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15. Abstract <p>Cold In-place Recycling (CIR) is defined as a rehabilitation technique in which the existing pavement materials are reused in-place without the application of heat. The reclaimed asphalt pavement (RAP) material is obtained by milling, planning, or crushing the existing pavement. Virgin aggregate or recycling agent or both are added to the RAP material which is then laid and compacted.</p> <p>The objectives of this study are:</p> <ol style="list-style-type: none">1. To review the literature and survey practices related to the cold in-place recycling (CIR) of asphalt pavements in the northern tier states and provinces in the U.S. and Canada.2. To identify key practice, design, construction, monitoring, and research issues related to CIR of asphalt pavements in North Dakota and address the information needs of North Dakota DOT. <p>The study will entail the following tasks:</p> <p>Task 1: Confer with RAC regarding revised proposal and finalize the budget and scope.</p> <p>Task 2: Do state-of-the art literature review related to CIR of asphalt pavements in the northern-tier states in the U.S. and Canadian provinces neighboring North Dakota.</p> <p>Task 3: Interview key people in northern-tier states in the U.S. and Canadian provinces neighboring North Dakota involved in cold in-place recycling of asphalt pavements.</p> <p>Task 4: Using the gathered information and interaction with North Dakota DOT personnel; highlight and address, to the extent possible, all the relevant design, construction, monitoring, and research issues related to the use of cold in-place recycled asphalt pavements in North Dakota.</p> <p>Task 5: Develop a final report documenting the literature review, survey findings, and issues related to the potential applicability and usefulness of CIR pavements in North Dakota.</p> <p>Task 6: Executive Presentation to North Dakota DOT RAC in November 2002.</p> <p>While cold asphalt pavement recycling technologies are well established, there is still a need for additional performance information, particularly with regard to creep (rutting resistance), fatigue endurance, and durability. Further investigation is also needed to evaluate the ability of cold in-place recycled mixes to perform on higher traffic volume roadways.</p>			
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UNIVERSITY OF NORTH DAKOTA

Grand Forks



A State-of-the-Art Review of Cold in-Place Recycling of Asphalt Pavements in the Northern Plains Region

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EXPERIMENTAL PROJECT REPORT

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	EVALUATION FUNDING					NEEP NO.	PROPRIETARY FEATURE?
	48	1 X	HP&R	3	DEMONSTRATION		Yes
		2	CONSTRUCTION	4	IMPLEMENTATION	49	No X
SHORT TITLE	TITLE 52 A State-of-the-Art review of Cold in-Place Recycling of Asphalt Pavements in the Northern Plains Region						
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KEY WORDS	KEY WORD 1			KEY WORD 2			
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CHRONOLOGY	Date Work Plan Approved	Date Feature Constructed:	Evaluation Scheduled Until:	Evaluation Extended Until:	Date Evaluation Terminated:		
	05 - 2002				07- 2003		
	277	281	285	289	293		
QUANTITY AND COST	QUANTITY OF UNITS (ROUNDED TO WHOLE NUMBERS)		UNITS			UNIT COST (<i>Dollars, Cents</i>)	
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EVALUATION	CONSTRUCTION PROBLEMS			PERFORMANCE			
	1	NONE		1	EXCELLENT		
	2	SLIGHT		2	GOOD		
	3	MODERATE		3	SATISFACTORY		
	4	SIGNIFICANT		4	MARGINAL		
	318	SEVERE		319	UNSATISFACTORY		
APPLICATION	1	ADOPTED AS PRIMARY STD.		4	PENDING		
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REMARKS	321 While cold asphalt pavement recycling technologies are well established, there is still a need for additional performance information, particularly with regard to creep (rutting resistance), fatigue endurance, and durability. Further investigation is also needed to evaluate the ability of cold in-place recycled mixes to perform on higher traffic volume roadways.						

University of North Dakota
Department of Civil Engineering

**A State-of-the-Art Review of Cold in-Place Recycling
of Asphalt Pavements in the Northern Plains Region**

Final Report Submitted to the

North Dakota Department of Transportation
Bismarck, ND

2002

By:

Dr. Nabil Suleiman, Principal Investigator

Grand Forks, ND 58202

Disclaimer

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Finally, the author hopes that NDDOT will continue its research educational relationship with the CE department at UND in the future.

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1. INTRODUCTION

BACKGROUND

Cold In-place Recycling (CIR) is defined as a rehabilitation technique in which the existing pavement materials are reused in-place without the application of heat [28, 2]. The reclaimed asphalt pavement (RAP) material is obtained by milling, planing, or crushing the existing pavement. Virgin aggregate or recycling agent or both are added to the RAP material which is then laid and compacted [3, 23].

Cold in-place recycling can be performed in two ways: full depth and partial depth. In full depth recycling (reclamation or stabilization), both bound (asphalt) and portions of unbound (base, subbase) layers are crushed, mixed with binder, and placed as a stabilized base course. In partial depth recycling, a portion of the asphalt layer, normally between 2 and 4 inches, is used to produce a base course for generally low-to-medium traffic volume highways [23, 2]. With the improvement in cold milling techniques, full depth recycling can now be used to include a substantial portion of underlying unbound materials. As a result, the Asphalt Recycling and Reclaiming Association (ARRA) [3] considers partial depth recycling as cold in-place recycling and full depth recycling as full depth reclamation, which is considered a separate procedure. To follow the ARRA guidelines, this report presents cold in-place recycling as a partial depth recycling method only.

The overall process of Cold in-place asphalt recycling can be summarized as follows [43, 28, 23, 3, 34]:

1. Old asphalt pavement milled (typically 3 to 4 inches) and sized (crushing/screening) to minus 1 ½ in (some agencies specify minus 1 in);
2. About 1.5% emulsion added (typically polymer modified high float emulsion for early strength advantage) along with water to give a total emulsion a moisture content of about 4.5% (some agencies specify 4.0%);
3. About ½ to 2 hours cure/aeration time after placement, compaction is done with a large rubber tired roller (typically 28 tons) followed by a vibratory steel drum roller (typically 12 tons);

4. Curing and traffic compaction time of 10 to 14 days (moisture content less than 2% and 96% compaction); and
5. Placement of a wearing surface, typically a 1 ½ to 2 in hot mix asphalt (HMA) overlay (some agencies specify a surface treatment for less than 1,000 average annual daily traffic, AADT).

PROJECT SELECTION

Project selection is among the most important factors in assuring the success of a cold in-place recycling project [2]. The selection process should include an assessment of existing pavement conditions; sampling and testing of the old asphalt pavement, base, sub-base and subgrade materials; and a study of the pavement's construction and maintenance history, and traffic conditions [2, 30, 44, 46]. In addition, the assessment process should include an evaluation of the potential risk involved of the pavement not supporting the cold recycling equipment and traffic through construction until the new asphalt surface is applied [2].

Pavement Condition Evaluation

Although most types of pavement distress can be rehabilitated by cold in-place recycling; but cracked pavements with structurally sound, well-drained bases and subgrades are the best candidates [2, 3, 20, 23, 30]. Thus, old oxidized asphalt pavements with fatigue cracks, thermal cracks, reflection cracks, rutting due to unstable mix, shoving, and raveling all can be successfully recycled using CIR [2, 28, 30, 41].

However, not all pavements are good candidates for CIR. Among the pavement distresses that are less successful if corrected with CIR are [2, 30]:

- Rutted pavements caused by too high asphalt content;
- Failure caused by wet, unstable base, sub base, or subgrade;
- Failure caused by heaving or swelling occurring in underlying soils; and
- Pavements that exhibit stripping of the asphalt from the aggregate.

In addition to pavement distress issues, several other existing conditions warrant special consideration when using cold in-place recycling that includes the following:

- The presence of several manholes or drainage inlets within the pavement area;
- Long steep grades or those exceeding 5% and 2500 ft in length will reduce production

and may require extended traffic control;

- Extensive heavily shaded areas where little or no sunlight reaches the pavement will require longer curing times;
- The minimum asphalt pavement thickness to be cold recycled should be 2 inches; and
- Addition of new gravel to the RAP to obtain the minimum treatment depth should not exceed 25% by weight of the RAP. Otherwise, a significant increase in emulsion content, thus higher associated cost will occur.

Some other considerations in deciding whether a project is a good candidate for cold recycling include the project size, pavement and shoulder width and traffic volumes and congestion. Projects of 48,000 yd² or more are the most economical but some smaller size jobs may be feasible. For smaller projects, the distance for mobilization, proximity of other jobs, and the cost for other rehabilitation methods must be evaluated when determining the feasibility of cold in-place recycling.

Traffic Considerations

Cold recycling projects have been successfully completed on various highway classifications, ranging from very low-volume rural county roads (<400 ADT) to interstate highways with heavy truck traffic (>3,000 ADT) [2]. However, maintaining traffic through or around the construction zone needs to be a major consideration on certain roads or highways with limited shoulder width and/or few alternate bypass or detour routes.

Testing for Project Evaluation

After the initial assessment of a pavement's suitability for cold recycling, sampling of the pavement should be conducted. Pavement samples obtained by coring and/or milling at a minimum of one every 1 mile per lane will establish pavement thickness and any stripping problem, if existing. Also, the samples can be solvent-extracted to determine the asphalt content and aggregate gradation and penetration and viscosity of the recovered asphalt. This information assists in determining the correct type and amount of asphalt emulsion, and whether corrective aggregate should be added to improve the gradation or adjust the binder content.

Historical project records can provide useful information such as the asphalt mix type

and thickness, type and gradation of aggregate and type and thickness of base and sub-base materials. An investigation and testing of the strength of granular base and sub-base, when present, and sub grade are recommended. A Dynamic Cone Penetrometer (DCP) can be used to determine the in situ California Bearing Ratio (CBR) of the materials underlying the asphalt pavement at the same time as the pavement cores are obtained. Some highway agencies are conducting nondestructive deflection testing to determine the overlay thickness that includes using the Falling Weight Deflectometer (FWD).

MOTIVATION AND BENEFITS

The use of cold in-place recycling can restore old cracked pavements to the desired profile, rejuvenate aged asphalt pavements, correct poor aggregate gradations, eliminate existing wheel ruts, restore the crown and cross slope, and fix irregularities and rough areas [10, 23, 36]. It can also eliminate transverse, reflective, and longitudinal cracks [2, 28]. Some of the major reasons for the increased use of cold in-place recycling are the increased scarcity of materials, particularly gravel and crushed rock, the method's high production rate and potential of cost savings, minimum traffic disruption, ability to retain original profile, reduction of environmental problems, and a growing concern for depleting petroleum reserves [2, 9, 23].

OBJECTIVES

The objectives of this study are:

1. To review the literature and survey practices related to the cold in-place recycling (CIR) of asphalt pavements in the northern tier states and provinces in the U.S. and Canada.
2. To identify key practice, design, construction, monitoring, and research issues related to CIR of asphalt pavements in North Dakota and address the information needs of North Dakota DOT.

SCOPE

The study will entail the following tasks:

- Task 1: Confer with RAC regarding revised proposal and finalize the budget and scope.
- Task 2: Do state-of-the art literature review related to CIR of asphalt pavements in the northern-tier states in the U.S. and Canadian provinces neighboring North Dakota.
- Task 3: Interview key people in northern-tier states in the U.S. and Canadian provinces neighboring North Dakota involved in cold in-place recycling of asphalt pavements. The targeted interviewees could be State/Province DOT personnel, contractors, material suppliers, researchers, and others. The purpose of the interviews and surveys would be to solicit information not readily available in published or documented literature or information, which may require further explanation. In particular, data, procedures, and practices related to CIR pavements will be collated. The collected data may include traffic data such as average daily traffic (ADT), equivalent single axle loads (ESALs), percent truck in the traffic stream (% truck), and others.
- Task 4: Using the gathered information and interaction with North Dakota DOT personnel; highlight and address, to the extent possible, all the relevant design, construction, monitoring, and research issues related to the use of cold in-place recycled asphalt pavements in North Dakota.
- Task 5: Develop a final report documenting the literature review, survey findings, and issues related to the potential applicability and usefulness of CIR pavements in North Dakota.
- Task 6: Executive Presentation to North Dakota DOT RAC in November 2002.

2. CIR DESIGN METHODS

Currently, there is no universally accepted or standardized mix design method, structural design method, laboratory testing procedures, or quality control specifications for Cold In-Place Recycling [3]. However, most agencies that use CIR have their own design procedures and specifications.

MATERIAL EVALUATION

The material evaluation phase for cold in-place recycling consists of sampling and testing of RAP materials, corrective aggregates, and recycling additives [20, 28]. Material from the existing pavement must be sampled in a systematic way to obtain representative samples. The important properties of the reclaimed asphalt pavement (RAP), which could affect performance of the recycled mix, should be determined to ensure proper selection of new asphalt binder and virgin aggregates, if required [2, 3, 23, 28].

Field Sampling and Material Testing

Using the information gathered during the field investigation, the CIR project is divided into relatively homogeneous sections. At least five or six locations for sampling have been suggested by some researchers [23], whereas others suggest a minimum of five samples per mile or one per block in city work [4]. A representative sample (approximately 100 lbs) of the in-place bituminous material is extracted from the pavement in each section. Samples are extracted from the pavement with coring machines or with a small milling machine. Bituminous materials obtained from cores, crushed in the laboratory or with the train crusher, provide a more representative sample of the bituminous aggregate produced in the field with CIR equipment than does bituminous aggregate obtained from a small milling machine [43]. The small milling machine tends to pulverize the material more, producing samples with more fines.

The laboratory work conducted on the bituminous aggregate field sampling may include the following tests [2, 43, 46]:

- moisture content (if dry coring has been used)

- gradation of the crushed RAP
- asphalt binder content
- aggregate properties including gradation, angularity, etc.
- recovered asphalt binder properties including penetration, absolute and/or kinematic viscosity, and perhaps Superpave PG grading for research projects if possible.

This information will assist in the selection of the type and amount of liquid recycling additive and with determining whether or not new granular materials are needed to improve the characteristics of the RAP or are needed to address a deficiency in the original asphalt pavement such as flushing, etc. The field samples may be examined for evidence of binder stripping from the aggregate to determine if an anti-stripping agent is required [2, 4, 20].

New (or Corrective) Aggregate

Corrective aggregate may be required to strengthen the mineral skeleton of the mixture and/or to lower the binder content [20]. New aggregates may be required to satisfy the gradation requirement or structural improvement of the recycled mix [20]. Gradation of the RAP (as received from milling or crushed from cores), may not meet the specification requirements for the intended recycled course such as base course and binder course. The RAP gradation is affected by the fines generated due to milling and pulverization, or contamination from the underlying layers or due to degradation by traffic (conglomeration of fine particles under traffic densification forming coarse angular particles) [20, 49]. In some cases, RAP may consist of sand-asphalt mix. In such cases, the recycled mix gradation can be made coarse by adding new aggregate [2, 3].

Additional aggregate may also be needed to increase the structural capacity of the pavement by increasing its thickness. This may be required by increased traffic loading. New aggregate may also be needed to improve recycled mix properties such as stability, durability, or workability [3, 23].

The gradation of the selected new aggregates should be determined by sieve analysis (AASHTO T 27-93) [2, 28]. The new aggregate and the RAP material must be combined in proportions to meet the specified gradation [28].

Recycling Additives

Only a very small amount of new bitumen can be added to a bituminous aggregate before the new material becomes too rich and unstable. Consequently, the success of a CIR project is highly dependent on the performance of a relatively small amount of virgin bitumen. The selection of a bitumen emulsion is based on the following requirements [1]:

- Adequate softening of the old bitumen;
- Proper coating of both the bituminous aggregate and the added virgin aggregate;
- Sufficient cohesion and adhesion at an early age to prevent raveling under traffic and to resist rainfalls; and
- Insensitivity to small variations in emulsion content.

The additives generally used for cold recycling are asphalt emulsions and emulsified recycling agents (ERAs). The types of asphalt emulsions most used have been cationic medium setting (CMS) and anionic medium setting, usually high float (HFMS) [2, 18, 28]. Some of these emulsions have been polymer modified. Slow setting asphalt emulsions, usually CSS-1 or CSS-1h, are used occasionally.

A few state highway agencies also are using Portland cement or class C (self cementing) fly ash to increase mixture early strength and resistance to rutting and water damage [27, 46]. Hydrated lime slurry is being used in combination with asphalt emulsion to produce cold recycled mixtures with higher early strength and greater resistance to water damage [17, 45]. Besides the properties of the RAP, availability, cost and performance must be considered when selecting the type of additive [23, 28].

BITUMINOUS MIX DESIGN

Despite the lack of a unified method for designing cold in-place recycled asphalt pavements, several agencies [2, 3, 4] have developed general design methods for CIR mixes based on modifications to hot-mix asphalt methods. Such methods can serve as a starting point for developing CIR mix design methods for specified conditions or climatic regions. However, mix design is for field guidance, as it will be necessary to continuously monitor the process and recycled mix and make emulsion and water content adjustment, as necessary, to produce the desired in-place cold mix [3, 43].

General Mix Design Procedures

The Asphalt Institute has recommended a modified Marshall mix procedure for the design of CIR mixes [6]. Such a design initially involves obtaining samples of the candidate pavement to determine the gradation of the aggregate, the asphalt content, and the penetration and viscosity of the asphalt binder [32]. American Association of State Highway and Transportation Officials/the Associated General Contractors of America/American Road and Transportation Builders Association (AASHTO-AGC-ARTBA) Joint Committee Task Force 38 Report [2] contains modified mix design procedures for both Marshall (ASTM D-1559 or AASHTO T-245) and Hveem (ASTM D-1560 and D-1561 or AASHTO T-246 and T-247) test methods. There is also research underway to adopt Superpave technology to CIR mixtures [19, 37, 38]. The main steps in CIR mix design are [2, 3, 4, 12, 20, 23, 28, 30, 36, 43, 46]:

1. Obtain Samples of Rap from the field;
2. Determine RAP gradation, RAP binder content, gradation of extracted aggregate, and aged binder;
3. Select amount and gradation of additional granular material, if required;
4. Select type and grade of recycling additive;
5. Estimate recycling additive demand;
6. Determine pre-mix moisture content for adequate coating;
7. Test trial mixtures: initial cure properties, final cure properties, and water sensitivity;
8. Establish job mix formula; and
9. Make adjustments in the field.

CIR mix design serves as an initial job mix formula, the same as in hot mix asphalt (HMA) construction. Adjustments are generally required for workability, coating, and stability [3]. Most mix design methods for CIR mixes involve the application of asphalt emulsions, emulsified recycling agents or cutbacks as the recycling additive although foamed asphalt and chemical recycling additives have also been used [23, 24, 35, 43].

Three basic theories have been proposed for designing CIR mixes with these recycling additives [2]. The first theory assumes that the RAP will act as a black aggregate and the mix design consists of determining a recycling additive content to coat the aggregate.

The second theory evaluates the physical and chemical characteristics of the recovered asphalt binder and adds a recycling agent to restore the asphalt binder to its original consistency. The assumption is that complete softening of the old asphalt binder occurs. The third and most prevalent theory is a combination of the first two, where some softening of the old asphalt binder occurs. This theory is referred to as the **effective asphalt theory**, where the recycling additive and the softened aged asphalt binder form an effective asphalt layer. The degree of softening is related to the properties of the old asphalt binder, recycling additive, and environmental conditions. Because the degree of softening is difficult to quantify, it is recommended that mechanical tests on the CIR mix be a part of all mix designs [2, 20, 45].

Emerging CIR Mix Design Methods

Recently, many mix design methods have emerged in an effort to improve the CIR process as a viable method for pavement rehabilitation. Reviews of the modified Marshall and Oregon State Mix design methods, modified Superpave Mix design methods, and Koch's ReFlex system for CIR are discussed below.

Modified Marshall and Oregon State Mix Design Methods

A cold in-place recycled asphalt mix design approach has been adopted based on a cold Marshall and Oregon State methods [2, 3, 32, 43], including the important role of water, on a laboratory scale. A key preliminary step in the mix design is obtaining representative RAP samples of each section and determining the properties of these samples (moisture content, asphalt cement content, gradation and Abson recovery asphalt cement penetration and viscosity) [10, 17, 38]. The steps in the mix design procedure, which reflect the Marshall method and Ontario Ministry of Transportation (MTO) procedures for preparing cold in-place recycled mix briquettes and selecting the optimum emulsion addition level, are summarized and displayed in [Appendix A].

The overall testing and design procedure for cold in-place asphalt recycling of the Ontario study [43] involves the six steps:

1. Evaluating the pavement section for suitability;

2. Determining the properties of representative processed reclaimed asphalt pavement (RAP) for the section;
3. Preparing briquettes with a range of emulsion contents using the “cold” Marshall mix design method;
4. Testing the briquettes for air voids, stability and flow;
5. Selecting the optimum emulsion (and water) conditions in terms of air voids, stability and coating; and
6. Completing quality control and testing during recycling of the section.

Modified Superpave Mix Design Methods

A pilot volumetric mix design using the Superpave Gyratory Compactor (SGC) was performed for the Kansas and Ontario RAPs [38]. The method is based on the Task Force #38 modified Marshall Mix design method [2] with some adjustments. The optimum emulsion content (OEC) can be obtained using this method.

Mix design guidelines for a CIR project in the Regional Municipality of Ottawa-Carleton (RMOC) of Ontario were developed [37]. The Superpave Gyratory Compactor (SGC) was used in that study to produce field representative specimens. Cores were obtained and evaluated to project field conditions and adjust the number of Gyration. The N_{design} or N_{max} for the RMOC study was then determined [37].

In another study [19], the mix design compactive effort (N_{design}) that is needed to match the field density of CIR mixtures using the SGC was determined. The study included RAP from seven CIR projects along with the emulsified asphalt cement for each project. The laboratory testing protocol included testing the RAP and aggregate properties, compaction of samples, permanent deformation, and indirect tensile strength. Moreover, the N_{design} was determined to be between 30 and 35 gyrations.

Koch Reflex CIR Design Method [24, 34]

Reflex is a new mix design protocol that includes a new chemistry emulsion formulated for cold recycling, an engineered design procedure and four performance tests for raveling, rutting resistance (strength), thermal cracking resistance, and moisture susceptibility

(stripping). Additionally, early strength is tested in the field, and laboratory evaluations of Reflex mixes show that the higher asphalt contents lead to longer durability.

The Reflex system uses the Marshall Stability test for rut resistance; a retained stability test for moisture (or stripping resistance), a raveling test, and an indirect tensile test for low-temperature cracking. Three different gradations: coarse, medium, and fine are used in the design procedure and adjusted in the field.

Traditional CIR has suffered from long curing times. The improved chemistry of the solventless ReFlex CIR-EE emulsion was developed to set up very quickly. Normally, the ReFlex recycled pavement is ready for compaction within minutes. The strength is determined in the field using a Humboldt GeoGauge. Early strength means construction moves more quickly, and the road can be opened and resurfaced in two to seven days [33, 34] compared with at least two weeks using conventional CIR pavements.

STRUCTURAL DESIGN

Currently, there is no universally accepted structural coefficient for CIR [20]. The structural capacity of CIR material is dependent on the nature of the in-place bituminous material, the added binder and the curing time [2, 3, 28]. Most US road agencies assume that the structural capacity of the recycled mixture is equivalent to standard hot bituminous mixtures [20, 23, 28]. AASHTO layer coefficients between 0.25 and 0.40 are assumed by other agencies without differentiating between full-depth reclamation (FDR) and standard CIR [23]. The State of California assumes a gravel base equivalency ranging from 1.5 to 2.5 without differentiating between FDR and standard CIR [23]. Table 2.1 displays some of the structural coefficients as reported by various agencies [23, 24, 26, 33].

Most cold recycled mixtures are used as an intermediate layer for the rehabilitation of asphalt pavements but also may be used as the base course when constructing a new pavement [2]. Whatever the application, pavement structural or thickness design is recommended. Besides the laboratory preparation and testing of cold recycled mixtures for structural design, nondestructive deflection testing of existing pavements, most recently with the FWD, is being used to determine the overlay or surface course thickness required when cold recycling [2, 20, 22, 28, 29, 34, 40].

Table 2.1 Structural coefficients and gravel equivalencies for CIR projects reported by various agencies.

Agency	AASHTO Coefficient		Gravel Equivalent (GE)		Basis of Coefficient
	Range	Representative Value	Range	Representative Value	
AASHTO	0.25-0.40				
California			1.5-2.5	1.5	Pavement deflection
Pennsylvania		0.3			
Purdue	0.25-0.40				Lab tests and pave. deflection
Texas A&M	0.22-0.49	0.39			Lab tests and pave. deflection
ARRA	0.20-0.44	0.30			
Colorado	0.29-0.35	0.30			
New Mexico		0.30			
Ontario [43]			1.8-1.9	1.8	Lab and BISAR software
South Dakota	0.30-0.35		1.4-1.75	1.5	
Kansas		0.30		1.5	

After completion of the mixture design, specimens can be fabricated, normally at the optimum additive content and resulting voids, for determination of cold recycled mixture strength or modulus [2, 23, 28]. Test specimens typically are prepared using the compacting procedures of ASTM D 1559 or AASHTO T 245 and ASTM D 1561 or AASHTO T 246 [2].

A reduction of structural equivalency of up to 40 % may be anticipated for full-depth reclamation when compared to standard CIR [43]. The reason for that is because full-depth reclamation is considered a base stabilization process that includes lower quality materials as well as less compaction effort on thicker layers is usually performed.

New Mexico pavement designers have historically used a structural coefficient of 0.25 for their Cold In-Place Recycled mixtures. This number was assigned several years ago, and New Mexico engineers have recently recommended that 0.30 may be more accurate. Colorado assumes a value of 0.30 for CIR [23, 33].

For a clearer understanding of material properties and the value of recycled pavements, Koch labs have used the Superpave Shear Tester (SST) to test structural coefficients for several projects [24, 33, 34]. Cores taken from a cold in-place recycling job on I-25 in Colorado had structural coefficients ranging from 0.29 to 0.35 [33]. On a job in Wichita, Kansas RAP was mixed cold with Koch XP emulsion at a central plant, transported,

and placed on the roadway. Mixtures from the Kansas project were tested to have a structural coefficient of approximately 0.41 [33]. It should be noted that a cold mix gains strength as it cures and ages. The values given here are on fully cured (typically 100 days) recycled mixtures [30, 33, 34]. However, in designing pavements, stiffness isn't everything. Flexibility and water durability should also be considered [28, 34].

The granular base equivalency (GBE) of cold recycled material has previously been conservatively assumed to be 1.4 or 1.5 based on limited experience. It was considered important to establish the appropriate GBE for cold recycled binder course from a range of Ontario cold in-place asphalt recycling projects completed since 1991 [14, 43]. This was done by determining the resilient moduli (MR) of cold recycled binder course and asphalt concrete binder course core samples in the Nottingham asphalt Tester (NAT) and then using these resilient moduli in the BISAR mechanistic design analysis procedure to determine the comparative GBE. Gravel equivalencies for different CIR structures as reported by various agencies were also displayed in Table 2.1.

3. CONSTRUCTION PROCESS AND EQUIPMENT

The recycling train is one of the most important innovations in pavement recycling technology. Different types of CIR trains with different equipment configurations are available to better fit the various needs of the CIR construction process [2, 3, 20, 28].

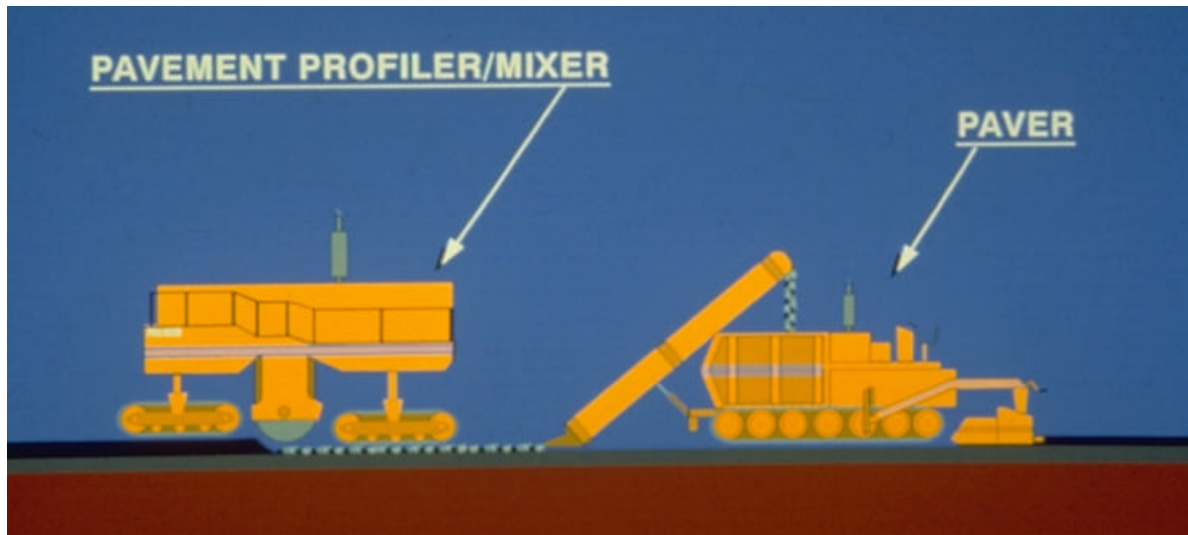
In the CIR process, the old pavement is milled, then crushed and screened to size, and ultimately mixed with a liquid recycling agent as well as new aggregate and other additives, if needed. A paver following the CIR train lays the cold mix, and it is compacted as soon as the emulsion recycling agent breaks and sets up, releasing the moisture from the mix (usually 15 to 90 minutes after paving) [2, 3, 20, 28, 36]. The process is completed with the laying of a wearing surface over the CIR mix (usually at least 1.5 inches of hot-mix asphalt), though low-traffic-volume roads sometimes are treated with chip seals [3, 36].

RECYCLING EQUIPMENT

Cold-in-place recycling trains range in size and sophistication. They differ from one another by how the RAP is removed and sized, how the recycling additives and modifiers are added, how they are mixed and controlled, and how the resultant mix is placed [3, 20, 30, 43]. Generally, recycling trains consist of single-unit, two-unit, and multi-unit trains.

The traditional single-unit train is based on a machine that mills the pavement to the specified depth and cross slope, sizes the recycled asphalt, and blends the recycling additive [2, 3, 28, 34, 36]. One of the unique features of the single-unit recycler is the use of a down-cutting milling head (most mills cut on the up cycle) [20, 36]. The down-cutting milling head lets the operator control RAP size by adjusting the forward speed of the machine [2, 20, 36].

Some examples of single-unit trains are shown in Figures 3.1 through 3.4. Figure 3.1 shows a single machine which basically consists of a paver mixer. RAP is added to the machine either by cold milling (by a milling machine) or by a dump truck. Virgin material, if required, is spread on existing surface ahead of the recycling equipment. One pass of this machine is sufficient to mill, pulverize, add recycling agent and lay down. The recycling agent is added in the milling chamber of the paver-mixer.



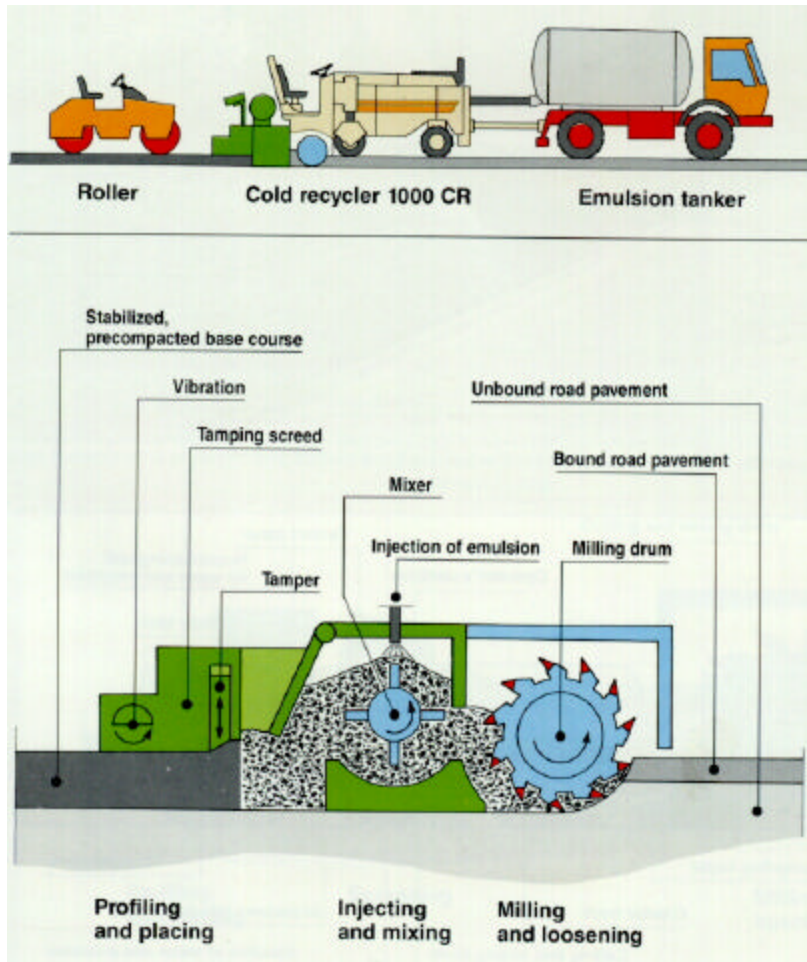
(a)



(b)

Figure 3.1. A paver-mixer single-unit machine.

More sophisticated single-unit trains (see Figure 3.2) use a self-contained CIR machine that mills, screens the recycled asphalt, crushes oversized particles, blends the recycling additive and the mix in a pugmill, and finally pre-compact it with a screed. [2, 3, 28, 36].



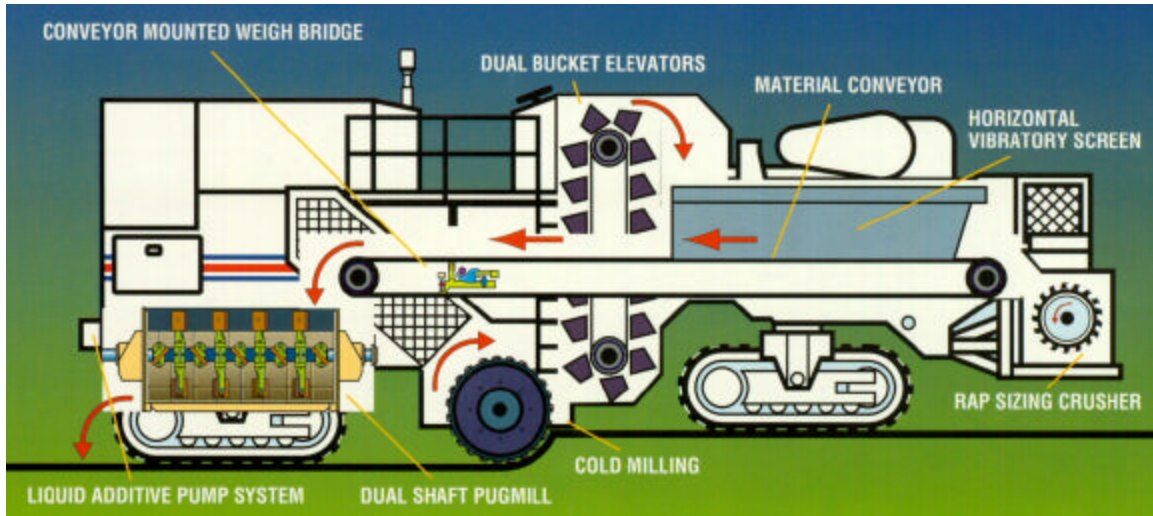
(a)



(b)

Figure 3.2. A self-contained CIR single-unit machine.

In another type of single machine (Figure 3.3), the existing material is milled, mixed with recycling agent, and deposited in a windrow. The recycled material is picked up by a paver which lays it down and pre-compacts it with a screed. An emulsion tanker is used with this type of machine.



(a)

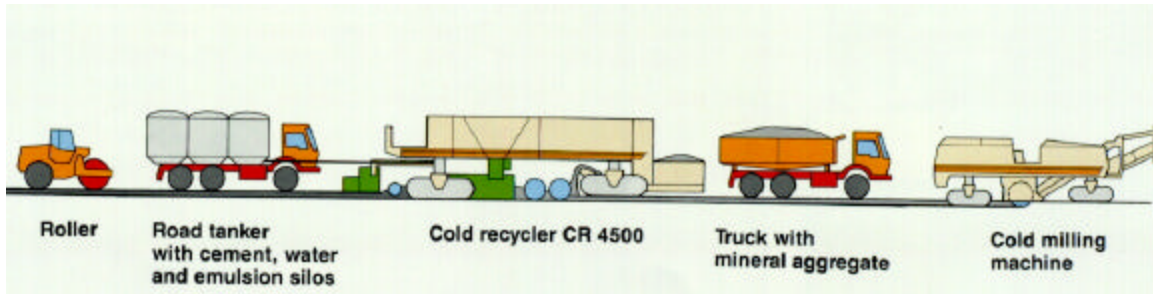


(b)

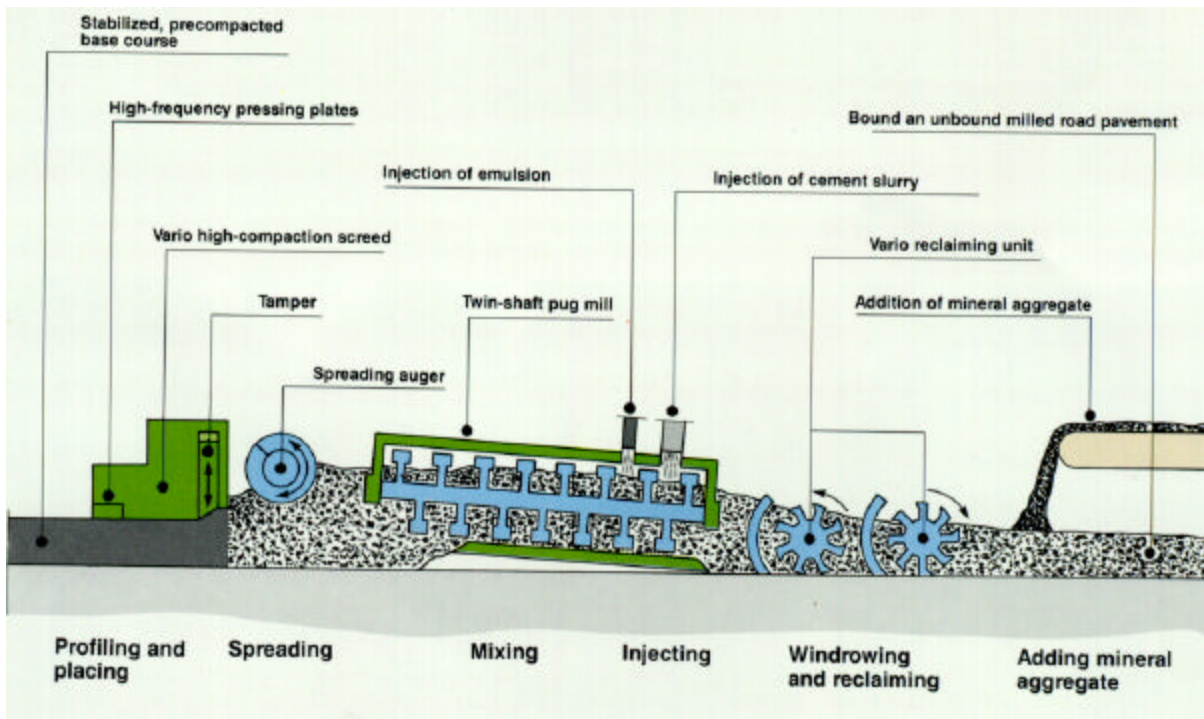
Figure 3.3. A single-unit machine deposits RAP in a windrow

Figure 3.4 shows a schematic of the equipment which is used if virgin aggregate is needed to modify the existing material. A truck with virgin aggregate is positioned in

between the cold milling machine and the single machine. In this case the emulsion tanker generally follows the single machine. The single machine injects recycling agent on the mixed virgin aggregate and existing material, spreads the recycled mix, and pre-compacts with a screed.



(a)



(b)

Figure 3.4. Single unit train CIR with addition of new aggregate.

A two-unit train links the milling machine with a pugmill mix-paver which blends the recycling additive and places the mix; this process adds precision to the injection and mixing of the recycling additive [20, 28, 36].

Single-unit and two-unit trains are often deployed in municipal areas because their compact dimensions are less intrusive than the multi-unit trains. Single-unit trains measure about 70 feet in length, while multi-unit trains can stretch 150-feet long or more [3, 28, 36].

Multi-unit trains are designed for high production and optimum process control. They have separate machines for milling, screening and crushing, and mixing; providing more control over the size of the recycled asphalt than the other methods [2, 20, 30, 36]. A schematic of a multi-unit train is shown in Figure 3.5. The different machines are shown in Figures 3.6 through 3.9 [28].

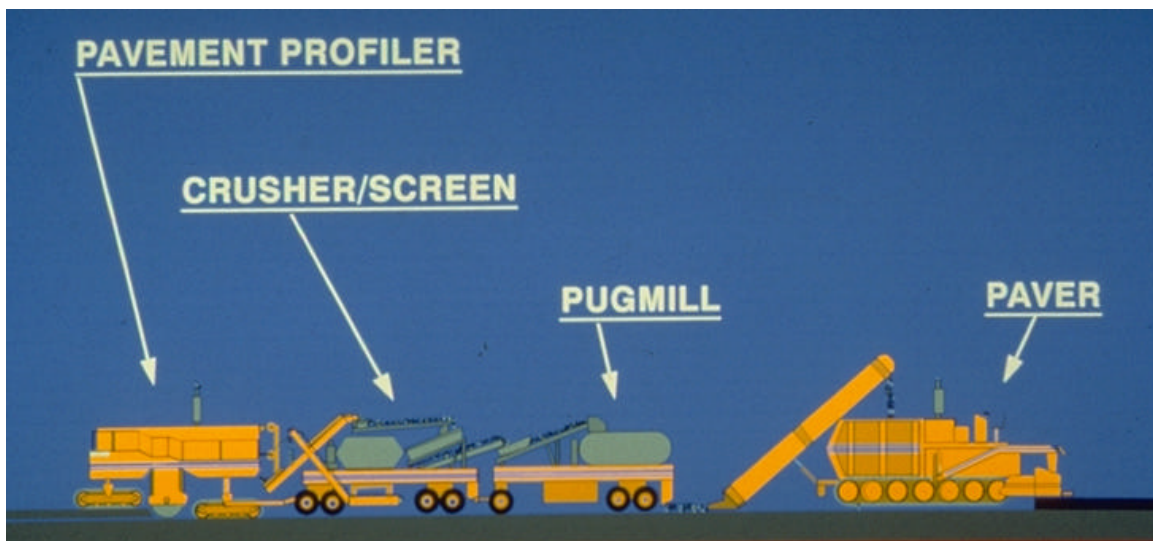


Figure 3.5. A schematic of a multi-unit recycling train.



Figure 3.6. Portable crusher attached to cold-milling machine.



Figure 3.7. Cold-milling machine.



Figure 3.8. Travel-plant mixer.



Figure 3.9. Laydown machine.



Figure 3.10. An overview of the recycling units of a multi-unit train.

Moreover, the crushing and screening unit on the multi-unit train crushes and screens the oversized material from the milling machine, and deposits the processed material into a pugmill, where the recycling agent is added [20, 36]. After mixing, the material is either deposited onto the hopper of a self-propelled laydown machine, or deposited in windrow [2, 3, 20, 28, 36, 43]. If the mix is placed on a windrow, it is then picked up by a paver for laydown. Moreover, Figures 3.10 and 3.11 show an overview of the recycling units in action.



Figure 3.11. A multi-unit recycling train in action.

CONSTRUCTION PROCESS

Cold In-place recycling consists of the following steps [2, 3, 20, 23, 28, 43]:

- Preparation of the construction area;
- Milling or reclaiming the existing bituminous concrete pavement;
- Crushing and sizing the reclaimed pavement into a calibrated bituminous aggregate;
- Addition of a corrective aggregate if required;
- Addition of a new binder;
- Mixing of all the components;
- Laydown of the new mixture;
- Aeration of the mixture;
- Compaction of the mixture;
- Curing of the mixture; and
- Application of a wearing course.

Preparation of Construction Area

Prior to construction, areas of non-uniform materials, non-uniform pavement thickness, insufficient pavement thickness, or inadequate subgrade strength to support the weight of the recycling train should be identified [3, 20, 28]. These areas of insufficient

support must be corrected prior to recycling or risk the CIR equipment breaking through the pavement, causing construction delays and added expense [23, 28]. Weak or frost susceptible material should be removed and replaced with suitable patching material.

RAP is an excellent choice for patching material. Aggregates may be used, but an increase in the recycling additive for proper coating may be required. Portions of the project that were identified during mix design as requiring different recycling additive content should be identified and construction personnel made aware of the situation [28].

Field Adjustments to Mix Design

Field adjustments are carried out on a continuous basis during a CIR operation to account for the variability of the field conditions [7, 28, 30]. Field adjustments of the emulsion content and of the water content should not exceed $\pm 10\%$ of the job mix formula. Even though the adjustments are relatively minor, they are very important to obtain uniform performance of the mat. When the emulsion content is adjusted, an equal and opposite adjustment is made in the water content and vice versa.

The field adjustments of the water and of the emulsion content are based on the appearance of the mat after the initial rolling. Additional emulsion (during construction) may be required if the mat remains brown or is prone to raveling. Emulsion content may be reduced (also during construction) in the following cases [20, 23, 28]:

- the mat is very black and shiny and no raveling is apparent;
- pushing or rutting of the recycled mixture occurs under traffic; and
- bleeding or flushing arises.

When the material looks wet and cannot be compacted, the water content may have to be reduced. Water may be added when the mixture looks dry, when the mixture does not show uniform coating, and when the compacted mat raveling [3, 28].

Laydown (Placement) of Mix

Most cold recycled mixes are placed with conventional self-propelled asphalt pavers. The recycled mix is either deposited in a windrow and picked up with a windrow elevator or deposited directly into the paver hopper. It is normally specified that the paver be equipped with automatic screed controls for both longitudinal grade and cross slope control [2, 3, 28].

Due to the coarseness or larger size particles in many of the cold recycled mixes, the recommended minimum lift thickness for placement is 2 inches. Also, this thickness is recommended to prevent slippage over underlying pavement. When fly ash is used, the minimum thickness should be not less than 4 to 6 inches [2, 28].

Because cold recycled mixes are stiffer than hot mix asphalt, proper operation of the paver is even more important to achieving good mat uniformity and smoothness [2, 3, 20, 28]. Also, cold recycled mixes generally have higher amounts of coarse material that requires care in placement to prevent segregation. The placement of cold recycled mixes with emulsions is generally limited to a maximum lift thickness of 4 inches but has been up to 6 inches with fly ash [2, 3, 20, 28, 36, 43].

Either conventional asphalt pavers or cold mix pavers are used to place the mix. Some contractors use pavers with oversize hoppers to allow for RAP surges caused by fluctuations in the existing pavement section. The screed should be operated cold as a heated screed causes RAP to stick, tearing the mat, and will not promote extra density or reduced breaking time. The laydown machine should be operated as close to the milling machine as possible, reducing the fluids necessary for placement and the aeration time required before compaction [2, 3, 28].

Compaction

The rolling equipment normally used for compaction is a large pneumatic-tired roller of 25 tons or more and a double drum vibratory roller of 12 tons or more [2, 3, 28]. When an asphalt emulsion or ERA is the additive, the breakdown or initial rolling may be with either type of roller. However, for stiff mixes placed in a lift thickness of 3 inches or greater, breakdown with a large pneumatic-tired roller may prove to be most effective in achieving density [2, 3, 28].

The delay time between mix placement and the beginning of rolling depends upon a number of factors that include type of recycling additive and the rate of moisture loss or evaporation [2, 3, 28]. With asphalt emulsions, breakdown rolling normally does not begin until the emulsion begins to break or change from a brown to a black color. The delay typically is from 1/2 to 2 hours depending on the type of emulsion; cold recycle lift thickness; and curing conditions of temperature, humidity, and wind [2, 3, 28, 34]. With

Portland cement and fly ash the additive, breakdown rolling begins immediately after placement and all rolling are completed as soon as possible and before the mix sets up [2, 3, 16, 21, 28]. A set retarder is usually necessary with Class C fly ash to allow sufficient time for proper placement and compaction [2, 3, 15, 16, 28].

In the cold recycling process, the contractor has no control over the existing pavement conditions, such as the firmness of underlying materials. If the base were wet and soft, then it could be very difficult or even impossible to achieve a specified minimum laboratory density (usually 96%) [2, 3, 28, 34]. Therefore, with this condition, field control strips have been utilized and are necessary for density control [2, 3, 28].

Curing

A certain time period is necessary to allow the recycled mixture to cure and build up some internal cohesion before being covered with a wearing course [2, 3, 28]. A time period of 14 days is typically specified [2, 3, 20, 28, 43]. Low moisture content may be a criterion to evaluate the curing of the mixture. However, such a criterion may be misleading because the moisture content is increased by rain. The material may have built up adequate internal cohesion, but rainfalls may have maintained the moisture content at a high level, incorrectly suggesting that the mixture has not sufficiently cured. As a rule of thumb, whenever a complete core can be extracted from the mat relatively easily, the material has built up enough internal cohesion to be covered [2, 3, 28].

Wearing Course Selection

Due to the high voids in total mix (VTM) content, CIR mixes need a wearing surface to protect the mixture from intrusion of surface moisture [3, 4, 28]. For pavements with low traffic volumes (i.e. <400 ADT), single and double chip seals have been successfully employed [3, 4, 28]. For pavements with higher traffic volumes (i.e. >400 ADT), conventional HMA wearing surfaces has been used. A tack coat should be applied at a rate similar to the fog seal, to promote good bond between the CIR layer and the HMA overlay [3, 4, 28].

The minimum recommended HMA overlay thickness is 1 inch with 1 1/2 inches preferred [2, 3, 4, 23, 28]. Thin HMA lifts are hard to adequately compact and a poorly

compacted surface mix will not protect the CIR from moisture intrusion. The thickness of the HMA overlay should be based on the traffic level and existing roadway strength [1, 2, 3, 28]. Some agencies use the Falling Weight Deflectometer (FWD) to evaluate the pavement section prior to designing the thickness of the HMA overlay [2, 3, 4, 34]. Others assign a structural coefficient of 0.25 to 0.35 to the CIR layer for use with the 1993 AASHTO Thickness Design Guide [1]. These coefficients are based on resilient modulus testing but each agency will have to develop their own coefficient [1, 3, 4].

SPECIFICATIONS

The current trend in the construction industry is to move away from method specifications, where the owner agency describes in detail how to construct the project, and to move toward end result specifications [2, 3]. With end result specifications, the owner agency tells the contractor what level of performance or end result it expects from the project, and how that performance level will be measured. The contractor then decides how to best meet the performance requirements. The contractor could select construction method and equipment, job mix formula, recycling additives, and construction sequence [2, 3, 23]. At the end of the project, the owner agency would perform testing to assure that the minimum performance level was achieved.

Specifications for CIR vary and cover a large range of topics such as materials, equipment, construction method, compaction, weather conditions, traffic control, and others. For example, specifications of the cured/compacted CIR require a moisture content of less than 2% and compaction of at least 96% of the laboratory density. The moisture content requirement is typically achieved 10 to 14 days after recycling [2, 3, 43]. A complete list of section 5 of the AASHTO's guide specifications is included in [Appendix B].

QUALITY CONTROL AND QUALITY ASSURANCE

With the high production rate equipment involved, potential section variability and sensitivity of the recycled asphalt mix to emulsion content, it is very important that the contractor has a quality control system and make any necessary field adjustments. This then followed by agency quality assurance activities.

To achieve a properly constructed cold-recycled pavement, equipment must be selected, operated, and sequenced to do the following [2, 3, 4, 20, 23, 28, 30, 43, 46]:

- Pulverization of the recycled pavement material;
- Proper water content (uniformly mixed);
- Proper binder content (uniformly mixed);
- Attainment of some minimum specified density;
- Favorable temperature and moisture conditions for strength development during the curing time; and
- Protection of the stabilized surface from traffic to prevent abrasion, and ensure adequate time for strength development.

Quality control and assurance are mostly based on the experience of the contractors and highway agencies. Most guidelines from experienced agencies include [23, 43, 46]:

- Cold in-place recycled layers should not be thicker than 3 to 4 in, because curing can be a problem, nor should they be less than 2 in thick, because of possible segregation during construction;
- Softening of the recycled mix may occur within the first two to three days. Some agencies re-roll the pavement at that time to obtain additional density;
- Initial over-compaction can cause problems. However, several states, including New Mexico and Pennsylvania, do not re-roll their pavements after construction;
- Traffic should not be allowed on the recycled pavement for a minimum of two hours after compaction;
- If raveling occurs under the action of traffic (not related to the mix itself), traffic should be controlled and a finish roller should continue to compact the pavement;
- Rain within 24 hours of construction can cause performance problems;
- Before placing the wearing surface, curing should be allowed to reduce the moisture content to the 1.0% to 1.5% range. In summer, curing time is typically between 7 to 14 days. However, late-season construction can cause performance problems;

- An asphalt wearing course that is placed over the recycled base should be an open-graded mix to allow curing to continue for an extended period of time. A dense hot-mix can trap water;
- Problems with density control are common. Nuclear density devices provide relative numbers. Samples may not be cored without proper curing (which may be one year).

Drawbacks do exist with CIR. There is not yet an established mix design process available, and laboratory tests are yet to be developed, let alone correlated with performance [3, 20, 23, 28, 43]. Quality control is more difficult because of a number of factors that include [2, 3, 20, 23, 28, 43]:

- limited ability to control the gradations;
- changes in the existing asphalt properties, particularly on older roads with patching;
- vulnerability to weather; and
- long curing process for the CIR bituminous layer, even after the initial break.

Typical quality assurance activities may include [2, 3, 20, 23]:

- Testing the emulsion;
- Taking dry cut core;
 - Representative samples,
 - Strength adequate when cutting possible,
- Determining moisture content and thickness;
- Determining bulk density (in-place density);
- Determining recompact (60° C) density of representative recycled mix;
- Reporting;
 - Emulsion test results,
 - Site and sample location,
 - Moisture content and thickness,
 - Bulk and re-compacted density,
 - Percent compaction,
 - Conformance with specifications,

Testing of the hot-mix asphalt overlay may also be involved.

4. CIR PERFORMANCE

Currently, there is no comprehensive nationwide information system on performance of cold in-place recycling. However, some states and agencies have kept performance records of various CIR projects and studies. These case studies or histories are a good source of data for evaluation of CIR performance. Performance here refers to field performance.

PERFORMANCE EVALUATION

Typically, performance evaluation includes both qualitative and quantitative measures to rate performance [20, 26, 47, 50]. The qualitative evaluation measures depend on appearance (visual distress surveys) and ride comfort [21, 39, 43]. The Present Serviceability Index (PSI) rating is often used [1, 47]. The quantitative assessment measure may include pavement condition surveys, Falling Weight Deflectometer (FWD), Dynamic Cone Penetrometer (DCP), and Digital Incremental Profilometer (Dipstick) [14, 20, 21, 22, 23, 24].

The Pavement Condition Index (PCI) is a numerical assessment method that evaluates pavements based on severity of distress [47]. A value between 0 (least favorable) and 100 (most favorable) is assigned to the pavement. Additional deductions are taken as the condition of the pavement worsens. FWD is a non-destructive deflection testing technique to back-calculate the in situ pavement moduli throughout the performance period [21, 48, 49]. It can also check for the adequacy of the HMA overlay thickness. Moreover, the DCP is used to determine the in situ California Bearing Ratio (CBR) of the materials underlying the asphalt pavement at the same time the cores are obtained. Furthermore, the Dipstick is used to measure rut depth [14, 21, 49].

Rejuvenating Effect of the Added Emulsion

The rejuvenating effect depends on our consideration of the old bitumen. One theory considers the aged bitumen as inert; therefore, the RAP is treated as black aggregate. The other theory categorizes the old bitumen as active, and that the addition of a rejuvenating agent will restore the old bitumen to its original characteristics [3, 20].

Field observations and laboratory work indicate that a portion of the aged bitumen remains inert and a portion combines with the added virgin bitumen contained in the emulsion to eventually produce a new “effective” binder [2]. The portion of the aged bitumen that combines with the added virgin bitumen depends on the gradation of the bituminous aggregate, the bitumen content and the softness of both the aged and the virgin bitumen [3, 20, 23, 28].

Added Binder Performance

Three categories of emulsion are available for CIR. The emulsion may be a standard emulsion, a modified bitumen emulsion, or a rejuvenating type emulsion. The standard emulsion may be cationic, anionic, or anionic high float. The modified bitumen emulsion contains polymer, and the rejuvenating type emulsion is composed of bitumen and rejuvenating maltene type oil. Emulsion with an intermediate setting time (medium setting) is most often used with CIR.

The usage of high float emulsions as well as polymer-modified emulsions (high float or non-high float) is growing rapidly. The gel structure provided by the high float emulsion residue improves the resistance to moisture and draindown. Furthermore, this emulsion coats the bituminous aggregate well and the coating is not affected by the presence of fines or small emulsion content variations [2, 8, 20, 23].

The polymer-modified emulsions provide higher early strength in cohesion and adhesion. The polymer also allows the usage of softer bitumen, which flux through and rejuvenate the aged bitumen more effectively, without the permanent deformation associated with emulsions made with unmodified soft bitumen. Furthermore, because of the enhanced characteristics of polymer-modified emulsion, CIR may be carried out on higher volume roads [4, 7, 8, 41, 43].

Moreover, a chemically engineered emulsion “ReFlex” that does not contain a polymer or a rejuvenator was developed for cold in-place recycling [34]. Initial performance results on the ReFlex emulsion are encouraging [24, 33, 34, 36, 48].

Properties of Recycled Mixtures and Structural Impact

Modulus and Fatigue

Modulus and fatigue life of recycled mixtures, increase during the first few months of service [45]. This phenomenon may be associated with the fluxing of the virgin bitumen with the aged bitumen as well as the decrease in air voids [20, 45].

With Similar air voids, CIR mixtures have slightly greater modulus values and significantly greater fatigue lives than standard HMA. These properties indicate that a recycled mixture may behave more like an open graded mixture rather than a dense graded mixture. Open graded mixtures are known to provide more fatigue resistance but less stiffness than regular HMA. Field performances of recycled mixtures confirm the similarity between open graded mixtures and recycled mixtures [2, 3, 4, 20, 24, 34].

Pavement Deflection

The average deflections before and after CIR have been compared and have been found to be equivalent or smaller after CIR [29, 45]. The deflection results indicate that the structural strength for standard CIR may be assumed to be at least equivalent to the in-place material prior to CIR. It has also been observed that there is less variation in the individual deflection results after the CIR than prior to CIR operation [20, 41].

Reflective Cracking

Cold In-place recycling is considered the most effective process to mitigate reflective cracking in a cold environment [3, 14, 43]. The CIR process destroys the existing crack pattern and produces a crack- free layer for the new wearing course such as a HMA or an asphalt surface treatment [3]. For CIR to be effective in mitigating the cracking, at least 70 percent of the existing asphalt pavement thickness needs to be treated. The treatment depth is also affected by the maximum depth that can be treated at one time. Generally, the treatment depth is 2 to 4 inches for mixes modified with liquid recycling additives such as asphalt emulsions and emulsified recycling agents [3, 20, 34, 43].

Using additional recycling modifiers such as lime, Portland cement, or type C fly ash increases treatment depths to 5 to 6 inches; hence increases the probability of mitigating

reflection cracking [3, 9, 16, 18, 21, 30, 45]. Wherever possible, paved shoulders should also be treated in order to prevent propagation of shoulder cracks into the adjacent treated driving lane [3].

PERFORMANCE DATA

Typical performance data related to performance evaluation may include visual distress and condition surveys, ride quality information, pavement surface roughness, pavement deflection, dynamic penetration values, rut depths, amount of reflective cracking, layer moduli, structure numbers (SN) and layer coefficients, traffic counts (AADT, %Truck), and cores for laboratory analysis [11, 14, 15, 16, 17, 18, 21, 24, 26, 33, 39, 41, 43, 45, 50].

CASE HISTORY DEMONSTRATIONS

Mercer County Project, Pennsylvania [28]

An in-place recycling project was completed in Mercer County, Pennsylvania on Traffic Route 208 (west of I-79 London interchange) in May 1985. The recycling train (Figure 4.1) consisted of an emulsion tanker, a milling machine, a crusher, a mixer, and a paver. The milled material passed over 1.5-inch scalping screen. The oversized material was fed into the crusher by a conveyor to reduce its size. The material was milled and recycled to a 3 inch depth. Since there was no provision for adding water before the material was mixed with the CSS-1h emulsion, the latter was mixed with water in 50:50 ratios to provide an acceptable dispersion of the binder.

It was noted that the gradation of the RAP on this project was significantly finer than the laboratory-generated RAP. About 3% (approximately 7.5 gal per ton) CSS-1h emulsion by weight of the RAP was used. Compaction was performed with a vibratory and a pneumatic-tired roller. Because the average daily traffic on this road was 2,000 to 3,000, the recycled base course was overlaid with 3.5 inch HMA overlay. The recycled pavement had been performing satisfactorily when it was inspected in 1986 after one year.



Figure 4.1. Recycling train used on the Mercer County project.

US 64 Project, New Mexico [28]

This cold in-place recycling operation was performed on US 64 in New Mexico in 1984. The existing pavement consisted of 3 inch HMA over 6 inch sand and gravel base. The existing surface exhibited extensive medium to high severity transverse, shrinkage and fatigue cracking (Figure 4.2), and extensive moderate to high severity rutting. The surface



Figure 4.2. Condition of US 64 (in 1984) before CIR construction.

also had extensive maintenance patching. Cold in-place recycling was done to fix the problem. A polymer modified, high float emulsion was used at rate of 1% to 3%. The quantity of recycling agent was based on laboratory mix design, but was adjusted on the basis of field requirements. A 4-inch HMA overlay was used on the recycled base.

The equipment train used for recycling consisted of a milling machine, crusher, mixer, and paver (Figure 4.3). The milling machine milled the existing pavement and



Figure 4.3. Recycling train used on the US 64 project.

transferred the material to the crusher. The milled RAP material was screened and sized in this equipment. The maximum size of the RAP material was reduced to 1.25 inch. The screened and sized RAP material was mixed with emulsion in the mixer. A truck supplied the emulsion to the mixer. The mixer then laid down the recycled mix in a windrow. The paver picked up the recycled mix from the windrow and laid it down with a screed. Heavy pneumatic-tired rollers (30 ton) were used for breakdown compaction. Steel-wheel rollers were used for final compaction (Figure 4.4). Survey results reported in 1996 indicated that the pavement was performing adequately.



Figure 4.4. Pneumatic-tired breakdown roller.

Baltimore County, Maryland [28]

Cold in-place recycling was done to rehabilitate a deteriorated road in Baltimore County in Maryland. The existing road had thermal cracking, rutting, poor profile and alligator cracking and patching (Figure 4.5). Since this road is the only artery feeding a hospital emergency room and general business, traffic had to be maintained. Hence the road could not be totally closed. Both sides of this road had concrete gutters. Following



Figure 4.5. Existing road (Baltimore County).

rehabilitation through recycling, the hot mix wearing surface needed to meet the top of the gutter. This means that the 4 inch recycled base course had to be 1.5 inch lower than the top of the gutters when compacted. With CIR, it was decided to move the recycled material into the center of the road and build a cross slope. Recycling was done with an asphalt tanker, pushed by a down-cutting full lane width (10-ft wide) milling machine, with an appropriately computerized asphalt additive system. The old roadway material was milled and mixed with new asphalt in a single operation, then deposited directly into a paver and re-laid to the desired depth (Figure 4.6).



Figure 4.6. The recycling train used on the job (Baltimore County).

The recycled material could be driven on without major problem. Traffic flowed around the construction equipment under restricted lanes and speed. The recycled mix was left to cure for a period of seven days. Traffic was allowed to use the newly recycled section with no restriction. To achieve ideal compaction, a combination of a pneumatic 30 ton smooth-tired roller and a steel wheel 12 ton vibratory roller were used (Figure 4.7).

Recycling Around Utilities [28]

Generally, a box is painted around the utility to first guide the operator of a small milling machine as to how much of the roadway must be milled to accommodate the larger recycling machine (Figure 4.8).



Figure 4.7. Rollers used for compaction.



Figure 4.8. Marking utility.

The 16 inch head of a small milling machine goes around the utility to the depth of the new base course (Figure 4.9). The milled material stays in-place around the utility until the larger recycling machine approaches. Then, all of the milled material is excavated out



Figure 4.9. Milling around utility.

from the cut area, and placed on the old roadway where it is processed with the recycling machine. As the recycling machine pulls the paver behind it, it lays the new recycled base course around the utility, recycling 100% of the existing material (Figure 4.10).



Figure 4.10. Recycled material around utility.

PERFORMANCE CASE STUDIES

Iowa Performance Study [26, 27]

A systematic survey of the performance of low-traffic-volume CIR roads in Iowa was conducted. Detailed analysis was performed on 18 of the 96 roads that had been recycled between 1986 and 1996. The roads were rated both quantitatively and qualitatively.

In general, the roads have been performing well. It is apparent that CIR is effective in mitigating transverse cracking and that this method is associated with few problems of rutting. The source of transverse cracks in finished CIR pavements appears to be preexisting cracks in the un-recycled pavement in about 50% of the cases. The rest seem to originate in the HMA overlay as thermal cracks.

Based on the performance to date, the expected service life is projected to be between 15 and 26 years. Subgrade stability has been cause of three failed attempts to recycle in Iowa. Contracting authorities should avoid selecting CIR as a rehabilitation technique for pavements with instability problems, particularly if the work must be accomplished early in the season while the subgrade is still saturated from the spring thaw.

Blue Earth County Cash 20 Project, Minnesota [24, 33]

The implementation of a defined engineered design procedure including performance testing, an improved chemistry emulsion, performance-based specifications, and a QC/QA plan led to a successfully placed cold in-place recycling project in Blue Earth County, Minnesota. The design procedure allowed a better-defined matching of emulsion content to the gradation of the millings. Average emulsion content of the new CIR sections was estimated to be 3.25%, while the conventional section was 1.5%, from readings taken from the computers on the recycling train equipment. A visual examination showed the new CIR had a better coating, and the compacted pavement was blacker than the conventional section.

A new laboratory raveling resistance performance test showed the new CIR process to be better than the conventional, which also proved to be true in the field. Small sections of the conventional CIR exhibited minor raveling shortly after construction, while there was none observed in the new CIR sections.

The laboratory strength testing gave higher initial strengths for the new method. FWD testing in the field also showed higher moduli for the new CIR sections than for the conventional CIR ones, both immediately after construction and after overlay placement. Superpave Shear Testing indicates stiffnesses were roughly equivalent for the conventional and new mixtures. Indirect tensile testing indicated the new process CIR should be more resistant to thermal cracking, with a lower predicted thermal cracking temperature than the conventional CIR mixture.

The Structural Number (SN) of the conventional CIR section was 1.71, and that of the new CIR section was 2.29, (both of these sections had HMA overlays). The SN of the conventional CIR sections with double chip seal was 1.67, and the new CIR section with double chip seal was 2.10.

While cold in-place recycling has been successfully done using conventional CIR emulsion for many years, this project demonstrated that a new chemistry emulsion improves the early strength of the recycled pavement, allowing faster compaction (one hour for the conventional and ten minutes for the new process) and return to traffic. The emulsion also allowed the addition of higher asphalt content with a resultant better coating. The higher asphalt binder coating should give a mixture that is more durable and resistance to thermal cracking, as indicated by the indirect tensile testing. This project will continue to be monitored for long-term performance.

While it's too early to make definitive conclusions about long term field performance, initial field performance of the new system shows that the engineered design protocol leaves less chance for premature failure.

Frontenac County Road 2, Ontario [14]

Approximately 20-mile long reconstruction project was constructed on County Road 2 (formerly Provincial Highway 2) in Frontenac County, Ontario. The project constituted a municipal implementation of Superpave performance graded asphalt binder and volumetric mix design technology over cold in-place recycling.

Three long-term performance monitoring test sections have been established at representative locations on County Road 2. The performance related tests completed for each section included: visual distress surveys and Pavement Condition Index (PCI)

determinations; structural capacity testing using FWD; and transverse profiling using the digital incremental profiler.

Visual condition surveys were completed in 1996, 1997, and 1998. Where applicable, the pavement surface distresses were categorized by type, severity, and density and recorded on pavement inspection form. A Pavement Condition Index (PCI) value was calculated based on the pavement distress. The most recent visual condition survey (May 1998) did not identify any structural or climate-related distresses. Based on the current pavement condition, a PCI value of 100, where 100 is the best and 0 is the worst, has been assigned to each section.

A program of load/deflection testing was completed on each section using the Dynatest 8081 High Capacity FWD. At each test location, three load levels (6.75, 9.0 and 11.25 kips) were used to determine the deflection response of the pavement. The 9.0 kip load level simulates the wheel load of a standard heavy truck (18 kip single axle load) which is equivalent to one Equivalent Single Axle Load (ESAL). FWD tests were completed every 33-ft throughout the length of the test section, in the middle of eastbound and westbound traffic lanes.

Following the collection of the FWD load/deflection data, the test results were analyzed using the AFTER computer analysis program. The normalized deflection and the pavement surface modulus were calculated. A summary of the averaged (east bound and westbound lanes) mean deflection and mean surface modulus for each section is given. In addition, a subjective description of the pavement support quality is provided based on the pavement surface modulus and general pavement characteristics. The structural condition of the pavement in one section was considered very good, while in the other two sections was considered good.

Transverse profiling was completed using the digital incremental profiler with a foot spacing of 4 inches. Transverse profiles were developed using the elevation data and graphed using a spreadsheet program. The rut depth, measured from a 4-ft straight edge, was calculated in accordance with the Ontario Ministry of Transportation (MTO) procedure. The profiles were measured in 1996, 1997 and 1998. The 1998 results indicate little change from the previous year's data, with no apparent rutting.

Finally, the reconstruction of the 20-mile project on County Road 2 was considered to be very successful. Three years after reconstruction, the pavement is in very good condition, exhibiting no significant surface distresses or rutting. There are no visible reflective or low temperature cracks. The pavement's structural condition is good to very good. Further monitoring of pavement condition on each section has been recommended to the County. Based on the positive 1996 Superpave experience, the County of Frontenac adopted Superpave technology for 1997 reconstruction projects.

CIR Evaluation on Kansas US-283 [18, 48]

A distress survey was performed in November 1999. Transverse cracks were measured in three fly ash sections and three emulsions with lime slurry sections. The three fly ash sections measured were at mile marker 34, mile marker 36, and mile marker 38; the full 24 foot width was evaluated for transverse cracking. The sections were 500 feet in length and went north for mile markers 34 and 38 and south for mile marker 36. The emulsion plus lime slurry sections measured were at mile marker 43, mile marker 45, and mile marker 47. The sections were 500 feet in length, the full 24 feet width of pavement, and went north for mile markers 43 and 47 and south for mile marker 45.

A total of 711 feet of cracking in the three fly ash sections was measured, and a total of 369 feet of transverse cracking in the emulsion with lime slurry sections was measured. The fly ash sections has nearly twice the amount of cracking as the emulsion with lime slurry sections, and it is believed that the excess cracking originated in the recycle fly ash layer. Of course, some of the cracking probably originated in the hot mix overlay, but it can not be separated from the cracking in the CIR layer below it. No cracks were wider than 1/4 inch with most cracks about 1/16 inch wide. Superpave indirect tensile thermal cracking tests in the laboratory verified field transverse cracking.

The fly ash section is also showing longitudinal cracking throughout much of the length of the section; crack lengths were not measured in the field survey. In some cases the cracking was in both wheel paths and in other cases just in the outside wheel path. In some cases, there were two longitudinal cracks side by side in the outside wheel path. There was either no longitudinal cracking in the emulsion plus lime slurry section or short areas of cracking with lengths of 10 to 30 feet. These cracks were also low severity. The longitudinal

cracks are believed to be load associated, especially since they are predominantly in the wheel paths. The greater severity of longitudinal cracking in the fly ash section indicates a greater tendency for fatigue associated damage. The tendency of the fly ash section for greater fatigue damage is indicated by the greater stiffness as measured in shear modulus testing.

There was slight to no rutting observed in the field and no notable difference between the sections. Laboratory measurements with the APA and shear modulus testing indicate low susceptibility for rutting of the recycle layers.

Wisconsin Experience with Fly Ash Stabilized CIR [21]

The findings on the construction and first year performance of cold in-place recycled (CIR) pavement sections constructed along Highland Avenue in Mequon, Wisconsin are discussed below. Constructed sections include a control section (4-inch HMA surface over an 8-inch pulverized CIR base layer), a fly ash stabilized test section (4-inch HMA surface, 5-inch fly ash stabilized CIR base layer, and 3-inch pulverized CIR base layer), and an asphalt emulsion stabilized test section (3.5-inch HMA surface, 4-inch emulsion stabilized CIR base layer, and 4-inch pulverized CIR base layer).

Performance data collected through the first year of service indicates that all sections are performing well with no surface distress evident. Nondestructive deflection testing indicates that fly ash stabilization of the CIR base layer produced an increase in the structural capacity of the pavement, as compared to the structural capacity of the control and emulsion stabilized test sections. Using pavement SN values back-calculated from deflection data, the estimated structural coefficient of the fly ash stabilized CIR materials is 0.15 compared to 0.11 for untreated CIR materials and 0.13 for asphalt emulsion stabilized CIR materials. Based on allowable traffic estimates determined by AASHTO guidelines, the increased structural capacity of the fly ash test section relates to a performance life increase of 58% compared to the control section and 28% as compared to the emulsion stabilized section.

The data collected to date indicate potential benefits can be realized through fly ash stabilization of CIR base materials. However, these benefits can only be realized if the fly ash stabilization process is efficient, environmentally friendly, and cost-competitive. During the construction of this test section, problems encountered during the transfer and laydown of

the fly ash materials could be considered as serious detriments to the efficiency and environmental friendliness of this process as applied to urban settings with live traffic during construction. It is recommended that efforts be focused on developing equipment capable of transferring sufficient quantities of fly ash materials directly from the fly ash supply tankers to the pulverizer chamber, thereby eliminating the time delays and dusting problems associated with the spreader trucks.

Based on material quantities used on this project, a fly ash transfer rate of approximately 2.45 Mg/min would be required. Alternatively, modifications to the spreader trucks may be possible to eliminate the dusting problem during laydown. Under this scenario, additional spreader trucks and supply tankers would be required to maintain a sufficient spread of fly ash materials ahead of the pulverizer.

State of Maine Experience [23]

Deflection, rut depth, ride quality, and a crack study have been performed on recycled pavements in Maine. Based on three years of performance, cold in-place recycling has virtually eliminated reflective cracking problems. Deflection and rut measurements indicate that cold in-place recycling with or without the addition of binder does not produce the same load-carrying ability as that of conventional black bituminous base. Strength reductions were noted with moisture and frost action. Bituminous binder should be used with cold in-place recycling when excessive fines are present.

Highway 19-06 CIR Project – Saskatchewan [9, 10, 11]

The Highway 19-06 field test sections were designed and constructed to evaluate the effectiveness and performance of alternative cold in-place recycled and full depth waste co-product cementitious stabilized systems in Saskatchewan field conditions. Performance evaluation of the Highway 19-06 test sections was performed after two years of performance in the field and included a visual distress survey, ground penetrating radar survey, and Benkelman beam deflection measurements.

A visual distress survey was performed across the SDHT Hwy 19-06 test sections in June 2001 after two years performance in the field. The results indicate that the class C flyash stabilized seal on subgrade test sections are showing signs of moderate to severe edge

substructure failures. The un-stabilized control test section is showing minimal edge or seal failures, but is increasing in roughness most likely due to early stages of freeze-thaw heaving. The class C flyash with base overlay and all the TerraCem stabilized test sections are showing minimal distresses after two years of performance in the field.

A ground penetrating radar survey was performed across the Highway 19-06 test sections to identify potential moisture accumulation within the stabilized layers. The dielectric permittivity profile of the flyash seal on subgrade test sections increased to just under ten compared to average of seven across the flyash test sections constructed with a base overlay. This slight increase in the dielectric permittivity indicates an increase in moisture content of the subgrade material. The increase in subgrade moisture content was later confirmed with core samples retrieved from the grade which showed a 1.5% increase in the subgrade moisture content above optimum. The dielectric permittivity profiles of the TerraCem stabilized test sections ranged from 6 to 8. Dielectric permittivity profiles of the unstabilized control test section ranged from 7 to 9.

Benkelman beam surface deflection measurements under an 18-kip standard single axle load were taken in November 1999, July 2000, and June 2001. Surface deflections across all test sections in the first year were found to be slightly above or below 1 mm. After two years of performance in the field, surface deflection of the unstabilized control test section increased to 3.15 mm, surface deflections of the flyash stabilized test sections with no base increased to 2.56 and 2.50 mm, surface deflections of the flyash stabilized test sections with base overlay increased to 1.38 and 1.88 mm, and surface deflections of the TerraCem stabilized test sections have increased only slightly to 0.88 and 1.08 mm.

Based on the two-year performance of the SDHT Hwy 19-06 pilot cold in-place recycling and full depth stabilization project, cold in-place recycling and full depth stabilization appears to be a viable road strengthening solution for northern climates. To this end, industrial waste co-products such as flyash, bottom ash and kiln dusts are being designed as effective structural cementitious soil stabilizers. Field performance of cementitious waste coproducts after two years show cold in-place recycling and cementitious stabilization to be a technically and economically feasible solution for strengthening Saskatchewan thin paved roads built on clay-till subgrades. Subgrade stabilization with blended cement and flyash, and kiln dust (TerraCem) appears to provide considerable

structural benefits relative to the unstabilized control and class C flyash stabilized test sections.

Limited experience with cold in-place recycling and full depth strengthening in Saskatchewan has limited the implementation of cold in-place recycling and full depth strengthening of roads. As a result, there is a clear need for continued development of more scientific engineering materials characterization and road structural assessment and design methods in order to fully adopt cold in-place recycling and full depth strengthening of Saskatchewan thin paved roads.

New Mexico Experience [30]

New Mexico Transportation Department (NMDOT) began using CIR for rehabilitating asphalt pavements in 1984 and just reported the results of their comprehensive evaluation at the 1997 TRB Meeting. They concluded that performance of CIR pavements will far exceed the 10-year service life assumed during design. Wheel path rutting due to compaction under traffic is not evident except on a few projects where specific deficiencies have been identified. The structural coefficient of 0.25 currently used should be increased to 0.30 immediately and an increase to 0.35 should be evaluated through field testing under service loads.

Analysis of cost data shows the use of CIR saved significant construction dollars (\$11,318 per lane-mile) when compared to the previous mill/inlay rehabilitation technique for HMA pavements. Maintenance costs are also reduced based on the reduction in cracking and the consequent reduced costs of crack sealing.

Finally, the use of cold in situ recycling is cost effective and provides excellent performance for a service life that is yet to be determined, certainly exceeding ten years.

Oregon Experience [30]

Several reports have been issued by Oregon documenting CIR performance on roads in the high desert, central, and eastern regions of the state. The treatment has been primarily used as a low cost remedial maintenance alternative to blade patching topped by a 2-inch HMA overlay. Even though almost all CIR has been only to a depth of 2 inches or less and surfaced with a single chip seal, performance has been very good. With an expected service

life of 7 or 8 years for the CIR a chip seal versus 12 years for the 2 inch HMA overlay, life cycle costs of CIR projects were 37 to 82 % of the 2 inch overlay alternate.

Results of mix property testing in Oregon show increases with time in resilient modulus (ASTM D4123) values and fatigue life over a period of years. This is likely due to curing of the emulsion and reduction of air voids with traffic.

CIR of pavements which have exhibited extensive stripping has been accomplished with the addition of quicklime to reduce moisture sensitivity. Laboratory tests and field results look promising but long term evaluation has yet to be done. New lime slurry equipment has been developed to make additions easier and more precise.

Kansas Experience [30]

In Kansas most CIR was completed in the western part of the state where the aggregate quality and fine gradation result in low strength of CIR mixes with emulsions. This combined with the higher air voids of CIR pavements resulted in pavement lives of only 5 years on some state highways. In the early 1990's Type C fly ash was used as the stabilizing additive to increase mix strength and resistance to moisture damage. Since 1994, Kansas DOT has used only Class C fly ash on the stabilizing agent in CIR. Long term results are not yet available.

Earlier research in Kansas documented how CIR greatly reduced reflective cracking in a pavement that was cold recycled prior to overlay versus a control section with a 4 inch overlay on a cracked pavement. The study also concluded that the greater the depth of recycling relative to the total existing pavement thickness, the longer the delay in reflective cracking in an overlay. After six years, 40% of the original cracks reflected through the 3.5-inch CIR plus a CIR and 2.5-inch HMA overlay; and 14% reflected through the 3.5-inch CIR and 2.5-inch HMA with an additional 2.5 inch of the original cracked pavement removed by milling.

Highways 155-03 and 15-10 CIR Studies- Saskatchewan [7, 10, 11]

Saskatchewan Department of Highways and Transportation is investigating cold in-place recycling and full depth stabilization as a potentially cost effective rehabilitation alternative for strengthening thin paved roads. Pilot studies undertaken in 1999 on Highways

15-10 and 155-03 revealed considerable in situ structural variability due to different construction practices at the time of initial construction and years of maintenance and rehabilitation treatments. As a result, the design and QC/QA of in-place recycled road systems can be highly variable in terms of materials and structural composition. The effect of in situ variability is further exacerbated if stabilization additives such as asphalt emulsion, foamed asphalt, cements, fly ash, and/or chemical stabilizers are used for adding strength to the in situ materials given the sensitive nature of many additives when exposed to different materials.

Based on the cold in-place recycling performed during the Highway 15-10 and 155-03 pilot case studies, GPR has been found to be an effective pre-engineering diagnostic tool that can be used to help reduce the uncertainty associated with in-place recycling existing road structures. Future work should be undertaken to evaluate the use of GPR as an ongoing performance-monitoring tool to quantify changes in layer thickness, moisture content, and/or density of recycled road systems over time.

NovaChip and CIR Study – Ontario [29]

NovaChip is an ultra-thin HMA overlay consisting of a thin layer HMA placed over a heavy tack coat. The HMA consists of a gap-graded mix of single-sized crushed aggregate, fine crushed sand and binder. The heavy tack coat is a polymer-modified emulsified binder. This ultra-thin HMA overlay is placed in a single pass with a paving machine that combines the functions of a binder distributor and a laydown machine.

The demonstration project is located on Highway 86 west of the town of Listowel. A two-lane rural collector, Highway 86 has an average AADT of 3,600, of which 19% is commercial. The existing crossfall was 1.5% on the westbound lane and 1.6% on the eastbound. In 1996, the pavement condition rating (PCR) of this section was 42, which is considered unsatisfactory and hints at an uncomfortable ride. Generally, pavements with a PCR of 60 are considered for rehabilitation. The PCR is based on a survey of the distresses and a measurement of roughness. The pavement was distressed throughout with high wheel track and transverse cracking and a rough ride. The contract requirements for the CIR included a recycling depth of 4 inches; a roadway crossfall of 2%; and pavement widening of 10 inches on both sides of the highway, using the CIR material.

After one winter, the rehabilitated pavement is in good condition. The NovaChip provides a smooth and uniform surface, except for the rough joints. No ravelling, flushing, delamination or snowplow damage have been noticed. The surface texture produces a different tonal noise compared to the adjacent HMA, but whether this difference actually results in a quieter riding surface has not been determined.

The relative frictional resistance of a pavement is given in terms of a skid number (SN), obtained by field measurement. Prior to construction, the skid number was 37 for both the west- and eastbound lanes. Just a few weeks after construction, the skid number had risen slightly to 40 for the eastbound lane and 41 for the westbound. By April 1998, five months after construction, the skid numbers had risen to 52 and 53. This significant increase in the skid resistance after one winter is tied to asphalt film removal from the exposed aggregate by traffic. The latter high skid resistance numbers are similar to that experienced on high quality HMA surfaces used on freeways.

Rutting surveys were done before construction, after the CIR, immediately after the NovaChip, and five months after construction, using the Automatic Road Analyzer (ARAN). Before construction, the average rut depths were low at 0.2 inch in the eastbound lane and 0.18 inch in the westbound. After CIR and before overlay, the measurements increased slightly to 0.22 and 0.19 inch in the eastbound and westbound lanes, respectively. After the NovaChip, the rut depths fell to slightly below the depths experienced before construction at 0.16 inch for both the east- and westbound lanes. After one winter, the rut depths stayed relatively the same at 0.17 inch in the eastbound and 0.16 inch in the westbound lane.

Roughness surveys were taken before construction, after the CIR, after the NovaChip, and five months after construction, using a Portable Universal Roughness Device (PURD), a trailer-mounted accelerometer-based measuring device operated at a constant speed on the highway. It uses the root mean square of the vertical acceleration of the trailer axle (PURD) to calculate roughness, and convert the numbers into a Riding Comfort Rating (RCR).

The RCR of Highway 86 before construction was low, in the uncomfortable range at 5.9 in both the east- and westbound lanes. The PURD measurements after CIR show that the RCR increased to 7.4 and 7, indicating a comfortable ride. After the NovaChip the ride increased to 8.4 in the eastbound lane and 8.5 in the westbound. These values are typical for a rehabilitation treatment. Readings taken in the early spring of 1998 showed a slight

reduction in roughness, corresponding to RCR values of 7.9 in the westbound lanes and 7.8 in the eastbound lane. Whether this reduction is a result of roughness testing in cooler weather or deterioration of the poor quality transverse joints will be established in future roughness surveys.

Deflection testing was done using the falling weight deflectometer (FWD) to determine the dynamic deflection characteristics of the pavement at each phase. The deflection values before CIR averaged 0.0008 inch. They almost doubled to 0.015 inch after the CIR, indicating a reduction in the stiffness of the pavement. These results are typical of deflection values obtained, at an early age, on other CIR projects in Ontario, and they are expected to decrease as the CIR mix continues to cure and stiffen. The deflection results did not change significantly after the NovaChip, which was expected because an ultra-thin surfacing adds no structural stiffness to a pavement.

Based on the short-term results of this project, the following observations may be made:

- NovaChip must be placed on a relatively smooth crossfall-corrected surface, which is free from significant distresses and distortions;
- NovaChip provides a well bonded, highly skid-resistant ultra-thin wearing surface; and
- The high macro texture results in noticeable tonal differences.

Further work is needed to determine if NovaChip is suitable as an ultra-thin surfacing for high-volume freeways, especially as an alternative to OGFC. The work would include:

- Confirming if sound levels are reduced from a typical dense graded mix (DFC) used on freeways to a similar level as those for an OGFC;
- Continued monitoring of the performance of the Hwy. 86 demonstration project; and
- Application of NovaChip on a freeway in an urban environment.

5. ECONOMICS OF RECYCLING

Economic evaluation of alternative pavement rehabilitation strategies should consider initial and recurring costs. These costs include agency costs, user costs, and nonuser costs [23, 28]. Agency costs may include initial capital costs of rehabilitation, future capital costs of rehabilitation (overlays, seal coats, etc.), maintenance costs recurring throughout the design period, salvage return at the end of the design period, engineering and administration costs, and costs of investments. Moreover, user costs may include costs related to travel time, vehicle operation, accidents, discomfort, and time delay and extra vehicle operating costs during resurfacing or major maintenance [3, 20, 23, 28].

However, simplistic methods of economic analysis consider only initial capital costs, future costs of rehabilitation, maintenance costs, and salvage values [23].

A review of the literature indicates the following component costs for the cold in-place recycling operations [23]:

- Materials: 46.6%
- Equipment: 29.7%
- Labor: 23.7%.

The main economic advantage that recycling offers is in material cost savings. The majority of the material costs are associated with new binder.

ECONOMIC ANALYSIS – COMPARISONS

The ARRA Economic Analysis of CIR

The expected service lives of the various CIR rehabilitation techniques, when undertaking a life-cycle economic analysis, generally fall within the following ranges [3]:

- CIR with surface treatment 6 - 8 years
- CIR with HMA overlay 7 - 15 * years

Note: * Equivalent to agency's thick lift HMA service life.

The effectiveness and performance of the various CIR rehabilitation techniques varies from agency to agency and is dependent on [3]:

- local conditions
- climate
- traffic
- type of technique and quality of materials used
- quality of the workmanship

The FHWA Economic Analysis of CIR

The reported costs of cold in-place recycling are shown in Table 5.1 [23, 28]. The representative cost varies from approximately \$1.37/yd² to \$7.90/yd² depending upon many factors such as depth of recycling, equipment type, and thickness of overlay [28]. The reported relative savings of using cold in-place recycling in lieu of conventional construction methods are also shown in table 5.1. The initial savings have varied from 6 to 67%.

The mean cost from Oregon DOT cold in-place recycling projects in the 1989-1990 period was reported to be \$2.00/yd² for a 2-inch cold in-place recycling with a chip seal, and about \$1.44/yd² without a chip seal [25].

The mean cost for 48 New Mexico cold-in-place recycling projects ranged from \$0.27 to \$0.92/yd²-in, with a mean of \$0.54/yd²-in [25]. Recycling cost increases with an increase in the use of virgin aggregates.

On a per square yard per inch basis, cost of recycling is reduced with an increase in depth of cold in-place recycling. For the New Mexico state projects, the mean cost per square yard per inch have been reported to be \$0.64/yd²-in for 3 in, \$0.56/yd²-in for 3.4 in, \$0.52/yd²-in for 4 in, and \$0.44/yd²-in for 4.5 in of cold in-place recycling [25].

A recent study shows that the CIR savings in New Mexico amount to approximately \$1.52/yd² in initial cost and \$1.64/yd² on the basis of life cycle costs. Table 5.2 shows typical sections resulting from conventional rehabilitation and recycling operations. Cost figures based on initial cost and life cycle cost are also indicated in the table. The savings on a life cycle basis results from reduced frequency of maintenance for CIR pavements. Generally, maintenance for cracking is required after every four years for mill and overlay projects, whereas maintenance for cracking is required after eight years for CIR projects.

Table 5.1 Full and partial depth cold in-place recycling cost differences [23, 28]

Agency	Year	Cost Difference (%)		Cold In-Place Recycling (\$)	
		Range	Rep. Value	Range	Rep. Value (\$)
California	1979-83	15-43	31	14.71-24.32/ton	20.16/ton
California			37		22.00/ton
California	1980		21		5.17/yd ²
Illinois	1982				3.80/yd ²
Indiana	1976			11.95-22.00/ton	
Iowa	1988		67		6.90/ton
Kansas	1977		53		
Kansas	1988				
Missouri	1978		50		
Montana	1978		21		21.59/ton
New Mexico	1984-86			1.05-2.00/yd ²	1.40/yd ²
N. Carolina	1977		6		3.99/yd ²
Oklahoma	1979				3.46/yd ²
Oregon	1984		24	1.81-2.42/yd ²	2.00/yd ²
Pennsylvania	1983		16		
Vermont	1978		28		7.90/yd ²
Vermont	1982		31		1.37/yd ²
Wisconsin	1978				0.29/yd ²
FHWA					4.72/yd ²

Table 5.2 Initial and life cycle cost comparisons between CIR and conventional rehabilitation options [28].

Savings	Initial Construction cost (\$)		
	Maximum	Minimum	Average
\$/lane-mile	22,874	2,549	11,350
\$/square-yard	2.57	0.48	1.74
Life Cycle Cost (\$/square-yard)			
Rehabilitation Option	Initial Costs (\$)	Maintenance Cost (\$)	Total Cost (\$)
Mill and Overlay (total)	8.780	0.314	9.090
CIR (total)	6.880	0.159	7.040
Cost Savings with CIR	1.900	0.155	2.050

Ontario Study [43]

Life cycle cost comparison of three typical flexible pavement rehabilitation alternatives in Ontario are summarized in Table 5.3. The alternatives are: (1) pulverize existing old asphalt concrete and overlay, (2) cold in-place recycle old asphalt concrete and overlay, and (3) mill some old asphalt concrete and overlay.

Table 5.3 Life cycle cost comparison (\$/lane/mile) for 30 years analysis period [43]

	Rehabilitation Alternative		
	Pulverize 8 in 1.5 in of HL 8 2 in of HL 3	Cold in-place recycle 4 in 2 in of HL 3	Mill 1.5 in 2.5 in of recycled HL 8 2 in of HL 3
Initial Cost	\$47,242	\$50,040	\$57,120
Present worth of Maintenance costs	\$19,731	\$21,944	\$19,731
Present worth of rehabilitation costs	\$35,965	\$13,930	\$35,965
Present worth of residual value	\$16,285	\$3,480	\$16,443
Total present worth of costs	\$86,158	\$82,434	\$96,373
Rank	2	1	3

The three illustrative alternatives are based on maintaining an equivalent overall pavement structure in terms of granular base equivalencies. The costing is based on typical Ontario Ministry of Transportation data with no consideration of used costs. The maintenance and rehabilitation costing and scheduling is based on short-term practical experience. However, it is well established that cold in-place asphalt recycling does mitigate asphalt concrete overlay reflection cracking and this is considered in the life-cycle performance cost comparison.

The rehabilitation alternative of CIR with asphalt concrete overlay is the most attractive on a life-cycle performance cost basis for the alternatives and assumptions mentioned above, and shown in Table 5.3. The life-cycle cost of CIR may be even more attractive when the recycling process is accompanied with improved asphalt concrete overlay technology.

PG binder asphalt and CIR Study– Regional Municipality of Ottawa -Carleton (RMOC) [14, 43]

Thermal distress, in the form of transverse cracking, reduces the effective length of a pavement's lifecycle, as well as reducing the performance of the pavement. Hence, it can be hypothesized that a decrease in thermal distresses could prolong the life of a road.

The CIR process with integral overlay is shown to provide about additional 25% in cost-effectiveness when compared to the conventional resurfacing strategy over their lifecycles. The RMOC has implemented the CIR process combined with a PG binder hot mix overlay with the expectation of obtaining superior transverse cracking resistance.

Limited data to date on PG binder asphalt have already provided indications that a very conservative extension of life cycle by more than 2 years can easily be attained and is likely to be exceeded for conditions in the Ottawa-Carleton area. Use of SUPERPAVE PG 58-34 binder mixes in RMOC will definitely provide significant pay back given the premium to use such mix is about 10% for the anticipated lifecycle extension mentioned above.

Blue Earth County CSAH 20 Project [24]

The pavement costs for 5-inch of conventional CIR; 5-inch of the new CIR, and 3.3-inch of new Superpave were compared for both the areas that were regraded and not regraded. These pavement sections have a similar granular equivalent (GE) of 7.5 for both CIR mixes. The costs are summarized in Table 5.4.

These costs do not include the cost of new gravel base for the regraded sections or salvage value for materials removed from the project site. They do not consider the potentially higher GE for the new CIR, but do include a 25% lower production rate for the new CIR (due to smaller screen size on the recycling train).

A cost comparison was made between the pavement types for the full pavement rehabilitation process that includes material salvage value, gravel base, CIR and new Superpave wearing course. Each alternative has a total GE of 21. The initial costs of these (as displayed in Table 5.4) indicate that the new CIR is about 10% higher in initial cost than the conventional CIR. However, the binder content for the new CIR is twice as much of the conventional CIR, therefore, durability is expected to more than offset the initial cost and show savings during the lifecycle of the project (the breakeven point is one year).

Table 5.4 Preliminary Cost Estimates and Assumptions

Costs per square yard	Conventional CIR	New CIR	Superpave
For Granular Equivalent = 7.5			
Regraded Section	\$4.43	\$6.01	\$5.70
In place Section	\$2.58	\$4.15	\$5.70
For Granular Equivalent = 21			
Regraded Section	\$10.93	\$11.54	\$9.58
In place Section	\$6.01	\$6.62	\$9.58

Structure assumptions for costs estimating for GE = 21

Activity	Granular Equivalent
Traditional Reconstruction	
Salvage bituminous material value, costs to haul away and crush	
Salvage aggregate value, costs to haul away	
12" aggregate base	12
4" Superpave HMA overlay	9
Total	21

Pavement/Regraded section (CIR)	
Mill, stockpile bituminous material	
8" aggregate base	8
Replace milled bituminous material	
Shoulder aggregate (salvaged from stockpile)	
5" CIR	7.5
2.5 " Superpave	5.6
Total	21.1

Pavement/In place section (CIR)	
8" aggregate base remains in place	8
Shoulder aggregate (salvaged from stockpile)	
5" CIR	7.5
2.5" Superpave	5.6
Total	21.1

6. SURVEYS/INTERVIEWS

Dan Wegman, P.E.
Koch Pavement Solutions
St. Paul, MN

Mr. Wegman indicated that CIR technology has improved tremendously in the past 10 years. He attributes this improvement to a newly engineered binder (emulsion) as well as to the newly developed performance testing and specifications (ReFlex technology). The chemically improved emulsion, he says, is providing better coating, high durability, and flexibility to the CIR pavement which is highly favorable in cold climate regions such as Minnesota and North Dakota.

Mr. Wegman stipulates that the new mix design performance tests: raveling, thermal cracking, and long term and retained strength have proved effective for obtaining mix designs that can match field conditions. The selection of three gradations: coarse, medium, and fine will help in finding an optimal binder content. This results in higher structural values for CIR, better cohesitivity, and resistance to cracking.

The new CIR technology, according to Mr. Wegman, is about 10% more expensive than the conventional CIR, however when life cycle cost is performed, the new CIR technology is expected to be more economical.

Todd Thomas
Koch Materials Company
Salina, KS

Regarding economic analysis of the Blue Earth County project, Mr. Thomas points out the breakeven point between the new CIR technology and conventional CIR is one year. However, without any performance data, and depending on available laboratory and field performance testing results as well as engineering judgment, Mr. Thomas expects that the new CIR will outlast the conventional CIR by at least 3 years, thus more economical.

Construction practices are improving as well, says Mr. Thomas. Currently, Koch Company's crew is handling the QC part of these projects while training contractors to

handle this process in the future. He also is seeing contractors improving their equipment (retrofitting) to cope with the new specifications.

The new CIR can be compacted almost immediately (within minutes) after placement with no need for aeration time adds Mr. Thomas. Traffic can also be allowed shortly (2-3 hours) after compaction without a need for a fog seal, since raveling is not a concern. Resurfacing (HMA overlay, chip seal, etc.) can be done within few days on the new CIR compared to two weeks or more for the conventional CIR.

Additives such as lime and fly ash can be used to improve CIR performance, but one should be careful not to add too much, otherwise, moisture susceptibility and cracking problems may occur, respectively.

Mr. Thomas agrees that to mitigate reflective cracking, almost all the asphalt concrete layer need to be milled. This can be done only if the base is strong enough to support the CIR equipment, otherwise, a one inch of the old asphalt concrete is usually left in place to support the equipment and protect the base, with a minimal chance of reflecting cracks. He adds that up to 5 inches can be milled and processes successfully with CIR. If the AC thickness is more than 5 inches, a two lift process can be done, although not highly recommended.

As to the structural strength of the CIR, Mr. Thomas feels comfortable with a layer coefficient value of 0.3. He estimates the resilient modulus of a CIR pavement to be between 250 and 400 ksi, based on FWD results.

Darrel Nixon
Director, Geotechnical and Surfacing
Saskatchewan Highways and Transportation
Saskatoon, Saskatchewan

According to Mr. Nixon, CIR in Saskatchewan is 100% conventional (no emulsified or foamed asphalt). Most of Saskatchewan low volume roads were built in the 1960s and 70s to provide mud-free dust-free environment. The structure of such roads consisted of a thin membrane surface, which is nothing but a surface treatment on subgrade. However, due to elevator consolidation and railroad branch abandonment, a considerable increase of truck

traffic ended up on these roads, which were not designed for that purpose. The end result is fast deterioration of the low volume road system, which extends to 4,700 miles.

TerraCem, a cementitious material product has been successfully used in Saskatchewan as an additive to improve the structural strength of CIR, said Mr. Nixon. This season, about 30 to 40 miles of full depth reclamation of 8 to 12 inches are being done. Other additives typically used with CIR include fly ash, CBR plus, and flax straw (a mechanical additive).

Conventional cold milling, as described by Mr. Nixon, is usually carried out by milling about 2 inches of RAP and mixes it with binder and new aggregates at a central plant. The RAP to new aggregate ratio is about 1:5. As can be seen, only 20% of RAP material is being harvested; it will still reduce the cost and help saving the depleting aggregate sources.

Chuck Valentine
Owner and CEO
Valentine Surfacing Company
Vancouver, WA

Mr. Valentine indicates that his company has built over 5,000 miles of CIR covering 8 western states. He says that few years ago, he did some CIR work in the cold region areas such as South Dakota, Montana Yellow Stone Park, and Idaho.

Mr. Valentine says that the CIR process evolved over the years with many improvements along the way. Mr. Valentine explains that the process of CIR starts with asphalt grinding by a milling machine, followed by crushing and screening, where 100% of the RAP should pass the 1¼ to 1 inch sieves. The RAP is then goes to a pug mill or a mixing unit (sometimes on the same trailer). The RAP going to the pug mill is weighed on the conveyer belt and a 1 to 2% (by weight) emulsion is added. The mix is placed in a windrow, and then picked up by a windrow elevator to the paver for laydown. Lime slurry additive (1½ % by weight), usually injected at the cutter head, is typically added as an anti-strip agent or to provide early strength since the CIR mix is considered tender.

According to Mr. Valentine, 1 to 2 hours are allowed for emulsion to break before compaction. Large rubber tired rollers (1 to 2 rollers) weighing 25 tons each are typically

used. Steel-wheeled rollers with vibratory capability weighing 10 to 12 tons can also be used for compaction. A thin overlay of 1½ to 2 inches is typical as a surface treatment on top of the CIR says Mr. Valentine.

Mr. Valentine states that the key to success for CIR depends on: innovations in binder quality (e.g. Koch ReFlex), proper use of additives (e.g. lime slurry), contractor experience, and proper project selection criteria. On the last point, Mr. Valentine adds that contractors constantly communicate to agencies about the problems they face on the job in an effort to improve project selection criteria. For example, if there is a problem in the subgrade, then CIR is not the correct rehabilitation option says Mr. Valentine.

The main advantage for North Dakota, Mr. Valentine says, is that it can benefit from other peoples failures.

**Ron Gillen
Mitchell Area Engineer
Mitchell, SD**

Ron Gillen has worked with CIR for several years. He has worked on 7 projects in the southeast area of South Dakota. In general, Mr. Gillen says, CIR is a good rehabilitation technique if the right thickness is placed and the right amount of oil (emulsion) is added. But trouble arises when you end up with a CIR project that does not have enough oil and/or the CIR layer is too thick or too thin.

Mr. Gillen explains that if the amount of emulsion is not adequate, then raveling occurs almost immediately. Moreover, if the milling depth is too shallow (e.g. 1 inch), reflective cracking may still be a problem. On the other hand, if the CIR is too thick (greater than 8 inches), then you can't compact it properly, thus will never gain enough strength to carry the load and end up failing. Typically, a 3 to 4 inch CIR layer with a 2 inch HMA overlay gives you good economical rehabilitation treatment.

South Dakota uses emulsion "AE150S" as the binder and quartzite as the aggregate for CIR mixes, says Mr. Gillen. The only gradation specification for the RAP is that the top size should not exceed 1 inch. Contractors determine the binder content at the beginning of the project. However, the actual field binder content is usually less than the design value.

Greg Brown
Secretary-Treasurer
Brown and Brown, Inc
Salina, KS

Mr. Brown thinks that CIR thickness ranges between 2½ and 5 inches, or not thinner than what is needed to support the equipment and not thicker than what can be compacted properly. However, tamping rollers may be used to enhance compaction effort.

Mr. Brown recommends the use of the newly developed emulsion, ReFlex, that has been chemically engineered for cold in-place recycling with mix design criteria and performance testing specifications. Lime slurry can be added to the emulsion, says Mr. Brown, which is done for the purpose of gaining early strength. Fly ash on the other hand, can improve early strength as well, but it is not recommended for less than 6 inches of CIR for cracking considerations. There are also environmental and worker safety hazard reservations associated with fly ash use.

The CIR option, according to Mr. Brown, is economical that can save anywhere between 25% and 50% compared to other rehabilitation methods. Mr. Brown sees many applications related to CIR such as a cold-recycled base below a Superpave mix.

Alan Forsberg
Blue Earth County
Mankato, MN

In choosing the right project for CIR, according to Mr. Forsberg, there should not be changes in vertical or horizontal curves. In other words, if there is excessive amount of regrading involved, CIR will not be the correct option to use.

Traditionally, emulsions were used in CIR because they were less expensive (less amount is used), more durable, and has unique temperature characteristics, says Mr. Forsberg. North Dakota would need asphalt that does not crack such as polymerized asphalt with characteristics similar to Superpave PG grade asphalt.

Typical surface treatment is a 4 inch thick HMA overlay says Mr. Forsberg. Gradation is characterized with the top size not exceeding 1 inch. Milling can be up to 5

inches, otherwise, 2 passes of 3 to 5 inches each can be milled. For moduli back calculation, FWD testing before, immediately after and 1 year after is needed. A gravel equivalency (GE) of 1.5 is usually assigned for CIR compared to 2.25 for a Superpave mix.

Dave Soanes
Technical Resources Supervisor
JEGEL John Emery Geotechnical Engineering Limited
Toronto, Ontario

Mr. Soanes indicates that the use of polymer modified asphalt or an emulsion with a rejuvenator help in mitigating reflective cracking. These types of mixes have the ability to mend themselves if any of the cracks appear. The high float asphalt HF150 is one that is typically used in Ontario. Moreover, CIR has been successfully used on highways with traffic volumes up to 5,000 vehicles per day.

Regarding the CIR mix design, modifications to the original Oregon method have been used in Ontario, says Mr. Soanes. Mix designs using the gyratory compactor have been also used. Fatigue and modulus testing have been used for structural and performance evaluation.

Mr. Soanes adds that Koch's ReFlex emulsion for cold in-place recycling is also proven suitable for cold climates. Many research studies are recommending this new technology.

7. CONCLUSIONS AND RECOMMENDATIONS (NORTH DAKOTA PERSPECTIVE)

Although the current state of the art for cold in-place recycling of asphalt-surfaced pavements is relatively new, CIR has proven to be a viable engineering and economic rehabilitation alternative for moderate to low volume roads. However, to date there is no universally accepted design, construction, or monitoring methodology, but a sizable leap has been taken towards establishing that goal.

A great deal of CIR projects and research studies have been conducted in the past decade creating a wealth of information for researchers and agencies to establish methods, procedures, specifications, and guidelines for the various issues regarding the design, construction, or monitoring CIR asphalt pavements.

This report gathered and reviewed such information (from published and unpublished sources); and conducted interviews with personnel involved in the various aspects of CIR technology in the United States and Canada, especially in the cold regions. The conclusions and recommendations of the review and the interviews are offered from the perspective of the needs and requirements of the cold climate regions in general and the State of North Dakota, in specific.

CONCLUSIONS

Generally, CIR has been found to be an economical, environmentally friendly and effective asphalt pavement rehabilitation method for many types of distress. At current asphalt prices, a 4-inch thick CIR pavement costs less than a 1.5-inch HMA overlay. A significant amount of energy is also saved due to the elimination of trucking and heating of the pavement mix. Bridge clearances and guide rail elevations are maintained and side road tie-ins and shoulder paving are minimized when CIR is used. Ride quality will be improved as well as pavement profile, crown, and cross-slopes. High production rates (1.5 to 2.5 miles per day) reduce the disruptions to the traveling public.

Other general conclusions and findings of this study include:

- Cold in-place recycling is not only an effective rehabilitation strategy to mitigate reflective cracking, but also adds structural value to the recycled pavement. Layer

coefficients ranging between 0.25 and 0.35 were observed in many projects, with values up to 0.41 were recorded in some of the CIR special projects;

- CIR primarily uses existing asphalt-bound materials and typically recycles 2 to 4 inches in depth. Higher-quality, more uniform paving mixtures are usually produced from the CIR process;
- Mix design methods have been developed for CIR operations. Emulsion contents of 0.5 to 3.0% are used. Quantities in the range from 0.5 to 1.5% are used for the conventional CIR operations, whereas quantities in the range from 1.5 to 3% are used for the new “ReFlex” CIR operations. Medium-setting and high-float emulsions and emulsified recycling agents are typically used with the conventional CIR, while a new chemically-engineered emulsion is used with the new CIR technology. Mixing water contents are established as part of the design process;
- Physical properties of cold in-place recycled materials are typically between those of an asphalt concrete mixture and a cold, asphalt-stabilized base material. Because properties vary from project to project, laboratory tests should be used to establish strength coefficients;
- Construction equipment and contractor capability are available to perform quality cold in-place recycled projects. Contractors have developed high-capacity, mobile equipment that creates minimum disruption to traffic during construction;
- Surfacing materials should be placed on all cold in-place recycled projects. Chip seals and hot-mixed dense and open-graded mixes are typically used as surface courses. Moisture contents in the recycled material should be reduced to 1 to 1.5% before placement of the surface. Summer curing of 7 to 14 days is typically required to achieve these moisture contents, depending on local climate;
- General performance data have been collected by several states. Overall performance has been very good on a large percentage of the projects. Some problems with raveling, rutting, and cracking have been noted. There is a lack of data on long-term performance;
- Additives in the form of hydrated lime, Portland cement, or fly ash are often used to provide early strength for the CIR layer. An increase of 58% in pavement performance life has been reported; and
- Adequate specification and quality control guidelines have been developed by state

highway agencies.

However, drawbacks do exist with CIR. Quality control is more difficult because of a number of factors that include:

- limited ability to control the gradations;
- changes in the existing asphalt properties, particularly on older roads with patching;
- vulnerability to weather; and
- a long curing process for the CIR bituminous layer, even after the initial break.

RECOMMENDATIONS

While cold asphalt pavement recycling technologies are well established, there is still a need for additional performance information, particularly with regard to creep (rutting resistance), fatigue endurance, and durability. In addition, there is a need to assess whether RAP can be used in wearing surface cold mixes. Further investigation is also needed to evaluate the ability of cold in-place recycled mixes to perform on higher traffic volume roadways.

Despite the recent advances in developing some performance testing procedures (e.g. Koch ReFlex system), there is still a need for more correlation of field and laboratory measurements to establish guidelines for laboratory prediction of field performance, including, for instance, laboratory curing procedures that can simulate field conditions. Some specific issues that require resolution include:

- further informations on the variability of RAP, especially from blended stockpiles;
- a consensus regarding mix design and testing procedures for CIR asphalt mixtures; the suitability of CIR for use with surface treatments and/or rubberized paving materials;
- a more accurate determination of the structural layer coefficient for CIR asphalt mixtures;
- an environmental evaluation of any potentially harmful impacts from CIR;
- Life-cycle costs (first costs, life-cycles, needed rehabilitation, and maintenance alternatives);
- Field density control techniques;
- Equipment that will offer better control of the gradation of the mix produced;
- Effects of different diluents in the recycling agents;
- Use of cold-recycled bituminous concrete as a base on high- volume highways;

IMPORTANT CONSIDERATIONS

The following conclusions and recommendations are given to identify and discuss the issues that concern the state of North Dakota the most in regard to cold in-place recycling of asphalt pavements:

- The modified Marshall Mix design method for cold in-place recycling can be modified again to better match North Dakota's climate and material properties. However, the modified Superpave Gyratory method is recommended with an N_{design} of 30 to 35 gyrations [38];
- An initial CIR structural coefficient of 0.30 is recommended for use in North Dakota. However, the coefficient value can be increased to 0.35 if it can be verified with field and laboratory performance testing procedures;
- Performance testing for mix design as well as for structural design of CIR pavements is encouraged to develop for North Dakota. The performance tests that were developed for the Blue County project in Minnesota [24, 34] can be used as a model to follow;
- To effectively mitigate reflective cracks of cold in-place recycled pavements in North Dakota, the following recommendations need to be carried out:
 - Mill the existing asphalt pavement to at least 70% of its thickness. Theoretically, a 100% milling of the pavement thickness will be the perfect solution. However, practically, at least 1.5 inches need to be left without milling to support the recycling equipment and protect the base.
 - A flexible type binder is recommended. Flexibility promotes durability in cold climates. The ReFlex emulsion or rubber modified asphalt seem to be the best choices.
- A careful look into the candidate CIR project is very important to the success of that project. The following recommendations are given:
 - A thorough investigation of the site is needed for possible variation in pavement thickness or weak spots in the underlying layers. If the problems are too severe, CIR may not be the correct rehabilitation option to take. Otherwise, corrective measures are needed before the start of the CIR operations to avoid unnecessary delays and associated cost increase.

- A good projection of heavy traffic is needed, so the pavement can be design appropriately (e.g. choose appropriate surface treatment).
- Performance monitoring of CIR projects is encouraged to help build up information data base, so CIR design and construction methods can be improved continuously.
- North Dakota DOT must develop its own QC/QA specifications for cold in-place recycling. Many guidelines were given in the review. However, special attention should be given to the following:
 - Contrary to the HMA, CIR pavement does not densify under traffic, thus the minimum density (typically 96%) should be obtained from compaction;
 - CIR is a tender mix, therefore, a better control of moisture and temperature is needed;
 - An open-graded asphalt wearing course is an option for placement on top of the recycled base to allow curing to continue for an extended period of time if freeze damage is not a concern;
- The ReFlex emulsion cold in-place recycling provides flexibility and excellent coating (double asphalt content of that for conventional emulsion), thus high durability in cold climates. Moreover, past research supports its effectiveness against raveling, thermal cracking, reflective cracking, rutting, and moisture susceptibility. Although initial cost is 10% higher than conventional CIR, I would like the ND DOT to consider its use. Nevertheless, I recommend its use for pilot research projects in North Dakota.

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APPENDIX A

Ontario Ministry of Transportation procedures for CIR mix Design

- 1) Prepare briquettes for range of emulsion additions:
 - a) 0.5, 1.0, 1.5, 2.0 and 2.5% emulsion addition
 - b) Emulsion can be
 - i) Polymer modified high-float emulsion for some early handling and strength advantage.
 - ii) Conventional high float emulsion.
 - iii) Recycling high float emulsion
 - c) Batch 3500 gm sample of representative millings for briquettes
 - i) Determine moisture content of air dried sample
 - ii) Place in 60⁰C for 1 hour
 - d) Add water and emulsion to estimated field total fluid content (4.5%)
 - i) Add warm emulsion (60⁰C)
 - ii) Mix to check coating
 - e) Spread mixed sample in pan, cover and allow to cure.
 - i) 60⁰C for 1 hr
 - ii) simulate time between laydown and initial compaction.
 - f) Compact cured sample in Marshall Mold.
 - i) Rod and compact each face 50 blows
 - g) Cure sample in mold and recompact
 - i) 20±4 hrs in mold at 60⁰C
 - ii) each face 25 blows
 - h) cure re-compacted sample
 - i) 24 hrs in mold on its side at 60⁰C
 - ii) extrude 'briquette'
 - iii) allow to cool to room temperature
 - iv) cure for 72 hrs at room temperature

- 2) Test briquettes for each emulsion addition level
 - a) determine bulk relative density
 - i) three briquettes
 - b) determine maximum theoretical density for mix
 - c) compute air voids
 - d) determine Marshall stability and flow
 - i) two briquettes at 25⁰C
 - ii) one briquettes at 60⁰C and

- 3) Select optimum emulsion content
 - a) plot density, air voids and stability against percent added emulsion
 - b) optimum emulsion content
 - i) minimum stability at 25⁰C-8900 N
 - ii) minimum stability at 60⁰C-4500 N
 - iii) air voids 8 to 12 percent range
 - iv) adequate coating.

APPENDIX B

AASHTO's Guide Specifications for Highway Construction

Comments in Section 5 of this guide are based upon specifications in SECTION "411. Cold Recycled Asphalt Pavement" of AASHTO's *Guide Specifications for Highway Construction*. These subsections as well as references to other subsections of *Guide Specifications for Highway Construction* are shown in italics.

5.1 Description (411.01). This work shall consist of cold milling and pulverizing existing asphalt pavement to a specified depth and maximum size or processing accepted stockpiled asphalt pavement, mixing a recycling agent, water and additives with the reclaimed material, and spreading and compacting the mixture.

5.2 Materials (411.02).

Recycling agents shall include asphalt emulsions or emulsified asphalt rejuvenators. Materials shall meet the requirements of the following Subsections:

Portland Cement	701.01
Asphalt Emulsions	702.03
Water	714.01
Quicklime	714.10
Fly Ash	ASTM C 618 and D 5239
Emulsified Rejuvenators	Specifications will be provided by the User Agency
Blotter Sand	Specifications will be provided by the User Agency

A. Composition of Mixtures. The cold recycled mixture shall be composed of reclaimed asphalt pavement (RAP), a recycling agent and additives as specified. The composition of the mixture shall be established by the Contractor and approved by the Engineer and required shall be the following:

1. The sieve size where 100% passing is required_____ (31.5-mm (1 1/4-inch) sieve is recommended).
2. The beginning percentage of recycling agent_____, water_____ and additives_____ to be added to the RAP.

The cold recycled mixture shall be sampled for testing for job compliance at the spreading operation.

B. RAP Material. For cold in-place recycling, RAP shall be accepted by samples taken from the milling machine conveyor if no screening and crushing unit and from the discharge

conveyor of the screening and crushing unit if being used. RAP shall be accepted in a stockpile if a central plant without a screening and crushing unit and from samples from the discharge conveyor if screening and crushing.

C. Recycling Agents. These materials shall be accepted under Subsection " 106.04, Certification of Compliance."

D. Additives. Additive sources shall be approved by the Engineer.

5.3 Construction Requirements (411.03)

A. Weather Limitations. Cold recycling operations shall be performed with asphalt emulsions when the atmospheric temperature in the shade is 10° C (50° F) and rising and it is not foggy. When using cement or fly ash, the atmospheric temperature in the shade shall be 4° C (39° F) and rising. Recycling operations shall not be performed when rain is occurring or night temperatures are forecast to fall below freezing.

B. Cold Milling Equipment and Mixing Plants. Cold milling equipment shall conform to Subsection "409.03, Cold Mixing Asphalt Pavements-Construction Requirements."

A continuous pugmill mixing plant shall be equipped with a belt scale and automatic controls to obtain the proper amount of recycling agent and liquid additives, such as hydrated lime or cement slurry.

C. Hauling Equipment. Trucks used for hauling shall conform to subsection 401.03C.

D. Asphalt Pavers. Self-propelled asphalt pavers shall conform to subsection 401.03D.

E. Rollers. Rollers shall conform to Subsection 401.03E except that a minimum of one 23 t (25 ton) pneumatic-tired roller and one 11 t (12 ton) or larger double drum vibratory steel-wheeled roller shall be provided.

F. Temperature of Recycling Agent. A recycling agent shall be used within the temperature range specified for the mixing of the material being used. If required, the recycling agent shall be heated to within the desired temperature range without overheating.

G. RAP Moisture Content. The RAP for the cold recycled mixture shall have water added prior to mixing with the recycling agent as specified or required by the Engineer to provide proper coating/dispersion and compaction.

H. Mixing Operation. The RAP, recycling agent and additives shall be combined in the quantities required by the specifications or as directed by the Engineer. The mixing operation shall result in the RAP being completely and uniformly coated with recycling agent and additives, if used.

I. Spreading and Finishing. Asphalt pavers shall be used to spread the cold recycled mixture

to the established grade and cross slope.

The paving operations shall be conducted to protect existing and finished pavement sections. Traffic control and paving operations shall be completed according to the approved traffic control plan unless otherwise approved by the Engineer.

If blotter sand is required to prevent pick-up of the cold recycled mixture by traffic, it shall be applied by a mechanical spreader at a rate of from _____ to _____ (2.71 to 5.42 kg per square meter (5 to 10 lbs per square yard) is recommended).

J. Rolling. After the cold recycled mixture has been spread and any surface irregularities corrected, the mat shall be uniformly compacted without undue displacement and cracking.

The number, weight and type of roller furnished shall be sufficient to obtain the required compaction of the cold recycled material. The sequence of rolling operations shall provide the specified density. The longitudinal joint shall be rolled first followed by the regular rolling procedure. The initial passes for all regular rolling should begin on the low side and progress toward the high side by overlapping of longitudinal passes parallel to the pavement centerline. When using an asphalt emulsion, the initial rolling shall not begin until the emulsion has started to break (turn from brown to black color). The time of beginning initial rolling shall be determined by the Engineer. With cement or fly as the recycling agent, the initial rolling shall begin immediately after spreading of the cold recycled material and be completed as soon as possible.

Rollers shall move at a uniform speed that shall not exceed 8 km/hour (5 miles/hour). For static rollers, the drive drum normally shall be in the forward position or nearest to the paver. However, on steep grades, the unpowered drum shall be nearest to the paver, if required, to prevent the mixture from shoving and tearing. Vibratory rollers shall be operated at the speed, frequency and amplitude required to obtain the required density and prevent defects in the mat.

To prevent picking up of the mixture by rollers, drums and tires shall be uniformly wetted with water or water mixed with very small quantities of detergent or other approved material.

Any pavement shoving or other unacceptable displacement shall be corrected. The cause of the displacement shall be determined and corrective action taken immediately and before continuing rolling. Care shall be exercised in rolling the edges of the cold recycled mixture so the line and grade of the edge are maintained.

A minimum density of _____ percent (88% recommended) of the theoretical maximum density, AASHTO T 209, or a minimum density of _____ percent (93% recommended and method used in determining laboratory density specified) of laboratory specimens made of production materials should be obtained.

When the control strip method of density control is specified, the control strip shall be constructed of mixture produced with the cold recycling equipment and within the pavement

section. The Contractor shall select compaction patterns from which the Engineer (assisted by testing results using airflow nuclear gauge or other testing procedures) will select the coverage that provides the specified minimum density of percent (minimum of 97% recommended). Whenever there is a change in the cold recycled material or compaction method or equipment, or unacceptable results occur, a new test control strip shall be constructed, tested and analyzed. Revised compaction methods will be selected by the Engineer.

K. Joints. Adjacent recycling passes shall overlap the longitudinal joint a minimum of 102 mm (4 inches). Any fillet of fine, pulverized material which forms adjacent to the vertical face of longitudinal joints shall be removed prior to spreading the cold recycled material, except that such fillet adjacent to existing pavement which will be removed by a subsequent overlapping milling need not be removed. The cold recycling widths selected shall not result in longitudinal joints being located in wheelpaths.

L. Pavement Smoothness. The surface shall be tested with a 3-meter (10-foot) straightedge at locations selected by the Engineer. The variation of the surface from the testing edge of the straightedge between any two contacts, longitudinal or transverse with the surface, shall not exceed (5 mm (3/16 inch) recommended). Irregularities exceeding the specified tolerance shall be corrected by and at the expense of the Contractor by grinding/cold milling or leveling with cold or hot mix asphalt as directed by the Engineer. Following correction, the area shall be retested.

5.4 Method of Measurement (411.04)

In-place cold recycling will be measured by the station along the centerline of the lanes according to Subsection 109 or by the square meter (square yard).

Water will not be measured for payment.

Liquid recycling agent will be measured by the liter (U.S. gallon) or metric ton or mega grams (short ton) as provided in Subsection 109.1. Cement and fly ash will be measured by the metric ton or mega grams (short ton).

Cement, when dry cement or cement slurry is specified, shall be measured by the metric ton or mega grams.

Quicklime, when hydrated lime slurry is specified, shall be measured by the metric ton or mega grams (short ton).

Blotter sand will be measured by the metric ton or mega grams (short ton) or cubic meter (cubic yard) in the truck at the point of usage for the quantity applied on the pavement.

5.5 Basis of Payment (411.05)

Payment for accepted quantities will be made as follows:

Pay Item	Pay Unit
In-Place Cold Recycled Asphalt Material	Station or Square Meter (Square Yard)
Recycling Agent	Liter (Gallon) or Metric Ton or Mega grams (Short Ton)
Blotter Sand	Metric <i>Ton</i> or Mega grams (Short <i>Ton</i>) or Cubic Meter (Cubic Yard)
Quicklime	Metric Ton or Mega grams (Short Ton)
Cement	Metric Ton or Mega grams (Short Ton)

APPENDIX C

GLOSSARY OF TERMS

ABRASION: the wearing away of a surface material of a pavement structure by tire friction or snowplow scraping.

ABSOLUTE VISCOSITY: a method of measuring viscosity using the poise (Pascal. second) as the basic measurement unit utilizing a partial vacuum to induce flow in the viscometer. Test temperature of 140°F (60°C) is typical for an asphalt binder.

AGE-HARDENED: decrease in the penetration and/or increase in viscosity of asphalt binder caused by loss of volatiles and oxidization of the asphalt binder during manufacture (pre-dominantly during mixing) and subsequent exposure to weather.

AGGREGATE: a hard, inert, granular material of mineral compositions such as sand, gravel, shell, slag or crushed stone.

ALLIGATOR CRACKING: cracks which occur in asphalt pavements in areas subjected to repeated traffic loading which develop into a series of interconnected cracks, with many-sided, sharp-angled pieces, characteristically with an alligator pattern.

ASPHALT: a dark brown to black cementitious material in which the predominating constituents are bitumens that occur in nature or are obtained by petroleum processing.

ASPHALT BINDER (CEMENT): a dark brown to black cementitious material, in which the predominant constituents (+99%) are bitumens which occur in nature or are obtained as residue in petroleum manufacturing, and are used as binder in asphalt-aggregate mixes.

ASPHALT CONCRETE: a high quality mixture of asphalt binder and carefully graded coarse and fine aggregates.

ASPHALT EMULSION: an emulsion of asphalt binder and water that contains a small amount of an emulsifying agent. A heterogeneous system containing two normally immiscible phases (asphalt and water) in which the water forms the continuous phase of the emulsion, and minute globules of asphalt form the discontinuous phase. Asphalt emulsion may be either anionic i.e., electro-negatively charged asphalt globules or cationic, i.e., electro-positively charged asphalt globule types, depending upon the emulsifying agent.

ASPHALT LEVELING COURSE: a layer of asphalt concrete, of variable thickness, used to eliminate irregularities in the contour of an existing pavement surface prior to a superimposed treatment or construction.

ASPHALT PAVEMENT: pavement consisting of asphalt concrete layer(s) on supporting courses such as concrete base (composite pavement), asphalt treated base, cement treated base, granular base, and/or granular subbase placed over the subgrade.

ASPHALT REJUVENATOR: a liquid petroleum product, usually containing maltenes, added to asphalt paving material to restore proper viscosity, plasticity, and flexibility to the

asphalt.

ASPHALT -RUBBER: a blend of asphalt binder, reclaimed tire rubber, and certain additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt binder sufficiently to cause swelling of the rubber particles.

ASPHALTENES: the high molecular weight hydrocarbon fraction precipitated from asphalt by a designated paraffinic naphtha solvent at a specified solvent-asphalt ratio.

ATTERBERG LIMITS: soil moisture values used to define liquid and plastic conditions and thus to identify, silty, clayey, and organic soils in the Unified Soil Classification System.

AVERAGE ANNUAL DAILY TRAFFIC (AADT): the average daily amount of vehicles in all lanes and both directions in a one year period.

BASE COURSE: a layer of specified or selected material of planned thickness constructed on the subgrade or subbase for the purpose of serving one or more functions such as distributing load, providing drainage, minimizing frost action, etc. It may be composed of crushed stone, crushed slag, crushed or uncrushed gravel and sand, reclaimed asphalt pavement or combinations of these materials.

BATCH PLANT: a manufacturing facility for producing asphalt concrete that proportions the aggregate constituents into the mix by weighted batches and adds asphalt binder by either weight or volume.

BENKELMAN BEAM: a device for measuring the rebound deflection of a pavement surface, under a standard load, to assess/evaluate its structural adequacy.

BINDER: an adhesive composition of asphalt binder modifies asphalt binder, etc. which is primarily responsible for binding aggregate particles together.

BITUMEN: a class of black or dark-colored (solid, semisolid or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalts, tars, and pitches are typical.

BITUMINOUS: containing or treated with bitumen.

BLEEDING (FLUSHING): presence of excess asphalt material on the pavement surface caused by too much asphalt binder in the mix, too heavy of an application of an asphalt sealant, excessive crack or joint sealant, and/or low mix air void content. Traffic action and warm temperatures can contribute to the occurrence of bleeding.

CAPE SEAL: a surface treatment where a chip seal is followed by the application of either a slurry seal or micro-surfacing.

CATIONIC EMULSIONS: emulsions where the asphalt binder globules in solution having a positive charge.

CHIP: particles of crushed coarse aggregate that can be one size or uniformly graded.

CHIP SEALING: a surface treatment using one or more layers of chips and asphalt emulsion binder.

CLASS C FLY ASH: A very fine ash produced from the burning of subbituminous and lignite coals and self-cementing when mixed with water.

CLAY: a cohesive soil composed of very fine particles, which is defined by the Atterberg Limits in the Unified Soil Classification System.

COARSE AGGREGATE: that portion of aggregate retained on the No.4 (4.75 mm) sieve.

COLD IN-PLACE RECYCLING (CIR): a rehabilitation treatment involving cold milling of the pavement surface and remixing with the addition of asphalt emulsion, Portland cement or other modifiers to improve the properties, followed by screeding and compaction of the reprocessed material in one continuous operation.

COLD PLANING (CP): a process which uses equipment where a rotating drum with helical placed teeth grinds up the pavement into pieces to the desired depth.

CONSISTENCY: describes the degree of fluidity or plasticity of asphalt binder at any particular temperature. The consistency of asphalt binder varies with temperature so it is necessary to use a common or standard temperature when comparing the consistency of one asphalt binder with another.

COMPACTION: the densification or compressing of a given volume of material into a smaller volume of a soil or pavement layer by means of mechanical manipulation such as rolling or tamping, with or without vibration.

COMPACTION CURVE: the curve showing the relationship between the dry unit weight (density) and the moisture content of a soil for a given compaction effort.

COST EFFECTIVENESS: an economic measure defined as the effectiveness of an action or treatment divided by the present worth of life-cycled costs.

CRACK FILLER: a material, usually bituminous or silicon-based, used to fill and seal cracks in existing pavements.

CRACK REPAIR: maintenance in which badly deteriorated cracks are repaired through patching operations.

CRACK SEALING: a maintenance treatment in which a crack is filled with a sealant. This may or may not include prior routing and/or drying with hot compressed air.

CROSS SECTION: a profile cut or illustration taken at right angle to the centerline of the longitudinal axis of a roadway.

CRACK TREATMENT: maintenance in which cracks are directly treated through sealing or filling operations.

CRUSHED GRAVEL: aggregate produced from the crushing of gravel, with most particles having at least one crushed face.

CRUSHER: equipment that is used to reduce larger stone and gravel to smaller, usable sizes.

CRUSHED STONE: aggregate produced from the crushing of quarried rock, with all faces fractured.

CUPPING: a depression in the pavement profile along crack edges caused by damaged or weakened sub-layers.

CUTBACK ASPHALT: asphalt binder that has been blended with distillates.

DEEP PATCHING: a maintenance treatment where the asphalt concrete and granular layers are removed and replaced with asphalt concrete with or without granular material below.

DEEP STRENGTH PAVEMENT: a flexible pavement with at least 7 inches (175 mm) of asphalt concrete on 6 inches (150 mm) or more of granular base.

DENSE-GRADED AGGREGATE: an aggregate that has a particle size distribution such that when it is compacted, the resulting voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, are relatively small.

DENSIFICATION: act of increasing the density of a mixture during the compaction process.

DENSITY: the degree of solidity that can be achieved in a given mixture that will be limited only by the total elimination of voids between particles of mass. The mass of material divided by the volume, expressed as pounds per cubic foot (kilograms per cubic meter).

DISTRESS MANIFESTATION INDEX (DMI): a numerical value representing the cumulative amount of various types and severity of pavement surface distress.

DRAINAGE LAYER: an open graded base, stabilized or unstabilized, for pavements, usually 4 to 6 inches (100 to 150 mm) in thickness, and connected to a positive drainage system.

DRYER: an apparatus that will dry aggregates and heat them to specified temperatures.

DRY MIXING PERIOD: the interval of time between the beginning of the charge of dry aggregates into the pugmill and the beginning of the application of bituminous material. ,

DRUM MIX PLANT: a manufacturing facility for producing asphalt concrete that continuously proportions aggregates, heats and dries them in a rotating drum, and simultaneously mixes them with a controlled amount of asphalt binder. The same plant may produce cold-mixed bituminous paving mixtures without heating and drying the aggregates.

DUCTILITY: the ability of a substance to be drawn out or stretched thin. Ductility is considered an important characteristic of asphalt binders. In many applications, the presence or absence of ductility is usually considered more significant than the actual degree of ductility.

DYNAFLECT: a device to measure the surface deflection of a pavement under a sinusoidal varying load in order to evaluate its structural adequacy.

EDGE DETERIORATION: secondary cracks and spalls that occur within a few mils (mm) of the edges of a primary crack.

END RESULT SPECIFICATION: the specification of an end result to be achieved in construction, as compared to a method type of specification.

EMBANKMENT: a raised fill structure whose surface is higher than the natural adjoining surface.

EMULSION: an abbreviated term for asphalt emulsion binder which is produced in a high shear mixing device using asphalt binder, water, admixture, and in some cases, distillates.

EQUIVALENT SINGLE AXLE LOAD (ESAL): a concept which equates the damage to a pavement structure caused by the passage of a non-standard axle load to a standard 18,000

pound (80 kN) axle load, in terms of calculated or measured stress, strain or deflection at some point in the pavement structure or in terms of equal conditions of distress or loss of serviceability.

EROSION: wear caused by the force of wind or moving water.

FALLING WEIGHT DEFLECTOMETER (FWD): a device to measure the surface deflection of a pavement under a dynamic load in order to evaluate its structural adequacy.

FATIGUE: decrease of strength due to repetitive loading.

FAULTING: a difference in elevation between opposing sides of a crack caused by weak or moisture-sensitive foundation material.

FILLER: general term for a fine material that is inert under the conditions of use and serves to occupy space and may improve physical properties.

FINE AGGREGATE: aggregate passing the No.4 (4.75 mm) sieve and predominantly retained on the No.200 (0.075 mm) sieve.

FINES: proportion of a soil or clay and silt particles in an aggregate, finer than No.200 (0.075 mm) sieve size.

FLEXIBLE PAVEMENT: a pavement structure usually composed of one or more asphalt concrete layers over an unbound aggregate or stabilized base and prepared sub grade soil.

FLUSHING: see bleeding.

FRACTURED FACES: an angular, rough or broken surface of an aggregate particle created by crushing, by other artificial means or by nature. ,

FRICTION: resistance to the relative movement of one body (tire) sliding, rolling or flowing over another body (pavement surface) with which it is in contact.

FRICTION COURSE: open graded mix or surface treatment to improve road surface friction.

FRICTION NUMBER: the ability of an asphalt paving surface, particularly when wet, to offer resistance to slipping or skidding. Aggregates containing non-polishing minerals with different wear or abrasion characteristics provide continuous renewal of the pavement's texture maintaining a high friction number surface.

FROST HEAVE: the rise in a pavement surface caused by the freezing of pore water and/or the creation of ice lenses in the underlying layers.

FULL DEPTH PAVEMENT: a flexible pavement structure which has asphalt concrete layer(s), usually greater than 6 inches (150 mm) in total thickness, placed directly in contact with the subgrade.

GEOSYNTHETIC: woven or non-woven man-made materials designed for such applications as drainage, filtration, separation, and strengthening. They can be subdivided into various groups: geotextiles, geowebes, geocomposites, geogrids or geodrains.

GRADATION: the proportions by the mass of soil, rock, granular or other materials distributed in specified particle size ranges.

GRADE: the elevation of a surface or the slope of the surface.

GRADIENT: the amount of slope along a specific line or route, such as road surface, channel or pipe.

GRANULAR BASE EQUIVALENCY (GBE): a measure expressing the contribution of each pavement component in terms of an equivalent thickness of granular base.

GRAVEL: granular material predominantly retained on the No. 4 (4.75 mm) sieve and resulting from natural disintegration and abrasion of rock or processing of weakly bound conglomerate.

HIGH FLOAT EMULSION: an emulsion with petroleum distillates that have a gel quality imparted by the addition of various chemicals.

HOT MILLER: a device that heats the pavement surface and uses a rotating milling drum that has cutting tools mounted over the cylindrical surface to mill off up to 2 inches (50 mm) of the heated surface.

HOT IN-PLACE RECYCLING (HIR): a rehabilitation treatment used to correct asphalt pavement surface distress involving heating, removal of old asphalt concrete, processing, mixing with new aggregates, new asphalt binder and/or recycling agents, relaying, and compacting to meet specifications for conventional asphalt concrete.

HVEEM METHOD: method to design hot mix asphalt concrete.

INFRARED HEATING: involves heating a pavement using invisible heat rays having wavelengths longer than those of red light, thus direct contact of flame on pavement surface is avoided. Sometimes referred to as radiant or indirect heating.

IMPERMEABILITY: the resistance to passage of air and water into or through a pavement.

IMPERVIOUS: resistant to movement of water or air.

INTERNATIONAL ROUGHNESS INDEX (IRI): a summary statistic which characterizes road surface longitudinal roughness, based on the simulation of a standard quarter car model moving over the longitudinal profile of the road.

KINEMATIC VISCOSITY: a method of measuring viscosity of an asphalt binder using the millimeters squared per second (stoke) as the basic measurement and is related to the absolute viscosity by the specific gravity of the asphalt binder. Test temperature of 275°F (135° C) is typical for an asphalt binder.

LIFE-CYCLE COST ANALYSIS: an investigation of the present and future costs of each repair alternative, taking into account the effects of both inflation and interest rates on expenses over the life of the project.

LIPPING: an upheaval in the pavement profile along crack edges. Lipping may be the result of bulging in underlying Portland cement concrete base or the infiltration and buildup of material in the crack.

LOAD EQUIVALENCY FACTOR: a ratio of relative pavement damage to the number of Equivalent Single Axes Loads (ESAL's) a particular loading on a vehicle axle assembly represents.

LONGITUDINAL CRACK: a distress manifestation where the crack or crack pattern in the pavement is parallel to the direction of travel.

MAINTENANCE: well timed and executed activities to ensure or extend pavement life until deterioration of the pavement layer materials and sub grades is such that a minimum acceptable level of serviceability is reached, and/or it is more cost-effective to rehabilitate the pavement.

MAINTENANCE MIX: a mixture of bituminous material and mineral aggregate applied at ambient temperature for use in patching holes, depressions, and distress areas in existing pavements using appropriate hand or mechanical methods in placing and compacting the mix. These mixes may be designed for immediate use or for use out of a stockpile at a later time without further processing.

MARSHALL METHOD: a method to design hot mix asphalt concrete.

MARSHALL STABILITY AND FLOW: design properties (resistance and deformation) of asphalt concrete determined from specific laboratory tests on a test specimen.

MAXIMUM SIZE (OF AGGREGATE): in specifications for or descriptions of aggregate, the smallest sieve opening through which the entire amount of aggregate is required to pass.

METHOD BASED SPECIFICATION: a specification involving the methodology or technique to be applied to a construction item, such as number of passes of a certain weight of roller.

MILLING: removing the surface of a pavement with a self-propelled machine equipped with a transverse rotating cutter drum.

MILLING MACHINE: a piece of heavy equipment that removes pavement to a prescribed depth and width while at the same time doing a considerable amount of sizing of the reclaimed asphalt pavement (RAP) produced. It can place the RAP in trucks, a windrow or to a processing unit or units. The texture of the milled surface is a direct result of the number, spacing, type, and quality of the teeth on the milling drum, as well as the forward speed of the milling machine.

MINERAL FILLER: a finely divided mineral product at least 70 percent of which will pass a No.200 (0.075 mm) sieve. Pulverized limestone is the most commonly manufactured filler, although other stone dust, hydrated lime, Portland cement, and certain natural deposits of finely divided mineral matter are also used.

NOMINAL MAXIMUM SIZE (OF AGGREGATE): in specifications for or descriptions of aggregate, the smallest sieve opening through which the entire amount of the aggregate is permitted to pass.

OPEN-GRADED AGGREGATE: an aggregate that has a particle size distribution such that when it is compacted, the voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, remain relatively large.

OVERLAY: a new lift(s) of asphalt concrete placed on an existing pavement to restore the ride or surface friction or strengthen the structure.

PASS: a single passage of a reclaimer, motor grader or roller.

PATCHING: a maintenance treatment to repair failures or replace surface material.

PAVING GRADE: a classification system used to define asphalt binder types used for the

production of hot mix asphalt for road, street, highway and other applications.

PAVEMENT: the layers above the subgrade.

PAVEMENT CONDITION INDEX (PCI): a composite measure of surface distress types, severity, and frequency.

PAVEMENT STRUCTURE: the subbase, base, and wearing surface layers.

PAVEMENT MANAGEMENT SYSTEM (PMS): a wide spectrum of activities including the planning or programming of investments, design, construction, maintenance, and the periodic evaluation or performance used to provide an effective and efficient road network.

PENETRATION: consistency of an asphalt binder expressed as the vertical distance that a standard needle penetrates a sample of the material under standard conditions of loading, time, and temperature.

PERFORMANCE BASED SPECIFICATION: a specification involving minimum or maximum levels of performance items at certain ages, such as roughness, surface distress, surface friction or structural adequacy.

PERMEABILITY: a property of a material measured in terms of the rate with which it allows passage of water or air.

PLASTICITY INDEX (PI): the numerical difference between the liquid limit and the plastic limit of a soil.

PLASTIC LIMIT (PL): the lowest moisture content at which a soil remains plastic.

PLATE LOAD TEST: a method to determine the load bearing capacity of a subgrade, subbase or base, by measuring the deflection of a plate under a static load.

POISE: a centimeter-gram-second unit of absolute viscosity, equal to the viscosity of a fluid in which a stress of one dyne per square centimeter is required to maintain a difference of velocity of one centimeter per second between two parallel planes in the fluid that lie in the direction of flow and are separated by a distance of one centimeter.

POLISHING: the phenomena caused by the abrasive action of vehicle tires on aggregate particles that reduces the frictional properties of the surface.

PORTLAND CEMENT: a hydraulic cement comprised of very fine grains produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates and calcium sulphate.

PORTLAND CEMENT CONCRETE (PCC): the product of mixing Portland cement (mineral aggregates, water, and in some cases additives such as an air entering agent which result in a hardened structural material after hydration.

POTHOLE: localized distress in an asphalt-surfaced pavement resulting from the breakup of the asphalt surface and possibly the asphalt base course. Pieces of asphalt pavement created by the action of climate and traffic on the weakened pavement are then removed under the action of traffic, leaving a hole.

POTHOLE PATCHING: the repair of severe, localized distress in asphalt-surfaced pavements. This maintenance activity is generally performed by the agency responsible for the roadway and is intended to be a temporary repair at best. Pothole patching is not intended

to be a permanent repair. Full-depth reconstruction of the distressed areas is necessary for a permanent repair in most instances.

PREVENTIVE MAINTENANCE: major maintenance treatments to retard deterioration of a pavement, such as chip seal, rout and crack seal, etc.

PRIME COAT: the application of low-viscosity liquid asphalt or asphalt emulsion to penetrate and bind a granular base prior to the placement of asphalt concrete.

PROFILE: (longitudinal) a chart line indication of elevations, grades, and distances and usually indicating the depth the cut and height of fill of the grading work commonly taken along the centerline of the proposed road alignment.

PROFILE: (transverse) a cross-sectional plot of surface elevations across a road.

PUGMILL: a device for mixing hot or cold aggregates and reclaimed asphalt pavement with an asphalt binder, recycling agent or stabilizing additive(s) to produce a homogeneous mixture.

QUALITY ASSURANCE (QA): a system of activities whose purpose is to provide assurance that the overall quality control job is in fact being done effectively. It involves a continuing evaluation of the effectiveness of the overall control program with a view to having corrective measures initiated where necessary. For a specific product or service, this involves verifications, audits, and the evaluation of the quality factors that affect the specification, production, inspection, and use of the product or service.

QUALITY CONTROL (QC): the overall system of activities whose purpose is to provide a quality of product or service that meets the needs of users. The aim of quality control is to provide quality that is satisfactory, adequate, dependable, and economic.

RAVELING: the wearing away of a pavement surface through the dislodging of aggregate particles and/or matrix of asphalt binder and fine particles.

RECLAIMED ASPHALT PAVEMENT (RAP): asphalt pavement or paving mixture removed from its original location for use in recycled hot mix asphalt, Cold Recycled mixes or for full Depth Reclamation.

RECYCLING AGENT: 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 a recycled asphalt paving mixture.

RECYCLED HOT MIX ASPHALT (RHM): a mixture of reclaimed asphalt pavement with the inclusion, if required, of asphalt binder, asphalt emulsion, cut-back asphalt, recycling agent, mineral aggregate, and mineral filler.

REHABILITATION: a term in pavement management involving the restoration of pavement serviceability through such actions as overlays.

REJUVENATOR: an additive used in the recycling of reclaimed asphalt pavement.

RIDING COMFORT INDEX (RCI): a measure to characterize the ride quality of a pavement on a scale of 0 to 10.

ROAD FRICTION: a general term related to the frictional or friction number properties of a road surface.

ROUT: a groove cut along a crack in asphalt pavements to act as a reservoir for crack sealant.

RUTTING: a distortion occurring in the wheelpaths of an asphalt concrete pavement.

SAND: granular material passing the No. 4 (4.75 mm) sieve and predominantly retained on the No. 200 (0.075 mm) sieve, either naturally occurring or the product of processing, i.e., manufactured sand.

SAND ASPHALT: a mixture of sand and asphalt binder, cutback or asphalt emulsion. It may be prepared with or without special control of aggregate grading and may or may not contain mineral filler. Either mixed-in-place or plant mix construction may be employed. Sand asphalt is used in construction of both base and surface courses.

SATURATES: a mixture of paraffinic and naphthenic hydrocarbons that on percolation in a paraffinic solvent are not absorbed on the absorbing medium. Other compounds such as naphthenic and polar aromatics are absorbed thus permitting the separation of the saturate fraction.

SCARIFICATION: ripping (usually with grader teeth), reshaping, and recompacting a pavement surface and/or base and/or subbase layer.

SCARIFICATION: removal of the top 1 to 2 inches (25 to 50 mm) of an asphalt pavement using a bank of tines/teeth or a rotating milling drum.

SCREEN: in laboratory work an apparatus, in which the apertures are circular, for separating sizes of material.

SECONDARY CRACK: a crack extending parallel to a primary crack.

SEGREGATION: a deficiency in pavement components where the coarse particles are separated from the fine matrix.

SERVICEABILITY: the ability, at time of observation, of a pavement to serve traffic that uses the facility.

SHALLOW PATCHING: a maintenance treatment where the surface layer(s) of asphalt concrete is removed and replaced with well compacted asphalt concrete. ,

SHOULDER: the non-travel portion of a road on each side of the pavement.

SHOVING: permanent, longitudinal displacement of a localized area of the pavement surface caused by the traffic-induced shear forces.

SIEVE: in a laboratory work an apparatus, in which the apparatus are square, for separating sizes of material.

SKID NUMBER (SN): a standard test measure of the friction between a tire and a wetted road surface.

SLAB: a load bearing layer of Portland cement concrete, with or without reinforcement, sized to control and minimize shrinkage cracking.

SLURRY SEAL: a surface treatment of asphalt emulsion, sand, Portland cement, and water, placed as a slurry. Single or multiple applications may be used.

SOIL: sediments or other unconsolidated accumulations of solid particles which are

produced by the physical and chemical disintegration of rock and which may or may not contain organic matter.

SPRAY INJECTION: repair technique for potholes in asphalt-surfaced pavements and spalls in PCC- surfaced pavements that uses a spray-injection device. Spray-injection devices are capable of spraying heated asphalt emulsion, virgin aggregate or both into a distress location.

STABILITY: the ability of asphalt paving mixture to resist deformation from imposed loads. Stability is dependent upon both internal friction and cohesion.

STABILIZATION: a mechanical, chemical or bituminous treatment designed to increase or maintain the stability of a material or otherwise to improve its engineering properties.

STABILIZING ADDITIVE: a mechanical, chemical or bituminous additive or material used to increase or maintain the strength, durability or moisture susceptibility of a material or to improve its engineering properties.

STANDARD PROCTOR: a test method where 12,375 foot-pounds per cubic foot (593 Kj/(cubic meter) of compactive effort is used to determine the optimum moisture content and maximum dry density of a soil aggregate.

STOKE: a unit of kinematic viscosity, equal to the viscosity of a fluid in poises divided by the density of the fluid in grams per cubic centimeter.

STRIPPING: a loss of adhesion of asphalt to aggregate in an asphalt pavement. It is influenced by the amount of water present, the type and source of aggregate, the temperature, the asphalt, the hydraulic forces acting on the pavement, and the age of the pavement.

STRUCTURAL ADEQUACY INDEX (SAI): a measure that uses deflections and Equivalent Single Axle Loads to characterize the structural adequacy of a pavement on a scale of 0 to 10.

STRUCTURAL CAPACITY: the load-carrying capacity of a pavement that can be determined by evaluating the materials and/or layer thickness of the pavement structure or the surface deflections.

STRATEGIC HIGHWAY RESEARCH PROGRAM (SHRP): a comprehensive, multimillion dollar research program in the USA and other countries involving research in Long Term Pavement Performance, Asphalt, Concrete, Structures and Highway Operation.

SUBBASE: the layer of select compacted granular material placed on the subgrade and which is overlain by the base of a flexible pavement structure or the Portland cement concrete slab of a rigid pavement structure.

SUBGRADE: the soil prepared and compacted to support a pavement structure.

SUPERPAVE: a general term encompassing the methodology developed in the Strategic Highway Research Program for selecting asphalt binders, for designing hot mix asphalt concrete and for estimating the fatigue, rutting, low-temperature cracking and moisture damage performance of the asphalt concrete.

SURFACE RECYCLING: a general term that describes the Hot In-Place Recycling of the upper portion of an asphalt pavement.

SURFACE TREATMENT: a maintenance or rehabilitation treatment used to seal a road surface, improve its ride or surface friction. Multiple applications of bituminous material and mineral aggregate may be used.

TACK COAT: an application of liquid asphalt or asphalt emulsion to an existing asphalt concrete surface prior to the placement of an asphalt concrete lift or overlay.

TEXTURIZATION: grooving, milling or otherwise abrading the top of a pavement surface.

THERMOPLASTIC (MATERIAL): a material that becomes soft when heated and hard when cooled.

THROW-AND-GO: repair technique for cold-mix patching materials in which material is shoveled into pothole, with no prior preparation of the pothole, until it is filled: compaction of the patch is left to passing traffic, while the maintenance crew moves on to the next distress location.

THROW-AND-ROLL: repair technique for cold-mix patching materials in which material is shoveled into pothole, with no prior preparation of the pothole, until it is filled: the material truck tires are used to compact the patch before the crew moves on to the next distress location.

TRANSVERSE: perpendicular to the pavement centerline or direction of laydown.

TRANSVERSE CRACK: a distress manifestation where the crack is perpendicular to the direction of travel.

TRAFFIC GROWTH FACTOR: a factor used to estimate the percentage annual increase in traffic volume.

TRUCK FACTOR: the number of Equivalent Single Axle Loads (ESAL's) represented by the passage of a truck.

VIRGIN AGGREGATE: new aggregate added to recycled asphalt pavement in the production of recycled hot mix asphalt concrete, Cold Recycled mixtures and for mechanical stabilization using Full Depth Reclamation.

VIRGIN ASPHALT BINDER: new asphalt binder added during recycling to improve the properties of the recycled asphalt concrete.

VOIDS: empty spaces in a compacted mix surrounded by asphalt coated particles.

WARRANTY: guaranteed performance of a work or physical item; e.g. contractor guarantee that pavement rutting on a project will not exceed "x" mils (mm) at "y" years.

WORKABILITY: the ease with which mixtures may be placed and compacted.