NCHRP

SYNTHESIS 421

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Recycling and Reclamation of Asphalt Pavements Using In-Place Methods

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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A Synthesis of Highway Practice

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TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation Research Board

In-place recycling and reclamation of asphalt pavements provides agencies with the ability to optimize the value of in-place materials, minimize construction time and traffic flow disruptions, and reduce the number of construction vehicles moving in and out of the construction area. This report discusses the use of hot in-place recycling, cold in-place recycling, and full-depth reclamation.

Information for this report was gathered by literature review, a survey of state departments of transportation and contractors, and selected interviews.

Mary Stroup-Gardiner, Gardiner Technical Services, LLC, Chico, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

RECYCLING AND RECLAMATION OF ASPHALT PAVEMENTS USING IN-PLACE METHODS

SUMMARY

In-place recycling and reclamation enable agencies to optimize the value of in-place materials and minimize construction time and traffic flow disruptions, as well as to reduce vehicle emissions from long traffic queues. In-place recycling and reclamation also reduce the number of construction vehicles moving in and out of the construction area and neighborhood truck traffic.

In recent years, petroleum and aggregate economics and supply have increased the need for high-quality, cost-effective alternatives to virgin paving mixtures. Transportation professionals are asking for methods that optimize the value of in-place materials while minimizing traffic congestion and the environmental impact of paving operations. Current in-place recycling processes answer all of these needs. Hot in-place recycling addresses distresses near the surface with the use of one of three hot in-place recycling methods: resurfacing, repaving, and remixing. Distresses in the upper 2 to 4 in. can be minimized using cold in-place recycling. Full-depth reclamation recycles the old asphalt pavement into a stabilized base material that provides good support for the final pavement layers.

The current state practices for these in-place recycling methods were assessed using an online survey (45 states responded). In addition to surveying the state agency materials engineers, contractor members of the Asphalt Recycling and Reclaiming Association were asked to answer the same survey questions (34 contractors responded). A comparison of the responses for the two groups of respondents provides insight into topics where there is a good understanding of when, where, and how to use recycling in the most economically and environmentally beneficial applications.

The benefits documented in the survey responses of both the agencies and the contractors were that in-place recycling (*a*) reduces the use of natural resources; (*b*) eliminates materials generated for disposal; (*c*) reduces fuel consumption; (*d*) reduces greenhouse gas emissions by between 50% and 85%; (*e*) minimizes lane closure times; (*f*) improves driver safety by improving friction, providing lane widening, and eliminating overlay edge dropoff; (*g*) maintains height clearances, which eliminates the need to adjust appurtenances; (*h*) addresses existing material deficiencies such as moisture damage; (*i*) reduces costs of preservation, maintenance, and rehabilitation; and (*j*) improves base support with a minimum of needed wearing course.

There are a number of key factors in achieving these benefits. Success starts with understanding key project selection criteria such as seasonal weather conditions, roadway geometry and features, and the ability of the existing roadway structure to support the recycling equipment. Improved use of technology and alternative combinations of new materials with additives and stabilizers are quickly minimizing historical objections to using in-place recycling on higher traffic volume roadways. Quality control of the construction process is also a key to project success. More than one-third of the contractors responding to the survey indicated that they routinely had a trained quality control technician on site.

Barriers to the increased use of in-place recycling cited by both agencies and contractors were identified as unsuccessful experiences, competing industries, and lack of specifications. Barriers cited more frequently by agencies than contractors were lack of mix designs, lack of agency experience, and lack of experienced contractors. Contractors felt that the lack of project selection criteria was a strong factor limiting the use of in-place recycling.

CHAPTER ONE

INTRODUCTION

BACKGROUND

In recent years, petroleum and aggregate economics and supply have increased the need for high-quality, cost-effective alternatives to virgin paving mixtures. Transportation professionals are asking for methods that optimize the value of in-place materials while minimizing traffic congestion and the environmental impact of paving operations. In-place recycling and reclamation enable agencies to optimize the value of in-place materials and minimize construction time and traffic flow disruptions, as well as to reduce vehicle emissions from long traffic queues. In-place recycling and reclamation also reduce the number of construction vehicles moving in and out of the construction area and neighborhood truck traffic.

Current pavement recycling and reclamation methods answer all of these needs, particularly the following:

- Hot in-place recycling (HIR)
  - Resurfacing
  - Repaving
  - Remixing
- Cold in-place recycling (CIR)
- Full-depth reclamation (FDR)

Different methods of recycling are applicable to different types, levels, and severity, and hence different periods in the pavement life (Figure 1). Typically, HIR is used when the majority of the pavement distresses are minimal and limited to the upper few inches of the surface of the roadway with no evidence of structural problems (i.e., longitudinal cracking in wheel path, alligator cracking, and edge cracking). CIR is used when there is a higher number, type, and severity of non-load-related distresses that may extend farther down from the surface. CIR with an overlay can be used to address some load-related distresses. FDR is an in-place rehabilitation process that can be used for reconstruction, lane widening, minor profile improvements, and increased structural capacity by addressing the full range of pavement distresses.

The anticipated depths of the distresses, combined with the overall existing asphalt pavement thickness, are used to identify the type of in-place recycling process(es) that can be expected to extend the life of the pavement most economically.

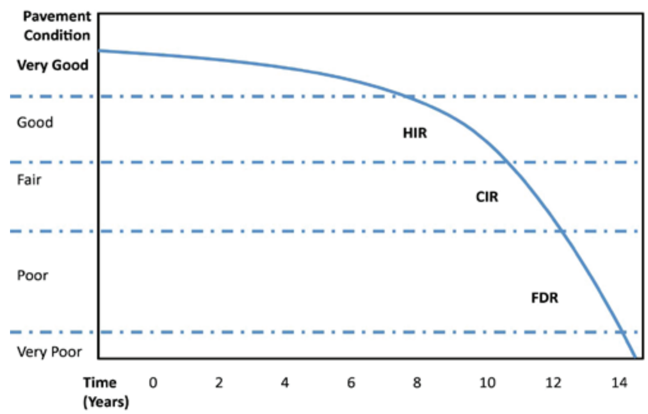


FIGURE 1 Pavement condition and type of in-place recycling method (Faster 2007).

A number of benefits can be realized with the use of in-place recycling processes. These options provide economical and sustainable solutions that reduce demand on raw materials, energy consumption, and production of greenhouse gases, while maintaining functionality and performance. Advantages include the following:

- Construction benefits
  - Minimizes traffic disruptions
  - Shortens lane closure times
  - Maintains height clearances
- Pavement condition improvements
  - Improves friction
  - Minimizes edge dropoff concerns
  - Reduces surface irregularities and distress type, severity, and extent
  - Addresses some existing material problems such as moisture damage
- Environmental benefits
  - Conserves nonrenewable resources
  - Reduces emissions
  - Reduces fuel consumption
  - Reduces number of haul trucks
  - Eliminates materials generated for disposal
- Cost benefit
  - Provides economical methods for pavement preservation and maintenance

IN-PLACE RECYCLING PROGRAMS IN THE UNITED STATES

The status of in-place recycling use across the United States was assessed using an online survey (Appendix A). The survey collected information from "choose all that apply" questions and open-ended requests for experiences. Responses were received from 45 states, although not all states had experiences with in-place recycling (Table 1). A total of 34 of the 45 states and one Canadian providence (Ontario) indicated experience with both HIR and CIR projects, and 33 of the 45 indicated experience with FDR projects. Of the states with experience using HIR processes, HIR remixing was the most frequently used (Table 2).

TABLE 1
NUMBER OF AGENCIES AND CONTRACTORS WITH EXPERIENCE*

In-Place Recycling Method	States with Experience	Contractors with Experience
HIR	34	24
CIR	34	24
FDR	33	28

*Agencies may use one or more of the methods.

TABLE 2
TYPE OF HIR USED BY AGENCIES

Question: What types of hot-in-place recycling do you use?

Type of HIR Used		
Surfacing	Repaving	Remixing
AR, CA, CO, FL, IL, IA, KS, KY, MT, NC, NE, NV, NY, TX, WY	AR, AZ, CO, FL, KS, KY, MO, NC, TX, WY	AR, AZ, CA, CO, FL, ID, IA, KS, KY, MD, MO, NC, NY, TN, TX, VT, WA, WY

The Asphalt Recycling and Reclaiming Association (ARRA) membership list was used to identify contractors to invite to complete the same survey. Of the membership list, 50 members were identified as contractors. In this case, companies providing materials and services for in-place recycling processes included asphalt contractors (e.g., for overlays) and aggregate producers. A total of 33 completed surveys were received. Responses were sorted by experience with a specific in-place recycling process (Table 2). Not all respondents had experience with all three methods.

The years of experience with a recycling process (Table 3) and the number of lane-miles typically paved per year were evaluated (Table 4). The number of states with fewer than 10 years of experience represents the potential growth of in-place recycling in the United States. FDR use has grown substantially over the past decade, followed by CIR use. Only a few states have implemented HIR in recent years. Between 14 and 18 states have more than 10 years of experience.

TABLE 3
AGENCY EXPERIENCE WITH IN-PLACED RECYCLING METHODS

Question: Indicate how long you have been using each type of in-place recycling.

Years of Experience	Type of In-Place Recycling Used		
	HIR	CIR	FDR
<5	MO, NV	DE, MO, NC, ND, OR, UT	AL, DE, MO, NC, NY, VA, WY
5 to 10	AZ, GA, IL	IL, WY	AK, CA, CO, GA, IL, IA, MN
>10	AR, ON, CO, FL, ID, IA, KS, KY, MD, MT, NC, NE, NY, TX, WA	AZ, CA, CO, CT, ID, IA, KS, MN, MT, NE, NH, NV, NY, RI, SD, VT, WA, WI	CA, CT, ID, MT, ND, NE, NH, NV, SC, SD, TX, UT, VT, WI
We Don't Use	AK, AL, CT, DC, DE, IN, MN, ND,NH, NJ, OR, RI, SC, SD, TN, UT, VT, WI, WY	AK, AL, AR, DC, FL, GA, IN, KY, NJ, SC, TN, TX	AR, DC, RL, IN, KS, KY, NJ, OR, RI, TN

TABLE 4
NUMBER OF LANE-MILES PER YEAR THAT ARE RECYCLED BY EACH METHOD

Question: Indicate the extent of your *annual* recycling program in lane-miles.

Lane-Miles Recycled	Type of In-Place Recycling Used		
	HIR	CIR	FDR
<50	AR, CA, CO, FL, IL, IA, KS, KY, MT, NC, NE, NV, NY, TX, WY	AZ, CA, CO, CT, DE, ID, IL, IN, KS, MN, MT, NE, NH, OR, RI, SD, TN, TX, UT, VT, WA, WY	AL, CO, CT, DE, GA, IL, IN, IA, MN, MO, MT, NH, NY, OR, RI, SD, TN, TX, UT, VA, VT, WI
50 to 100	CO	MO, NE, NY	AK, CA, ID, ND, NE, NV
>100	KS	IA, NV, WI	CA, SC

Figures 2 and 3 summarize state responses for the in-place recycling processes and the size of their annual programs. Also included in these figures is the maximum traffic level states consider acceptable for each process. These figures show that the use of HIR and FDR is distributed across the United States. However, CIR is noticeably missing from use in the Southern and Southeastern states. Reasons for the lack of use of CIR in the Southern and Southeastern states are likely related to weather conditions (e.g., humidity, temperature, rainfall) and should be identified in future research programs.

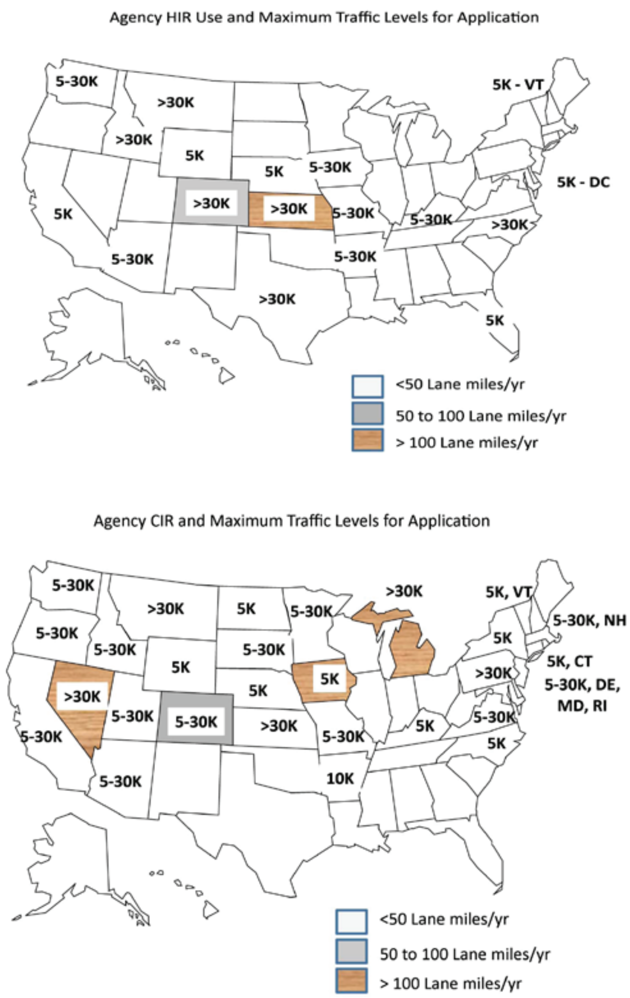


FIGURE 2 Use of HIR and CIR processes, size of programs (lane-miles per year), and maximum traffic levels acceptable for roadways.

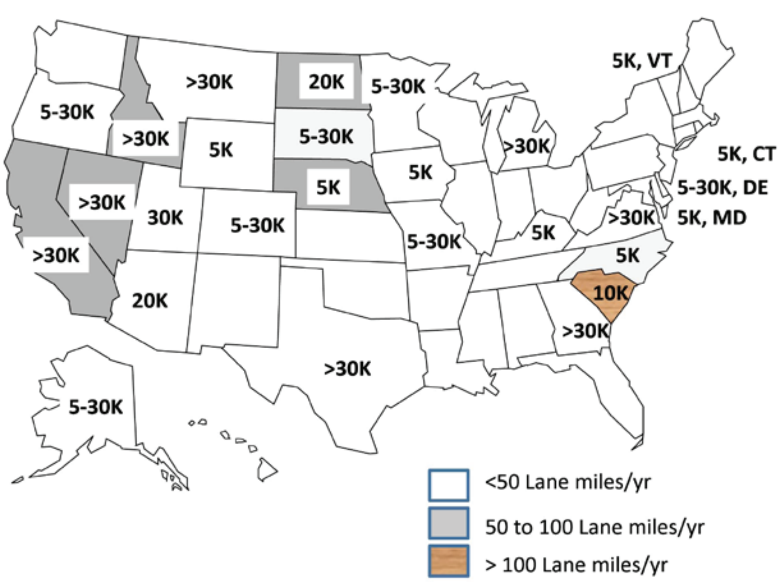


FIGURE 3 Use of FDR processes, size of programs (lane-miles per year), and maximum traffic levels acceptable for roadways.

CHAPTER TWO

DEVELOPMENT OF A RECYCLING PROJECT

Although each of the in-place recycling processes differs in purpose, the development of a recycling project has a number of common considerations. Figure 4 outlines the steps needed for project selection, material selections, mix designs, assessment of structural capacity, and construction sequences. The following sections are organized in order of the steps outlined in this figure. Each section identifies specific points in the development processes where different considerations are needed to select the best in-place recycling process for a given project.

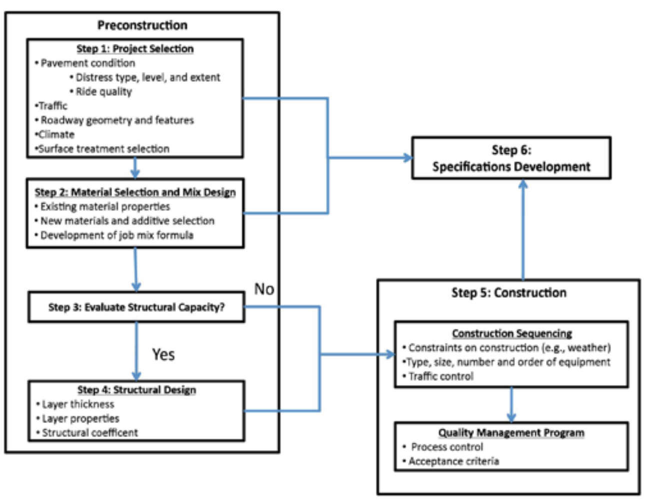
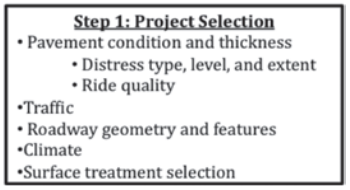


FIGURE 4 Steps in selecting, designing, constructing, and specifying in-place recycling projects.

PROJECT SELECTION CRITERIA



Project selection is the first step in development of a recycling project and consists of an assessment of existing pavement condition, traffic, geometric and environmental considerations, and identification of surface treatments needed for weather (e.g., snowplows, wet roads), restriction of water penetration, traffic, and anticipated capacity improvements.

The contractor members of ARRA were asked to answer the same survey questions as the state agency materials engineers. A comparison of the responses for the two populations of respondents provides insight into topics where there is good agreement and those in need of further education, research, and clarification (see Figure 5).

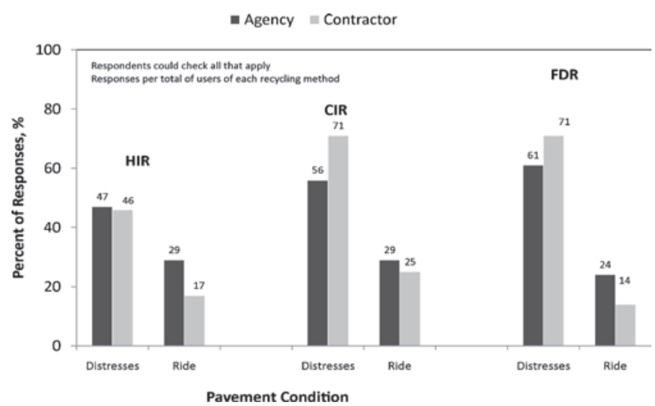


FIGURE 5 Comparison of agency and contractor responses for measurements of pavement condition used for in-place recycling projects.

Pavement Condition

Functional condition of an existing pavement describes roadway features that meet the users' need for ride quality (smoothness), safety (polishing, bleeding/flushing, friction), and geometry (e.g., lane widths). Distress measurements that influence the ride quality and safety include potholes, bumps, depressions, shoving, and slipping. Structural condition is the ability of the roadway to carry the traffic loads. Structural issues can be identified with nondestructive testing such as falling weight deflectometer (FWD) and by quantifying load- and support-related distresses such as longitudinal cracking in the wheel paths, edge cracking, and fatigue cracking.

Assessing Existing Pavement Condition

The two most common methods of assessing the condition of the pavement are distress surveys and smoothness. Most states, independent of in-place recycling processes, use distress surveys as the primary source of information for initially identifying potential preservation, maintenance, and rehabilitation activities (Table 5). A more limited number of states also include ride quality measurements before placing a recycling project. Specific layer properties and confirmation of layer thicknesses and properties are discussed in the sections on material selection and mix designs of this report.

TABLE 5
AGENCY RESPONSES FOR PRECONSTRUCTION FIELD TESTING FOR IN-PLACE RECYCLING PROJECTS

Preconstruction Field Testing: Before construction, I typically use:			
Preconstruction Work	States		
	HIR	CIR	FDR
Condition Distress Survey	AR, AZ, CA, CO, FL, ID, IA, KS, KY, MD, MO, MT, NC, NE, NY, TX, VT, WA	AZ, CA, CO, CT, DE, ID, IA, KS, MD, MN, MO, MT, NE, NH, NV, NY, OR, RI, SD, UT, VA, VT, WA, WI, WV	AR, AL, CA, CO, CT, DE, GA, ID, IA, MD, MN, MO, MT, NE, NH, NV, OR, SC, SD, TX, UT, VA, VT, WI, WY
Ride Quality (smoothness measurements)	AR, AZ, CA, CO, FL, GA, ID, KS, MD, MT, VT, WA	AZ, CA, CO, ID, MD, MN, MT, NH, NV, UT, VA, VT, WA, WY	AL, CA, CO, MD, MN, NH, NV, UT, VA, VT

Both agencies and contractors rely on distress survey information when considering projects for recycling. These assessments are increasingly important for CIR and FDR projects. Contractors are less likely to consider ride quality when evaluating preconstruction test results.

In summary, pavement condition, particularly distress surveys, is one of the most important factors in the selection of an in-place recycling method.

Milling Depths

The existing pavement condition and the type, extent, and severity of the distresses will indicate the depth of recycling needed for preservation, maintenance, and rehabilitation, and hence help identify the most useful recycling process. ARRA (2001) provides recommendations for the various distresses that can be addressed with a particular recycling process, along with the appropriate milling depths (Table 6). HIR projects are recommended for milling only the top 1 to 2 in., CIR from 2 to 4 in., and FDR for greater than 6 in. Table 6 includes typical distresses that can be addressed at each recycling depth.

The milling depths used by state agencies on HIR projects can go as deep as 4 in. when two passes are used (Table 7). Seven states mill CIR projects from 1 to 6 in. As with the other recycling processes, a limited number of agencies applied FDR outside the recommended depths. Written comments indicated that a maximum depth for FDR may be useful, as some states reported difficulty in achieving adequate compaction in lifts thicker than 12 to 14 in. Four states use

TABLE 6
GENERAL GUIDELINES USES FOR IN-PLACE RECYCLING BASED ON PAVEMENT DISTRESSES PRESENT IN THE EXISTING PAVEMENT (based on ARRA 2001)

Distress	HIR			CIR	FDR
	Surface Recycling	Remixing	Repaving		
Milling Depths					
25 mm (1 in.)	X	—	—	—	—
25 to 50 mm (1 to 2 in.)	X	X	X	X	—
25 to 75 mm (1 to 3 in.)	—	X	X	X	—
50 to 100 mm (2 to 4 in.)	—	—	—	X	X
100 to 150 mm (4 to 6 in.)	—	—	—	—	X
>150 mm (>6 in.)	—	—	—	—	X
Distresses					
Alligator Cracking	P	F	G	G	G
Bleeding, Flushing	F	F	F	F	G
Block Cracking	F	F	G	G	G
Bumps	F	F	F	F	G
Edge Cracking	P	F	F	F	G
Friction Improvement	P	F	G	G	G
Longitudinal Cracks (non-wheel path)	F	F	G	G	G
Longitudinal Cracks (wheel path)	F	F	G	G	G
Oxidation	G	G	G	G	G
Patches	F	G	F	G	G
Polishing	P	G	G	G	G
Potholes	F	G	G	G	G
Raveling	G	G	G	G	G
Rutting	F	G	F	G	G
Reflective Cracking	F	F	G	G	G
Shrinkage Cracking	—	—	—	—	—
Shoulder Dropoff	P	P	P	P	P
Shoving	F	G	F	G	G
Slippage	F	F	G	G	G
Transverse Cracks	F	F	F	G	G
Moisture Damage	P	F	G	G	G
Ride Quality (distress related)	F	F	F	F	G
Minor Profile Corrections	F	F	F	F	G

G = good process for addressing distress.
F = fair process for addressing distress.
P = not likely to fully address distress.
This table is included as a reference for general guidelines and should not be used exclusively to select a recycling process.

FDR at shallower depths of 4 to 6 in., which is likely a function of thin hot mix asphalt (HMA) layers common on low traffic volume roadways. Shallow depths of 2 to 4 in. reflect thin HMA layers or multiple surface treatments placed on the subgrade, which can be found on very low traffic volume roadways.

TABLE 7
AGENCY RESPONSES FOR MILL DEPTHS USED ON RECYCLING PROJECTS

Typical Milling Depth: Indicate the most common depth of milling for your recycling projects			
Mill Depths	Agency Responses		
	HIR	CIR	FDR
25 to 50 mm (1 to 2 in.)	AR, CA, CO, FL, ID, IA, KS, KY, MD, MO, NC, NE, TX, WA	NC	—
50 to 100 mm (2 to 4 in.)	AZ, MD, MT	AZ, CA, CT, DE, ID, IL, IA, KS, MN, MO, MT, ND, NE, NV, NY, OR, SD, UT, VA, VT, WA, WY	MN, NC
100 to 150 mm (4 to 6 in.)	—	CO, DE, IL, MO, RI, VA, WI	AL, DE, MO, VT
>150 mm (>6 in)	—	—	AL, CA, CO, GA, ID, IL, IA, MT, ND, NE, NV, NY, OR, SC, TX, UT, VA, VT, WY

Contractors frequently use milling depths of 50 to 100 mm (2 to 4 in.; 4 in. requires two passes) for CIR processes, with a significantly higher percentage of contractors than agencies using milling depths outside of this range (Figure 6). There is good agreement between agencies and contractors on milling depths greater than 6 in. for FDR projects. A higher percentage of contractors use shallow (50 to 100 mm or 2 to 4 in.) milling depths for FDR projects than agencies. This may represent more nonstate work on low traffic volume roadways by contractors.

A number of state agencies and contractors use the ARRA-recommended range of recycling depths for each process; however, the actual depth of recycling can vary depending on project needs. Guidance on the maximum FDR recycling depth (i.e., lift thickness) is needed so that the desired layer density can be obtained. Agencies appear to underuse FDR for thinner layers.

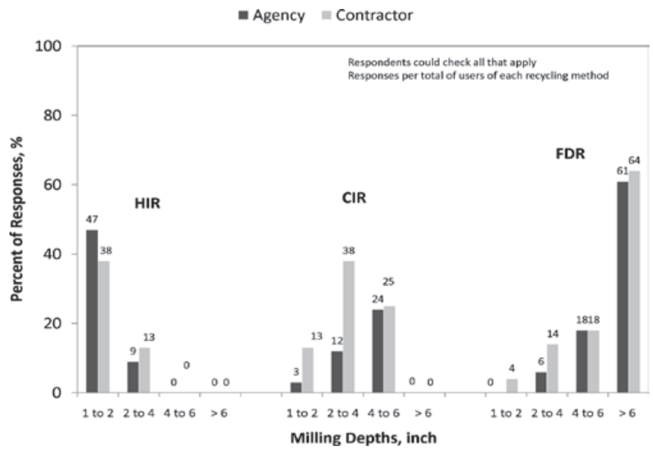


FIGURE 6 Comparison of milling depths used by agencies and contractors for each in-place recycling process.

Traffic

Traffic levels can limit the use of some recycling processes. When asphalt emulsions are used in CIR and FDR projects, the emulsion needs time to break (set) and the water needs time to evaporate before placing the surface course. During this curing time, the pavement needs to perform under traffic from 7 to 30 days. An appropriate selection of materials and additives can be used to minimize the time delay between recycling and placement of the surface course. Another consideration related to traffic level is the ability of the subgrade to support the weight of the presurface treatment traffic and recycling equipment.

All recycling processes have been used at traffic levels up to 30,000 annual average daily traffic (AADT; Table 8); however, some states may limit the traffic for specific processes to less than 5,000 AADT. At over 30,000 AADT, agencies consider using only HIR or FDR processes.

TABLE 8
TRAFFIC LEVELS FOR IN-PLACE RECYCLING PROJECTS

Question: I would consider recycling a roadway with annual average daily traffic (AADT) levels of up to:			
AADT	Type of In-Place Recycling Used		
	HIR	CIR	FDR
<5,000	CA, DC, FL, NE, VT, WY	CT, IA, KY, NC, ND, NE, NY, VT, WY	CT, IA, KY, MD, NC, NE, VT, WY
5,000 to 30,000	AR, AZ, IA, KY, MO, WA	AZ, CA, CO, DE, ID, MD, MN, MO, NH, OR, RI, SD, UT, VA, WA	AK, CO, DE, MN, MO, ND, NH, OR, SC, SD, UT
>30,000	CO, ID, KS, MD, MT, NC, TX	—	CA, GA, ID, MT, NV, TX, VA, WI

Significant differences between agencies and contractors were seen at traffic levels of less than 5,000 and greater than 30,000 AADT. Contractors are less likely than the agencies to consider HIR and CIR for the low traffic levels (Figure 7). This may be related to the lack of adequate support for the recycling equipment on the thinner low-volume roadways. Contractors are more likely to consider any of the processes acceptable for the higher traffic levels.

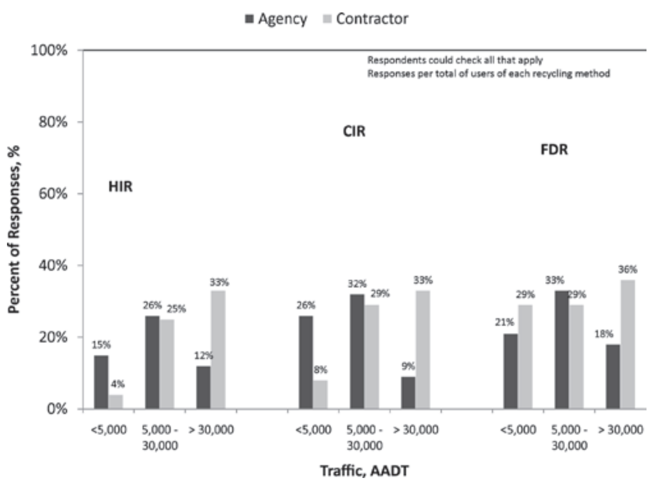


FIGURE 7 Influence of traffic levels on the selection of in-place recycling process.

The average of the percentage of positive responses from both the agencies and contractors was used to rank acceptable geometric features of roadways for each of the in-place recycling processes (Table 9). Four categories of acceptability of each of the factors are defined:

TABLE 9
MAXIMUM TRAFFIC LEVELS CURRENTLY USED FOR IN-PLACE RECYCLING METHODS

AADT	HIR	CIR	FDR
<5,000	F	F	G
5,000 to 30,000	G	G	G
>30,000	G	G	G

P = Poor, lower than 10% average of agency and contractor.
F = Fair, between 10% and 25% average of agency and contractor.
G = Good, between 25% and 50% average of agency and contractor.
VG = Very good, greater than 50% average of agency and contractor.

- VG = very good and represents that more than 50% of agencies and contractors consider the factor acceptable.
- G = good and represents that between 25% and 50% of agencies and contractors consider the factor acceptable.
- F = fair and represents that between 10% and 25% of agencies and contractors consider the factor acceptable.
- P = poor and represents that less than 10% of agencies and contractors consider the factor acceptable.

The percentages were calculated using the number of agencies or contractors indicating experience with a particular recycling process. The category groupings were arbitrarily selected after reviewing general trends in responses.

HIR, CIR, and FDR on roadways with AADT greater than 30,000 may be underused by agencies and overused on facilities with AADTs less than 5,000. Subgrade support for equipment needs to be considered. The reasons for the differences in acceptable traffic levels need to be explored.

Roadway Geometry and Features

Roadway geometry and features may also limit the use of in-place recycling processes. Different features will have varying impacts depending on the recycling process. Geometry and features evaluated in this survey include

- Tight turns < 12 m (40 ft) or switchbacks,
- Mountainous terrains with grades exceeding 8%,
- Manholes or other castings in the pavement layer,
- Minor roadway-widening needs,
- Superelevation or cross-slope correction required (minor profile corrections), and
- Curbs and gutters.

Features that limit state use of the HIR processes include tight turns, steep grades, castings, and the need for lane widening. Agencies consider HIR projects needing minor profile (typically less than ½ in. crossfall) corrections or with curbs and gutters acceptable features (Table 10). CIR use is limited by the presence of tight turns, steep grades, and castings. CIR is not limited by needs for roadway widening, limited profile corrections, and the presence of curbs and gutters. These features seem to have the least impact on selecting FDR for projects. Tight turns, mountainous terrains, and minor widening limit the state's use of HIR, CIR, and to some extent FDR. Minor profile correction limits the use of HIR but is considered acceptable for both CIR and FDR projects. Curbs and gutters can be addressed with any of the recycling processes. Contractors differ in choices of acceptable geometry and features in several cases (Figures 8 and 9).

Steep grades and castings present less of a concern for contractors than for agencies when using HIR processes. Contractors are less likely than agencies to consider tight turns and steep grades as acceptable features for CIR projects. The majority of contractors with experience placing FDR projects feel comfortable using this process with any of the features listed in this survey. There is better agreement between contractors and agencies on the impact of the need for lane widening, minor profile corrections, and curbs and gutters (Figure 9).

TABLE 10
INFLUENCE OF ROADWAY GEOMETRIC AND FEATURES ON THE SELECTION OF IN-PLACE RECYCLING PROCESSES

Question: I would consider recycling a roadway with:

ADT	Type of In-Place Recycling Used		
	HIR	CIR	FDR
Tight Turns (radius 12 m (<40 ft) or switchbacks	DC, KS, KY	DE, KY, MT, NC, NV, SD, UT	AK, DE, GA, ID, KY, MO, MT, NW, NH, NV, SD, UT
Mountainous Terrains with Grades Exceeding 8%	KY, MT, VT	DE, KY, MT, NV, UT, VT, WA	AK, DE, ID, KY, MT, NC, NH, NV, UT
Manholes or Other Castings Within Pavement Layer	CA, FL, IL, MO	CA, CT, DE, IL, ND, NH, NV, WI	AK, CA, CT, DE, ID, NC, NH, NV, SC, WI
Minor Roadway Widening Needs	CO, FL, ID	CO, DE, ID, IL, IA, KS, MO, NV, SD, UT VT, WI, WY	AK, AL, CA, CO, DE, ID, IL, IA, MO, MT, NC, ND, NV, OR, SC, DS, UT, VA, VT, WI, WY
Superelevation or Cross-slope Correction Required	AZ, CO, FL, IA, KS, KY	AZ, CO, DE, ID, IA, KS, KY, MO, MT, NE, NV, NY, RI, UT, VA, WA, WI	AK, AL, CA, CO, CT, DE, GA, ID, IA, KY, MO, MT, NC, ND, NE, NV, SC, SD, UT, VA, VT, WI, WY
Curb and Gutter	AZ, CO, CT, FL, GA, ID, IL, KS, KY, MD, MO, MT, NC, NE, VT, WA	CO, CT, DE, ID, IL, IA, KS, KY, MS, MO, MT, ND, NV, UT, VA, WA, WI, WY	AK, AL, CA, CO, CT, DE, ID, IL, KY, MO, NV, SC, SD, UT, VA, WI, WY

Note: Agencies could respond to all that apply.

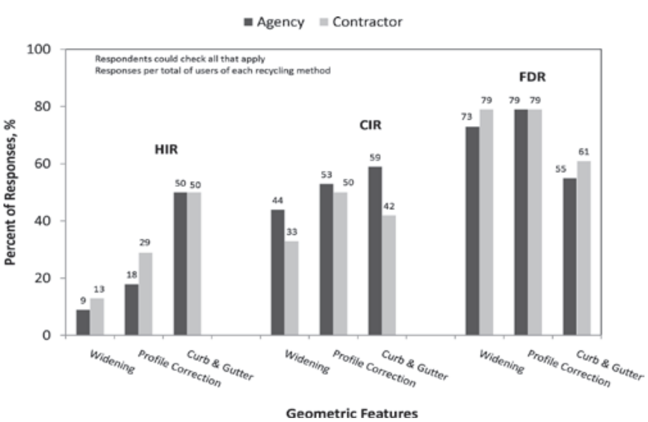


FIGURE 8 Influence of traffic levels on the selection of in-place recycling process (widening, minor profile correction, and curb and gutters). Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

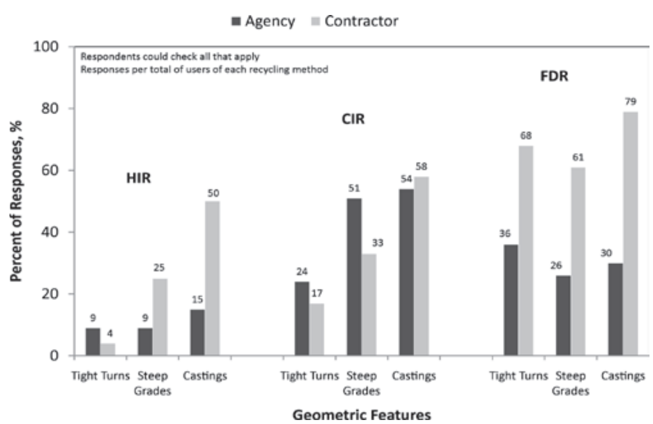


FIGURE 9 Influence of roadway geometry and features on the selection of in-place recycling process (tight turns, steep grades, and castings). Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

A written response from one agency noted experience with rutting problems when CIR was used on grades greater than 4%; however, the agency indicated that its experience was from 11 years ago. A single contractor noted that, depending on the extent of cross-slope correction required, off-site material may be needed, which must be considered in the contract documents. This contractor noted that it considers mountainous terrains on an individual project basis.

The agency and contractor responses were used to rank and summarize the responses for judging the ability of recycling processes to accommodate various geometry and roadway features (Table 11).

Information found in the literature revealed mixed opinions about acceptable and unacceptable roadway features. In 2002, Lee et al. found the following *not* to be appropriate features for CIR recycling projects:

- Numerous manholes or drainage outlets,
- Excessively steep grades [5% and 706 m (2,316 ft)],
- Heavily shaded areas, which increase cure times,
- HMA layers less than 50 mm (2 in.) thick, and
- Numerous branch roadway accesses (e.g., driveways).

Lane and Kazmierowski (2005a) noted that one of the advantages of CIR was the ability to use this process on projects with numerous entrances, side roads, and intersections because CIR would not result in raising the grade.

TABLE 11
INFLUENCE OF GEOMETRIC FEATURES ON PROJECT SELECTION

	Ranking of Acceptable Features for Recycling Projects		
Geometric Features	HIR	CIR	FDR
Tight Turns	P	F	VG
Steep Grades	G	G	VG
Castings	G	VG	VG
Widening	F	G	VG
Minor Profile Corrections	G	G	VG
Curbs and Gutters	G	G	VG

P = Poor, lower than 10% average of agency and contractor with experience.
F = Fair, between 10% and 25% average of agency and contractor with experience.
G = Good, between 25% and 50% average of agency and contractor with experience.
VG = Very good, greater than 50% average of agency and contractor with experience.

Roadway geometry and features need to be considered when selecting the most appropriate in-place recycling method(s) for a project. Further research is needed to identify the reasons for the differences between agency and contractor responses.

Climate

A number of specifications contain weather restrictions on when recycling projects can be constructed. The survey explored preferences for recycling processes used in four general climate regions:

- Cold and wet,
- Cold and dry,
- Hot and wet, and
- Hot and dry.

Fewer states use HIR and CIR processes in cold, wet climates (Table 12). Agencies prefer to use HIR in hot climates, either wet or dry. FDR use is somewhat independent of climatic conditions.

Several possible reasons were identified that limit HIR and CIR in wet weather conditions:

- Rainy weather interrupts construction work, which requires moving large, slow equipment units on and off the project. Parking large equipment during construction is an issue because of the size and very slow speed of the equipment.
- Damp or wet pavements slow the hot recycling construction process.
- Possible performance issues exist if rainy weather sets in before work is complete.
- Wet, cool weather delays the use of emulsion-based CIR and lengthens the curing time.

Contractors are more likely than agencies to limit construction of HIR and CIR in cold, wet and to some extent hot, wet conditions (Figure 10). Contractors are more likely to consider HIR and CIR processes appropriate choices in dry, cold or dry, hot climates. A significantly higher percentage of contractors construct FDR projects in any of the climatic regions.

The average agency and contractor responses are ranked to indicate the potential impact of climate on selecting an appropriate recycling process (Table 13). It should be noted that a good choice of materials used with a given recycling process can overcome some climate limitations. The usefulness of a recycling process ultimately should be considered on a project-by-project basis. Communication between the agency and the contractor is needed to select the best options for a given climate.

TABLE 12
AGENCY CLIMATE PREFERENCES FOR RECYCLING METHODS

Question: Environmental Conditions: I would consider recycling on roadways in the following climate regions:

Climate	Climate conditions		
	HIR	CIR	FDR
Cold and Wet	CA, GA, ID, IL, IA, KS, KY, MO, NC, NY, TX, VT, WA	CA, DE, ID, IL, KS, KY, MN, MO, MT, NC, NH, NV, NY, RI, WI	AK, CA, CO, DE, GA, ID, IL, KY, MN, MO, MT, ND, NH, NV, OR, SD, TX, WI, WY
Hot and Wet	AR, CA, CO, FL, GA, ID, IL, IA, KS, KY, MT, NC, NU, TX, VT, WA	CA, CO, DE, ID, IL, IA, KS, KY, MT, NC, NH, NB, NY, RI, VA, VT, WA	CO, DE, GA, ID, IL IA, KY, MD, MT, ND, NH, NV, OR, SC, SD, TX, VA, WY
Cold and Dry	AZ, CA, CO, GA, ID, IL, IA, KS, NY, TX, VT, WA	AS, CA, CO, DE, ID, IL, KS, MT, NH, NV, NY, RI, SD, UT, VT, WA, WY	CA, CO, DE, GA, ID, IL, IA, MK, MT, ND, NH, NV, OR, SD, TX, UT, VT, WY
Hot and Dry	AR, AZ, CA, CO, DC, FL, GA, ID, IL, IA, KS, MS, MT, NE, NY, TX, VT, WA	AL, AR, AZ, CA, DE, FL, IL, IN, KS, MD, MO, NE, NJ, OR, SD, TX, UT, VA, VT, WA, WI, WY	AL, AR, AZ, CA, CL, DE, FL, IL, MO, ND, NE, NJ, OR, RI, SD, TX, UT, VA, VT, WA, WI

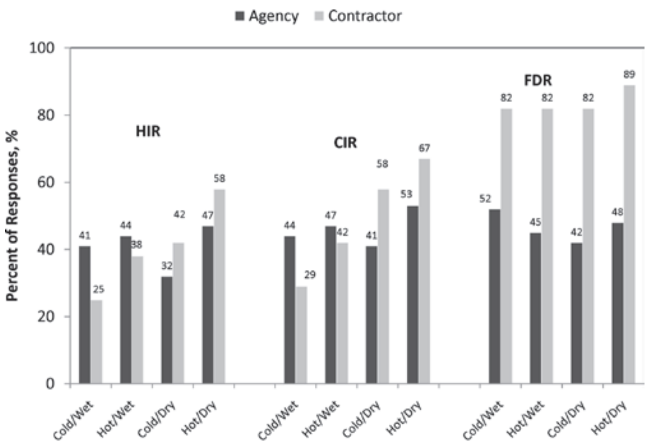


FIGURE 10 Influence of climate conditions on the selection of in-place recycling process. Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

TABLE 13
RANKING OF CLIMATES THAT CAN INFLUENCE THE CHOICE OF IN-PLACE RECYCLING PROCESSES

Climate	HIR	CIR	FDR
Cold/Wet	F	G	VG
Hot/Wet	G	G	VG
Cold/Dry	G	VG	VG
Hot/Dry	VG	VG	VG

P = Poor, lower than 10% agencies and contractor with experience.
F = Fair, between 10% and 25% agencies and contractors with experience.
G = Good, between 25 and 50% agencies and contractors with experience.
VG = Very good, greater than 50% agencies and contractors with experience.

In summary, climate conditions need to be considered when selecting an in-place recycling process. Specific reasons for contractors' and agencies' climate preferences need to be defined in future research efforts.

Surface Treatment Selection

Surface treatments for HIR and CIR projects are commonly selected on the basis of climate considerations (e.g., drainage of surface water, providing impermeable membranes, snowplows), noise reduction, and friction improvement. In some cases, overlays are selected to improve the structural capacity of the roadway. Survey results show that a structural overlay is commonly used as the final wearing surface for all types of recycling projects (Table 14). If an overlay is not used, then a combination fog and chip seal is the next most popular surface. Several states reported using slurry seal or microsurface treatments, but none use a fog seal by itself, a microsurface, or an open-graded friction course (OGFC) for HIR projects.

The written responses indicate that other surfacings have been used, including a chip seal (without fog), rubberized OGFC, stone matrix asphalt, and unreinforced concrete overlay.

An additional question was included in the surveys to assess the impact of climate conditions on the selection of the surface treatment. Only a few states indicated that climate is a consideration. Agencies rely more on the use of traffic [AADT, equivalent single-axel loads (ESALs), percentage of trucks], functional classification of roadway, existing distresses, expected performance of surface course mix, cost, and experience.

Surfaces placed by contractors for FDR projects are frequently a structural overlay, integral overlay, or a fog–chip combination. However, contractors use a wider range of other surface treatments (Figure 11) for all types of recycling projects. A key criterion for two contractors was whether snowplows would be used on the surface mix. Contractors consider traffic, structural designs, existing distresses, performance (raveling, texture, ride quality, rut resistance), cost, and experience when selecting a surface treatment.

TABLE 14
STATE RESPONSES FOR TYPE OF SURFACE TREATMENT USED

Surface Treatment: Indicate the typical top layer used for recycling projects.			
Surface Treatments	Agency Responses		
	HIR	CIR	FDR
Fog and Chip Seal	ID, KS, MT, NE	CA, ID, IL, IA, MO, MT, NV, WA	CA, GA, IL, IA, MT, SC, TX
Fog Seal	—	—	CA
Structural Overlay	AR, AZ, CO, FL, ID, IL, IA, KS, MD, MO, NC, NE, NY	AZ, CA, CO, CT, DE, ID, IL, IA, KS, MN, MO, NC, ND, NE, NH, NV, NY, OR, RI, SD, UT, VA, VT, WA, WI, WY	AZ, CA, CO, CT, DE, ID, IL, IA, MN, MO, NC, ND, NE, NH, NV, NY, OR, SC, SD, TX, UT, VA, WI, WY
Integral Overlay	AZ, CO, IA, KY, MO, TX	CA, SD, VA, WA	SD, VA
Microsurfacing	—	CA, IL, UT	CA, DE, IL, UT
OGFC	—	NV	NV
Non-Structural Overlay	AZ, CA, IL, KS, KY, NY, TX	AZ, CA, IL, NY, VA, VT, AK	AK, CA, GA, IL
Slurry Seal	ND, NE	IL, WI	IL, MD

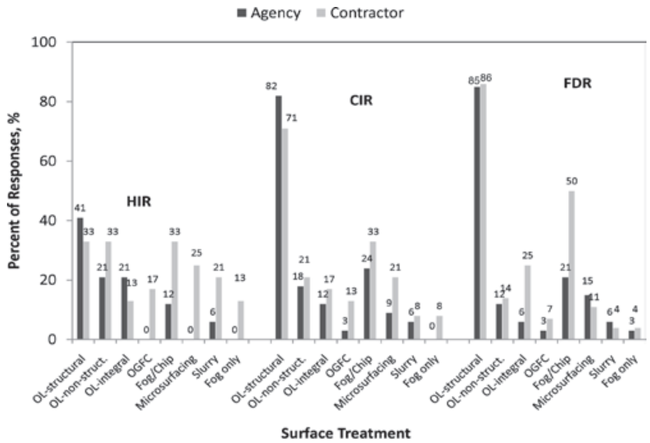


FIGURE 11 Types of surface courses used with in-place recycling processes. Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

The agency and contractor responses were ranked and summarized to indicate currently used surface treatments for in-place recycling projects (Table 15).

TABLE 15

SURFACE TREATMENT SELECTION

Type of Surface Treatment		HR	CIR	FDR
Overlays	Structural	Often	Frequently	Frequently
	Non-Structural	Sometimes	Sometimes	Sometimes
	Integral	Sometimes	Sometimes+	Sometimes*+
OGFC		Rarely*	Rarely	Rarely
Fog/Chip		Sometimes*	Sometimes	Often*
Microsurfacing		Sometimes*	Sometimes*	Sometimes
Slurry		Sometimes*	Rarely	Rarely
Fog Seal		Rarely*	Rarely	Rarely

Rarely = lower than 10% average of agency and contractor with experience.
Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
*Contractor response was significantly higher than agency with experience.
+By definition, "integral" refers to HIR processes, however some state agencies indicated use on CIR ad FDR.

The preference for using a structural overlay when structural capacity improvement is not needed requires further research to define the criteria required to select this option. The ability of other surface treatments to provide acceptable surface courses needs to be explored.

MATERIAL SELECTION AND MIX DESIGN

The second step in the development of an in-place recycling project includes assessing the in-situ layer and reclaimed asphalt pavement (RAP) properties, selecting materials, and providing mix designs for setting the job mix formulas. The information varies on the basis of the recycling process (Figure 12).

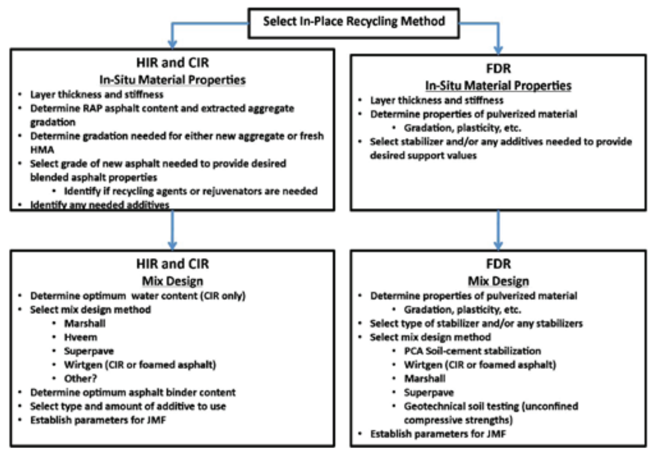


FIGURE 12 Work needed to select materials and establish job mix formulas.

In-Situ Layer Properties

In-situ properties are needed to evaluate the need for different designs for different segments of the project. The ability of the underlying layers to support the construction equipment and the variability in layer thicknesses that can affect a reasonable selection of milling depths also need to be determined. A number of approaches can be used to define the thickness and stiffness of the underlying layers. The most common methods of assessment include coring, boring logs for base and soils classifications, dynamic cone penetrometer testing (DCP), California bearing ratio, or resistance value (R-value) from soils testing or historical records, FWD layer modulus, ground-penetrating radar (GPR), or local experience (Jahren et al. 1999; Loizos and Papavasiliou 2006; Loizos 2007; Malick et al. 2007). The initial use for this testing is to

- Determine the ability of the subgrade to support the weight of the recycling equipment,
- Evaluate needs for increased structural capacity,

- Provide information for the structural design (FDR), and
- Identify sections in need of different treatments.

States typically use the same preconstruction field testing, regardless of the recycling process (Table 16). Agency preferences for field-testing methods are borings and coring investigations. Fewer than a third of the agencies use FWD testing for determining the layer modulus and project variability. Fewer than 9% of the states use GPR for preconstruction project assessments. The use of GPR testing will likely increase as the technology becomes more widely available in the coming years because it can provide information quickly on layer thickness, presence of moisture, and sections of the project in need of different designs.

TABLE 16
AGENCY TESTING FOR LAYER PROPERTIES

Preconstruction Field Testing: Before construction, I typically use:			
Preconstruction Work	States		
	HIR	CIR	FDR
Coring to Determine Thickness	AK, AL, CA, CO, DE, GA, ID, IA, MD, MN, NC, ND, NE, NV, OR, SC, SD, TX, UT, VA, VT, WY	AR, AZ, CA, CO, FL, GA, ID, IA, KY, MD, MO, MT, NE, NH, NV, NY, OR, RI, SD, UT, VA, VT, WA, WY	AK, AL, CA, CO, CT, DE, GA, ID, IA, MD, MN, MO, MT, NE, NH, NV, OR, SC, SD, TX, UT, VA, WY
Boring to Check Depth of Base and HMA	CO, ID, KS, MD, MO, MT, TX, WA	CO, CT, DE, ID, KS, MD, MO, MT, NH, NV, OR, SD, UT, VA, WA, WI	AR, AZ, CA, CO, FL, ID, IA, KS, KY, MD, MO, MT, NC, NE, NY, TX, VT, WA
FWD Testing	AR, AZ, CO, FL, ID, MD, NC, NE, TX, VT, WA	AZ, ID, MD, MN, NC, NE, NV, OR, RI, SD, UT, VA, VT, WA, WY	AK, AL, CA, ID, MD, MN, MT, NC, NE, NV, OR, SD, TX, UT, VA, VT
GPR Testing	MT, TX	MN, MT	MN, MT, TX, AK

Fewer field tests are conducted on HIR projects by contractors and agencies compared with CIR and FDR projects (Figure 13). Core thickness, boring logs, and samples are the most commonly used preconstruction field tests. Contractors are significantly more likely than agencies to conduct field tests for FDR projects.

The average of the percentage of agencies and contractors using a given method of assessing the in-place material properties was used to rank method preferences (Table 17).

Wirtgen (2004) provides a suggested comprehensive testing plan for conducting a detailed investigation. The testing program includes cutting a test pit, coring, and DCP testing (Figure 14). A combination of the distress surveys and field tests provides the engineer with sufficient information to evaluate any design adjustments needed for various sections of roadway.

In summary, the availability or collection of in-place material properties information needs to be considered when developing the project design, specifications, and agency estimates of project costs.

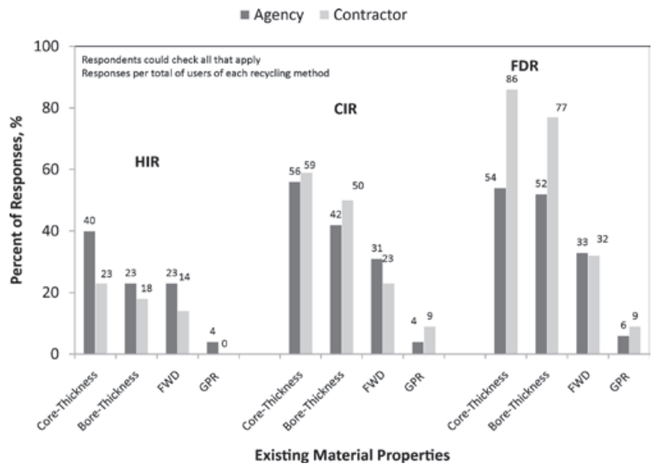
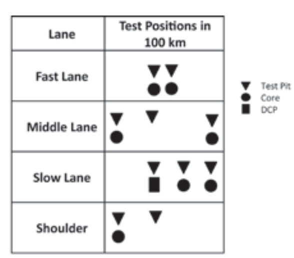


FIGURE 13 Methods of assessing in-place layer properties by agencies and contractors. Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

TABLE 17
SOURCES OF EXISTING IN-PLACE MATERIAL PROPERTIES
(average of agency and contractor percentages)

Layer Property Testing	HIR	CIR	FDR
Coring to Determine Thickness	Often**	Frequently*	Frequently*
Boring to determine thickness	Sometimes	Often	Frequently
FWD	Sometimes	Sometimes	Often
GPR	Rarely	Rarely	Rarely

Rarely = lower than 10% average of agency and contractor with experience.
Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
*Contractor response was significantly higher than agency with experience.
**Agency response was significantly higher than contractor with experience.



	Thickness, cm		Modulus, Mpa		Laboratory Test Results		
	Range	95% Percentile	FWD	DCP	CBR	PI	GM
HMA Layers	11 - 19	13	3,500				
Asphalt Stablized Limestone	18.5 - 22	19	280		102	NP	2.36
Crushed Limestone	12 - 19	15	210		110	NP	2.29
Meathered Limestone	In-Situ		145	165	59	9	2.04

FIGURE 14 Example of comprehensive preconstruction testing program (based on original figure by Wirtgen 2004).

RAP Properties

RAP binder content, RAP binder properties, and RAP aggregate gradation are needed for the appropriate selection of grades of new aggregates, new binders, recycling agents, and additives. The most common agency preconstruction laboratory testing focuses on RAP gradations and binder contents, material properties, and recovered binder properties (Table 18). The same testing program is used regardless of the recycling process; however, agencies are more likely to test the recovered binder properties for HIR projects than for either CIR or FDR projects.

TABLE 18
AGENCY RESPONSES FOR PRECONSTRUCTION LABORATORY TESTING FOR IN-PLACE RECYCLING PROJECTS

Preconstruction Laboratory Testing: Before construction, I typically determine:			
Laboratory Testing	States		
	HIR	CIR	FDR
Aggregate Gradations of Cores or Millings	AR, CA, FL, ID, KS, KY, MF, NC, NE, TX, WA	CA, CT, DE, ID, KS, MD, MN, ND, NH, NY, RI, SD, UT, VT, WY	AK, AL, CA, DE, GA, IA, MD, MN, SD, UT, VT
Application Rates of Binders or Other Additives	CA, CO, IA, KS, MD, NE, NY, TX, WA	CA, CO, CT, IA, KS, MD, MN, NE, NH, NY, SD, UT, VT, WY	AL, CA, CO, GA, ID, IA, MD, MN, NE, SC, UT, VT, WY
Binder Content of Cores or Millings	AR, CA, FL, ID, KS, KY, MD, NC, NE, TX, WA	CA, CO, CT, ID, KS, MD, MN, ND, NE, NH, NY, WY	AL, CA, GA, MD, MN, WA
Material Properties of Any Liquids, Stabilizers, Rejuvenators, Additives, or Admixtures to Be Added	CA, CO, FL, GA, IA, KS, MD, NC, NE, NY, TX, WA	CA, CO, IA, KS, MD, NE, SD, UT, WY	AL, CA, CO, GA, IA, MD, NE, TX, UT, VT, WY
Percent Fines of Millings	CA, FL, ID, KY, MD, NC, NE, TX	CA, ID, MD, UT, VT, WY	AK, CA, ID, IA, MD, NE, UT
Recovered Binder Properties from Cores or Millings	CA, FL, GA, KY, MD, NC, NY, TX, VT, WA	CA, MD, WY	AK, CA, MD

Contractors conduct more tests before construction than the agencies (Figure 15). Contractors and agencies tend to agree more often on testing of HIR than on either CIR or FDR projects.

The agency and contractor responses were used to rank and summarize current practices for laboratory testing (Table 19).

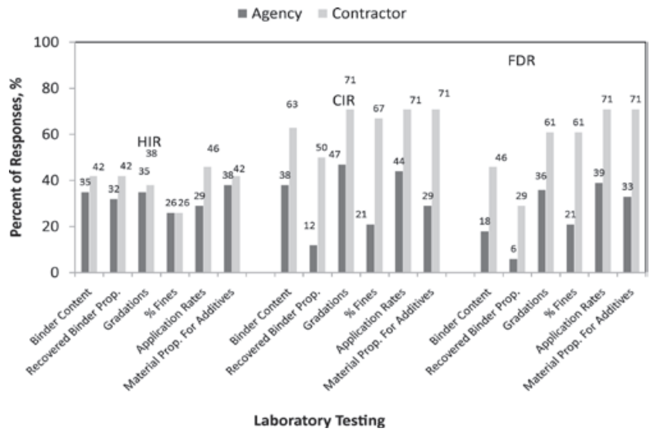


FIGURE 15 Comparison of testing for RAP properties between agencies and contractors. Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

TABLE 19
LABORATORY TESTING PROGRAMS

Preconstruction Laboratory Testing	HIR	CIR	FDR
Binder Content	Often	Frequently*	Often*
Recovered Binder Properties	Often	Often*	Sometimes*
Gradations	Often	Frequently*	Often*
% Fines	Often	Frequently*	Often*
Application Rates	Often	Frequently*	Often*
Material Properties for Additives	Often	Frequently*	Often*

Rarely = lower than 10% average of agency and contractor with experience.
Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
*Contractor response was significantly higher than agency with experience.

Preconstruction testing is key to designing recycling mixes. The time needed for this testing as well as the costs to the project need to be considered in developing cost estimates and project timelines.

New Materials and Additives

A range of new materials and additives can be used to produce desired mix properties and early performance. New aggregates may be added to adjust the final gradation. New binders (paving-grade asphalts, emulsions) are used to soften aged asphalt in the RAP and provide more flexibility of the final asphalt concrete layer. Recycling agents and rejuvenators can be used instead of, or in conjunction with, the new binders to improve the binder performance properties. Although each material can be added individually, it is common practice to introduce new aggregates and asphalt by adding new HMA to the recycled materials. Additives and stabilizers can be added to improve stiffness, moisture resistance, and rut resistance; reduce raveling; help dry moist RAP and soils; and control the rate of set of emulsions.

New Aggregates

When new aggregates are added, existing aggregate grades are typically used such as 3/8 in. minus, no. 57 stone, ½ in. minus sizes. Standard aggregate gradations locally available are typically used when gradations of the final mix need to be adjusted.

Asphalt Binders

Asphalt binders used in recycling processes can be typical paving-grade asphalts or emulsions:

- Emulsions
  - CSS-1, CSS-1h, and CSS-1hP
  - CMS-2S
  - HFMS-2, HFMS-2S
  - HF-150, HF-300P
  - Proprietary solventless emulsions
- Asphalt binders in fresh mix
  - Performance-graded asphalt, softer grades
  - Viscosity-graded asphalts (e.g., AC 10, AC 20)
  - Foamed asphalt

Emulsions are a combination of small asphalt globules suspended in water by the use of surfactants. A sample of the emulsion grades used in recycling projects is shown in Table 20. Regardless of the source of the emulsion specification, three groups of material property tests are typically needed to determine the properties of emulsions (water, asphalt, additives), distillation of emulsions (removal of water), and the recovered base asphalt (resi-

TABLE 20
REQUIREMENTS FOR CATIONIC EMULSIFIED ASPHALTS (based on ASTM D2387-05; D977-05; Oregon DOT 2010)

Type	Medium Setting								Slow Setting			
Grade	HFMS-2		HFMS-2s		HF-150		CMS-2S		CSS-1		CSS-1h	
	Min	Max	Min.	Max	Min	Max	Min	Max	Min	Max	Min.	Max
Tests on Emulsions												
Viscosity, Saybolt Furol at 25ºC (77ºF) SFS	100		50		35	150			20	100	20	100
Viscosity, Saybolt Furol at 50ºC (122ºF) SFS							100	450				
Storage Stability Test, 24-h, %		1		1		1.5		1		1		1
Demulsibility, 35 mlL, 0.8% Dioctyl Sodium Sulfonsuccinate, %					40							
Coating Ability and Water Resistance												
Coating , Dry Aggregate	good		good				good					
Coating, After Spraying	fair		fair				fair					
Coating, Wet Aggregate	fair		fair				fair					
Coating, After Spraying	fair		fair				fair					
Particle Charge Test							positive		positive		positive	
Sieve Test, %		0.1		0.1		0.1		0.1		0.1		0.1
Cement Mixing Test, %										2		2
Tests on Distillation												
Oil Distillate, by Volume of Emulsions, %					0.5	4		12				
Residue, %	65		65		62		60		57		57	
Tests on residue from distillation test												
Penetration, 25ºC (77ºF), 100g, 5 s	100	200	200		150	250	100	250	100	250	40	90
Ductility, 25ºC (77ºF), 5 cm/min, cm	40		40				40		40		40	
Solubility in Trichloroethylene, %	97.5		97.5		97.5		97.5		97.5		97.5	
Float Test, 60ºC (140ºF), s	1,200		1,200		1,200							

due). Traditional emulsion specifications use one or more tests to define the asphalt residue properties: absolute and kinematic viscosity, penetration, and ductility testing. The existing specifications rely on older methods of grading asphalts (e.g., penetration grades, viscosity grades); however, most states now specify asphalt products using the performance grading (PG) specifications.

Clyne et al. (2003) explored PG specification testing (AASHTO MP1) to classify the asphalt residue from three emulsions used in the same region of Minnesota (Table 21). Based on these results, the engineered emulsion (EE) and HFMS-2P would be expected to remain more flexible at colder temperatures than CSS-1. Both CSS-1 and HFMS-2P would be expected to be less sensitive to movement under traffic at summer temperatures than the EE product. This is also supported by research for Federal Lands (Johnston and King 2008). Research by Epps et al. (2001) suggested that emulsion specifications use the concept of PG binder properties so that recycling binders can be selected for project-specific environmental conditions.

TABLE 21
PG GRADING FOR MINNESOTA EMULSIONS (based on Clyne et al. 2003)

Emulsion	Performance Grade
CSS-1	PG 52-28
Engineered Emulsion (EE)	PG 46-34
HFMS-2P	PG 52-34

Emulsions historically used in the same environmental conditions may have base asphalts with a wide range of performance-graded asphalt properties that will likely influence the success or failure of recycling projects. Emulsion specifications need to be updated so that users can select binders on the basis of performance properties.

Asphalts—Paving Grades

Paving-grade asphalt can be specified by the standard PG specification by using the desired properties of the combined asphalt (i.e., combination of new and RAP asphalt). A formal blending program can be conducted to select the fresh binder PG specification, or a less formal "bumping" down one grade to account for the stiffening of the fresh binder because the aged RAP binder can be used. The Texas Department of Transportation is conducting research into the use of Superpave® PG specifications for asphalts used in near-surface applications.

Specific guidance is needed for using PG specifications for recycling project asphalts.

Asphalt—Foamed Asphalt

One method of adding fresh binder to cold recycling processes (CIR and FDR) is to foam it during the mixing process in the recycling train. Foamed asphalt is produced by injecting a small amount of water into hot asphalt as it is mixed with the recycled materials (Figure 16). As the hot liquid and water mix, the liquid expands as the water turns to steam, creating a thin film of asphalt with about 10 times more coating potential. Foaming facilitates better dispersion of the asphalt into the materials to be recycled. The two key parameters that control the quality of the foam are the:

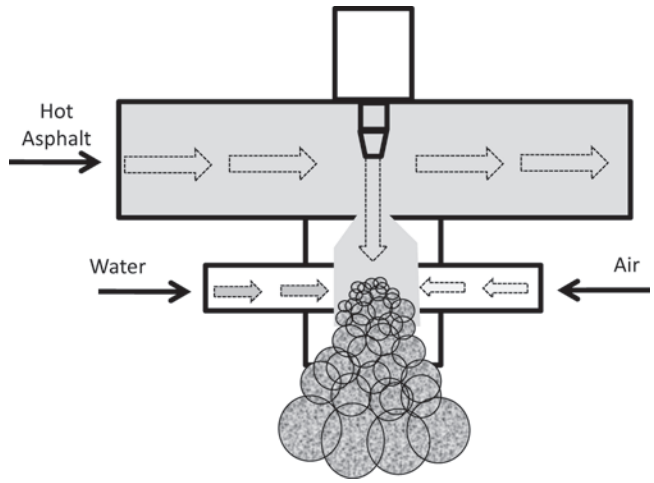


FIGURE 16 Foamed asphalt process during construction (based on original figure by Wirtgen, 2004).

- Expansion ratio (minimum of 10 times; Wirtgen 2004) and
- Half-life of the foam (minimum of 8 s; Wirtgen 2004).

The expansion ratio is defined as the ratio between the maximum achieved volumes of the foam to its original volume. The half-life is defined as the time elapsed from the time the foam was at the maximum volume to the time it reaches half of the maximum volume. Larger expansions and longer half-life are considered desirable properties for foamed asphalt.

Marquis et al. (2002) noted that the quality of foamed asphalt mix is strongly related to the quality of the foam as measured by the expansion ratio and the half-life. Optimum settings for the foaming process need to be set in the mix design phase on the basis of parameters needed to produce peaks in stiffness or modulus of the mix. It should be noted that there need to be between 8% and 20% fines in the FDR to achieve the desired results for foamed asphalts, although 100% RAP mixes can be prepared with lower percentages of fines (Matthews 2008). The Wirtgen (2004) manual recommends a range of gradations suitable for foamed asphalt (Figure 17). One of the main advantages to using foamed asphalt instead of emulsions is that the roadway can be opened to traffic immediately after compaction because no curing time is needed (Lane and Kazmierowski 2005a). If the fines content of the RAP is insufficient, then additional mineral filler will be needed (see the section on additives and stabilizers).

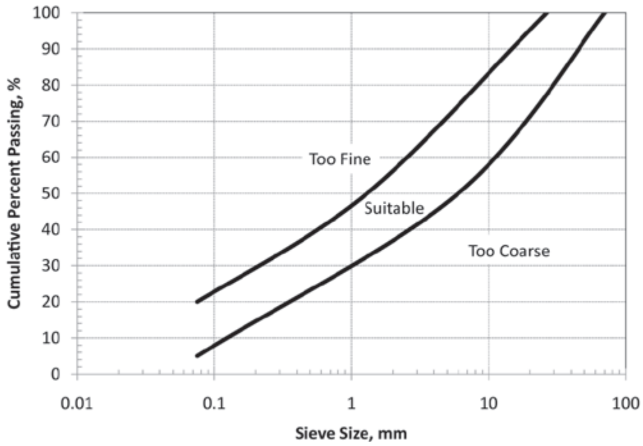


FIGURE 17 Suggested gradation range for foamed asphalt (based on original figure by Wirtgen 2004).

New HMA

Fresh mix is commonly used in HIR, but it is used very rarely in CIR and not at all in FDR. The new HMA is used to easily adjust the gradation of the HIR. The gradation of the new HMA is selected to achieve the desired final gradation, and the binder grade of the new HMA is selected to help soften and rejuvenate the RAP binder. Mixes reported as used include minus 1.9 mm (¾ in.) dense-graded HMA, fine-graded HMA, minus 12.5 mm (1/2 in.) open-graded HMA, and stone matrix asphalts.

The simplest means of obtaining economical and timely new HMA supplies is to use HMA mixes typically produced by the plant supplying the mix. The amount of new HMA needed for a recycling job is small compared with the typical hourly HMA plant production, and plant operators will be reluctant to change plant operations for small orders of HMA. When they are willing to change mixes, the cost of the specialty mix will be substantially higher than typical HMA, and the availability will depend on the plant's ability to interrupt its production schedule. The most economical and practical approach is to start with the properties of the typical new HMA that is locally available and adjust the RAP gradation if at all possible.

Recycling Agents and Rejuvenators

Recycling agents (RAs) are used to restore the aged asphalt to the desired binder properties. ASTM D4552 (Table 22) classifies petroleum product additives specifically for hot mix recycling methods. The RA classifications are viscosity graded, with the lower the number designation representing the lowest viscosity. Products meeting the RA 1 through RA 75 designations are typically used for recycled mixes with more than 70% RAP in the mixes. When more than 30% of new aggregate is used, the RA 250 and RA 500 grades are more appropriate. The Pacific Coast Conference on Asphalt Specifications defines RAs as hydrocarbon products with physical characteristics selected to restore the aged asphalt binder to the current asphalt binder specifications. By this definition, a softer grade of asphalt can be classified as an RA.

ASTM D5505 provides specifications for emulsified recycling (ER) agents (Table 23). The base asphalt in these products increases in stiffness (viscosity) with increases in the grade number. The ER-1 is a petroleum derivative compatible with asphalts. Its main function is to rejuvenate aged asphalt. The ER-1 material is viscosity graded, and there are no requirements for viscosity measurements on the residue after rolling thin film oven (RTFO) testing. The ER-2 and ER-3 grades are a combination of rejuvenators and asphalt components. These ER agents are typically used when the recycled HMA needs additional asphalt (e.g., when adding new aggregate). They are considered a penetration-graded

TABLE 22
ASTM D4552 CLASSIFICATIONS FOR HOT MIX RECYCLING AGENTS (ASTM D4552 2009)

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	4,500	4,501	12,500	12,501	37,500	37,501	60,000
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	—	—	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 23
ASTM D5505 SPECIFICATIONS FOR EMULSIFYING RECYCLING AGENTS (ASTM 2009)

Tests	Test Method	ER-1		ER-2		ER-3	
		Min	Max	Min	Max	Min	Max
Testing on emulsion							
Viscosity, 50°C, SSF	D224		100	20	450	20	450
Sieve, %	D6933		0.1		0.1		0.1
Storage Stability, 24 h, %	D6930		1.5		1.5		1.5
Residue, by Distillation, %	D6997	65		65		65	
Dilution	—		Report[A]				
Specific Gravity	D70		Report		Report		Report
Compactibility[B]	varies		Report		Report		Report
Testing on residue from distillation							
Viscosity, 60°C, cSt	D2170	50	200		30		30
Saturates, %	D2007		30				
Solubility in Trichloroethylene	D2042	97.5		97.5		97.5	
On residue from distillation after RTFO[C]							
Penetration, 4°C, 50 g 5 s	D5			75	200	5	75
RTFO, Weight Change, %	D2872		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.

material because the penetration is used to set limits on the residue after RTFO conditioning.

In addition to the ASTM recycling agents and ASTM ER agents, some states may include a state-developed specification such as the one from Kansas (Table 24). There are also proprietary recycling products on the market, such as engineered emulsions specifically designed to address disadvantages of conventional recycling agents, in particular in-place recycling methods. Proprietary products specifically designed for in-place recycling that have been used by agencies and contractors are

- CIR-EE,
- Reflex,
- Fortress,
- Pass-R,
- ERA-25,
- ARA-1P, and
- Reclamite.

Additives and Stabilizers

Geiger et al. (2007) summarized the reasons for using stabilization to improve the characteristics of base materials as

- Reducing plasticity index,
- Reducing swelling potential of the in-situ soils,
- Increasing base durability and strength,
- Reducing dust during construction,
- Waterproofing the in-situ soils,
- Drying wet in-situ soils,
- Conserving natural resources (aggregates),
- Reducing construction costs, and
- Providing a temporary wearing surface.

TABLE 24
ASPHALT REJUVENATING AGENT (based on Kansas specification 1205)

Property	Requirement
Viscosity, Saybolt–Furol at 25ºC, s	15–100
Residue, % min.	60
Sieve Test, % max.	0.1
Oil Distillate, % max.	2
Storage Stability, 24 h, % max.	1
Tests on Residue from Distillation	
Asphaltenes, % max.	15
Penetration @ 4°C, 100g, 5 sec.	150–250

The types of additive(s) used with CIR processes are based on the desired mix property improvements, such as improved stripping resistance, rut resistance, layer stiffness for higher traffic levels, controlled rate of set of emulsions, minimized raveling until the wear course is placed, and additional fines needed to meet the desired gradation. FDR materials can be stabilized with most of the additives used for HIR and CIR improvements. Stabilization improves the load-bearing qualities of the mostly unbound pulverized materials and is classified by how it improves base properties (ARRA 2001):

- Mechanical,
- Chemical,
- Bituminous, and
- Combinations.

Mechanical stabilization is developed by using particle interlock typically achieved by pulverizing RAP and base materials and then compacting to the desired density. Because all of the recycling methods include compaction, mechanical stabilization can be considered a secondary stabilizing mechanism for all of the methods.

Chemical stabilization mixes the pulverized RAP and base or subgrade materials with cementitious materials such as calcium chloride, magnesium chloride, lime (hydrated or quicklime), fly ash (Class F or C), kiln dust (cement or lime), portland cement, or other chemicals (ARRA 2001). Some of these chemical stabilizers can be added either dry or in slurry form.

Bituminous stabilization uses an asphalt emulsion, ER agent, or foamed (expanded) asphalt. It is not unusual to see combinations of stabilizers such as fly ash and asphalt emulsion or fly ash and portland cement. Combinations of stabilizing methods and additives are commonly used to improve properties.

Liquid calcium chloride is used to improve freeze/thaw resistance by lowering the freezing point of reclaimed base material. The stiffness of the base is improved by the bonding of the soil and RAP particles. The first application of the liquid is blended with the pulverized material; the stabilized base is shaped and graded and then sealed with a second application of calcium chloride.

Portland cement is used to increase compressive strengths of bases by providing a cementitious bonding of the soil and RAP particles. Portland cement works best with a plasticity index of less than about 10 (Matthews 2008; Thompson et al. 2009) and fewer than 10% fines (Franco et al. 2009). Higher percentages of fines can be tolerated while still improving the load-carrying capability of the soil. Cement-stabilized bases continue to slowly gain strength over time and work best with granular materials with low plasticity. Another advantage to using cement as a stabilizer is that excess moisture can be quickly removed from the pulverized material. One disadvantage is when used as a stabilizer, the recycled material has a tendency to show shrinkage cracking.

Lime (calcium hydroxide) works best when there is reactive clay in base materials, as lime reduces the plasticity of the clay materials. Lime is typically used when the plasticity index (PI) is greater than 8 (Matthews 2008) and fines contents are greater than 10% (Franco et al. 2009). Thompson et al. (2009) recommend using 1% hydrated lime when the PI is between 10 and 16 and 2% when the PI is greater than 16. The reduction in plasticity helps minimize swelling, reduce moisture damage, and improve the base strength. Like portland cement, lime can help reduce initial excess moisture in the pulverized base materials. Too much lime can result in shrinkage cracking.

Quicklime (calcium oxide) reacts with water to form calcium hydroxide, a reaction that generates heat, and the solid nearly doubles in volume. Because of the fast reaction of the quicklime, it is used for set control or early strength gains. The benefits are the same as using hydrated lime.

Fly ash, a pozzolanic material, also provides improved base strength through a cementitious bonding of the particles when in the presence of water. Moisture resistance is improved by a reduction in the permeability of the base materials.

Asphalt emulsions, a mixture of asphalt cement, water, and an emulsifying agent, improve the strength and moisture resistance of the base material, soften the aged asphalt binder in the RAP, and reduce shrinkage cracking seen with cement and lime stabilizers. When the emulsion breaks, the asphalt droplets join, and the water separates from the asphalt. Compaction helps force the water out of the stabilized base, but sufficient time for the moisture content to drop below about 1.0% is still needed for all of the moisture to evaporate before the placement of the next lift.

Combinations of additives and stabilizers have been used with asphalt binders to improve properties of the final product. For example, Naizi and Jalili (2009) found that using emulsions with lime slurry or portland cement improved moisture resistance and increased both the final mix stiffness and indirect tensile strength. Thomas et al. (2000) evaluated the combination of fly ash and lime, which showed improved mix stiffness but promoted shrinkage cracking. A combination of EE and lime slurry provided improved flexibility at cold temperatures and minimized shrinkage cracking. The Wirtgen (2004) manual notes that cement is routinely used with bitumen emulsions to improve moisture resistance, tensile strength, fatigue resistance, and retained strengths. Cement and emulsion combinations need less curing time before traffic can be permitted on the recycled surface.

Information on the use of typical additives and stabilizers compiled from the survey responses and from the literature is summarized in Table 25.

TABLE 25
SUMMARY OF USES FOR ADDITIVES AND STABILIZERS IN RECYCLING PROCESSES

Additive or Stabilizer	CIR						FDR	
	Moisture Resistance	Freeze/ Thaw Resistance	Rut Resis-tance	Layer Stiffness	Rate of Set Control	Minimize Raveling	Mechanical Stabilization	Chemical or Bituminous Stabilization
Calcium Chloride		X				X		X
Portland Cement	X	X	X		X	X		X
Lime	X	X		X		X		X
Quicklime	X	X		X		X		X
Fly Ash			X	X				X
Limestone Fines			X	X			X	X
Fibers			X	X			X	
Asphalt	X	X	X	X		X		X
Recycling Agents		X	X	X		X		X

In summary, additives and stabilizers need to be selected on the basis of their ability to improve key material and mix properties.

Mix Designs

Regardless of which recycling process is used on a project, the steps in the mix design process are similar (Figure 18).

New and RAP Binder, RA Selection

Once the gradation blend of RAP and new aggregate is determined, the binder grade, quantity, and any recycling or rejuvenating agent need to be identified. For HIR, this can be done by the use of blending charts, which can be adapted for viscosity or Superpave PG binder tests (Figure 19). The viscosity or $G^*/\sin\delta$ for the RAP binder is plotted on the left y-axis and the properties of the new asphalt, or RA for CIR, are plotted on the right. A line is drawn horizontally across the graph, from left to right, until it intersects the diagonal viscosity line. The percentage of new asphalt or RA needed is read off the bottom horizontal axis. More comprehensive selection methods will blend the anticipated percentages of RAP, and new binder will use the full Superpave binder property to select the new binder grade.

Mix Design Methods

The most commonly used mix design methods vary by the in-place recycling process. HIR mix designs are usually based on standard HMA mix design methods. CIR and FDR are based on emulsion or foamed asphalt methods, which include

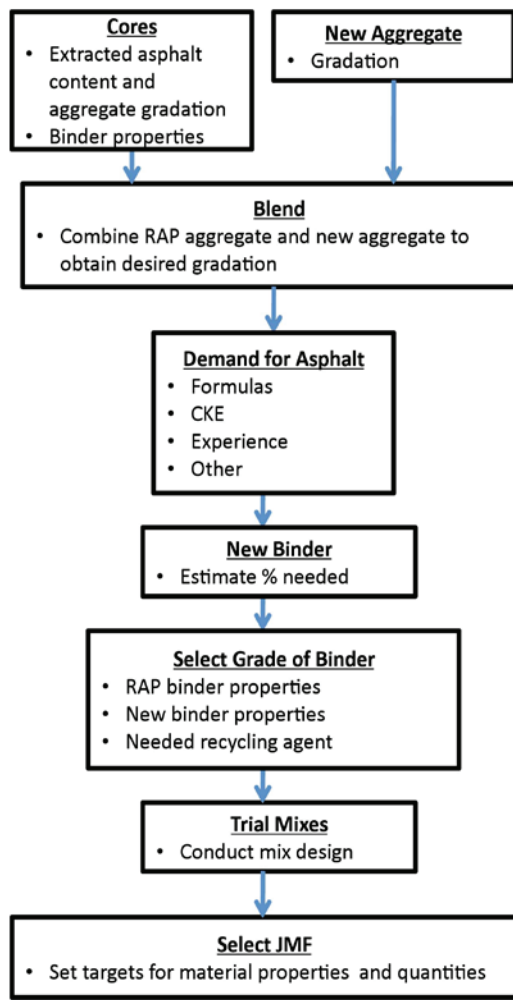


FIGURE 18 Basic steps in recycled mix designs (based on FHWA 1997).

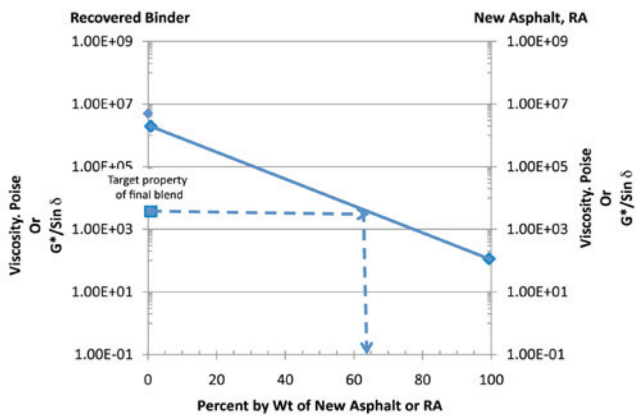


FIGURE 19 Blending chart used to select the percent of new asphalt or additive needed to provide the desired binder properties (based on FHWA 1997).

- EEs
  - Caltrans: 75 blow Marshall
  - Iowa DOT: 4-in. gyratory with 30 revolutions
  - SemMaterials: 6-in. gyratory with 30 gyrations
- Emulsions
  - Wirtgen: 75 blow Marshall
  - Ontario Ministry of Transportation (MTO): 75 blow Marshall
- Foamed asphalt
  - Iowa DOT: 4-in. gyratory with 25 revolutions
  - Wirtgen: 75 blow Marshall
  - Ontario MTO: 75 blow Marshall

Because mix designs are intended to represent field conditions, curing periods before testing are included in emulsion (engineered or traditional) and foamed asphalt mix designs. As with the compaction methods, each mix design method varies in its curing procedures (Thompson et al. 2009):

- EEs
  - Caltrans: Cure at 140ºF to constant weight
  - Iowa DOT: 48 h at 140ºF
  - SemMaterials: 72 h at 140ºF
- Emulsions
  - Wirtgen: 72 h at 104ºF. For high traffic (i.e., greater than 5 million ESALs), the specimens are compacted at the anticipated final field moisture content and cured in sealed containers for 40 h at 104ºF.
  - Ontario MTO : 48 h at 140ºF, soaked for 24 h at 77ºF, or vacuum saturated for 60 min at mmHg pressure.
- Foamed asphalt
  - Iowa DOT: 72 h at 105ºF
  - Wirtgen: Same as for emulsions
  - Ontario MTO: Same as for emulsions

Once the specimens have cured, various properties of the specimens are determined:

- EEs
  - Caltrans: Marshall stability at 104ºF
- 1,250 lb minimum dry stability
- 70% minimum retained strength ratio
  - Iowa DOT: Marshall stability at 100ºF
- 1,000 lb minimum stability
  - SemMaterials: Indirect tensile strength, resilient modulus, and modified cohesiometer
- 35 to 40 psi minimum (dry)
- 20 to 25 psi minimum (wet)
- 70% minimum ratio
- 120 to 150 ksi minimum for resilient modulus
- Emulsions and foamed
  - Ontario MTO: Indirect tensile strength (dry and wet), retained strength ratio
- 50 psi minimum (dry)
- 25 psi minimum (wet)
- 50% minimum for ratio

The most common approach by state agencies in designing recycled mixes is to do nothing (Table 26). When agencies do mix designs, either the Superpave or Marshall methods are commonly used. None of the agency respondents indicated that they use the standard Hveem method, and only four states use the Wirtgen (2004) method for CIR or FDR. For states indicating "other," the design methods mentioned were the Portland Cement Association (PCA) soil–cement mix design (PCA 2005), Proctor method (optimum dry density and moisture content), modified Proctor (Kim and Labuz 2007), and unconfined compressive strengths (geotechnical testing).

TABLE 26
AGENCY AND CONTRACTOR RESPONSES TO MIX DESIGN METHODS

Mix Design Testing: Before construction, I or my contractor design our recycled mixes based on the following method:			
Mix Design Methods	*Agency Responses*		
	HIR	CIR	FDR
Do Not Do Mix Designs	CA, ID, IA, MO, VT, WA	CA, DE, ID, IA, NC, NH, NV, RI, SD, VT, WA, WI	CT, DE, ID, MN, MT, NC, NH, NV, NY, SD, VT, WI
Hveem	—	—	—
Marshall	AZ, KY, NE	AZ, MN, NE, OR, VA, WY	VA
Superpave	CO, KS, MO, ND, UT, VT	CO, KS, MO, ND, UT, VA	MD, MO, UT, VA
Wirtgen	—	VA	AK, CA, IA, VA
Other	NY, TX	CT, MT, NY	AL, CO, GA, NE, NY, SD, WY

Between 20% and 42% of the states do not develop mix designs for recycling projects (Figure 20). Comments by the states indicated that they require the contractor to supply the designs. Contractors typically design using the Marshall or Superpave mix designs. Contractors are more likely to use either Marshall or Wirtgen or no mix design at all for FDR designs.

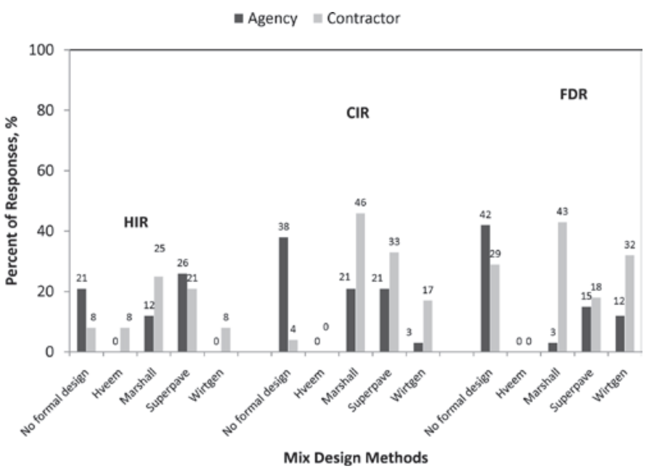


FIGURE 20 Comparison of mix design methods used by agencies and contractors. Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

AASHTO, the Associated General Contractors of America, and the American Road and Transportation Builders Association Joint Committee Task Force 38 adapted Marshall (50 blow) and Hveem mix designs (ARRA 2001) for use with recycled mixes. Since the Task Force report came out, several researchers have evaluated the suggested designs, primarily the 50 blow Marshall method, which consists of two parts: determination of optimum water content and determination of optimum binder content. Two studies (Salomon and Newcomb 2000; Lee et al. 2002) evaluated this CIR mix design method and noted the following disadvantages:

- Time needed to complete mix design is 8 days.
- Information on when new aggregate should be added to the mix (i.e., no suggested gradation bands) was missing.
- Time needed for emulsion to break was not considered in sample preparation.
- Heating time for emulsion was not specified.
- Temperature differences for different emulsions were not addressed.
- Applicability of using standard HMA testing for bulk specific gravity (i.e., direct immersion of high air void mixes in water) was not addressed, but should be considered because of the high air voids in recycling mixes.
- Specific procedures for determining optimum values of water and emulsions were not clearly defined.

Preparation, mixing (order of addition), mixing temperatures, curing times (before and after compaction), curing temperatures, and determination of specific gravities are the focus of a number of current agency and academic research projects.

Recent published results indicate that gyratory compaction is useful for preparing samples for all of the recycling processes. In particular, using gyratory compaction for FDR seems to provide a compacted density closer to actual in-situ densities than the other methods. Mallick et al. (2002) and Kim and Labuz (2007) found 50 gyrations produced laboratory-compacted samples with densities similar to those found in the field projects. Other researchers investigated using 30 gyrations for preparing FDR samples (Cross 2002; Lee and Kim 2007b; Thompson et al. 2009). Some concern was expressed about the need to provide drainage for the water pressed out of the CIR and FDR mixes (Mallick et al. 2007), and a slotted gyratory mold was used when compacting these mixes. Gyratory compaction can also be used for foamed asphalt samples (Kim and Lee 2006; Kim et al. 2007b).

The load-carrying capability of the recycled mix is evaluated with Marshall or Hveem stabilities. The indirect tensile strength test (IDT) is also used either in place of, or in addition to, the stabilities. Both dry and wet IDTs are used by a number of agencies and contractors to determine the moisture sensitivity by evaluating the retained strengths (i.e., tensile strength ratio, TSR). States that evaluate rutting potential with loaded wheel testers (i.e., asphalt pavement analyzer, Hamburg) for their HMA mixes also use these tests for the recycled mixes.

The PCA (2005) and general unconfined compressive strength approaches to design recommend a range of compressive strengths at various times after curing. For example, the PCA method uses limits for strengths between 2.07 to 2.76 MPa (300 and 400 psi) at 7 days. Franco et al. (2009) recommend including the determination of the Atterberg limits in the mix design methods for FDR.

The FDR mix design method used depends on the type of stabilizer. Because FDR is essentially a method of producing a stabilized base material, typical geotechnical tests are commonly used by agencies. These include using a Proctor or modified Proctor determination of optimum moisture content and maximum dry density. Strength testing is conducted using unconfined compressive strength, California bearing ratio, or R-value tests. When cement is used, the PCA method for soil–cement stabilization may be used (PCA 2005). Other stabilized base mix designs for fly ash and lime stabilization can be used for CIR and FDR mixes. Combinations of additives and stabilizers such as emulsions and cement can be designed with CIR mix designs or by using geotechnical tests.

Regardless of the mix design method used, there was general agreement that there is a lack of established curing times, temperatures, or humidity conditions. There is some agreement that gyratory compaction for FDR samples is appropriate; however, the use of this compaction device for CIR mixes that still have significant water content needs to be evaluated.

The average of the agency and contractor responses was used to rank and summarize the types of mix designs currently used (Table 27).

TABLE 27
MIX DESIGN PRACTICES

Mix Design Methods	HIR	CIR	FDR
No Formal Design	Sometimes	Sometimes**	Often**
Superpave	Rarely	Rarely	Rarely
Marshall	Sometimes	Often	Often*
Hveem	Sometimes	Often*	Sometimes
Wirtgen	Rarely	Sometimes*	Sometimes*

Rarely = lower than 10% average of agency and contractor with experience.
Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
*Contractor response was significantly higher than agency with experience.
**Agency response was significantly higher than contractor with experience.

Superpave mix design methods need to be developed for designing recycled mixes. Curing times, temperatures, and humidity need to be standardized for CIR and FDR regardless of the type of compaction used to prepare the samples.

STRUCTURAL DESIGNS

Step 3: Evaluate Structural Capacity?

Step 4: Structural Design
- Layer thickness
- Layer properties
- Structural coefficent

Structural design methods rely on the assessment of remaining pavement life and the needed structural changes for future traffic. Layer properties, thickness, and distress information are needed to determine the appropriate changes during maintenance and rehabilitation activities. In some cases, neither the agency nor contractor assesses the structural capacity (i.e., the "No" answer option to the question in Step 3). In this case, the process moves directly to construction (chapter three).

Established structural coefficients for the traditional AASHTO design are the most commonly used design approach by the agencies, followed by the use of FWD testing for layer properties (Table 28). Specific information on the value(s) of structural design coefficients was not collected in this survey; however, several values commonly used were found in the literature. A coefficient of 0.44 was recommended for HIR layers (In-Place Recycling Conference 2008). For CIR materials, coefficients of between 0.25 and 0.28 were recommended by Kansas, 0.26 by Nevada, and 0.35 in a NCHRP Report 224 (Harrington 2008). Romanoschi et al. (2004) recommended a coefficient of 0.18 for foamed asphalt-stabilized FDR. The Ontario MTO uses 0.20 to 0.28 (estimated from gravel equivalent) for foamed FDR (Thompson et al. 2009).

TABLE 28
STATE AND CONTRACTOR RESPONSES TO STRUCTURAL DESIGN CONSIDERATIONS

Structural Design: During project development, I consider the structural capacity of the recycled layer using:			
Structural Design Considerations	Agency Responses		
	HIR	CIR	FDR
Established Structural Coefficients	AZ, CO, IA, MT, NE, UT, WA	AZ, CO, IA, MN, MT, NE, NV, OR, RI, SD, UT, WA, WI, WY	AL, CO, IA, MN, NE, NV, OR, SD, UT, WI
FWD	AR, AZ, ID, MD, NE, TX, UT, VT, WA	AZ, ID, ND, NE, NV, OR, SD, UT, VA, VT, WA	AK, AL, CA, ID, MD, MT, ND, NE, NV, OR, SD, TX, UT, VA, VT
Pre-Determined Layer Thickness	AZ, FL, NC, WA	AZ, CA, DE, NC, NV, SD, WA	CA, DE, MD, NC, NV, SC, SD
Laboratory Resilient Modulus	MD	VA	MD, NE, VA

Wirtgen (2004) uses a nomograph to estimate the layer coefficient, other layer properties, and anticipated amount of foamed asphalt (Figure 21). The nomograph is used by identifying a given property and then moving vertically up or down to obtain estimates for the other layer properties. For example, given a structural number coefficient of 0.16 after stabilization, the anticipated initial stiffness would be about 750 MPa, a steady stiffness of 450 MPa, and indirect tensile strength of 150 kPa when using about 4% foamed asphalt for a range of AASHTO soil classifications. The advantage to the graph is that material properties are tied to the selection of the coefficients. This graph can also be used to estimate material properties for use with newer mechanistic–empirical design methods. Alternatively, FWD testing to determine the existing pavement layer stiffness (i.e., modulus) can be used to estimate structural coefficients.

A number of agencies simplify their design process by using predetermined thicknesses for each of the recycling methods. Only a limited number of states use laboratory resilient moduli values for their designs.

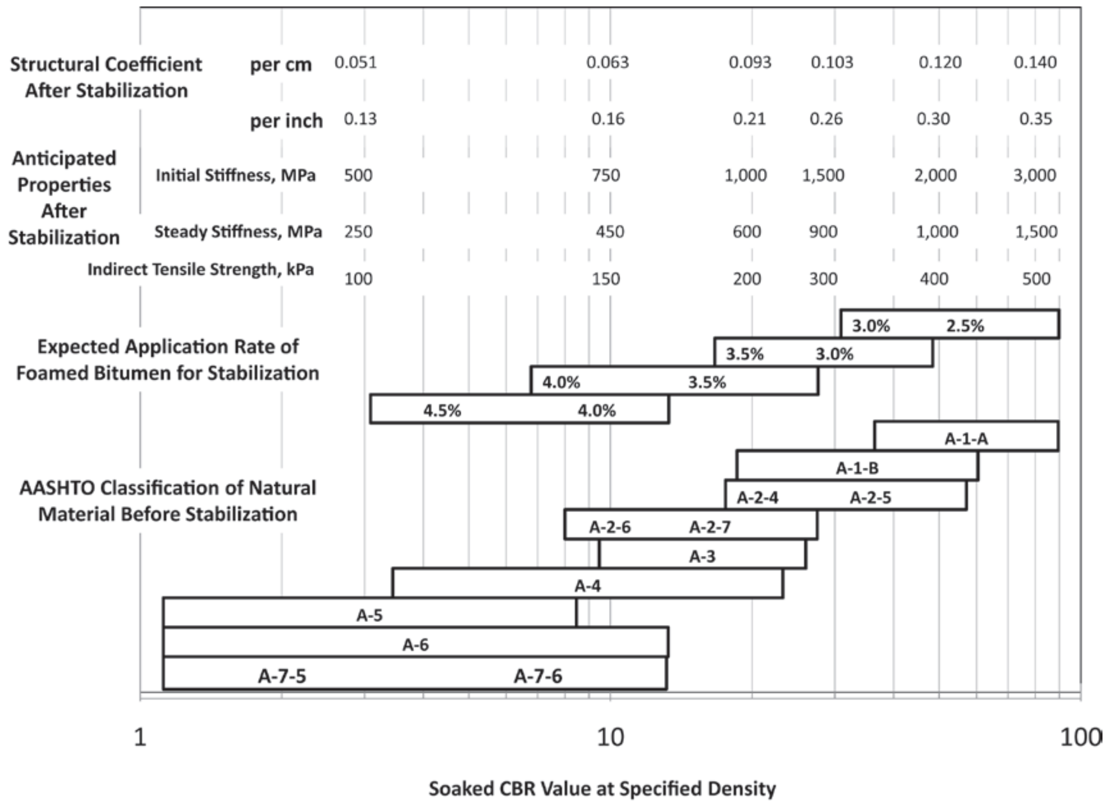


FIGURE 21 Relationships between layer properties and layer coefficients (based on original figure by Wirtgen 2004).

Contractors are most likely to use structural coefficients and FWD values for structural design considerations (Figure 22). Contractors are more likely than agencies to use either set recycled mix thickness or mix stiffness (resilient modulus) information for their designs. Differences between contractors and agencies are more noticeable in their choice of FDR designs. Other design considerations noted in the written responses include the use of compressive strength, distress level, and R-value.

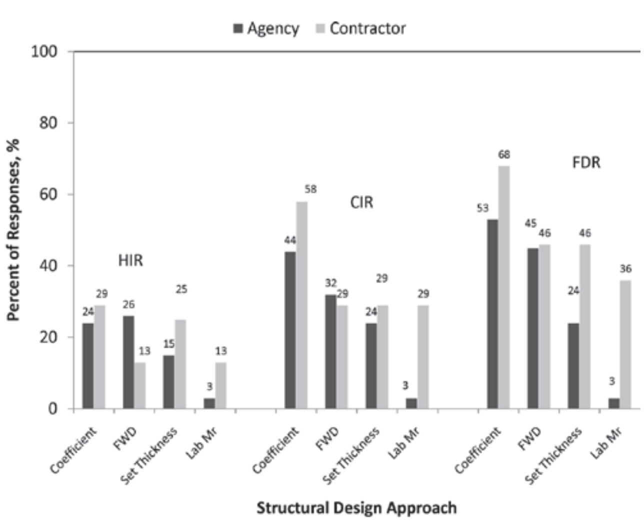


FIGURE 22 Information used for structural design approaches by agencies and contractors. Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

The average of the agency and contractor responses was used to rank and summarize the current use of structural design approaches for in-place recycling (Table 29).

TABLE 29
STRUCTURAL DESIGN APPROACHES

Design Information Used	HIR	CIR	FDR
Structural Coefficient	Sometimes	Frequently	Frequently
FWD	Sometimes	Often	Often
Set Thickness	Sometimes	Often	Often*
Lab Resilient Modulus	Rarely	Sometimes	Often*

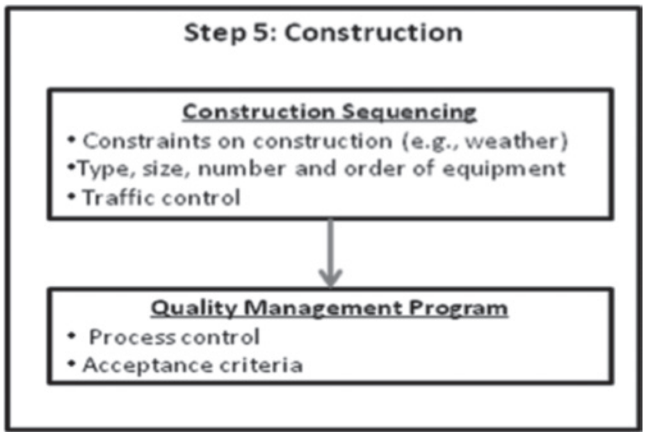
Rarely = lower than 10% average of agency and contractor with experience.
Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
* Contractor response was significantly higher than agency with experience.

Information regarding structural coefficients and layer stiffness is needed for structural design considerations. These design parameters need to be agreed on before construction so that the final product meets or exceeds the desired performance.

CHAPTER THREE

CONSTRUCTION

WEATHER CONDITIONS



A number of recommended weather conditions for paving were found in several presentations posted to the In-Place Recycling Conference (2009) and ARRA website (2010). Variations found in the presentations depend on the properties of the binders and additives used in the recycling. Typical ranges of weather conditions include

- Ambient temperature above
  - 40°F to 50°F
  - 45°F to 65°F
- Pavement temperature above
  - 50°F
  - 50°F to 70°F
- No anticipated overnight freeze
- Dry roadway
- Construction dates limited to between
  - May 15 to Oct. 15
  - May 1 to Sep. 30
- Weather conditions that allow for the proper placement
- Curing conditions for CIR or FDR (depend on additives and stabilizers) range from a
  - Minimum of 14 days to maximum of 30 days (CIR)
  - One to 7 days (foamed asphalt stabilized)
  - Once moisture content is below 1.0% (CIR)

Better-defined guidance for weather conditions for each in-place recycling process is needed for successful in-place recycling projects.

SURFACE PREPARATION AND COMPACTION

Equipment used in front of recycling and for compaction after recycling is that typically used in conventional maintenance and HMA overlay placement projects. Surface preparation is not specific to a particular recycling process. Roller selection is typical of that used in standard roadway construction. Various recommendations for surface preparation are archived in ARRA (2009) presentations and Wirtgen (2004) project summaries. The most commonly cited practice is to remove any vegetation in cracks, scrub dirt deposits, and broom the surface before recycling. When lane widening is to be completed, the vegetation along the shoulder needs to be removed. Wirtgen (2004) provides some guidance on selecting the appropriate type of primary roller based on the general gradation of the mix (Figure 23). Sandy (i.e., coarse) mixes, such as FDR mixes, need a sheep's foot roller first, whereas clayey (i.e., fines) mixes, such as CIR mixes, can use either a steel wheel or pneumatic roller.

HIR Construction

HIR is an on-site, in-place process that preserves or maintains deteriorated asphalt pavements while minimizing the use of new material. The HIR method is used to correct surface distresses that are not caused by structural problems (i.e., stable and adequate base). One of three types of HIR processes is used, depending on the distresses present in the existing roadway:

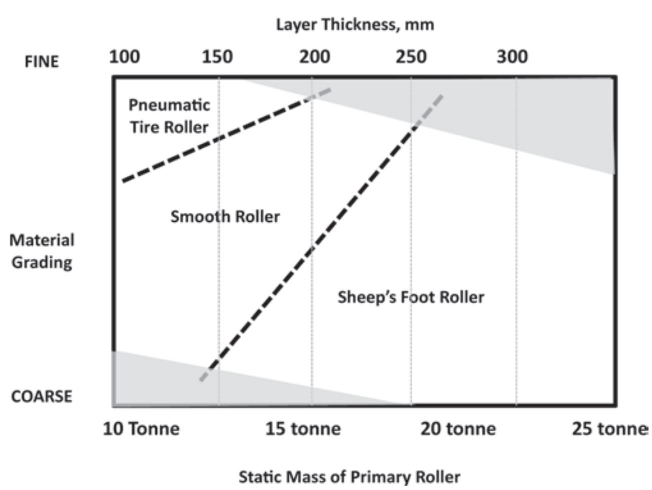


FIGURE 23 Suggested primary roller selection (based on original figure by Wirtgen 2004).

- Surface recycling—heater scarification,
- Repaving, or
- Remixing.

These processes are single-stage and multistage HIR trains. The single-stage train processes the complete depth in one pass, whereas the multistage unit processes half of the depth per pass.

Surface recycling is a preservation/maintenance process that restores cracked, brittle, and irregular pavement in preparation for a final thin wearing course. A single-pass method recycles and places the HIR material in one pass of the equipment. Repaving combines surface recycling with the simultaneous overlay of the new HMA overlay. Remixing heats, scarifies, collects material, and places it in a windrow that is picked up and mixed in a pugmill with new aggregates, rejuvenators, and new HMA (as needed).

HIR processes may not be applicable to recycling pavements with multiple seal coats (FHWA 1997), crumb rubber surface treatments, or porous HMA mixes (Stroup-Gardiner, 2008). In these cases, the properties of the upper layers act as an insulator against the heat transfer to the underlying pavement. In some cases, the excess binder or additives, such as crumb rubber, may also create smoke and potential fire hazards (Caltrans-METS 2005). Excessive crack sealant can pose similar problems. Each category of the HIR process has its own sequence of standard and specialized heavy equipment.

All of the HIR processes use one or more preheaters to soften the existing pavement so that it can be scarified or milled. The older style of preheater uses a simple set of burners fueled by propane. The disadvantage of this type of preheater is that open flames can be seen during use. The open flames may pose a fire hazard when there is dry brush near the roadway or in neighborhoods with landscaping near the project edge, and they can readily burn the pavement surface. Newer styles of preheaters include infrared, skirted recirculating heating systems, and most recently, a combination of heating systems.

The size and weight of HIR equipment are highly variable:

- Preheaters
  - Weights range from 4,990 to 44,906 kg (11,000 to 99,000 lb).
  - Heights range from 2.3 to 3.6 m (7.6 to 11.8 ft).
  - Lengths range from 2.1 to 18.9 m (7 to 62 ft).
- Scarifiers and miller units
  - Weights range from 7,711 to 39,463 kg (17,000 to 87,000 lb).
  - Heights range from 3.1 to 4.9 m (11 to 16.5 ft).
  - Lengths range from 9.1 to 16.8 m (30 to 55 ft).
- Recycling combination units
  - Weights range from 15,876 to 83,008 kg (35,000 to 183,000 lb).
  - Heights range around 4.3 m (14 ft).
  - Lengths range from 8.3 to 22.3 m (28 to 73 ft).

Any type of preheater may be in use, according to agency and contractor responses (Figure 24).

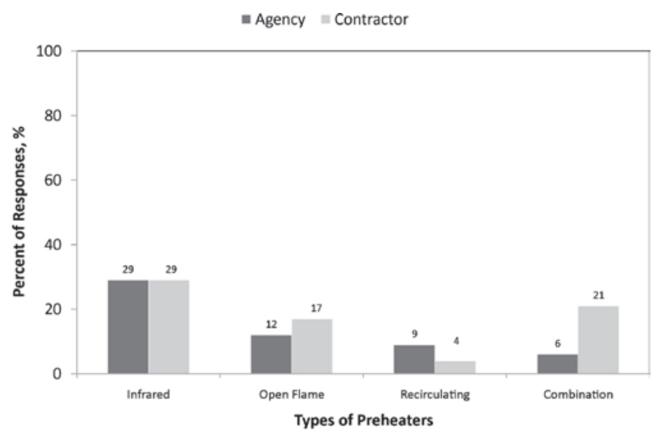


FIGURE 24 Types of preheaters currently in use. Percentages are based on the number of agencies and contractors with experience using HIR processes.

HIR surfacing equipment consists of a preheater followed by a combination preheater–scarifier (Figure 25, *top*). The heated, scarified HIR material is compacted using conventional compaction equipment.

HIR repaving uses a standard haul truck to transport new HMA and load it into the front hopper of the recycling unit (Figure 25, *middle*). The mix is moved through the equipment to the paving screed at the back. A series of heaters is used to soften the existing pavement, and a scarifier is used to loosen the RAP. This is followed by the addition and mixing of binders or rejuvenators, and the mixture is spread across the lane. Mixing augers blend the materials and place the mix with the recycling screed. For an integral overlay, the new HMA is placed on top of the hot recycled mix (paving screed), and compaction is achieved using standard pneumatic and steel wheel rollers.

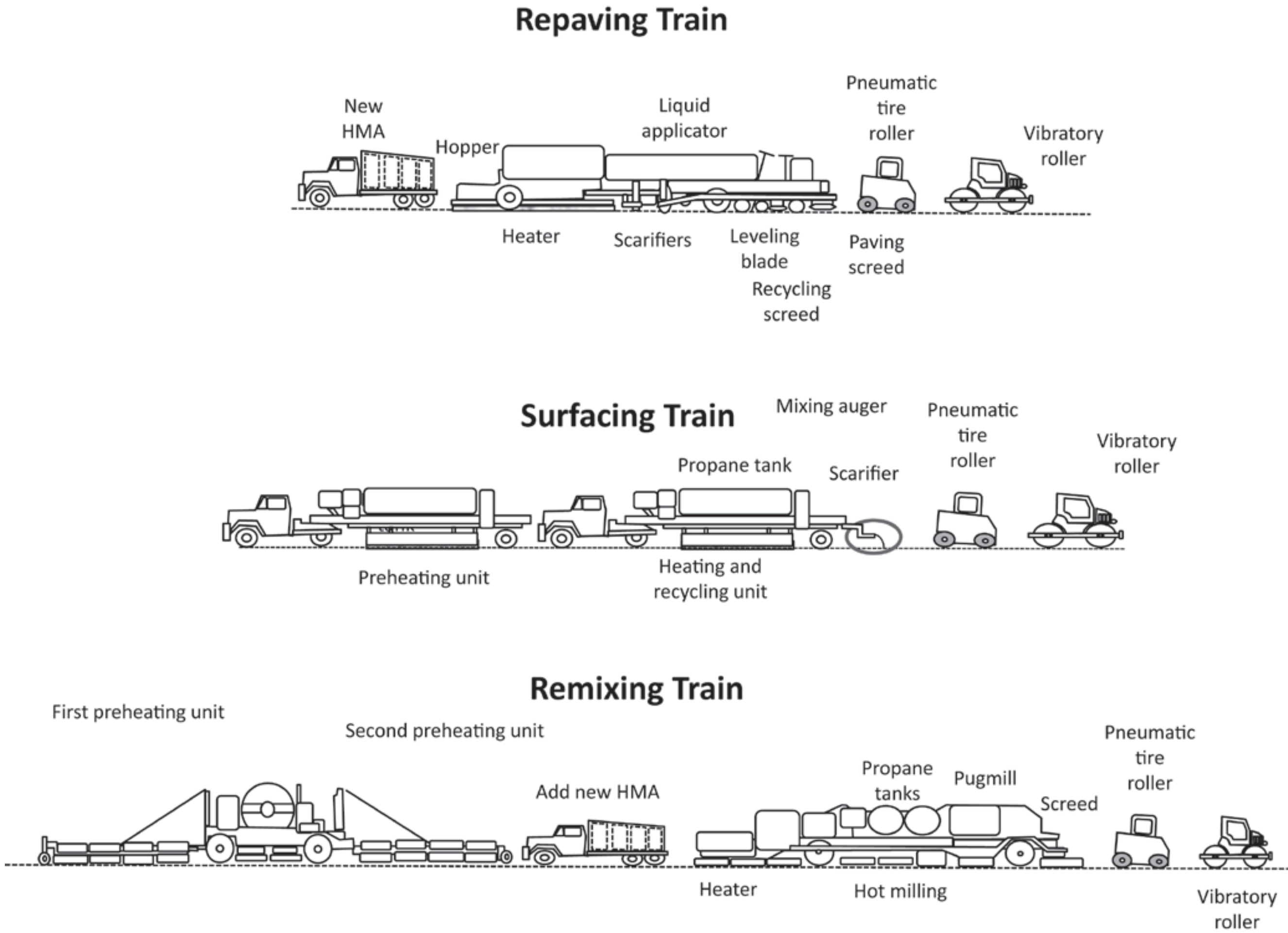


FIGURE 25 Typical sequence of construction equipment for HIR processes (based on FHWA 1997; ARRA, 2001).

HIR remixing mills provide the deepest milling depths of the HIR processes. Typically, two preheating units precede the miller-mixer (Figure 25, *bottom*). The miller-mixer is usually equipped with a front hopper for the new HMA mix, and the bottom front of the miller is fitted with another heater pushed in front of or pulled behind the recycling. The milled material is mixed with fresh materials and additives and placed using a heated, vibratory, or tamping screed. Compaction is accomplished with standard compaction units.

CIR Construction

CIR mills only the existing HMA pavement surface. Screening decks and onboard crushers size the reclaimed asphalt pavement. The sized material is then transferred to a twin-shaft pugmill and mixed with the emulsion or foamed asphalt. Wirtgen (2004) provides a comparison of the construction parameters for the typical asphalt binders used in either CIR or FDR processes (see Table 30). Note that "cold" refers to the ambient temperature of the milling and aggregate temperature. CIR can still use hot paving-grade binders with the foamed asphalt process. Breaking time (i.e., rate of set) for the emulsion will limit when the surface course can be placed because sufficient time may be needed for water evaporation after placement.

Standard haul trucks are used to provide new aggregates (typical East Coast practice) or new HMA (typical West Coast practice; Figure 26). Unlike the HIR recycling trains, one or two nurse trucks are usually in front of the recycling profiler and mixer unit to provide a continuous supply of liquids for the mix (e.g., recycling agents, water). The recycling unit mills, processes, and mixes the recycled materials and then transfers them to a paver. Standard compaction practices are used to place and compact.

FDR Construction

The FDR method pulverizes the existing HMA pavement along with underlying granular materials. Stabilizers are added to the pulverizers or through separate passes of other units. The steps involved in the FDR construction process are shown in Figure 27. The first construction activity is to deposit fresh materials or additives and spread them evenly over the old roadway surface (Figure 28). Nurse trucks provide liquids to the pulverizing and mixing unit.

TABLE 30
COMPARISON BETWEEN DIFFERENT TYPES OF BITUMEN APPLICATIONS (based on Wirtgen 2004)

Factor	Bitumen Emulsion	Foamed Bitumen
Aggregate Types Applicable	– Crushed rock – Natural gravel – RAP, cold-mix – RAP, stabilized	– Crushed rock – Natural gravel – RAP, stabilized – Marginal (sands)
Bitumen Mixing Temperature	68°F to 15°C	320°C to 356°F (before foaming)
Aggregate Temperature During Mixing	Ambient (cold)	Ambient (cold)
Moisture Content During Mixing	90% of OMC minus 50% of emulsion content	65% to 95% of optimum moisture content
Type of Coating of Aggregate	Partial coating of coarse particles and cohesion of mix	Coating of fine
Construction and Compaction Temperature	Ambient	Ambient
Rate of Initial Strength Gain	Slow	Medium
Modification of Binder	Yes	Unsuitable
Important Parameters of Binder	– Emulsion type (anionic, cationic) – Residual bitumen – Breaking time – Curing	– Half-life – Expansion Ratio

Initial compaction can be accomplished with a sheep's foot roller. An additional water truck may be needed (additive/stabilizer dependent) to provide sufficient moisture content for optimum density. Once the pulverized materials are mixed and the initial compaction completed, the profile is restored using a standard motor grader. The FDR surface can be broomed to remove any loose particles before opening to traffic.

When more than one admixture is used in the FDR activities, admixes are typically added sequentially (Harris 2007). For example, one project in Delaware County, Ohio, placed a lime–fly ash FDR section by first milling and removing 4 in. of the old asphalt surface. Care is needed when the surface is milled before pulverizing because the remaining pavement layer has to support the pulverizing equipment (Jahren et al. 1999). The second step prepulverized the remaining asphalt concrete layers to a depth of 12 in. Four percent lime was applied, repulverized, and allowed to mellow for 24 h. The second admixture, which was 6% fly ash, was blended into the lime-treated material. Water was added to the mix, which was compacted immediately. The stabilized base was then completed using 4 in. of new HMA.

QUALITY MANAGEMENT PROGRAM

Inspection

FHWA (2005a,b) has developed pocket-sized guides for HIR and CIR processes. These guides provide a useful checklist for agency inspection staff.

The checklist for HIR project inspection includes information for

- Preheaters,
- Milling/scarifying units,
- Additive or admixture system,
- Mixing unit/spreader,
- Paver (repaving), and
- Rolling.

The checklist for CIR project inspection includes information for

- Milling, crushing, and mixing;
- Additives and mixtures;
- Pick-machine and paver; and
- Rolling procedure.

Quality Control and Quality Assurance

Quality management programs are used to ensure that contractors meet or exceed the project requirements (specifications) and include systematic management throughout the process from

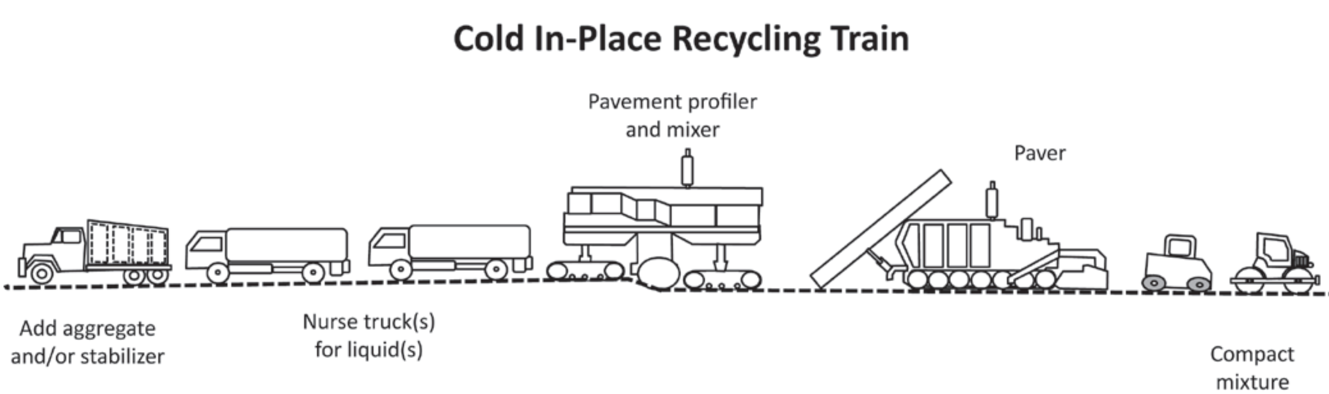


FIGURE 26 Typical equipment in CIR recycling train (based on FHWA 1997; ARRA 2001).

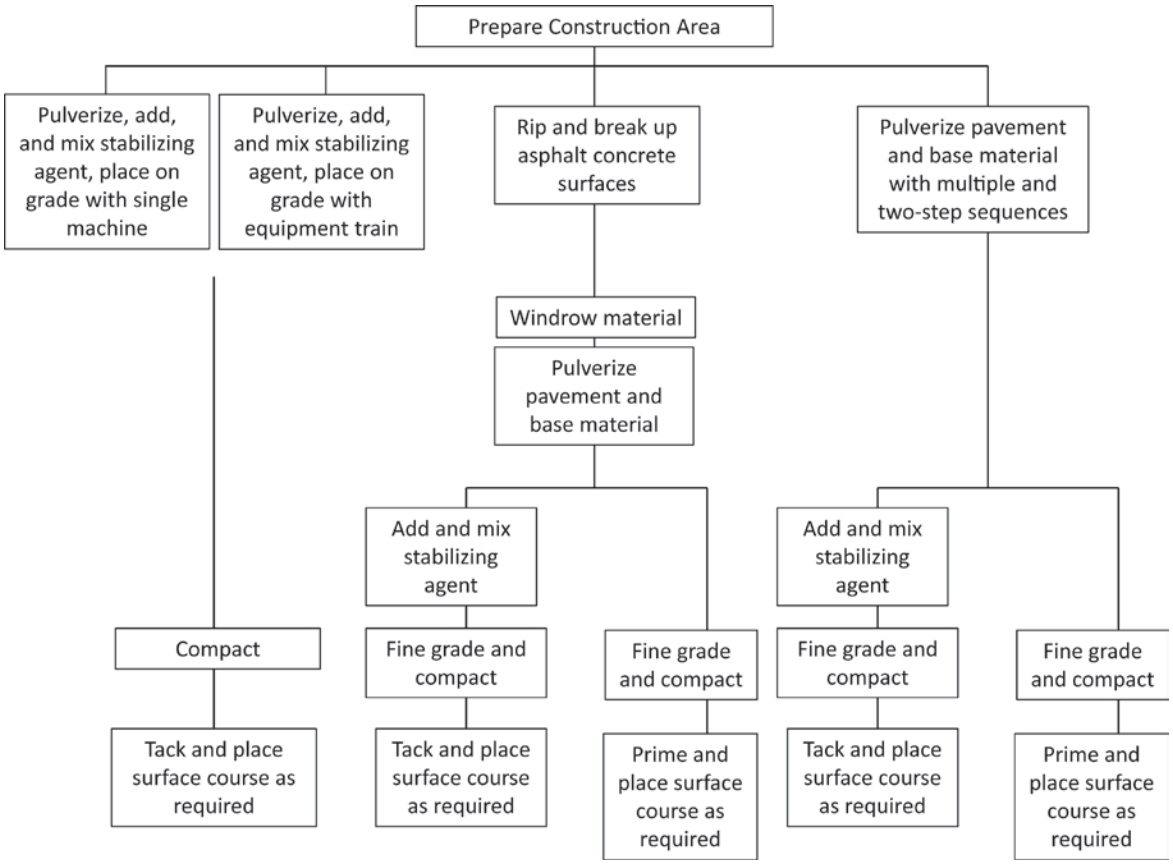


FIGURE 27 Flow chart of activities for FDR projects (based on FHWA 1997).

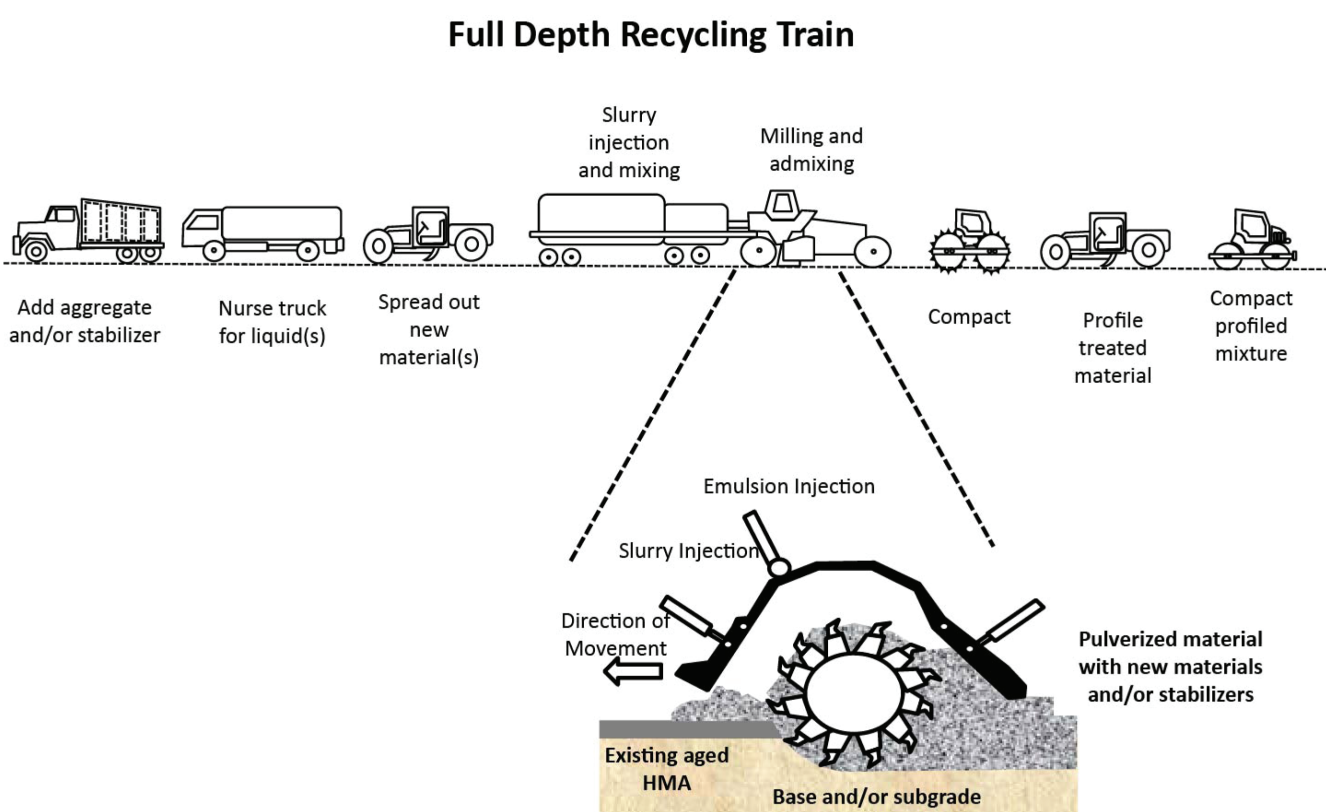


FIGURE 28 Typical equipment used for FDR reclamation trains (based on FHWA 1997; ARRA 2001; Wirtgen 2004).

quality planning, quality control (QC), quality assurance (QA), and quality improvement (Miron et al. 2008). Areas of concern to agencies, as noted in the ARRA *Basic Asphalt Recycling Manual* (2001), are summarized in Table 31. Aspects associated with QC (process control) and QA were evaluated in the survey.

TABLE 31
SUMMARY OF POINTS OF CONCERN FOR MONITORING PROCESS CONTROL AND ACCEPTANCE OF IN-PLACE RECYCLED MIXES

Project Topics of Concern to Agencies	HIR	CIR	FDR
Heating of the existing pavement	X		
Blue or black smoke emissions from heating unit	X		
Scorched or charred pavement surface	X		
Excessive temperature variation across the mat	X		
Existing surface sufficiently softened for scarification	X		
Treatment depth	X	X	X
Addition of additives (type and quantity)	X	X	X
Additives thoroughly mixed	X	X	X
Placement of recycled mix	X	X	X
Adequate temperature for compaction	X		
Excess moisture removed	X	X	X
Compaction of recycled mix	X	X	X
Surface appearance (need consistency)	X	X	X
Grade and cross slope			X
Recycled Mix Properties of Concern to Agencies			
Gradation of final mix	X	X	X
Asphalt content of final mix	X	X	X
Recovered binder properties	X	X	X
In-place density	X	X	X
Recycled mix strength properties	X	X	X
Uniformity of compaction	X	X	X

Process control is a contractor program that is intended to provide a uniform final product and consists of evaluations during preconstruction and construction. Survey responses indicate that contractors use a range of process control options, including

- QC technician on the job (about one-third of contractors),
- Real-time mix design adjustments for variable existing pavement materials,
- Verification of density (compaction),
- Verification of gradations,
- Mix design property verifications,
- Monitoring and verification of applications rate,
- Verification of moisture content,
- Verification of indirect tensile strengths, and
- Short-term performance before surface course is placed.

Recommendations for QC approaches found in the literature include emulsion testing to determine the percentage of residue from distillation (Thompson et al. 2009). Field-testing recommendations include depth measurements, compaction monitored with nuclear density gauge (direct transmission), and moisture content verified before overlay (CIR and FDR).

Contractor QC programs include field technician training; validation of mix design properties, material properties, and density; and documentation of application rates.

Acceptance

The acceptance of the project by the agencies includes a number of approaches:

- Construction of acceptable test strip (establishing rolling patterns, optimum moisture and dry density requirements, acceptable equipment);
- Measurements of one or more of the following: density, thickness, profile deviations, material properties, material quantities, and mix properties.

Materials testing noted in the written responses include emulsion testing, residual binder testing (penetration), and aggregate gradations. Mix properties evaluated by agencies cover a wide range of tests such as binder content, indirect tensile strength, Hamburg rut testing, moisture sensitivity (boiling water, TSR), and other standard HMA tests (e.g., volumetrics).

SemMaterials recommends that QC/QA testing for FDR projects include the following:

- Asphalt emulsion: residue from distillation, oil distillate by distillation, sieve test, and penetration;.
- Added rock or dry additive:
  - Confirmation of quantity and type used in mix design,
  - Minimum material size,
  - Moisture content before emulsion.

Suggestions for QA testing and parameters were found in the literature and included 97% of the laboratory density or 92% to 98% of the theoretical maximum specific gravity. Thompson et al. (2009) summarized a range of requirements, including

- Density
  - 97% of laboratory density (laboratory-compacted samples, nuclear density, and moisture),

  - 92% to 98% of theoretical maximum density (In-Place Recycling Conference 2008),
  - Maximum dry density and optimum moisture content (Franco et al. 2009);
- Dry Marshall stability, minimum, of
  - Greater than 5.56 kN (1,250 lb) (Caltrans; for EE),
  - Greater than 4.44 kN (1,000 lb) (IowaDOT, at 100°F);
- Indirect tensile strengths, minimum, of
  - 241 to 276 kPa (35 to 40 psi; dry) and 138 to 173 kPa (20 to 25 psi; wet) (SemMaterials);
  - Dry indirect tensile strengths of 300 to 345 kPa (43 to 50 psi; dry) and 150 to 175 kPa (22 to 25 psi; wet) (Ontario MTO);
- Retained TSRs of
  - Greater than 70% (SemMaterials; Caltrans),
  - Greater than 50% (Ontario MTO; foamed asphalt);
- Greater minimum resilient modulus of 837 to 1,034 MPa (120 to 150 ksi) (SemMaterials).

Lane and Kazmierowski (2005a) noted that the Ontario MTO uses the following for both QC and QA testing:

- Indirect tensile strengths, minimum, of 300 to 350 kPa (43 to 50 psi; dry) and 150 to 175 kPa (22 to 25 psi; wet) for CIR with expanded asphalt;
- Target density of 96.0% of job mix formulas, with no result below 95.0%;
- Moisture content of less than 2.0%, with no sublot value above 3.0%.

QC/QA programs include measurements of density, moisture content, recycling layer depth, verification of material properties, and performance-related mix testing.

CHAPTER FOUR

SPECIFICATIONS

Step 6: Specifications Development

The content and extent of what is defined in a specification depend on the type of specification used by an agency. Regardless of the type of specification, they generally contain the following sections:

1. *Description:* Define the type of process to be used.

2. *Materials:* List all materials, specifications, test methods, and mix composition to be used (method specification). For end result, performance, and warranty specifications, identify who is responsible for these decisions.

3. *Construction Requirements:* Identify key requirements for weather, surface preparation, equipment, material properties (e.g., moisture content of RAP, mix temperatures) for method specifications. For end result, performance, and warranty specifications, identify who is responsible for these decisions. Information on minimum expectations for materials, workmanship, and performance criteria is also included in this section.

4. *Method of Measurement:* Define the units for each product or material to be measured (e.g., liquid RA in gallons, cement slurry in tons, square yard of surface) and how performance criteria are measured.

5. *Basis of Payment:* Define payment for accepted quantities and include description of what is included in the units.

State agency respondents were asked to identify the type of specifications used for in-place recycling projects. Method specifications are most frequently used (Table 32), which indicates that the states define what materials will be used and how they will be placed. End result specifications are used by some states, and neither performance nor warranty specifications are commonly used by states. The responses to the use of warranties for recycling projects show that only two states use warranties of 3- and 5-year durations (Table 33). The use of a method specification tends to contradict state preferences for allowing the contractor to design the recycled mix and field adjust the designs as needed.

TABLE 32
WRITTEN RESPONSES FOR USE OF WARRANTIES

Warranty: Does your agency specify a warranty period for the different in-situ recycling processes. If so, what is the length of the warranty and what type of assurance is required?	
Written Responses from Agencies	Written Responses from Contractors
Warranty—3 yr for rutting, cracking, delaminations, raveling, and smoothness (FL) Warranty—5 yr period; bond required (WI) Warranty—none (AL, AK, AZ, AR, CA, CO, CT, DC, DE, GA, IA, ID, KS, KY, MO, MT, NC, ND, NE, NV, NY, PA, SC, SD, TX, UT, VA, WA, WY) Warranty—under consideration (VT) Warranty—under development (IL)	1-yr warranty (4) 2-yr warranty bond for 100% (2) 3-yr warranty bond for 100% 3-yr warranty materials; bonding company has issues with 3 years 4-yr warranty bond for 50% of construction cost; Performance measures: fatigue, edge cracking, rutting, potholes; nothing HMA related No experience (3)

TABLE 33
STATE RESPONSES FOR TYPE OF SPECIFICATION USED FOR RECYCLING PROJECTS

Question: Specifications: What type of specifications does your agency use?			
Surface Treatments	Agency Responses		
	HIR	CIR	FDR
Method	AR, AZ, CA, FL, IA, ID, KY, MD, MO, MT, NC, NE, WI	AZ, CA, CO, DE, FL, IA, ID, MN, MO, MT, NC, ND, NE, NH, NV, OR, RI, SD, UT, VA, VT, WI, WY	CA, CO, DE, GA, IA, ID, MD, MN, MO, MT, NC, ND, NE, NH, NV, OR, SD, TX, UT, VA, VT, WY
End Results	CO, KS, KY, MO, TX	CO, IA, KS, MO, NV, ONT	AK, CO, GA, IA, MO, NV, SC
Performance	CA, CO, DC, TN, TX	CA, DC, TN	CA, DC, TN
Warranty	FL	FL, WI	NY

Note: Some states indicated they may use more than one type of specification.

Contractors are likely to have some experience with a range of specification types (Figure 29). The length of the warranty period ranges from 1 to 4 years. Shorter warranties (3 years or less) require the full cost of the recycling to be bonded but are reduced to 50% for longer warranty periods. Distresses specifically related to the surface treatment (e.g., HMA overlay) are excluded from the warranty. Performance measurements include fatigue cracking, edge cracking, rutting, and pothole formation. A closer examination of these nonstate agency warranty programs could provide key information regarding performance history, performance criteria limits, warranty successes, and warranty administration.

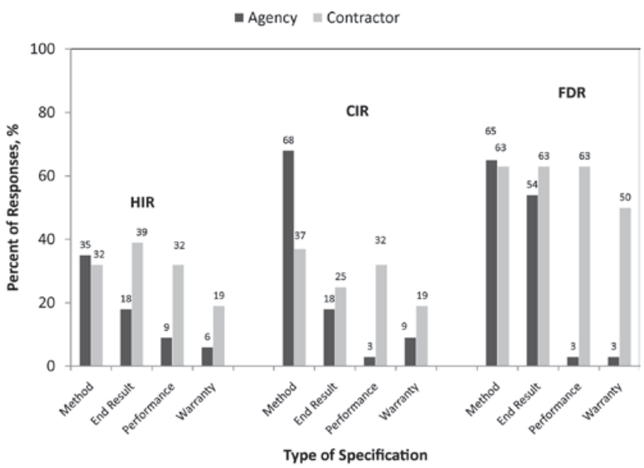


FIGURE 29 Experience of agencies and contractors with different types of in-place recycling specifications. Percentages are based on the number of agencies and contractors with experience using the specific recycling process.

The agency and contractor responses were used to rank and summarize the current use of different types of specifications for in-place recycling projects (Table 34).

TABLE 34
TYPES OF SPECIFICATIONS USED FOR IN-PLACE RECYCLING

Type of Specification	HIR	CIR	FDR
Method	Often	Often**	Frequently
End Result	Sometimes*	Sometimes	Frequently
Performance	Sometimes*	Sometimes*	Often*
Warranty	Sometimes*	Sometimes	Often*

Rarely = lower than 10% average of agency and contractor with experience.
Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
*Contractor response was significantly higher than agency with experience.
**Agency response was significantly higher than contractor with experience.

Method specifications are commonly used by agencies for in-place recycling projects. However, agencies also routinely require the contractor to select additives and provide mix designs and make field adjustments for in-place recycling projects, which suggests that end result or short-term performance specifications are more appropriate types of contracting approaches.

Materials testing, mixture testing, and specification particulars were not well defined from the survey responses. Therefore, a combination of agency survey information, a search for existing state specification in the National Highway Specification website (FHWA 2010), and a literature search was used to help define typical characteristics of in-place recycling specifications.

Key word searches of the National Highway Specification website were conducted for this information (Table 35). The key word search was conducted for "all agencies" and "all categories," which include standard specifications and supplements as well as innovations and emerging specifications. The majority of the titles for each hit were evaluated for descriptions of in-place recycling methods of HMA. Unfortunately, a number of the search hits were related to a range of other topics (e.g., fly ash, slag, glass, and shingles). Cold planning was usually associated with milling for removal and use in central plant applications.

TABLE 35
SPECIFICATION SEARCH PARAMETERS

Key Word(s)	No. of Hits
Reclamation	56
Pulverized	134
Cold planning	445
Reconditioning	51
Reclaimed	228
Reclaimed base	165
Full depth recycling	228
Recycling, recycled	343
CIR	133
HIR	3
Hot-in-place	Crashed
Cold-in-place	8

The specifications referring to in-place recycling of HMA had little consistency in titles or terms (Table 36). The lack of consistent terminology made key word searching difficult and a simple summary impossible. Examples of the range of specifications found in the search are provided in Appendix B.

Wisconsin Specification Section 325 is an example of the simplest version of an FDR specification. The only specifics provided in this specification are requirements for a maximum of 97% of the 50-mm (2-in.) RAP, timing of general recycling activities, types of compactors for different lift thicknesses, and a description of what is included in the payment measurement (square yard).

TABLE 36
IN-PLACE RECYCLING SPECIFICATIONS FOUND IN NATIONAL HIGHWAY SPECIFICATION WEBSITE

State	Section	Title
California	Special Provisions	CIR and full depth reclamation
Connecticut	4.03	Cold reclaimed asphalt pavement
Illinois	Article 663	Asphalt pavements—hot-in-place recycling
Iowa	2318	Cold-in-place asphalt pavement recycling
	2125	Reclaiming present surfacing material (in-place or central plant)
	2318	Cold-in-place asphalt pavement recycling
Georgia	403	Hot-in-place recycled asphaltic concrete
Kansas	605	Surface recycled asphalt construction
Maine	307	Full depth reclamation
Massachusetts	403	Reclaimed base course
Mississippi	305	In grade modification
Missouri	JSP-04-12A	One inch continuous process hot-in-place recycling with alternate methods of surfacing
	JSP-04-12B	Two inch continuous process hot-in-place recycling with alternate methods of surfacing
Montana	302	Bituminous pavement pulverization
New Hampshire	306	Reclaimed stabilized base
New York	402.6	Hot-in-place recycling of hot mix asphalt
Oklahoma	311	Processing existing base and surface
Pennsylvania	341	Cold recycled bituminous base course, cold-in-place
Texas	Item 358	Asphalt concrete surface rehabilitation
Utah	02962	In-place cold recycled asphaltic base
Vermont	310	Reclaimed stabilized base
	409	Cold mixed recycled bituminous pavement
Wisconsin	325	Pulverized and re-laid pavement
Ontario, Canada	OPSS 333	Construction specification for cold-in-place recycling
	OPSS 331	Construction specification for full depth reclamation
	OPSS 335	Construction specification for cold-in-place recycling with expanded asphalt

Kansas and Georgia specifications had errors on state specification sites.

A more complex specification is Maine Specification 307 for FDR. This specification includes information on the size of the pulverized materials, new aggregate (as needed to meet gradation), equipment (pulverizer, grader, rollers, pulverizing), weather limitations, and testing for density control (nuclear gauge).

Other specifications may or may not include specific directions for surface preparation (sweeper or cutter to protect adjacent surfaces), pulverizer features (self-propelled, automatic depth control), mixer (self-propelled, automatic depth control, liquid distributor, rotary pugmill), water truck for optimum moisture content or dust control, paver (pick up, screed), construction timing and sequencing, weather conditions for paving (no foggy, rainy conditions), curing (calcium chloride curing compound, until 1% moisture), testing (gradation, density, optimum moisture), payment measurement (square yard, square meter, tons of new materials, gallons of liquid stabilizers), and what is included in the area measurement payment.

There is no consistent use of in-place recycling terms or specification content. It would be useful if there were uniform guidelines for specification development and standardization of terms.

CHAPTER FIVE

BENEFITS AND BARRIERS

BENEFITS

A number of advantages to using in-place recycling processes are routinely cited in the literature. Survey questions were included to assess state and contractor perceptions of benefits. The most frequently cited benefit is a savings of virgin materials (Table 37). Other benefits include shorter lane closures, reduced fuel consumption, and reduced emissions. Potential cost savings with recycling are addressed in the following section.

TABLE 37
STATE AND CONTRACTOR RESPONSES FOR TYPE OF SURFACE TREATMENT USED

Question: Environmental Benefits: Indicate environmental benefits, which you have documented on your projects	
Surface Treatments	Agency Responses
Saves Virgin Materials	AK, AR, CA, DC, DE, FL, GA, IA, ID, IL, KY, MD, MN, MO, MT, NC, NE, NV, NY, ONT, OR, UT, VT, WY
Reduces Fuel Consumption	CA, DC, ID, KY, MN, NV, ONT, UT, VT
Reduces Emissions	CA, DC, ID, MN, NV, ONT, UT, VT
Shortens Lane Closures	CA, DC, FL, ID, IL, MN, NV, ONT, UT
Other	AZ, NV

Contractors noted benefits associated with in-place recycling more frequently than did state agencies (Figure 30). The agency written responses suggest that agencies subjectively assume that benefits are achieved, but they do not specifically measure the benefits (Table 38). On the other hand, contractors provided a number of specific quantifiable examples of environmental benefits.

Additional information on environmental benefits was found in the literature. Alkins et al. (2008) reported that CIR and CIR-expanded asphalt mixes (CIREAM) had twice the production rate compared with the traditional mill and overlay option, reducing traffic disruptions and worker exposure to traffic. These processes generate less noise and conserve natural resources by using recycled materials on the roadway. An evaluation of emissions using PaLATE found a reduction in greenhouse gases. CIR and CIREAM programs in Ontario, Canada, reduced carbon dioxide by 52%, nitric oxide/nitrogen dioxide by 54%, and sulfur dioxide by 61% compared with the mill and overlay option. CIREAM also reduces the typical curing time from about 1 to 2 weeks for CIR to 2 days for CIREAM (Lane and Kazmierowski 2005b).

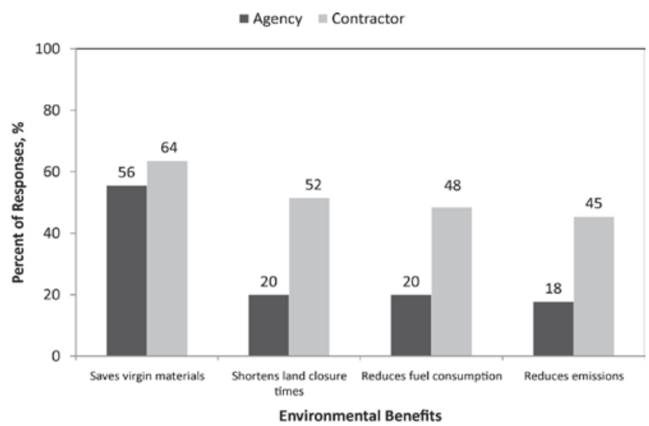


FIGURE 30 Environmental benefits from in-place recycling reported by agencies and contractors. Percentages are based on the total survey respondents.

The agency and contractor responses were used to rank and summarize the benefits gained from in-place recycling (Table 39).

TABLE 39
BENEFITS FROM IN-PLACE RECYCLING

Benefits from In-Place Recycling	Frequency of Benefit
Saves new materials	Frequently
Shortens lane closure times	Often*
Reduces fuel consumption	Often*
Reduces emissions	Often*

Rarely = lower than 10% average of agency and contractor with experience.
Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
*Contractor response was significantly higher than agency with experience.

Contractor project records can be used to provide quantifiable environmental benefits from in-place recycling. Future research is needed to quantify benefits.

TABLE 38

WRITTEN RESPONSES FOR ENVIRONMENTAL BENEFITS

Environmental Benefits: Can you quantify these environmental benefits? If so, please provide a summary of these quantified benefits.

State Responses	Contractor Responses
FDR reduces pavement structure requirement 20%–50% CIP sometimes reduces overlay thickness required up to 50%. (IA) Less use of virgin materials and use of resources. (MD) No—varies by project. (WY) No Experience to quantify (DE) No. Information is not available. (ID) Not enough projects to quantify benefits. (AZ) The emission savings are quantified using PaLATE software. The emissions savings for using CIR or CIREAM are: 52% reduction in carbon dioxide; 54% reduction in nitrogen oxide; 61% reduction in sulfur dioxide compared to traditional HMA paving operation. (MTO) There also is a reduction in the hauling of material to the site. Actual quantities are hard to estimate as full implementation has not been done. (UT) We have not documented any environmental benefits, but it is assumed that these projects use less virgin material then a non-recycled project. (ND)	By virtue of the CIR process, the city estimates that over 840 truck trips were eliminated from traveling over city streets during the construction operation. In addition, the process saved 1,649 barrels of oil, while reducing the overall carbon emissions by approximately 80% compared with the alternative methods of rehabilitation the city considered. It reduced the entire project time by 5 working days and at the same time saved over $262,000 for the city CIR Foamed Asphalt Project I-80, Caltrans data show the CIR process saved 101,909 metric tons aggregate, 2,545 metric tons bitumen, 9,200 truck trips @ 80 km round trip, 736,000 truck traveled km, 204,000 liters of diesel, and 7200 kg of 0x emissions. On a 5.5 mile segment constructed in two sections, the existing HMA pavement 22 ft wide was widened to a 28-ft wide bituminous base course using an FDR process. The material from the widening trench was stockpiled to be used as shoulder material after the paving was completed. The widening material came from milling the existing surface, placing the millings in the widening trench and processing the entire width—eliminating the longitudinal widening joint. This project saved 2,800 tons of aggregate that would have been used as shoulder material. This process also eliminated the need of providing 9,040 tons of a HMA widening material. Documented a 50% savings in CO^2 emissions, 55% savings in 0x emissions, and 60% savings in SO^2. Other contractor savings noted, but without quantities included reductions in: • CO^2 emissions • Collateral ESALs on adjacent roadways • Need for future maintenance (i.e., proven long-term solution) • Construction traffic congestion (i.e., fewer trucks) • Fuel consumption

COST BENEFITS

Cost savings reported in the literature include

- Canadian research, which showed that the net present value of the CIR option was 13% higher than an overlay; however, the cost–benefit ratio was 8 times greater (Cuelho et al. 2006).
- North Dakota research showed that selecting the most appropriate surface treatment for traffic conditions can result in significant savings. One project evaluation showed that CIR–double chip overlay was $180,000/mile for higher traffic sections, but changing to a CIR–single chip seal for lower traffic sections reduced the cost to $80,000/mile (costs also were lower because traffic control was provided by the county).
- HIR costs vary with the type of HIR used for the project. The Colorado DOT experience with HIR recycling from 2000 to 2008 showed the following differences in cost (Fisher 2008):
  - Heater scarifier treatment averaged $1.55 per square yard for 19 projects, with quantities recycled from 50,000 to more than 350,000 square yards of old pavement surface.
  - Heater remixing averaged $3.74 per square yard for 37 projects 50,000 to more than 500,000 square yards in size.
  - Heater repaving averaged $2.17 per square yard, but the database contained only two projects constructed over the 8-year period.
- FDR costs vary with the selection of additives and stabilizers (Mallick et al. 2002):
  - Pulverized material with water and mechanical stabilization was $2.00 to $2.10 per square meter.
  - Emulsion stabilization was $3.50 per square meter.
  - Emulsion with lime (2%) additive was $3.75 to $3.85 per square meter.
  - Emulsion with cement (5%) was $3.25 to 3.35 per square meter.
- FDR saved 25% of the project cost compared with standard reconstruction (Rosenmerkel 2003).
- Maine reported a cost savings by using FDR of $8.86 per square meter when compared with full conventional reconstruction, which included excavation, placement, grading, compaction, and paving (Harrington 2005).
- Nevada projects showed that
  - Savings of $104,000 per centerlane-mile savings could be realized if a 75-mm (3-in.) CIR with double chip seal wearing course was used instead of the conventional HMA.
  - Savings of $38,000 to $93,000 per centerline mile could be realized with FDR, CIR, and CIR with stockpiled millings compared with conventional HMA approaches to address structural deficiencies.

- Estimated network-level savings of $8,400,000 per year could be realized if strategies other than conventional HMA are used (Maurer and Polish 2008).
- Savings are achieved for FDR projects when the patching level is below 15% to 20% (PCA 2005).

Additional cost savings are obtained by using less fuel (energy) and by reducing disposal costs on recycling projects (PCA 2009). Figure 31 summarizes the savings in construction zone traffic, use of new materials, disposal costs, and fuel consumption.

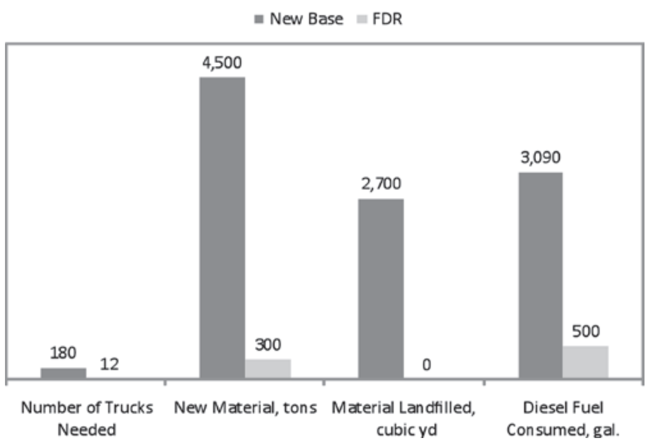


FIGURE 31 Potential reduction in construction zone traffic, use of new materials, disposal volume, and fuel consumption (based on PCA 2009).

Life-cycle costs are commonly achieved by increasing the service life of the pavement. The length of time a given process will delay the progression of pavement distresses and the deterioration of the overall pavement condition needs to be estimated when evaluating the potential reduction in life-cycle costs. The following life-cycle-related performance information was found in the literature.

HIR performance characteristics have been reported as

- Heater-scarified sections showed that the appearance of distresses had the following annual rates of progression:
  - International roughness index (IRI) increases of 15 in./mi annually,
  - Rutting increases of 1.5 mm (0.06 in.) annually,
  - Fatigue cracking increases of 22.3 m^2 (240 ft^2) annually,
  - Transverse cracking increases of 2 m (6.5 ft) annually, and
  - Longitudinal cracking increases of 30 m (97 ft) annually (Shuler and Schmidt 2008).

CIR performance characteristics have been reported as

- Kansas DOT showed that CIR sections with
  - Fly ash additives had twice the total amount of cracking compared with emulsion–lime slurry sections.
  - Fly ash additives had longitudinal cracking in one or both wheel paths compared with little or no cracking in emulsion–lime slurry sections (Thomas et al. 2000).
- An Arizona study by Mallela et al. (2006) evaluated the performance of 17 CIR projects:
  - CIR with double chip seal provided good performance for up to 20 years when traffic was below 5,000 AADT.
  - Overlays of 50 to 75 mm (2 to 3 in.) provided excellent performance for at least 7 years (maximum age of projects in study).
- Life expectancies reportedly used in life-cycle cost assessments included CIR life of
  - 13 years in Pennsylvania (Cuelho et al. 2006),
  - 12 to 20 years in Pennsylvania (with overlay) (Cuelho et al. 2006),
  - 17 to 25 years in Iowa (Lee and Kim 2007a),
  - 18 to 22 years in Iowa when constructed on poor soil support (<5,000 psi) (Heitzman et al. 2007),
  - 26 to 34 years in Iowa when constructed on good soil support (±5,000 psi) (Heitzman et al. 2007),
  - 10 to 18 years for Arizona CIR with consistently more reliable performance if a 2- to 3-in. HMA overlay is used with the CIR (Mallela et al. 2006).

FDR performance characteristics were not specifically separated out in the literature because this process provides only a stabilized base for the new HMA surface. Performance-related characteristics such as in-situ or laboratory base modulus are typically used in the structural design.

Research conducted by the Ontario MTO (Kazmierowski 2008) compared the performance of CIR and FDR projects over 11 years of service (Figure 32). This research indicates that slightly more improvement can be achieved using FDR than CIR. This is expected given that FDR addresses deficiencies in all pavement layers. However, after about 8 years of performance, the FDR showed significantly slower losses in ride quality (i.e., IRI) and pavement condition.

A well-designed experimental approach to evaluating the progression of pavement distresses and the overall decline in the pavement condition index for in-place recycling methods is needed to provide reliable life-cycle cost and life expectancy guidance.

BARRIERS

Both agencies and contractors were asked to indicate what they considered to be barriers that limit the use of in-place recycling methods (Figure 33). Agencies identified the lack of mix designs most frequently. Both agencies and contractors identified the frequently encountered barriers as

- Unsuccessful experiences,
- Competing industries, and
- Lack of specifications.

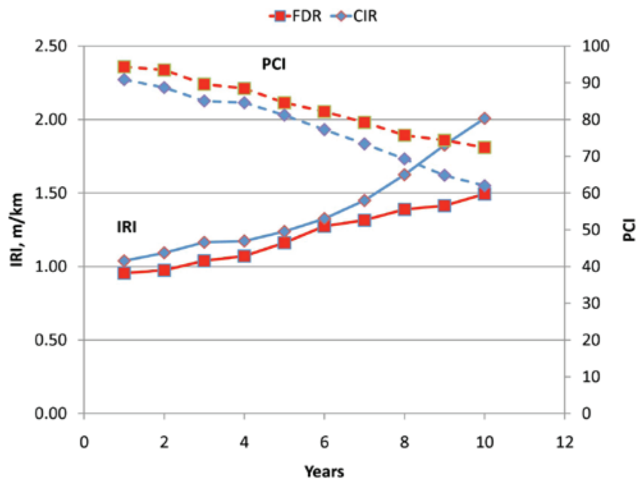


FIGURE 32 Ontario, Canada, experience with CIR and FDR performance as measured with IRI and PCI (based on Kazmierowski 2008).

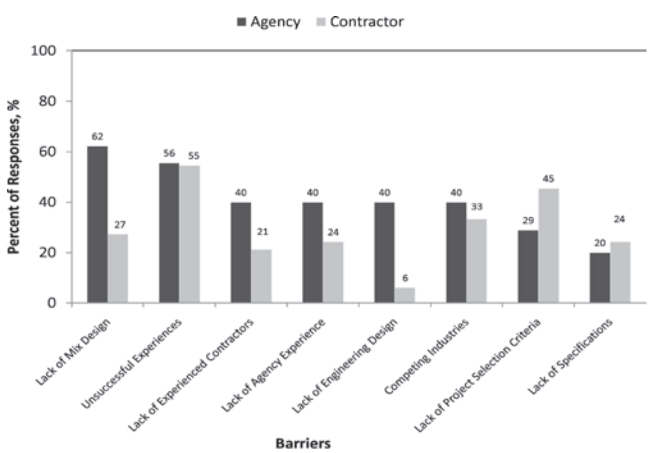


FIGURE 33 Perceived barriers to increased usage of in-place recycling by agencies and contractors. Percentages are based on the number of survey respondents.

Barriers more frequently cited by agencies than contractors are a lack of

- Mix design methods,
- Experienced contractors, and
- Agency experience.

The only barrier cited more often by contractors than agencies is a lack of project selection criteria.

Barriers were identified by Cuelho et al. (2006), who noted the following top five preservation treatment selection decision factors that need to be overcome or considered as potential limitations:

- Previous experience with a treatment,
- ADT or number of trucks,
- Urban versus rural roadway,
- Availability of contractors/equipment/materials, and
- Conclusive research in the state.

Cuelho et al. also noted the three least important decision factors:

- Weather,
- Availability of design standard/manual, and
- Availability of state equipment/workforce.

These lists generally agree with most of the agency and contractor responses.

The agency and contractor responses were used to rank and summarize the importance of various barriers to increased use of in-place recycling (Table 40).

TABLE 40
BARRIERS TO INCREASED USE OF IN-PLACE RECYCLING

Barriers to Increased Use	Frequency of Benefit
Lack of mix design	Often**
Unsuccessful experiences	Frequently
Lack of experienced contractors	Often**
Lack of agency experience	Often**
Lack of engineering design	Often**
Competing industries	Often
Lack of project selecting criteria	Often**
Lack of specifications	Sometimes

Sometimes = between 10% and 25% average of agency and contractor with experience.
Often = between 25% and 50% average of agency and contractor with experience.
Frequently = greater than 50% average of agency and contractor with experience.
*Contractor response was significantly higher than agency with experience.
**Agency response was significantly higher than contractor with experience.

SUCCESSFUL EXPERIENCES

The lack of successful experiences is a significant barrier to using in-place recycling processes. This section provides brief summaries of successful in-place recycling projects found in the literature. More detailed project descriptions can be found in the associated references and references for the case studies listed in Appendix C. Successful agency experiences with various in-place recycling projects are provided for the following topics:

- HIR cost benefits in Colorado,
- HIR surfacing in Wisconsin,

- CIR additives used to minimize presurfacing traffic damage in Kansas,
- CIR with foamed asphalt in Canada,
- CIR use on steep grades in Nevada,
- CIR surface treatment selection for traffic considerations in North Dakota,
- CIR subgrade support in California,
- FDR using emulsion stabilization for rehabilitation and lane widening FDR in Georgia,
- FDR choice of additive in Mississippi,
- FDR cement stabilization in Alabama,
- FDR selection to meet environmental policy in Texas, and
- FDR cost benefits in Georgia.

HIR Cost Benefits in Colorado

Denver, Colorado, has 5 years of experience using HIR on its 1,800 centerline miles of roadway network (Udelhofen 2006). Over the 5 years, Denver used HIR to preserve about 1.1 million square yards of HMA, saving the agency more than $5 million compared with conventional mill and fill. Most of the roadways were in residential streets with limited truck traffic. The projects typically used a 50-mm (2-in.) recycled leveling course and a 25-mm (1-in.) overlay with 20% RAP in overlay HMA. A double screed allowed work to be completed in one pass, and most projects were finished within 1 to 2 days of the start of construction.

Benefits noted by the agency included cost savings, shorter construction times than mill and fill, life extension of the roadways, and an improved bond between leveling course and overlay.

HIR Surfacing in Wisconsin

VanTimmeren (2009) summarized a project in the city of Mequon, Wisconsin, which needed to address more surface distresses than could be handled using crack sealing. Streets were evaluated to determine whether any drainage problems needed to be corrected before resurfacing. Culverts were replaced as needed and the roadways were patched with HMA as needed. One preheater and a preheater/scarifier were used to loosen the top 50 mm (2 in.) of existing HMA, and a rejuvenator was added to soften the oxidized HMA. Conventional equipment was used to place and roll the HMA, which was finished with a seal coat. Excess aggregate was swept off the surface treatment before opening to traffic.

The benefits noted by the agency were that no shouldering or driveway-matching work was needed and no waste material was produced in the process. Challenges noted by the agency included determining which streets were best suited for HIR. Coring was used to determine thickness and whether there was adequate base thickness to support the equipment. If there was insufficient base, an alternative recycling method was needed, such as FDR. It was important to make sure the excess aggregates were swept and the public was kept informed.

CIR Additives Used to Minimize Presurfacing Traffic Damage in Kansas

Thomas et al. (2000) documented a Kansas CIR project where the initial problem was rutting and raveling in the CIR under traffic and before the placement of the surface course. The agency used a Class C fly ash additive to solve this problem. A subsequent problem resulting from the use of the fly ash was premature cracking. Alternative combinations of emulsion and additives were evaluated with test sections. Fly ash (10% by weight of millings) was used in the first section, and the second test section used a combination of solventless asphalt emulsion formulated for recycling and lime slurry (1.5% hydrated lime by weight of millings). The lime was used to improve early strength gain and moisture resistance.

Equipment used on the project included one 3.6-m (12-ft) milling machine, a trailer-mounted screening and crushing unit, and a mixing unit with belt scale and computer control. A conventional asphalt paver with pickup device was also used. Rollers consisted of a heavy 30-ton, seven-tire pneumatic roller for breakdown and a double drum vibratory roller for intermediate and finish rolling (static).

The results showed that transverse cracking was twice as frequent in the fly ash section as in the emulsion–lime combination. No cracks were wider than 4.75 mm (¼ in.), with most cracks being about 1.6 mm (1/16 in.) wide. Longitudinal cracking was prevalent in the fly ash sections in one or both wheel paths; if only one wheel path was cracking, then the cracking usually occurred in the outside wheel path. In some cases, the longitudinal cracks were side-by-side in the outside wheel path. There were few longitudinal cracks in the emulsion–lime section. Rutting was either low or nonexistent in either of the sections. Field results were substantiated with a laboratory-loaded wheel rut tester and shear modulus testing. The emulsion–lime combination with the CIR minimized cracking typically seen in CIR with fly ash.

CIR with Foamed Asphalt in Canada

Lane and Kazmierowski (2005b) reported on the use of CIREAM. The emulsion sections needed a minimum curing time of 14 days, with fixed requirements for maximum moisture and minimum compaction. The foamed CIREAM sections needed a curing period of only 3 days, which was the time needed to achieve compaction and TSR requirements. The foamed asphalt binder curing time was less dependent on warm, dry weather conditions for placement to achieve the desired properties.

The equipment consisted of a milling machine, a mobile screening and crushing deck, and a mix paver where emulsion was added and the material was placed. Rollers were pneumatic tire rollers for breakdown and a steel drum for finish rolling. For CIREAM, the mix paver was replaced with an onboard twin-shaft pugmill where the expanded foam was added and mixed. The mix was fed into a heavy-duty paver with dual tamping bards in the screed.

Project requirements included compaction to 96% of the target density established by laboratory testing, with no single result below 95%, and moisture contents of less than 2%, with no sublot exceeding 3%.

Results showed that the CIREAM sections were ready to cap within 2 days of placement. FWD testing immediately after construction showed slightly higher deflections for the CIR compared with the CIREAM sections, which was attributed to the CIR section not being fully cured. FWD testing after 1 year showed that the deflections were similar for both CIR (emulsion) and CIREAM sections (Chan et al. 2009). The IRI was used to measure ride quality. IRI values were similar for both sections, but the CIR values were slightly lower than those for the CIREAM section. However, this section was micromilled before CIR for minor profile corrections, which could have helped improve the ride in this section. Both sections had little to no rutting after 1 year. Laboratory resilient modulus testing showed similar stiffness for both mixes.

Benefits of using CIREAM were an extension of the construction season and reduced curing time.

CIR Use on Steep Grades in Nevada

VanTimmeren (2008) reported various strategy considerations for maintaining the roadway at the Pequop Summit on I-80 in Elko County, Nevada. The desired life expectancy for the project was 20 years. After evaluations, an 89-mm (3.5-in.) CIR with a 100-mm (4-in.) overlay was selected because other traditional options would have cost about $8 million dollars more for the same life expectancy.

Challenges encountered, but overcome, included traffic control, length of time for lane closures (cure times), steep grades (up and down), and nonrecycling infrastructure repair that needed to occur before paving. The pulling requirements uphill while milling to a depth of 89 mm (3.5 in.) slowed the process. Traffic speeds increase on the downhill side of the interstate and can pose safety issues. Pipe work and other non-pavement-related work components in the project area were completed before the recycling process. The success of the project depended on constant communication for planning work activities.

CIR Surface Treatment Selection for Traffic Considerations in North Dakota

Kronick (2009) reported on construction considerations of CIR equipment weights resulting in punch-through problems for a 100-mm (4-in.) milling depth on a 140-mm (5.5-in.) existing HMA layer. An alternative to the originally selected CIR with double chip seal was to use CIR with overlay, but this was considered less desirable because of rapidly increasing asphalt prices. A small portion of the project had higher traffic (1,800 AADT) compared with rest of the project (985 AADT); therefore, CIR plus a 37.5-mm (1.5-in.) overlay was kept as an alternative if the CIR and chipped sections showed too much early rutting. This option was eventually used in the higher traffic area.

Advantages associated with the CIR and double chip seal compared with the CIR with overlay for the county roads were the elimination of edge dropoffs and minimal change in roadway elevations. The edge dropoffs in the overlay sections are because the lifts are placed in progressively narrower lane widths, resulting in a lip at the edge of the pavement that can catch car tires and send a vehicle out of control.

The CIR with double chip had an acceptable ride, but it was not as good as the overlay. Some reflective cracking in a 1.5-mi section with overlay was seen, but it was much less than was typically seen in other overlay projects. Microsurfacing was planned for a later date to address any rutting in the CIR with double chip section.

Benefits noted by the agency were a substantial cost savings. The cost of the CIR plus double chip was $80,000 per mile (2007 prices), with the CIR plus overlay at $180,000 per mile. This was 56% less for CIR plus double chip. The costs did not include cost of traffic control, which was provided by the county.

CIR Subgrade Support in California

VanTimmeren (2009) reported the CIR experiences of the city of Santa Anna in Orange County, California. The project was to maintain 50-year-old streets for which a soils report showed the need for extensive full-depth base repairs. The desire to implement more environmentally friendly technologies and reduce the cost of rehabilitating the roadways led to consideration of CIR as the best choice. The planned work included header cuts at the gutters, 75 mm (3 in.) of CIR, with 25 mm (1 in.) of HMA.

Construction started on the two streets in the worst condition with respect to subgrade support for the heavy recycling equipment. Repeated problems and lost time because of punch-through problems were a significant concern. After extensive discussion between the city and contractor, the agency decided that CIR, although a good option, was not applicable in all cases. The city and contractor developed a plan for evaluating the soil-support characteristics for each street by coring, then using DCP testing to determine the structural capacity of the subgrade and base. More than 90% of the remaining streets were considered acceptable for CIR work. For roads with low support values, an FDR process was used to provide a cement-stabilized 200-mm (8-in.) base with an HMA overlay.

Benefits of this approach included a cost savings of 40% over conventional reconstruction, and that no waste materials were generated.

FDR with Emulsion Stabilization for Rehabilitation and Lane Widening in Georgia

In 2006, the Virlyn B. Smith Road in Fairburn, Georgia, needed significant repair and widening. Rather than install full-depth asphalt concrete patches for about 40% of the roadway, the agency chose to use FDR with EE for stabilization. The FDR project was approximately a mile of a 7-m (23-ft) wide, two-lane roadway that needed to be widened to 8.2 m (27 ft) and the base support improved (Besseche et al. 2009). About 0.6 m (2 ft) on either side of roadway was trenched, followed by pulverizing 240 mm (9.5 in.) of the existing HMA and base, which was spread over the new lane width. An extra 37.5 mm (1.5 in.) of prepulverized base was added to trenches using a motor grader. A second round of pulverization was made to a depth of 200 mm (8 in.), and emulsion was added as a base stabilizer for the new 27-ft-wide roadway. Two passes of the pulverizer were needed to complete the second round of pulverization. A motor grader was used to smooth the surface to grade, and additional rolling was completed with a pneumatic tire roller followed by a steel wheel roller. The FDR surface was covered with 37.5 mm (2.5 in.) of HMA 7 days later.

The two methods of mix design evaluated for the project were standard Marshall stability and the SemMaterials modulus. Cores were taken for determining the extracted gradation, which showed that 33% RAP and 66% gravel aggregate base were needed to achieve the FDR gradation.

Preconstruction testing showed that the original gravel aggregate base had a modulus of about 62 MPa (9,000 psi), which was increased to about 1,241 MPa (180,000 psi) after FDR using emulsion stabilization. DCP data were used to determine the consistency of the base, sub-base, and subgrade quality. In one area with 50 mm (2 in.) of sub-base silty clay soil, an additional 50 mm (2 in.) of aggregate was added before the emulsion. The average modulus value calculated from the DCP data showed an increase of 177% when comparing preconstruction to postconstruction properties (11 months). The short-term DCP results are shown in Table 41.

Both mix designs were ultimately compared at an optimum 4.5% of emulsion by weight. The criteria and results for these designs are shown in Table 42.

TABLE 41

SUPPORT DETERMINED FROM DCP FIELD TESTING FOR GEORGIA FDR PROJECT (Besseche et al. 2009)

Day of Testing	DCP Results from Field Testing		
	R-Value	kPa (psi)	Pulverizing Depth, mm (in.)
Pre-construction	116	400 (58)	280 (11.0)
Immediately after emulsion added	48	207 (30)	305 (12.0)
End of 7 days of curing	71	400 (58)	261 (10.3)

During construction, the moisture content was taken every 305 m (1,000 ft) to determine whether conditions to replicate mix designs could be met. Pre-emulsion moisture content was 1.7% immediately before the overlay, which increased to 3.2% to 3.5% after emulsion was mixed into the pulverized materials. Before placement of the overlay, the moisture content was reduced to 1.7%.

Density was monitored every 500 ft per lane using modified Proctor, nuclear gauge, and sand cone. The modified

TABLE 42

SUMMARY OF MODULUS AND MARSHALL MIX DESIGN CRITERIA AND RESULTS FOR ENGINEERED EMULSION FDR (based on Besseche et al. 2009)

Modulus Design, 4.5% emulsion content			Marshall Design, 4.5% emulsion content		
Test	Criteria	Results	Test	Criteria	Results
Indirect Tensile Strength, psi (ASTM D 4867)	35 min	36	Coating Test, Modified, % Retained (LADOTD TR 317-87)	80 min	90
Indirect Tensile Strength Ratio, psi (ASTM D4867)	20 min	26	Initial Marshall Stability (ASTM D1559), lb	1,500 min	3,493
Resilient Modulus, ksi (ASTM D4123)	120 min	144	Cured Marshall Stability (ASTM D1559), lb	2,000 min	5,820
Short-term Strength Test, Modified Cohesion (ASTM D1560)	150 min	187	Conditioned Marshall Stability after Soaking (ASTM D1599), lb	1,000 min	4,590

Proctor was used as the reference density for developing nuclear density gauge correlations (Table 43).

Cores taken 1 year after construction showed that the resilient modulus of the FDR layer ranged from 214 ksi to 474 ksi, with an average value of 349 ksi. The effective structural number was calculated as 3.36. This is equivalent to a structural coefficient for the FDR layer of 0.24, compared with the original coefficient of 0.07 for the gravel aggregate base (GAB). The structural coefficient from laboratory test results of the cores was calculated as 0.31, which gives a structural number of 3.91.

Problems encountered during construction included a subgrade that was too soft in a few locations in the southbound lane. There were also a few soft spots because of excess moisture in the clayey sub-base, and the problem areas were dug out. Good base material was placed to the side and the soft sub-base was removed [about 0.6 to 0.7 m (2 to 2.2 ft) deep] and replaced with GAB. The GAB was compacted, the good sub-base material returned, a 1.5% emulsion was added, and the stabilized sub-base was the compacted. Problem areas were typically between 15 and 30.5 m (50 and 100 ft) long and were too short to capture in preconstruction testing.

FDR Choice of Additive in Mississippi

Prokopy (2003) reported details for an FDR project where the selection of additives was based on the desired properties for the base. The original plan was to use foamed asphalt as the stabilizer, which worked well for the first 457 m (1,500 ft). At that point, unexpected variances in soil and moisture needed further consideration. Hydrated lime was used for next 305 m (1,000 ft) to help dry soil, but durability and density requirements were still not met. Portland cement was tried next and worked well. Portland cement (8,400 tons) was used for the remaining 30 mi of project.

Previous agency experience with cement-stabilized soil showed problems with high levels of cracking because of the high percentage needed to meet the requirements. Discussions with FHWA suggested that a low cement content of about 3.5% worked well, and this content was used. The project was successful and other projects were being considered. Construction equipment was required to be moved off roadway and parked remotely overnight. Extra care was needed to avoid damage to surrounding foliage and soils.

FDR Cement Stabilization in Alabama

Prokopy (2003) reported the benefits of an FDR-stabilized base using cement for a 1.7-mi project. This project incorporated 5% cement (440 tons) for stabilization, which produced a base with a minimum unconfined strength of 2,413 kPa (350 psi). The base was topped with a double surface treatment. This project was constructed with county forces, which used a nuclear density gauge to monitor compaction during construction. A pulverizer was used to rip up the old asphalt and base course. A motor grader was used to provide the cross section and grade. A spreader truck was used to place the cement, which was mixed with water. Compaction was accomplished with standard rollers.

Benefits associated with using the cement-stabilized FDR were a substantially reduced number of haul trucks, reduced fuel costs, no waste generation, and reduced project costs. This process allowed for recycling roadways with higher traffic than previously considered and required significantly less material.

FDR Selection to Meet Environmental Policy in Texas

PCA (2008) reported the construction of a cement-stabilized FDR where the main factor in the selection of the recycling process was defined by the waste management office in Dallas, Texas. The project used FDR with cement stabilization, an underseal, and a 50-mm (2-in.) HMA overlay.

Environmental benefits associated with this project included reduced use of new materials, complete recycling of existing materials with no generated waste, and a quick return of traffic to the roadway.

FDR Cost Benefits in Georgia

In 2005, Coweta County, Georgia, placed its first 1-mi FDR project to address reconstruction needs, as the county was experiencing accelerated damage from heavy construction equipment moving in and out of the area (Nickelson 2010). The initial county concerns were spread and cost of construction. Increasing use of FDR over the past few years has demonstrated that FDR with cement provides a stabilized base with significantly improved pavement life. By 2008, 35 major county roadways in Coweta County were completed, with another 10 mi of roadways planned for the next year.

TABLE 43
CONSTRUCTION TESTING FOR GEORGIA FDR PROJECT (BESSECHE ET AL. 2008)

Lane	Moisture, %	Modified Proctor		Nuclear Gauge, lb/ft^3		Sand Density, lb/ft^3		Compaction, %
		Wet	Dry	Wet	Dry	Wet	Dry	
North Bound	3.4	131.4	127.0	134.4	130.0	128.7	124.4	100
South Bound	3.7	132.2	127.5	136.0	131.3	133.8	129.1	101

CHAPTER SIX

CONCLUSIONS, GAPS, AND RESEARCH NEEDS

CONCLUSIONS

The following conclusions can be drawn from the information presented in this synthesis.

Project selection:

- The type, severity, and extent of distresses are used to identify the most useful in-place recycling method.
- Both the distresses and recycling process will help define the depth of the milling to be used. State agencies and contractors use the Asphalt Recycling and Reclaiming Association (ARRA)-recommended range of full-depth reclamation (FDR) recycling depths greater than 6 in. The actual depth of recycling is project specific.
- Agencies appear to underutilize FDR on thinner pavements (2 to 4 in.).
- Roadway geometry and features need to be considered during project selection.
- Climate conditions need to be considered during project selection.

Structural design:

- Structural design parameters need to be assessed before construction so that the final product meets or exceeds the desired performance.

Preconstruction testing:

- The availability or collection of in-place material properties information needs to be considered when developing the project design, specifications, and agency estimates of project costs.
- Preconstruction testing is key to designing recycling mixes and identifying areas that may need an alternative design. The time needed for this testing as well as the costs to the project need to be considered in developing cost estimates and project timelines.

Materials for in-place recycling projects:

- Emulsions historically used in the same environmental conditions may have base asphalts with a wide range of performance-graded asphalt properties, which will likely influence the success or failure of recycling projects.
- Additives and stabilizers need to be selected on the basis of their ability to improve key material and mix properties or facilitate construction processes.

Quality management program:

- Contractor quality control programs include field technician training; validation of mix design properties, material properties, and density; and documentation of application rates.
- Quality control/quality assurance programs include measurements of density, moisture content, recycling layer depth, verification of material properties, and performance-related mix testing.

Specifications:

- Method specifications are commonly used by agencies for in-place recycling projects. However, agencies also routinely require the contractor to select additives and provide mix designs for in-place recycling projects, which suggests that end result or short-term performance specifications may be more appropriate types of specifications.
- There is no consistent use of in-place recycling terms or specification content.

Benefits and barriers:

- Contractor project records can be used to provide quantifiable environmental and cost benefits from in-place recycling.
- Cost savings can be realized when using in-place recycling processes.
- The magnitude of the savings will be directly related to the appropriate choice of the surface treatment.
- Limited guidance is available for use in life-cycle cost analyses or for the life expectancy of the recycled roadway.
- Both agencies and contractors identified the common most frequently encountered barriers as
  - Unsuccessful experiences,
  - Competing industries, and
  - Lack of specifications.

- Barriers more frequently cited by agencies than contractors are a lack of
  - Mix design methods,
  - Experienced contractors, and
  - Agency experience.
- The only barrier cited more often by contractors than agencies is a lack of project selection criteria.

GAPS

The following information is lacking:

- Well-defined terms for in-place recycling processes and materials [e.g., differences between the ARRA definition of "integral overlay" and the use of the same term by agencies as it applies to cold in-place recycling (CIR) and FDR],
- Weather condition guidance for successful construction of in-place recycling projects,
- Climate considerations for each recycling project's long-term performance,
- Quantifiable performance characteristics,
- Education and information on how various roadway geometry and other features are handled during in-place recycling processes,
- Consistent curing procedures for laboratory preparation of CIR and FDR mix samples,
- Consistent compaction procedures for in-place recycling mixes,
- Emulsion binder specifications that are performance graded, and
- Rapid field tests to determine when CIR mats can be overlaid (e.g., when the moisture content is below 1%).

RESEARCH NEEDS

Specific research needs include

- Reasons for the lack of use of CIR in the Southern and Southeastern states are likely related to weather conditions (e.g., humidity, temperature, and rainfall) and should be identified by future research to facilitate the selection of the most appropriate in-place recycling process.
- The use of HIR, CIR, and FDR on roadways with annual average daily traffic (AADT) greater than 30,000 may be underused by agencies and overused on facilities with AADT less than 5,000. Subgrade support for equipment needs to be considered. The reasons for the differences in acceptable traffic levels need to be explored.
- Research on the maximum FDR recycling depth (i.e., lift thickness) is needed so that the desired layer density can be obtained.
- The impact of roadway geometry and features needs further research to identify the reasons for differences between agency and contractor responses.
- Specific reasons for contractors' and agencies' climate preferences need to be explained in future research efforts.
- Using a structural overlay when structural capacity improvement may not be needed requires further research to define the criteria for selecting this option. The ability of other surface treatments to provide acceptable surface courses in this circumstance also needs to be explored.
- Research is needed to quantify environmental and cost benefits.
- A well-designed experimental approach to evaluating the progression of pavement distresses and the overall decline in the pavement condition index for in-place recycling methods is needed to provide reliable life-cycle cost and life expectancy information.
- Structural coefficients for CIR and FDR can be better defined and based upon performance testing.

ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
AADT	Annual average daily traffic
ARRA	Asphalt Recycling and Reclaiming Association
CIR	Cold in-place recycling
CIREAM	Cold in-place recycling expanded foam asphalt
DCP	Dynamic cone penetrometer
EE	Engineered emulsion
ER	Emulsified recycling (agent)
ESAL	Equivalent single-axel load
FDR	Full-depth reclamation
FWD	Falling weight deflectometer
GPR	Ground-penetrating radar
HMA	Hot mix asphalt
IDT	Indirect tensile strength
IRI	International roughness index
OGFC	Open-graded friction course
PCA	Portland Cement Association
PG	Performance grading
PI	Plasticity index
QA	Quality assurance
QC	Quality control
RA	Recycling agent
RAP	Reclaimed asphalt pavement
RTFO	Rolling thin film oven (testing)
R-value	Resistance value (used to determine load-carrying ability of soils)
TSR	Tensile strength ratio

DEFINITIONS

Asphalt binder: An asphalt-based cement that is produced from petroleum residue either with or without the addition of modifiers (ASTM D6648-01).

Bituminous emulsion: A suspension of minute globules of bituminous material in water or in an aqueous solution.

Cold in-place expanded asphalt mix (CIREAM): A CIR process that uses expanded (foamed) asphalt cement instead of emulsion as the binder.

Cold in-place recycling (CIR): A process that uses cold milling of the surface and remixing with the addition of asphalt emulsion, portland cement, foamed asphalt, or other additives to improve the properties of the reclaimed asphalt pavement (RAP), followed by placing and compacting the new mix in one continuous operation.

Emulsified recycling agent: A suspension of minute globules of bituminous material in water or in an aqueous solution where the bituminous material is a blend of hydrocarbons with or without minor amounts of other materials that are used to alter or improve the properties of the aged asphalt in a recycled asphalt paving mixture.

Expanded asphalt (EA): See foamed asphalt.

Foamed asphalt: Produced by a process in which water is injected into the hot asphalt, resulting in spontaneous foaming. Also called expanded asphalt (Muthen 1998).

Full-depth reclamation (FDR): A pavement rehabilitation process that pulverizes an existing asphalt pavement along with one or more inches of the underlying base or subgrade. The pulverized material is mixed with or without additional binders, additives, or water, and then placed, graded, and compacted to provide an improved base layer before placement of the final surface layers.

Hot in-place recycling (HIR): A process that preheats the existing surface immediately before milling, mixing the RAP with asphalt binders, recycling agents, new aggregates, or other additives to improve the properties of the RAP, then placing and compacting the new mix in one continuous operation.

Milling: Fine particles (generally ranging in size from dust to less than 1 in.) of bitumen and inorganic material that are produced by the mechanical grinding of bituminous concrete surfaces (New Jersey Department of Environmental Protection 2010).

Pulverization: Mechanized process that transforms the existing flexible pavement surface layer and a portion of the underlying granular layer into a uniform granular material suitable for use as a base layer (Caltrans 2008).

Recycling agent (RA): A blend of hydrocarbons with or without minor amounts of other materials that is used to alter or improve the properties of the aged asphalt in recycled asphalt.

Rejuvenator: An additive used in the recycling of reclaimed asphalt pavement.

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APPENDIX A

Agency and Contractor Survey

NCHRP 40-13: Recycling and Reclamation of Asphalt Pavements Using In-Place Methods

This survey is designed to collect key information needed to develop this synthesis. There are a total of 25 questions about various aspects of in-place recycling. The majority of the questions are "check the box" type. There are also opportunities for "essay" answers so that we can capture construction information and projects for developing case histories. Thank you for taking the time to contribute your valuable information to our database.

When you click on the "Next Page" button, your answers up to that point will be saved. You can continue on with the survey or come back to it later and resume where you left off.

If you have any questions, call Mary Stroup-Gardiner at (530) 898-6032 or e-mail at mstroup-gardiner@csuchico.edu

1) Contact Information

Name ______________________________

Agency ______________________________

Address ______________________________

City ______________________________

State ______________________________

Zip Code ______________________________

Phone ______________________________

e-mail ______________________________

2) Indicate how long you have been using each type of in-place recycling.

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Less than 5 years	☐	☐	☐
5 to 10 years	☐	☐	☐
More than 10 years	☐	☐	☐
We don't use this method	☐	☐	☐

3) What types of hot in-place recycling do you use? (Check all that apply.)

☐ Remixing

☐ Repaving

☐ Surface heating

4) Indicate the extent of your *annual* recycling program in lane miles.

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Less than 50 lane miles	☐	☐	☐
50 to 100 lane miles	☐	☐	☐
More than 100 lane miles	☐	☐	☐

5) Traffic Levels: I would consider recycling a roadway with annual average daily traffic (AADT) levels of up to:

	Hot In-Place	Cold In-Place	Full Depth Reclamation
5,000 AADT	☐	☐	☐
10,000 AADT	☐	☐	☐
20,000 AADT	☐	☐	☐
30,000 AADT	☐	☐	☐
More than 30,000 AADT	☐	☐	☐

6) Traffic Levels: Please indicate your reasons for limiting recycling to certain traffic levels.

____

____

____

7) Roadway Geometry and Existing Feature Constraints: I would consider recycling on roadways with:

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Tight turns (radius < 40 ft) or switchbacks	☐	☐	☐
Mountainous terrains with grades exceeding 8%	☐	☐	☐
Manholes or other castings within pavement layers	☐	☐	☐
Minor roadway widening needs	☐	☐	☐
Superelevation or cross-slope correction required	☐	☐	☐
Curb and gutter	☐	☐	☐
Other (use comment box)	☐	☐	☐

8) Environmental Conditions: I would consider recycling on roadways in the following climate regions:

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Hot and Dry	☐	☐	☐
Hot and Wet	☐	☐	☐
Cold and Dry	☐	☐	☐
Cold and Wet	☐	☐	☐
Other	☐	☐	☐

9) Preconstruction Field Testing: Before construction, I typically use:

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Boring to check depth of base and HMA	☐	☐	☐
Condition distress survey	☐	☐	☐
Coring or milling to obtain material for lab testing	☐	☐	☐
Coring to determine thickness	☐	☐	☐
FWD testing	☐	☐	☐
GPR testing	☐	☐	☐
Ride quality (smoothness measurements)	☐	☐	☐
Other	☐	☐	☐

10) Preconstruction Laboratory Testing: Before construction, I typically determine:

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Aggregate gradations of cores or millings	☐	☐	☐
Application rates of binders or other additives	☐	☐	☐
Binder content of cores or millings	☐	☐	☐
Material properties of any liquids, stabilizers, rejuvenators, additives, or admixtures to be added	☐	☐	☐
Percent fines of millings	☐	☐	☐
Recovered binder properties from cores or millings	☐	☐	☐
Other	☐	☐	☐

11) Cold In-Place: Indicate the types of liquids and stabilizers you use for your cold in-place recycling projects.

Cold in-place: Types and grades of emulsions________________________________

Cold in-place: Stabilizers________________________________

Cold in-place: Rejuvenators________________________________

Cold in-place: Admixtures________________________________

Cold in-place: Corrective aggregates________________________________

Cold in-place: Any other additives________________________________

12) Hot In-Place: Indicate the types of liquids and stabilizers you use for your hot in-place recycling projects.

Hot in-place: Types and grades of emulsions________________________________

Hot in-place: Stabilizers________________________________

Hot in-place: Rejuvenators________________________________

Hot in-place: Admixtures________________________________

Hot in-place: Corrective aggregates________________________________

Hot in-place: Any other additives________________________________

13) Full Depth Reclamation: Indicate the types of liquids and stabilizers you use for your full depth reclamation recycling projects.

Full depth reclamation: Types and grades of emulsions________________________________

Full depth reclamation: Stabilizers________________________________

Full depth reclamation: Rejuvenators________________________________

Full depth reclamation: Admixtures ____

Full depth reclamation: Corrective aggregates _______________________________________

Full depth reclamation: Any other additives ____

14) Mix Design Testing: Before construction, I or my contractor design our recycled mixes based on the following method:

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Don't do formal mix designs	☐	☐	☐
Hveem mix design	☐	☐	☐
Marshall mix design	☐	☐	☐
Superpave gyratory compactor	☐	☐	☐
Wirtgen mix design	☐	☐	☐
Other	☐	☐	☐

15) Structural Design: During project development, I consider the structural capacity of the recycled layer using:

	Hot In-Place	Cold In-Place	Full Depth Reclamation
FWD testing	☐	☐	☐
Laboratory resilient modulus	☐	☐	☐
Established structural coefficients	☐	☐	☐
Predetermined layer thickness from experience	☐	☐	☐
Other	☐	☐	☐

16) Equipment: For hot in-place recycling, what types of preheaters do you allow?

☐ Infra-red

☐ Open flame

☐ Recirculating heated gases

☐ Combination of above

17) Typical Milling Depth: Indicate the most common depth of milling for your recycling projects.

	Hot In-Place	Cold In-Place	Full Depth Reclamation
1 to 2 inches	☐	☐	☐
2 to 4 inches	☐	☐	☐
4 to 6 inches	☐	☐	☐
Greater than 6 inches	☐	☐	☐
Other	☐	☐	☐

18) Construction: Indicate the number of people on the construction site for a typical project. The estimated number of people should include truck drivers, equipment operators, inspectors, supervisors, road crew, and traffic control people.

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Less than 5	☐	☐	☐
5 to 7	☐	☐	☐
8 to 10	☐	☐	☐
More than 10	☐	☐	☐

19) Surface Treatment: Indicate the typical top layer used for recycling projects.

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Fog and chip seal	☐	☐	☐
Fog seal only	☐	☐	☐
HMA overlay (structural)	☐	☐	☐
Integral HMA overlay	☐	☐	☐
Microsurfacing	☐	☐	☐
OGFC	☐	☐	☐
Other thin HMA overlay (non-structural)	☐	☐	☐
Slurry seal	☐	☐	☐
Other	☐	☐	☐

20) Surface Treatment: What criteria do you use to select the surface treatment?

____

____

____

21) Surface Treatment: Does your selection of the surface treatment depend on the climatic region of the project?

____

____

____

22) Quality Control: Briefly indicate your current quality control programs and/or practices.

____

____

____

23) Quality Assurance: Briefly indicate your current quality assurance programs and/or practices. What types of acceptance testing do you specify?

____

____

____

24) Performance Measures: What performance measures would you recommend for evaluating the quality of in-place recycled pavements? (e.g., 50% immediate improvement in smoothness).

25) Specifications: What type of specifications does your agency use?

	Hot In-Place	Cold In-Place	Full Depth Reclamation
Method specification	☐	☐	☐
End result specification	☐	☐	☐
Performance specification	☐	☐	☐
Warranty	☐	☐	☐
Other	☐	☐	☐

26) Warranty: Does your agency specify a warranty period for the different in-situ recycling processes? If so, what is the length of the warranty and what type of assurance is required?

27) Contracting: Does your agency specify an alternate bid for the in-place recycling process? Please specify the alternate design for the specific in-place recycling treatment.

28) Barriers to Implementation: Indicate all of the factors you think are likely to limit the use of recycled pavements.

☐ Lack of engineering design procedures.

☐ Lack of standard specifications.

☐ Lack of mix design methods.

☐ Lack of project selection criteria.

☐ Lack of experienced local contractors.

☐ Lack of agency experience.

☐ Previous unsuccessful experiences.

☐ Opposition from competing industries.

☐ Other (please specify):

If you selected other, please specify

29) Environmental Benefits: Indicate environmental benefits, which you have documented on your projects.

- ☐ Reduced use of virgin materials.
- ☐ Reduced time for lane closures.
- ☐ Reduced fuel consumption.
- ☐ Reduced emissions.
- ☐ Other (please specify):

If you selected other, please specify____

30) Environmental Benefits: Can you quantify these environmental benefits? If so, please provide a summary of these quantified benefits.

31) Case Study Information—Examples of best practices or, just as important, lessons learned: Do you have or do you know of any recycling projects that could be used in case studies? If so, please provide information on the project name, and contact name and number.

APPENDIX B

Examples of Specifications

Missouri specification for 1 inch HIR

Wisconsin FDR specification

Maine FDR specification

Missouri HIR 1-inch

http://www3.modot.mo.gov/JOBSPEC2.NSF/172856ff65ca19dc862567bb004c65cd/b416bfcb85fed19c8625745800
5ded53?OpenDocument

1.0 Description. This work shall consist of hot in-place recycling of the existing asphalt surface with a virgin hot mix overlay.

2.0 Material. All material shall be in accordance with Division 1000, Material Details, and specifically as follows:

2.1 The application rate of emulsified asphalt that is added to the recycled material shall be determined by the contractor prior to construction. The emulsified asphalt shall conform to the following set of requirements:

Asphalt Emulsion				
Test[a]	**EA-300P**		**ARA -1P**	
	Min.	**Max.**	**Min.**	**Max.**
Viscosity:				
SSF @ 50ºC	100	400	—	—
SSF @ 25ºC	—	—	15	100
Storage Stability[b] Test, 24 hour, percent	—	1	—	1
Sieve Test, 850 µm mesh (No. 20), percent	—	0.3	—	0.1
Distillation:				
Oil distillate by volume of emulsion, percent	—	3	—	2
Residue from distillation[c], percent	65	—	60	65
Test on Residue from Distillation				
Penetration:				
25ºC, 100 g, 5 seconds	300	—	—	—
4ºC, 100 g, 5 seconds	—	—	150	250
Ductility, 4ºC, 5 cm/minute, cm	25	—	100	—
Ash[d], percent	—	1	—	—
Float Test at 60ºC, sec.	1200	—	—	—
Elastic Recovery[e], percent	58	—	—	—
Asphaltenes ASTM D3279, D4124 or D6560	—	—	—	15

[a] All tests shall be performed in accordance with AASHTO T 59 except as noted.
[b] In addition to AASHTO T 59, upon examination of the test cylinder, and after standing undisturbed for 24 hours, the surface shall show no appreciable white, milky colored substance and shall be a homogeneous brown color throughout.
[c] AASHTO T 59 shall be modified to maintain a 204°C ± 5 C maximum temperature for 15 minutes.
[d] Percent ash shall be determined in accordance with AASHTO T 111, *Ash in Bituminous Material.*
[e] Elastic recovery shall be determined as follows. Condition the ductilometer and samples to be treated at 10ºC. Prepare the brass plate, mold and briquet specimen in accordance with AASHTO T 51. Keep the specimen at the specified test temperature of 10ºC for 85 to 95 minutes. Immediately after conditioning, place the specimen in the ductilometer and proceed to elongate the sample to 20 cm at a rate of pull of 5 cm/min. After the 20 cm elongation has been reached, stop the ductilometer and hold the sample in the elongated position for 5 minutes. After 5 minutes, clip the sample approximately in half by means of scissors or other suitable cutting devices. Let the sample remain in the ductilometer in an undisturbed condition for one hour. At the end of this time period, retract the half sample specimen until the two broken ends touch. At this point note the elongation (x) in cm.

Calculate the percent recovery by the following formula:

$$\% \text{ Recovery} = \frac{(20 - X)}{20} \times 100$$

2.2 The virgin hot mix asphalt shall conform to Section 403 of the standard specifications. When the virgin hot mix asphalt is placed simultaneously with the recycling operation, the point of sampling of virgin hot mix asphalt will be from the truck transports in accordance with AASHTO T168.

3.0 Equipment Requirements.

3.1 The contractor shall specify, to the engineer, the type of equipment intended for use. The contractor shall be required to demonstrate required rate, depth and satisfactory recycling operations on the roadway before being allowed to commence full operations.

3.2 The equipment shall be capable of uniformly heating the surface to a temperature high enough to remove excess moisture and allow dislodging of the material to a minimum depth of 1.0 inch, without breaking the aggregate particles. Heating shall be accomplished without burning or charring the existing pavement, without producing undesirable pollutants or damaging adjacent vegetation.

3.3 The emulsified asphalt shall be applied to the scarified material at a uniform rate as prescribed in the mix design or as directed by the engineer. Emulsified asphalt shall not vary more than 0.02 gallon per square yard from the mix design. The storage unit shall be able to maintain the emulsified asphalt within the temperature range specified by the supplier prior to mixing with the scarified material.

3.4 If the virgin hot mix asphalt overlay is applied simultaneously, the recycling equipment shall be capable of performing the functions of a bituminous paver as described in Section 403.

4.0 Construction Requirements.

4.1 The existing pavement surface to be recycled shall be cleaned of all dirt, fabric, oils, or any other objectionable materials before beginning the hot in-place surface repaving. Hot in-place recycling shall not take place when the roadway surface is wet, frozen or if the weather conditions prevent proper handling, finishing and compacting of the bituminous mixture.

4.2 The existing pavement surface shall be evenly heated, milled/scarified and reworked to a minimum depth of 1.0 inch from the lowest point in the pavement surface, and to the width shown on the plans. The surface temperature of the existing pavement shall not exceed 475°F, and the recycled mix temperature shall not be less than 225°F. The heating operation shall extend at least 2.0 inches beyond the width of scarification on both sides. On the second pass, the recycling shall overlap the previously recycled mat by at least 2.0 inches.

4.3 Virgin Hot Mix Asphalt

4.3.1 If the virgin hot mix asphalt overlay is to be placed in a continuous operation, the temperature of the recycled mix is to be maintained at a minimum of 225°F until the virgin mix is placed.

4.3.2 If the virgin hot mix asphalt overlay is to be placed with a separate operation, the following shall apply. The recycled asphalt mixture shall be compacted in accordance with Section 402. The recycled pavement shall be tacked in accordance with Section 407 prior to the virgin hot mix asphalt overlay. The virgin asphalt mixture shall be opened to traffic in accordance with Section 403. Traffic will be allowed to drive on the recycled mat; however, any damage to the recycled material shall be repaired by the contractor, at the contractor's expense, prior to placing the virgin asphalt mixture. Rutting shall not exceed 3/8 inch.

4.3.3 The virgin hot mix asphalt mat shall be thoroughly and uniformly compacted in accordance with Section 403. Joint compaction shall be in accordance with Section 403.

5.0 Method of Measurement.

5.1 Final measurement of the completed hot in-place recycling will not be made except for authorized changes during construction, or where appreciable errors are found in the contract quantity. Where required, measurement of hot in-place recycling, complete in place, will be made to the nearest square yard. The revision or correction will be computed and added to or deducted from the contract quantity.

5.2 Measurement of emulsified asphalt to the nearest 10 gallons will be made as specified in Section 1015. If water is added to the emulsified asphalt, the quantity to be paid for will be determined prior to the addition of water.

5.3 Measurement of the virgin hot mix asphalt will be in accordance with Section 403.

6.0 Basis of Payment.

6.1 Hot in-place recycling will be paid for at the contract unit price per square yard, complete in place, and will be considered full compensation for all material, testing, labor, tools, equipment and appurtenances necessary to complete the work, including cleaning of existing pavement, heating, scarifying, mixing and relaying recycled material.

6.2 The accepted quantity of emulsified asphalt will be paid for at the contract unit price. No direct payment will be made for water added to the emulsified asphalt.

6.3 Payment for the virgin hot mix asphalt will be in accordance with Section 403.

6.4 No direct payment will be made for the asphalt emulsion used for the Tack Coat.

6.5 Hot in-place recycling, including the Asphalt Recycling Emulsion, shall be included in the smoothness adjustment in accordance with Section 403.

Wisconsin FDR Specification

SECTION 325 PULVERIZED AND RE-LAID PAVEMENT

325.1 Description

(1) This section describes full depth in-place pulverizing of the existing asphaltic pavement along with a portion of the underlying base and relaying the pulverized material to construct a new base.

325.2 (Vacant)

325.3 Construction

(1) Pulverize the full depth of the existing asphaltic pavement until 97 percent or more will pass the 2-inch sieve. Also pulverize the existing base to the depth the plans show and mix with the pulverized asphaltic pavement. Windrow material as construction operations dictate.

(2) Immediately after pulverizing, relay the material with a paver, grader, or both a paver and grader.

(3) If sufficient material is available at a given location, match the lines, grades, and cross slopes the plans show. If there is insufficient material at a given location, shape the available material to create a smooth profile and cross slope for a good ride. Eliminate localized bumps, depressions, and ruts. Unless the engineer specifically directs, the contractor is not required to haul material from one location on the project to another.

(4) Immediately after relaying, compact the re-laid material first with either a rubber tired roller or vibratory padfoot roller and second with a vibratory steel roller. Add water, as required, both before and during compaction. Compact each layer to the extent required for standard compaction under 301.3. Use compaction equipment as follows:

1. For a compacted lift of 6 inches or less, use equipment as specified in 301.3.1.
2. For a compacted lift from 6 inches to 8 inches, use a 12.5-ton or heavier vibratory padfoot roller and an 8-ton or heavier vibratory steel roller.
3. For a compacted lift greater than 8 inches, split into lifts less than 8 inches and use the equipment specified for those lift thicknesses.

(5) Perform each day's pulverize and relay operations to avoid leaving abrupt longitudinal differences between adjacent lanes. Repair surface damage caused by intervening construction or public traffic immediately before paving as necessary to provide a good riding pavement.

325.4 Measurement

(1) The department will measure Pulverize and Relay by the square yard acceptably completed, measured using the centerline length and the width from outside to outside of completed base, but limited to the width the plans show or the engineer directs.

325.5 Payment

(1) The department will pay for the measured quantity at the contract unit price under the following bid item:

ITEM NUMBER	DESCRIPTION	UNIT
325.0100	Pulverize and Relay	SY

(2) Payment is full compensation for pulverizing, windrowing, relaying, furnishing and adding water, shaping, and compacting. If the engineer requires hauling material from one location on the project to another, the department will pay for that hauling as extra work.

(3) Payment also includes water for compaction and dust control except, if the contract contains the Water bid item, the department will pay separately for compaction and dust control water as specified in 624.5.

Maine FDR Specification

SECTION 305 - PREMIXED BITUMINOUS BASE Reserved

SECTION 306 - RECLAIMED MATERIAL FOR STABILIZED BASE Reserved

SECTION 307 - FULL DEPTH RECYCLED PAVEMENT

307.01 Description: This work shall consist of pulverizing a portion of the existing roadway structure into a homogenous mass, placing and compacting this material to the lines, grades, and dimensions shown on the plans or established by the Resident.

307.02 Pulverized Material: Pulverized material shall consist of the existing bituminous pavement and, if specified, a designated portion of the underlying gravel, pulverized, and blended into a homogenous mass. Pulverized material will be processed to 100% passing a 50 mm [2 in] square mesh sieve.

Recycled material, if required, shall consist of material from the project or from off-site stockpiles that has been processed before use to 100% passing a 50 mm [2 in] square mesh sieve. Recycled material shall be conditionally accepted at the source by the Resident. It shall be free of winter sand, granular fill, construction debris, and other materials not generally considered bituminous pavement.

DIVISION 200 -- EARTHWORK

307.03 Pulverizer: The pulverizer shall be a self-propelled machine, specifically manufactured for cold in-place recycled type work and capable of reducing the required existing materials to a size that will pass a 50 mm [2 in] square mesh sieve. The machine shall be equipped with standard automatic depth controls and must maintain a consistent cutting depth and width. The machine also shall be equipped with a gauge to show depth of material being processed.

307.04 Placement Equipment: Placement of the Full Depth Reclamation recycled material to the required slope and grade shall be done with an approved highway grader or by another method approved by the Resident.

307.05 Rollers: The Full Depth Reclamation recycled material shall be rolled with a vibratory pod/tamping foot roller with a minimum 1.4 m [54 in] diameter single drum. The drum shall have a minimum of 112 tamping feet, 75 mm [3 in] in height, and a minimum contact area per foot of 110 cm^2 [17 in^2]. Final rolling shall be accomplished by a minimum 2.15 m [84 in] width single drum vibratory soil compactor.

307.06 Pulverizing: The entire depth of existing pavement shall be pulverized together with approximately 25 mm [1 in] of the underlying gravel into a homogenous mass. All pulverizing shall be done with equipment that will provide a homogenous mass of pulverized material, processed in-place, which will pass a 50 mm [2 in] square mesh sieve.

307.07 Weather Limitations: Full Depth Reclamation work shall not be performed when weather conditions are such that proper pulverizing, spreading, or compaction of the pulverized material cannot be accomplished.

307.08 Surface Tolerance: The complete surface of the Full Depth Reclamation course shall be shaped and maintained to a tolerance, above or below the required cross sectional shape, of 10 mm [• inch].

307.09 Full Depth Reclamation: Procedure 50 mm [2 in] square mesh sieve and then shaped and compacted to the cross-slope and grade shown on the plans, typicals, or as directed by the Resident.

307.08 Surface Tolerance: The complete surface of the Full Depth Reclamation course shall be shaped and maintained to a tolerance, above or below the required cross sectional shape, of 10 mm [• inch].

307.09 Full Depth Reclamation Procedure: 50 mm [2 in] square mesh sieve and then shaped and compacted to the cross-slope and grade shown on the plans, typicals, or as directed by the Resident.

Extra material will be added if required by the contract or Resident to restore cross-slope and/or profile grade before pulverizing; locations will be shown on the plans or described in the construction notes. The Resident may add or delete locations while construction of the project is in progress. All extra material, whether shown on the plans or added, will meet the requirements of Subsection 307.021 - New Aggregate and Additional Recycled Material, of this Special Provision. The Contractor will use recycled pavement to the extent it is available, in lieu of untreated aggregate surface course. The Contractor shall be responsible for re-establishing the existing profile grade as directed by the Resident.

In areas where a variable gravel course is called for or required, the contractor shall pulverize, grade, and compact the existing pavement to allow for a consistent thickness of gravel.

Density of the Full Depth Reclamation material will be determined by the Department using Nuclear Density Gauges. A 90 m [300 ft] section at the start of the pulverizing operations will be designated as the control section. The control section will be pulverized, have water added until testing indicates that optimum moisture has been obtained, and rolled as directed until the nuclear density readings show an increase in dry density of less than 16 kg/m^3 [1 lb/ft^3] for the final 4 vibratory roller passes. This density will be used as the target density for the recycled material. The remaining Full Depth Reclamation material shall be compacted to a minimum density of 98% of the target density as determined in the control section.

307.10 Method of Measurement: Full Depth Reclamation will be measured by the square meter [square yard].

307.11 Basis of Payment: The accepted quantity of Full Depth Reclamation will be paid for at the contract unit price per square meter [square yard], complete in-place which price will be full compensation for furnishing all equipment and labor for pulverizing, blending, placing, grading, compacting, and for all incidentals necessary to complete the work.

The addition of materials to restore profile grade and/or cross-slope in areas shown on the plans or described in the construction notes will be paid separately under designated pay items within the contract.

Payments will be made under:

Pay Item Pay Unit

307.32 Full Depth Recycled Pavement Square Meter [Square Yard]

(Untreated Maineline Travelway)

307.33 Full Depth Recycled Pavement Square Meter [Square Yard]

(Untreated Shoulder)

APPENDIX C

References for Case Studies Found in the Literature

Reference Article	*Reference Publication*	Reference Date	City	State/Province/Country	Street Type	Street Name/Location	AADT	Recycling Type	Notes
Hot In-Place									
A Hot, In-Place In the Sun	*Roads & Bridges*	Oct. 1999	Hillsborough County	Florida/USA	Urban arterial	Columbus Drive	60,000	Hot in-place	Next to the Tampa Bay Buccaneers Raymond James Stadium; AADT 45,000–60,000
One Pass: Repaving Process Smoothes Missouri I-29	*Asphalt Contractor*	Jan. 2006	St. Joseph to Platte City	Missouri/USA	Interstate	Interstate 29	31,236	Hot in-place	
Hot-in-Place Recycling Key to Denver's Street Maintenance	*Asphalt Contractor*	June 2006	Denver	Colorado/USA	City streets	Multiple locations	Not available	Hot in-place	
In The Mix	*Roads & Bridges*	Feb. 2009	Mequon	Wisconsin/USA	City streets	Multiple locations	3,000	Hot in-place	With boiler slag seal
Cold In-Place									
Going in Cold	*Roads & Bridges*	March 2000	Minneola to Dodge City	Kansas/USA	Highway	US 283	2,520	Cold in-place w/ lime slurry	Truck AADT volume = 560
Cold In-Place Recycling a Success in the BadlandsCase	*Focus Magazine*	Oct. 2001	Badlands National Park	South Dakota/USA	National Park Service road	Badlands National Park	1,295	Cold in-place	Truck AADT volume = 118
Hard Doesn't Mean Stale	*Roads & Bridges*	Oct. 2001	Tazewell County	Illinois/USA	County road	Springfield Road	2,500	ReFlex Cold in-place	CIR w/ emulsion for specific environment
Hard Doesn't Mean Stale	*Roads & Bridges*	Oct. 2001	Tazewell County	Illinois/USA	County road	Washington Road	3,000	ReFlex Cold in-place	CIR w/ emulsion for specific environment
Feeling Bubbly	*Roads & Bridges*	May 2005	Perth	Ontario/Canada	2-lane highway	Highway 7	9,000	Cold in-place & CIREAM	AADT = 9,000; 8% = commercial vehicles
Peak Performance	*Roads & Bridges*	Feb. 2008	Elko, Pequop Summit	Nevada/USA	Interstate	Interstate 80	5,400	Cold in-place	
Foamed Asphalt Provides Cost-Effective Solution on Hwy. 166 Project	*Asphalt Contractor*	Dec. 2008	New Cuyama	California/USA	2-lane highway	Highway 166	4,200	Cold foamed in-place recycling	Farm-to-market road; heavy truck traffic
In the Mix	*Roads & Bridges*	Feb. 2009	Santa Ana	California/USA	City streets	Delhi residential neighborhood	26,772	Cold in-place	Some FDR was required
In the Mix	*Roads & Bridges*	Feb. 2009	Santa Ana	California/USA	City streets	Willard residential neighborhood	6,511	Cold in-place	Some FDR was required
Pavement Rehabilitation on a Budget	*Roads & Bridges*	Feb. 2009	Valley City—Barnes County	North Dakota/USA	National scenic byway	County Road 21	1,800	Cold in-place	AADT = 1,800

Full-Depth Reclamation									
Cement Cures	*Roads & Bridges*	Oct. 2003	Jackson	Missis-sippi/USA	National Park Ser-vice road	Natchez Trace Parkway	7,800	FDR w/ cement	
A Clean Dozen	*Roads & Bridges*	April 2005	Stephen-ville	Texas/USA	City streets	Multiple Locations	9,000	FDR w/ cement	
Idaho Overlay	*Pacific Builder and Engineer*	Oct. 2005	New Mead-ows (Idaho 55) north 7 mi to Cattle Crossing	Idaho/USA	Highway	US 95	3,000	FDR w/ cement (CRABS)	AADT of 3,000 vehi-cles at junction
Foamed Asphalt Recycling in Zion National Park	*Rocky Mountain Construc-tion*	Oct. 2006	Zion National Park	Utah/USA	National Park Ser-vice road	Zion Can-yon Scenic Drive	990	FDR w/ foamed asphalt & cement	
A Road Renaissance	*Roads & Bridges*	Oct. 2007	Fairburn	Georgia/ USA	County road	Virlyn B. Smith Road	940	Fortress FDR	Used asphalt emulsion for flexible base
Bolder Than Dirt	*Roads & Bridges*	Feb. 2008	Fairfield County	South Car-olina/USA	County roads			FDR w/ cement	
Recreation Building	*Roads & Bridges*	Feb. 2008	Hailey, Blaine County	Idaho/USA	Airport runway	Friedman Memorial Airport	50,000 operations	FDR w/ cement (CRABS)	
Recycling Hits the Road	*Contract Journal*	April 2008	Cambridge-shire County	Cambridge/ England	Residential & agricul-tural road	B1040 Road	11,000	FDR w/ cement	
Full-Depth Reclama-tion Means Sustain-able Paving	*The Dixie Contractor*	Sep. 2008	Coweta County (Newnan)	Georgia/ USA	County roads		4,170	FDR w/ cement	
Old Asphalt, New Foundation—Recy-cling Roads	*Construc-tioneer*	Dec. 2008	Dover	Delaware/ USA	City streets	Multiple locations	7,000	FDR w/ cement	
A Good Rap	*Roads & Bridges*	Feb. 2009	Rockford	Illinois/ USA	Tollway	I-90/I-39	> 20,000	FDR w/ cement	Fraction-ated recy-cled asphalt pavement & ground-tire rubber modifiers

City/Road Location	State/Province/Country	Road Type	Project Type	Construction Date	Weather (°F)	AADT	Notes
Hot In-Place—International							
Jing-Jin-Tang Expressway between Beijing and Tianjin	China	Expressway	Hot in place	April 2002	61	35,000	10% AADT = # heavies (3,500 vehicles)
Alsheim to Mettenheim	Germany	Roadway	Hot in place	Sep. 2004	61	10,000	B9 federal road; 4% = heavy traffic (400 vehicles)
Cold In-Place—International							
156th Street & Albert Trail	Edmonton/Alberta/Canada	Intersection approach to highway	Cold recycling/stabilization w/ foamed bitumen; asphalt overlay	June 2002	65	24,500	Heavy truck traffic @ intersection
Ellerslie Road (156th Street to 142nd Street)	Edmonton/Alberta/Canada	2-lane rural road	Cold foam in-place recycling	Aug. 2001	58	2,000	9,000 ESALs per year
Markham/Citizen Court	Toronto/Ontario/Canada	Industrial area	Cold in-place recycling using an emulsion	June 2003	63	35,000	Low to medium truck volume (mostly low)
Anshan/Heida Road	Liaoning Province/China	4-lane highway	Cold in-place recycling w/ foamed bitumen and cement	Sep. 2004	69	16,000	
Xibao Expressway	Shaanxi Province/China	Expressway	Cold in-plant recycling w/ foamed bitumen and cement	April 2005	54	8,000	30% = heavy traffic
Yingda Road, Yingkou (from Yingkou to Dashiqiao)	Yingkou/China	4-lane highway	Cold in-place recycling w/ bitumen emulsion and cement	June 2004	75	15,000	50% = heavy trucks
Bogotá/127th Street	Bogotá/Colombia	4-lane split carriageway	Recycled base w/ foamed bitumin and lime, geogrid, & hot mix asphalt	Oct. 2000– April 2001	62	Not available	Heavily trafficked urban arterial
Lliki–Athens–Korinthos Highway	Greece	Highway	Cold in-place recycling w/ foamed bitumen stabilization	Sep. 2003	77	40,000	25% = heavy vehicles
A 14 between Bologna and Rimini (km 116–km 111)	Italy	Freeway	Cold recycling with foamed bitumen	Aug. 2001	88	107,000	26,000 trucks & coaches daily (24% of AADT)
Road SS 236; Marmirolo (150 km east of Milan)	Italy	Main road through the town	Cold recycling w/ foamed bitumen	July 2003	82	25,000	20%–25% = trucks (5,000–6,250)
Modena, A1 Motorway	Italy	Motorway/bypass	Cold recycling w/ foamed bitumen and cement	Dec. 2003	42	150,000	43,000 trucks & coaches daily (30% of AADT)
Tabarja, Chekka Highway	Lebanon	Highway (major artery)	Cold recycling w/ foamed bitumen and cement	Dec. 2003	61	60,000	25-year design life; ESAL = 30,000,000
Road between Bucharest & Pitesti	Romania	Motorway	Cold recycling w/ foamed bitumen and cement	May 2003	83	21,450	
Durban	South Africa	Residential arterial & major bus route	In-plant cold recycling: RAP w/ foamed bitumen	Oct. 2003	82	15,000	Major bus route; arterial to large residential area

Cold In-Place—United States							
City/Road Location	**State**	**Road Type**	**Project Type**	**Construction Date**	**Weather (°F)**	**AADT**	**Notes**
Los Angeles County/Jamieson Avenue	California	Residential street	Cold in-place recycling	Dec. 2004	54	338	Paving operation covered one block
Los Angeles County/Elysian Park Road	California	City park road	Cold in-place recycling w/ foamed bitumen and cement	Dec. 2004	60	Not available	City park next to Dodger Stadium
Hwy 20 (PM 10.2 to PM 45.4 - west of Williams)	California	Highway	Cold foam in-place recycling	July 2001	73	5,000	20% = heavy vehicles
Hwy 89 (50 mi NW of Truckee); junctions 89 & 49 to Sierra/Plumas County line	California	Highway	Cold foam in-place recycling	July 2002	68	2,000	10%–15% trucks; 5,500 ft elevation; freeze & thaw conditions
Estes National Park (Hwy 36: Bear Lake Road to Hwy 34)	Colorado	National Park road	Cold in-place recycling w/ foamed bitumen and cement	Sep. 2002	53	4,000	ESAL count is 122 × 120 days = 14,650 ESALs per year; designed for .3 million ESALs
Hwy 30 (west of Ames), shoulder recycling	Iowa	State highway	Cold in-place recycling w/ foamed bitumen and cement	Oct. 2002	40	13,550	Shoulder rehabilitation
Route 8 (between Belgrade Lakes & Smithfield; NE of Augusta)	Maine	Rural route/2-lane highway	Cold foam in-place recycling/foamed asphalt stabilization	Sep. 2001	50	2,300	992,800 ESALs; 20-year design life
Route 138/Richmond (between 197 & 201)	Maine	Rural route/connector route	Foam mix/recycled RAP	Aug. 2004	60	985	Recycled RAP demonstration project
Helena National Forest (280 Lakeside to Nelson Road)	Montana	National Park road	Cold in-place recycling w/ foamed bitumen and cement	June 2004	55	2,660	
Tyler District/adjacent to Road 69	Texas	Interstate highway	Cold mix plant recycling RAP w/ foamed bitumen	Aug. 2000	78	24,000	

Full-Depth Reclamation							
City/Road Location	**State/Province/Country**	**Road Type**	**Project Type**	**Construction Date**	**Weather (°F)**	**AADT**	**Notes**
Inter City Express (ICE) high-speed rail line (Cologne to Frankfurt)	Germany	Base for rail line	Full-depth reclamation (soil stabilizer)	July 1999	72	Not applicable	Rail line
Tech Cominco Red Dog Zinc Mine	Alaska/USA	Haul road	Foam recycling project (w/ chip seal)	Oct. 2002	31	50	106 miles north of Arctic Circle; 10 years = 26,499,000 ESALs
Canyon de Chelly: lodge access road, Antelope House Overlook, Sliding House Overlook, Massacre Cave Overlook, Mummy Cave Overlook, & Ledge Ruin Overlook (17.6 lane miles)	Arizona/USA	National Park road	Cold recycling w/ foamed bitumen and either 2-in. overlay or chip seal	March 2003	25	2,470	
Los Angeles County/Mount Lee Drive	California/USA	Access road above "Hollywood" sign	In-situ recycling w/ foamed bitumen; slurry seal finish	Aug. 2003	74	Not available	At time of construction, light vehicles and six heavies per day (1.2 ESAL per heavy); road is now currently restricted from any public access; maintenance vehicle access only
Canal Road, San Luis & Delta - Mendota Water Authority; Los Banos	California/USA	The flanking road alongside a canal	In-situ foamed bitumen (w/ single chip seal)	Aug. 2000	61	Not applicable	Lightly trafficked; 50,000 ESALs

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Abbreviations used without definition in TRB Publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETY-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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