphalt Concrete

Table A-7. Project summary sheet.[3]

Description of Project:

Location: Southwestern United States
Type of Facility: Runway, length 975.36 m (3,200 ft) - width 22.8 m (75 ft)
Critical Aircraft: 10.89 Mg (24,000 lbs.) gross weight
Annual Departures: 3,000

Existing Pavement:

Type of Material	Thickness mm (in)	Condition	Equivalency Factor	Equivalent Thickness mm (in)
AC Surface	100 (4)	Fair	1.2	122 (4.8)
Untreated Base	254 (10)	Good	1.0	254 (10.0)
Subgrade				

Total: 376 (14.8)

Condition of Pavement:

Condition Survey: Alligator cracking, moderate 20 percent of area; transverse cracking, moderate, 1-4 per station; longitudinal cracks, moderate, 45.72 m (150 ft) per station.
Skid Resistance: Good
Required Thickness of New Pavement: 457 mm (18") min. 50 mm (2") AC, 127 mm (5") base
Equivalent Thickness of Old Pavement: 376 mm (14.8")
Required Overlay Thickness: 76 mm (3") AC

Rehabilitation Alternatives:

	First Cost $/m² ($/yd²)	Life Cycle PW, $/m² ($/yd²)	Time for Rehab.	Chance for Success
1. Asphalt-rubber chip seal to delay overlay	1.56 (1.25)	9.14 (7.31)	2 days	90
2. 75 mm (3 in) AC overlay	6.19 (4.95)	12.35 (9.88)	5 days	95
3. Heater scarification + 50 mm (2 in)	5.25 (4.20)	9.15 (7.32)	4 days	97
4. Asphalt-rubber interlayer + 50 mm (2 in) overlay	5.69 (4.55)	8.45 (6.76)	4 days	97
5. Fabric interlayer + 50 mm (2 in) overlay	5.62 (4.50)	9.52 (7.62)	4 days	97
6. Cold recycle with asphalt emulsion 152 + 50 mmAC (6" + 2"AC)	8.15 (6.60)	9.45 (7.56)	6 days	97
7. Hot recycle with AC 178 mm (7")	10.16 (8.10)	10.57 (8.46)	6 days	99

REFERENCES

1. J.A. Epps, D.N. Little, R.J. Holmgreen, and R.L. Terrel. *Guidelines For Recycling Pavement Materials,* NCHRP Report 224, TRB, National Research Council, Washington, DC, September, 1980.

2. American Association of State Highway and Transportation Officials (AASHTO). *AASHTO Guide for Design and Pavement Structures*, Washington, DC, 1986.

3. *Pavement Recycling Guidelines for Local Governments - Reference Manual*, Report No. FHWA-TS-87-230, FHA, U.S. Department of Transportation, Washington, DC, 1987.

4. Asphalt Recycling and Reclaiming Association. *An Overview of Recycling and Reclamation Methods for Asphalt Pavement Rehabilitation*, 1992.

APPENDIX B

NH-285-2 (17) 78
May 6, 1996

NEW MEXICO STATE HIGHWAY AND TRANSPORTATION DEPARTMENT
SPECIAL PROVISIONS
FOR
IN-SITU COLD RECYCLING WITH HOT HYDRATED LIME SLURRY
SECTION 305-A

All provisions of the New Mexico State Highway and Transportation Department's Standard Specifications for Highway and Bridge Construction shall apply in addition to the following:

305.1. DESCRIPTION

305.11. This work shall consist of pulverizing the existing surfacing to the specified width and depth, mixing an emulsified binder agent, hot hydrated lime slurry, and water if required, with the pulverized surfacing, spreading and compacting said mixture to the specified width and thickness, and sealing of the compacted surface if required. All work shall be as shown on the plans and as provided herein unless otherwise directed by the Project Manager.

305.2. MATERIALS

305.21. The emulsified binder agent shall be Polymerized High Float Emulsion of the type shown on the plans with the option to change one grade up or down at a change in unit price based on a difference in invoice prices for the different grades of emulsion. Changes in grade of binder agent shall be made only with the concurrence of the Project Manager. The Polymerized High Float Emulsion shall meet the requirements of Section 402 - Bituminous Materials, Hydrated Lime, & Liquid Anti-Stripping Agents.

305.22. The cold recycled material shall meet the following gradation requirements:

Table 1. Cold recycled pavement gradation requirements.

Sieve Size	Percent Passing
1¼"	100
1"	90-100

305.23. The sealing emulsion shall be diluted with High Float Emulsion, CSS-1h or other approved equal.

305.24. The lime used for the production of the hot hydrated lime slurry shall be a high calcium pebble quicklime meeting the requirements of ASTM C 977.

305.25. The water used for the production of hot hydrated lime slurry shall be clear and free of deleterious amounts of acid, oil, alkali, organic matter, salt, sugar, or other detrimental material. Water meeting the requirements of Subsection 510.25 Water, is acceptable.

305.26. The hot hydrated lime slurry shall have a minimum dry solids content of 35 percent by weight and shall consist of a uniform, pumpable suspension of solids in water.

305.3. CONSTRUCTION REQUIREMENTS

305.31. General. The existing surfacing shall be cold recycled in a manner that does not disturb the underlying material in the existing roadway.

Prior to initiating recycling operations or other inherent work, the Contractor shall clear, grub, and remove all vegetation and debris within the width of pavement to be recycled. Disposal of said vegetation and debris shall be as directed by the Project Manager.

The Contractor may add water to the pulverized material for the purpose of cooling the cutting teeth on the mill or pulverizing equipment or to facilitate uniform mixing with the emulsified binder agent. Water may be added prior to or concurrently with the emulsified binder agent. A means shall be provided for accurately metering and registering the rate of flow of water into the pulverized material.

When the typical section that is to be recycled is situated on a super elevated or sloped section, the initial pass of the milling equipment shall begin at the lowest portion of the section and proceed in succession towards the higher end of the slope.

Fillets of fine, pulverized material which form adjacent to a vertical face shall be removed prior to spreading the recycled mix, except that such fillets adjacent to existing pavement which will be removed by overlapping during a subsequent milling operation need not be removed.

If segregation occurs either in the windrow or behind the paver, the Project Manager may require the Contractor to make changes in the equipment or operations. These changes may include, but shall not be limited to, the following:

1. Reducing the forward speed of the milling operation.
2. Increasing the amount of material going through the crusher.
3. Adjusting the crusher to produce more fines.
4. Adjusting the height of free fall of material from the mixing unit.
5. Adjusting the amount of water in the mixture.

The Contractor may be required to make other changes in his equipment or operations, as necessary to obtain a satisfactory end-product.

When a paving fabric is encountered during the cold recycled in-situ operation, the Contractor shall make the necessary adjustments in the equipment or operations so that at least 90 percent of the shredded fabric in the recycled is five square inches or less in size. Additionally, no fabric piece shall have any dimension exceeding a length of four inches. These changes may include but not be limited to adjusting the milling rate, adding or removing screens, etc, in order to obtain a specification end product. The Contractor shall be required to waste material containing over-sized pieces of paving fabric as directed by the Project Manager. These changes will be made at not additional cost to the Department.

The recycled bituminous base shall be spread in one continuous pass, without segregation, to the typical section shown on the plans.

305.311. Surface Tolerance. The final surface of recycled bituminous base shall not deviate in excess of ½ inch from the testing edge with a 10-foot straightedge resting on any two points. all deviations from this tolerance shall be corrected at no additional cost to the Department.

305.32. Temperature & Weather Limitations. Recycling operations shall not be performed when the atmospheric temperature is below 60°F or when the chill factor is below 35°F or when the weather is foggy or rainy or when weather conditions are such that in the judgement of the Project Manager, proper mixing, spreading and compacting of the recycled material cannot be accomplished. The chill factor shall be as defined in Subsection 401.341 Temperature & Weather Limitations.

305.33. Binder Application. When commencing recycling operations, the emulsified binder agent shall be applied to the pulverized material at the rate determined by the Department based on samples obtained by the Contractor for the mix design. The exact application rate of the emulsified binder agent will be determined and varied by the Project Manager as required by existing pavement conditions. An allowable tolerance of plus or minus 0.2 percent of the initial design rate or of the rate determined by the Project Manager of application shall be maintained at all times.

305.34. Lime Slurry Addition. The quicklime shall be slaked with the required amount of water and uniformly incorporated into the pulverized surfacing at a rate that will result in 1.5% hydrated lime by dry weight of pulverized surfacing. The amount of lime slurry being added shall be controlled by the continuous weighing of the pulverized surfacing.

305.35. Density & Rolling Requirements. The Contractor shall establish a rolling pattern such that a minimum density of 96 percent of a laboratory briquette, prepared in accordance with Department molding and testing procedures, is obtained. The Project Manager may require a re-demonstration of rolling capabilities when a change in the recycled materials is observed, whenever a change in rolling equipment is made, or if densities are not being obtained with the rolling pattern being used.

Initial rolling shall normally be performed with a 30 ton pneumatic roller and continued until no displacement is discerned or until the pneumatic rollers have walked out. If necessary, in order to initially seat the mixture, one or two passes with a small pneumatic roller may be made prior to application of the 30 ton roller. Final rolling to eliminate pneumatic tire marks and achieve density shall be done by steel wheel roller(s), either in static or vibratory mode, as required, to achieve required density.

Rolling shall be performed in accordance with Subsection 401.35 Compaction.

Rollers shall not be started or stopped on uncompacted recycled material. Rolling shall be established so that starting and stopping will be on previously compacted recycled material or on existing PMBP.

Rolling which results in cracking, movement, or other types of pavement distress shall be discontinued until such time as the problem can be resolved. Discontinuation and commencement of rolling operations shall be at the sole discretion of the Project Manager.

305.36. Finishing Operations. After the recycled material has been spread and compacted, vehicles, including Contractor's equipment, shall not be permitted on the completed recycled bituminous base for at least two hours. The area may then be opened to all traffic and shall be allowed to cure such that the free moisture in the recycled material is reduced to one percent or less above the natural moisture of the material by total weight of mix, before placing the surfacing.

The surface of the recycled pavement shall be maintained in a condition suitable for the safe accommodation of traffic. All loose aggregate that develops on the surface of the recycled pavement shall be removed by power brooming. After the free moisture content of the recycled material is one percent or less above the natural moisture of the material, the Project Manager may require that the surface be sealed with emulsion at an approximate rate of 0.05 to 0.10 gallon per square yard in order to control surface raveling.

All unacceptable recycled bituminous base shall be repaired by the Contractor, as directed by the Project Manager prior to placing a subsequent surfacing course. Said repair(s) shall be made at no additional cost to the Department.

305.37. Equipment.

305.371. Cold In-Situ Machinery. The Contractor shall furnish a self-propelled machine capable of pulverizing in-situ bituminous materials to the depth shown on the plans in one pass. The machine shall have a minimum rotor cutting width of 12 feet, standard automatic depth controls and shall maintain a constant cutting depth. The machine shall also incorporate screening and crushing capabilities to reduce or remove oversize particles prior to mixing with emulsion. Oversize particles shall be reduced to size by crushing, however, the Contractor may, with concurrence of the Project Manager, waste up to a maximum of two percent oversize material prior to adding emulsion. This waste shall generally be limited to that material which is flattened out rather than broken down by the crusher.

The emulsified agent shall be applied through a mixing machine capable of mixing the pulverized material and the emulsified binder agent to a homogeneous mixture and placing the mixture in a windrow. The method of depositing the mixed material in a windrow shall be such that segregation does not occur.

A positive displacement pump, capable of accurately metering the required quantity of emulsified binder agent, into the pulverized material, shall be used. The pump shall be equipped with a positive interlock system which will permit addition of the emulsified binder agent only when the pulverized material is present in the mixing chamber and will automatically shut off when the material is not in the mixing chamber.

Each mixing machine shall be equipped with a meter capable of registering the rate of flow and total delivery of the emulsified binder agent introduced into the mixture. The meter shall be calibrated by the Contractor, in the presence of the Project Manager, before commencing recycling operations. Subsequent checks or calibrations of the meter shall be as directed by the Project Manager.

305.372. Lime Slurry Equipment. The lime slurry shall be produced at the job site using a batch type process. The equipment shall accurately proportion the quicklime and water; adequately mix the two to obtain proper slaking; and maintain a uniform, homogeneous slurry.

Transports used to convey the slurry to the roadway shall employ sufficient agitation to prevent settlement and maintain a uniform homogeneous mixture.

The lime slurry shall be added to the pulverized surfacing by a spray bar located at the cutting head on the milling machine. A metering device shall be used and it shall accurately measure the amount of slurry delivered to within plus or minus 10 percent by weight.

305.373. Pavers. Placing of the recycled bituminous base course shall be accomplished with a self-propelled bituminous paver meeting the requirement of Subsection 401.323 Pavers, except that heating of the screed will not be permitted. This equipment shall be capable of spreading the recycled bituminous base in one continuous pass, without segregation, to the typical section shown on the plans.

When a pick-up machine is used to feed the windrow into the paver hopper, the pick-up machine shall be capable of picking up the entire windrow down to the underlying materials.

305.374. Rollers. Rollers shall meet the requirements of Subsection 401.324 Compaction Equipment. The number, weight, and type of rollers shall be sufficient to obtain the required compaction while the mixture is in a workable condition except that one pneumatic roller shall be 30 ton minimum weight. All rollers shall be equipped with pads and a water system which prevents sticking of the recycled mixture to the roller wheels.

305.375. Brooms. The Contractor shall have on hand at all times a rotary power broom maintained in good working order and of a design suitable for removing aggregate that becomes dislodged from the surface of the recycled surface.

305.4. METHOD OF MEASUREMENT

305.41. In-situ cold recycling of existing surfacing will be measured by the square yard.

Polymer modified high float emulsion will be measured by the ton.

Sealing emulsion will be measured by the ton.

Quicklime will be measured by the ton.

305.5. BASIS OF PAYMENT

305.51. In-situ cold recycling of existing surfacing will be paid for at the contract unit price per square yard.

Polymer modified high float emulsion will be paid for at the contract unit price per ton.

Sealing emulsion will be paid for at the contract unit price per ton.

Quicklime will be paid for at the contract unit price per ton. This price will be full compensation for the quicklime, and production of the hot lime slurry including all necessary equipment, labor, and water.

Payment will be made under:

Pay Item	**Pay Unit**
In-Situ Cold Recycling of Existing Surfacing	Square Yard
Polymer Modified High Float Emulsion (Type)	Ton
Sealing Emulsion	Ton
Quicklime	Ton

APPENDIX C

MILL AND RELAY ASPHALTIC PAVEMENT. ITEM 90358.

A. Description. This work shall consist of constructing base course utilizing in-place milling and relaying of the existing asphaltic surface over the roadbed as shown on the plans and as hereinafter provided.

B. Construction Methods. The existing asphaltic surface shall be milled to the depth shown on the plans and to a maximum size of 37.5 mm. The milling machine shall be equipped with electronic devices which will provide accurate depth, grade and slope control.

Immediately after milling, the material shall be placed as shown on the plans. The laydown shall be accomplished using a paver or a grader or a combination of a paver and grader.

The relaid material shall be immediately compacted in the following sequence: first with either a rubber-tired roller or vibratory pads foot roller, and second with a vibratory steel roller. Water shall be added prior to and during compaction as required. Each layer shall be compacted to the extent required for Standard Compaction in Section 304.5 of the Standard Specifications. The compaction equipment shall be as follows:

> For a compacted depth of milled material, up to 150 mm, compaction equipment shall be in accordance with Section 304.4.4 of the Standard Specifications.
>
> For a compacted depth of milled material, greater than 150 mm and up to 200 mm, a minimum 22.68 megagram rubber-tired roller with 620 kPa tire pressure or 11335 kg pads foot vibratory roller, and a minimum 7.25 megagram vibratory steel roller shall be used.
>
> For compacted depths greater than 200 mm, split lift compaction according to the above described methods will be required.

At the completion of each working day, the ends of the mill and relay asphaltic pavement shall be as adjacent as practical for both traffic lanes.

C. Method of Measurement. Mill and Relay Asphaltic Pavement will be measured by the square meter of relaid material according to the finished typical section width and details shown on the plans.

D. Basis of Payment. Mill and Relay Asphaltic Pavement, as measured above, will be paid at the contract unit price per square meter, which price shall be full compensation for milling, windrowing, relaying, adding water, compaction, removing and disposing of excess material, and all labor, tools, equipment, and incidentals necessary to complete the work in accordance with the contract.
(022096)

PULVERIZE AND RELAY EXISTING BASE AND SURFACE. ITEM 90357

A. Description. This work shall consist of constructing base course utilizing in-place pulverizing and relaying of the existing asphaltic surface and base course over the roadbed as shown on the plans and as hereinafter provided.

B. Construction Methods. The existing asphaltic surface shall be pulverized full depth and to a minimum of 97 percent passing a 50 mm screen. The existing crushed aggregate base course shall also be pulverized to the depth shown on the plans and mixed with the asphaltic material.

Immediately after pulverizing, the material shall be placed as shown on the plans. The laydown shall be accomplished using a paver or a grader or a combination of a paver and grader.

The relaid material shall be immediately compacted in the following sequence: first with either a rubber-tired roller or vibratory pads foot roller, and second with a vibratory steel roller. Water shall be added prior to and during compaction as required. Each layer shall be compacted to the extent required for Standard Compaction in Section 304.5 of the Standard Specifications. The compaction equipment shall be as follows:

> For a compacted depth of pulverized material, up to 150 mm, compaction equipment shall be in accordance with Section 304.4.4 of the Standard Specifications.
>
> For a compacted depth of pulverized material, greater than 150 mm and up to 200 mm, a minimum 22.68 megagram rubber-tired roller with 620 kPa tire pressure or 11335 kg pads foot vibratory roller, and a minimum 7.25 megagram vibratory steel roller shall be used.
>
> For compacted depths greater than 200 mm, split lift compaction according to the above described methods will be required.

At the completion of each working day, the ends of the pulverize and relay asphaltic pavement and base course shall be as adjacent as practical for both traffic lanes.

C. Method of Measurement. Pulverize and Relay Asphaltic Pavement will be measured by the square meter of relaid material according to the finished typical section width and details shown on the plans.

D. Basis of Payment. Pulverize and Relay Asphaltic Pavement, as measured above, will be paid at the contract unit price per square meter, which price shall be full compensation for pulverizing, windrowing, relaying, adding water, compaction, removing and disposing of excess material, and all labor, tools, equipment, and incidentals necessary to complete the work in accordance with the contract.
(022096)