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Methods of Rehabilitating Pavements with Moisture Damaged Asphalt Layers: Technical Report

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16. Abstract

Moisture damage to old hot mix asphalt layers can result in surface cracking and greatly reduce the life of any new asphalt overlay. Buried moisture damage, generally called stripping, in asphalt layers can often go undetected, resulting in new overlays not reaching their design life. Conventional wisdom is to mill down to solid HMA and then place full depth new HMA. This strategy is costly and means that several inches of good materials will be sent to reclaimed asphalt pavement stockpiles. Recent developments for cold in-place recycling (CIR) and cold central-plant recycling (CCPR) technologies can be considered for addressing moisture-damaged asphalt layers by recycling the existing material in place to create a structurally sound asphalt treated base layer.

Through a thorough literature review, field sampling and testing, a comprehensive lab study, and evaluation of pavement design alternatives, this project identified lab methods to determine treatment options, documented binder type and temperature influences on material properties, used lab properties to predict pavement performance, and recommended special specification updates for use on future CIR or CCPR projects. These methods and specification updates should be considered to explore developing recycling options for identified moisture-damaged pavement sections.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Stephen Sebesta.

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TABLE OF CONTENTS

Page

List of Figures ... ix
List of Tables ... xi
Chapter 1. Introduction ... 1
Chapter 2. Literature Review ... 3
- Cold Recycling ... 3
  - Cold In-Place Recycling ... 3
  - Cold Central-Plant Recycling ... 4
  - Cold Recycling Applications ... 4
- Equipment ... 6
  - Cold Milling Machines ... 6
  - Wirtgen In-Situ Cold Recyclers ... 8
  - Roadtec In-Situ Cold Recycler ... 10
  - Cold Central-Plant Recycling Plants ... 10
- CIR/CCPR Specifications ... 11
- Mix Design Specifications of CIR/CCPR ... 14
- Field Performance of CIR and CCPR Nationwide ... 20
  - Virginia ... 20
  - Mississippi ... 21
  - Alabama and Virginia ... 23
  - Nevada ... 25
  - Iowa ... 26
  - Texas ... 27
  - Modulus of Cold Recycling Pavements ... 28
- CIR Experience in Texas ... 30
- Conclusions ... 31

Chapter 3. Project Investigations and Sampling ... 33
- US 60 Summary ... 35
- I-40 Summary ... 37
- FM 92 Summary ... 38

Chapter 4. Performance of Lab and Field Mixtures ... 41
- CIR Mix Design ... 41
- Performance Test on CIR Mixes ... 44
  - Hamburg Wheel Track Test ... 44
  - Illinois Flexibility Index Test ... 45
  - Indirect Tensile Asphalt Cracking Test ... 46
  - Resilient Modulus Test ... 47
  - Dynamic Modulus (E*) Test ... 48
  - Repeated Load Test ... 50
- Performance on Existing CIR Sections in Texas ... 52
  - Visual Observation ... 52
  - Results of Hamburg Wheel Track Test ... 53
  - Results of Cracking Tests ... 54

        - Results of Resilient Modulus Test 54
    - Conclusions 55
- **Chapter 5. Design and Construction Recommendation 57**
    - Introduction 57
    - Pavement Designs Using FPS21 57
    - Pavement Performance Prediction Using TxME 59
        - Simulation Inputs for TxME 60
        - Prediction Results 64
    - Construction Recommendations 66
- **Chapter 6. Conclusions and Recommendations 67**
    - Conclusions 67
    - Recommendations 67
- **References 69**
- **Appendix A. Laboratory Guidelines for Mixture Design 73**
    - Introduction 73
    - Sampling and Processing 73
    - Mix Design Procedure 74
- **Appendix B. Specification Recommendations for Cold-Recycled Asphalt Mixtures 77**

LIST OF FIGURES

Page

Figure 1. Combination of Machines for CIR Technology in the Field. 3
Figure 2. CIR Construction Steps (*1*). 4
Figure 3. Typical CCPR Construction Steps. 4
Figure 4. Three Different Cold Recycling Application Options. 5
Figure 5. Cold Milling Machines of Wirtgen. 6
Figure 6. Cold Milling Machines of Roadtec. 7
Figure 7. Cold Recycling Process with Cold Recyclers. 9
Figure 8. Roadtec RT-500 Cold Recycler. 10
Figure 9. Mobile Cold Recycling Mixing Plants. 11
Figure 10. Cross-Section of Pavement Structure: (a) Left Lane and (b) Right Lane. 21
Figure 11. US 49 Map Showing Six Pavement Sections. 22
Figure 12. NCAT Test Track Diagram. 24
Figure 13. Pavement Structure (As-Built) of Each Test Section. 24
Figure 14. Before and after CIR Construction on US 83 in Texas. 28
Figure 15. Dynamic Modulus Test Results of CCPR Mixture. 29
Figure 16. Small-Scale Dynamic Modulus Test Method for Cold Recycling Field Cores. 30
Figure 17. Dynamic Modulus Test Results of Cold Recycling Field Cores. 30
Figure 18. Example Field Sampling Activities. 34
Figure 19. FWD and Coring of existing CIR Section. 35
Figure 20. Example GPR and Core from US 60. 36
Figure 21. Typical Structure and Observations from US 60. 37
Figure 22. Example GPR from I-40. 37
Figure 23. Drill Logs from I-40. 38
Figure 24. Example GPR and Core from FM 92. 39
Figure 25. Gradation Plots from Three Different RAP Sources. 41
Figure 26. Lab Foaming Equipment and CIR Specimens after IDT Test. 42
Figure 27. IDT Strength Results of CIR Mixes. 43
Figure 28. Performance Tests Used for CIR Mixtures. 44
Figure 29. Results of Hamburg Wheel Track Test. 45
Figure 30. Results of Illinois Flexibility Index Test. 46
Figure 31. Results of IDEAL-CT. 47
Figure 32. Results of Resilient Modulus Test. 48
Figure 33. Dynamic Modulus Values Measured at 10 Hz and at Each Temperature. 50
Figure 34. Results of Repeated Load Test for Each RAP Source. 51
Figure 35. Visual Observation and Cores' Thickness Measurements. 53
Figure 36. Results of Resilient Modulus. 55
Figure 37. Possible CIR Design Options for Field Sections. 59
Figure 38. Performance Check Feature Connecting FPS 21 with TxME. 60
Figure 39. Climate Data Selection for US 60. 61
Figure 40. ESAL-Based Traffic Input for US 60 Entered in TxME. 61
Figure 41. Material Property Inputs of CIR Layer for US 60. 62
Figure 42. Resilient Modulus of Each CIR Mix for Field Sections. 63

Figure 43. Results of Repeated Load Test for Each CIR Mix of Field Sections. 64
Figure 44. Predicted Rutting Performance of Field Sections. 65

LIST OF TABLES

Page

Table 1. Summary of Main Features of Wirtgen Milling Machines.. 7
Table 2. Summary of Main Features of Roadtec Milling Machines.. 8
Table 3. Summary of Main Features of In-Situ Cold Recyclers... 10
Table 4. Weather Limitation Specifications. 12
Table 5. Pulverizing Specifications. 12
Table 6. Equipment Capability Specifications... 13
Table 7. Summary of Curing Criteria for CIR in the United States. 14
Table 8. CIR Mix Design Requirements of Texas.. 15
Table 9. CCPR Mix Design Target Values and Requirements of Texas...................................... 16
Table 10. CIR/CCPR Mix Design Requirements for Emulsified Asphalt, ARRA. 17
Table 11. CIR/CCPR Mix Design Requirements with Emulsified Asphalt in Virginia.............. 18
Table 12. CIR/CCPR Mix Design Requirements with Foamed Asphalt in Virginia. 19
Table 13. CIR Mix Design Parameters of FHWA Section 310... 20
Table 14. Information on US 49 Pavement Sections.. 23
Table 15. Performance Data of CIR Pavements Based on PCI.. 26
Table 16. Performance Data and Information for 26 CIR Test Sections in Iowa........................ 27
Table 17. Sections Used for Evaluating Cold Recycling Options.. 33
Table 18. Sections Sampled for Lab Testing... 41
Table 19. Results of Hamburg Wheel Track Test (mm)... 54
Table 20. Results of I-FIT Test: Flexibility Index (No Unit). 54
Table 21. Results of IDEAL-CT Test: CT_{Index} (No Unit)... 54
Table 22. Key FPS21 Design Inputs for Field Sections. 57
Table 23. Alpha and Mu Values for Each CIR Mix of Field Sections... 64
Table 24. Sampling Roadway Materials.. 73
Table 25. Master Gradation of Crushed Millings. 74
Table 26. Recommended Mix Design Requirements. 77
Table 27. Recommended Quality Control Tests.. 77

CHAPTER 1. INTRODUCTION

Stripping is moisture damage to old hot mix asphalt (HMA) layers, which are often buried several inches down in the pavement structure. Certain aggregates, such as gravels, are known more susceptible to stripping. While the current generations of asphalt mixtures often use antistripping additives, historically use of such additive was not always practiced. Consequently, many miles of pavements with a moisture-damaged layer near the surface may exist. The problem of buried moisture-damaged asphalt mixtures often goes undetected. The consequence of this situation is new overlays may not reach their design life due to the deteriorated materials' condition in the underlying stripped asphalt layer. The condition of the buried moisture-damaged layer also worsens with time, so the typical current permanent repair method is to mill the stripped layer out completely and replace it with new HMA.

Recent developments in cold in-place recycling (CIR) and cold central-plant recycling (CCPR) can be considered for addressing this stripping problem while recycling 100 percent of the existing HMA and placing it as a structurally sound black base layer. Due to environmental friendliness, the conservation of paving materials, and cost-effectiveness, CIR and CCPR technologies have been popular methods in rehabilitating existing asphalt pavements.

This research project determined if stripped asphalt materials can be recycled by treatment with an asphalt stabilizer to provide a solid layer exhibiting close to equivalent long-term performance as new virgin asphalt-base mixtures. Following the current introduction, Chapter 2 presents a literature review on identifying current and emerging techniques for cold recycling, relevant specifications and mix design approaches used for cold recycling, and documented performance of cold recycled pavement layers. Chapter 3 documents project investigations and sampling. Chapter 4 presents performance results from lab-designed CIR mixtures and field CIR cores. Chapter 5 recommends pavement designs and construction options for field sections that were evaluated in this project. Finally, Chapter 6 summarizes the overall project findings and conclusions.

CHAPTER 2. LITERATURE REVIEW

This literature review focused on identifying current and emerging techniques for cold recycling, relevant specifications and mix design approaches used for cold recycling, and documented performance of cold recycled pavement layers.

COLD RECYCLING

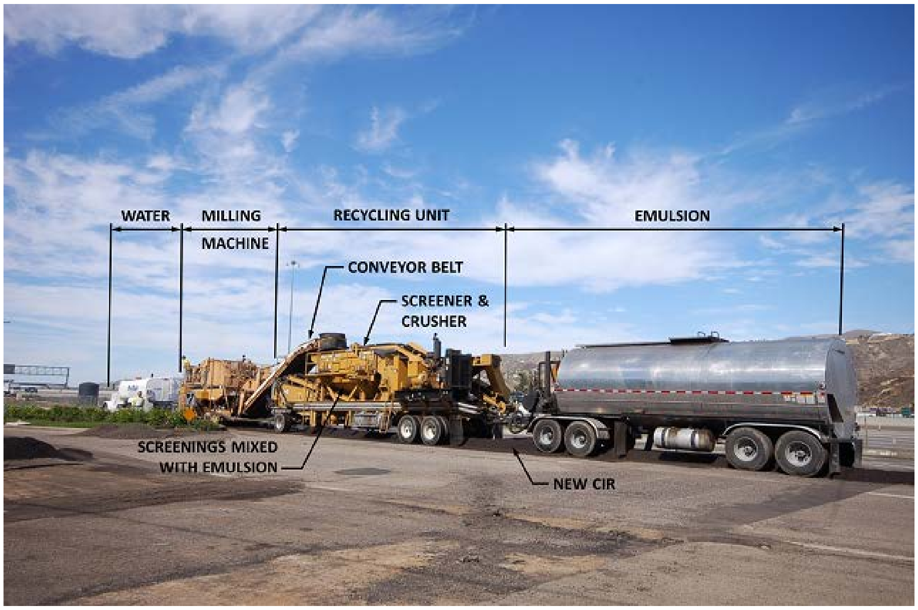
Cold recycling is the term used for reusing materials from an existing pavement without the addition of heat to produce a rehabilitated pavement. Two cold recycling methods are available:

1. CIR.
2. CCPR.

CIR is achieved in-place using a recycling machine on the construction site, whereas CCPR is used by hauling materials produced in-plant.

Cold In-Place Recycling

As shown in Figure 1, CIR requires a combination of milling machine, recycling unit, and asphalt transport for the rehabilitation process. The existing pavement is milled up, the reclaimed asphalt pavement (RAP) is mixed with emulsion or foamed asphalt, and then the recycled mix is placed by a paver. The combination of tankers coupled to the recycler is configured in accordance with the particular recycling application and the type of stabilizing agent that is applied. Last, the CIR layer is covered by a HMA layer, as shown in Figure 2.



Source: Los Angeles County Department of Public Works website.

Figure 1. Combination of Machines for CIR Technology in the Field.

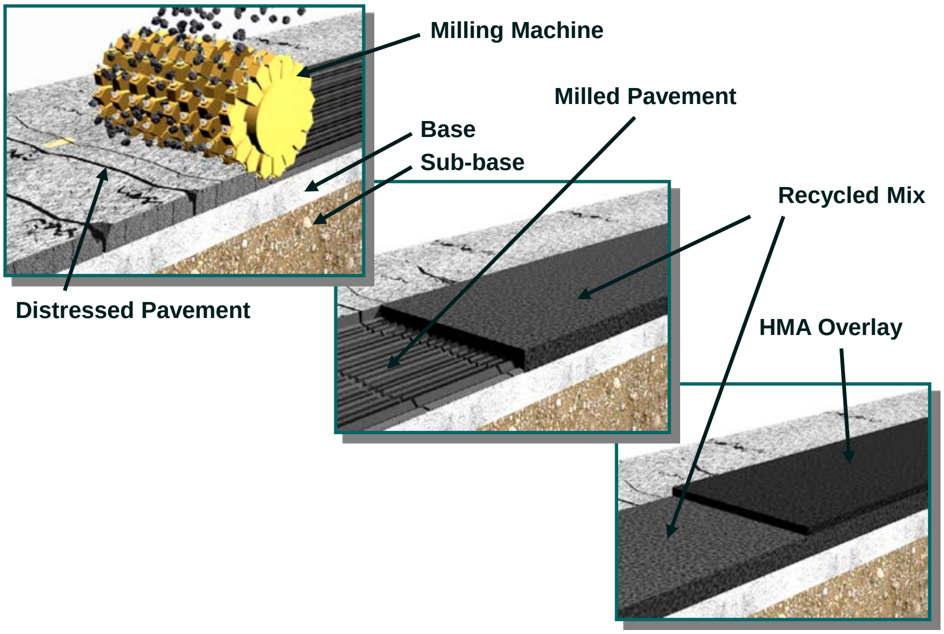


Figure 2. CIR Construction Steps (*1*).

Cold Central-Plant Recycling

CCPR involves the same process as CIR except that cold recycled materials are produced in-plant, as shown in Figure 3. The main benefit of using in-plant compared to in-place treatments is that recycled materials can be controlled better for quality mix. However, plant processing is typically a more expensive option than CIR due to transportation costs.

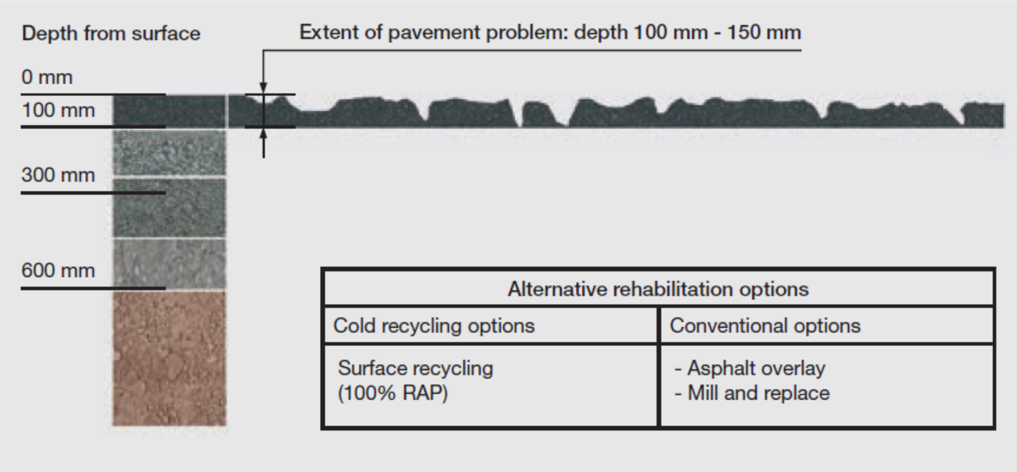
Figure 3. Typical CCPR Construction Steps.

Cold Recycling Applications

There are numerous possible cold recycling applications for maintaining and rehabilitating pavements. However, each application will be project specific, with three primary factors dictating the method of recycling that is appropriate:

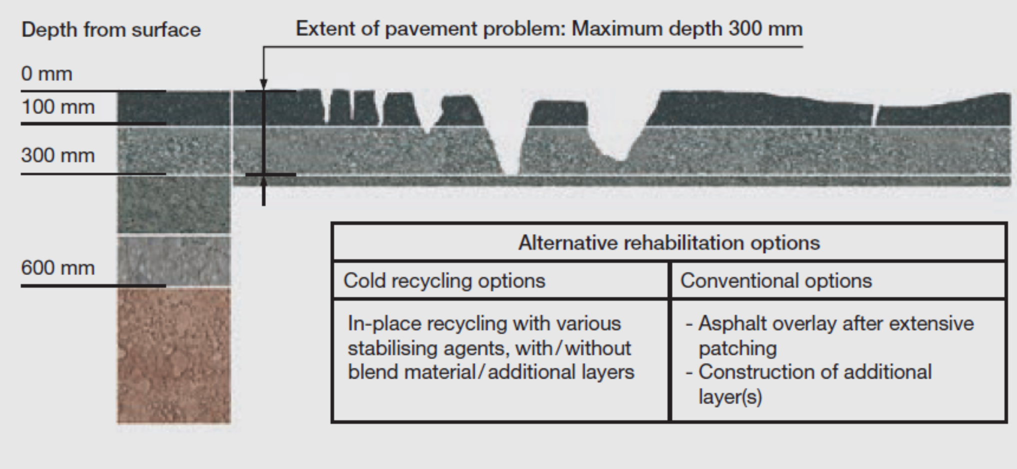
- The type of pavement distress that needs to be addressed.
- The quality of material in the recycling horizon.
- The outcome required (i.e., service life expectations).

Wirtgen (*2*) describes three different pavement distress conditions and some of the different options that can be applied for addressing the relevant distress, as shown in Figure 4.



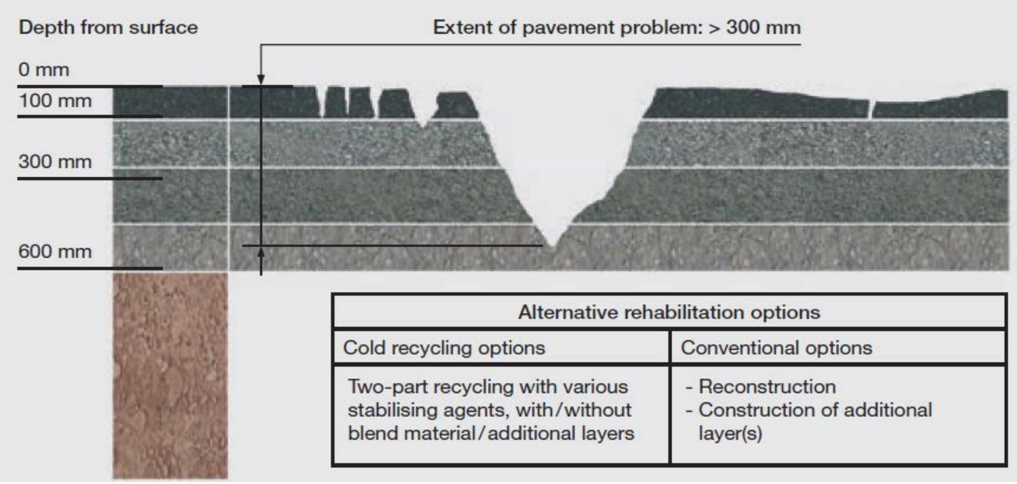
Alternative rehabilitation options	
Cold recycling options	Conventional options
Surface recycling (100% RAP)	- Asphalt overlay - Mill and replace

(a) Rehabilitation options for upper pavement/surfacing distress



Alternative rehabilitation options	
Cold recycling options	Conventional options
In-place recycling with various stabilising agents, with/without blend material/additional layers	- Asphalt overlay after extensive patching - Construction of additional layer(s)

(b) Rehabilitation options for structural distress in the upper pavement layers



Alternative rehabilitation options	
Cold recycling options	Conventional options
Two-part recycling with various stabilising agents, with/without blend material/additional layers	- Reconstruction - Construction of additional layer(s)

(c) Rehabilitation options for deep-seated structural distress

Figure 4. Three Different Cold Recycling Application Options.

EQUIPMENT

Cold Milling Machines

Cold milling machines are used to remove asphalt pavements either at full depth or in individual, thin pavement layers. Milling machines are equipped with wheel units and a milling drum (Figure 5[c]). Various milling machines are available and can be selected depending on work areas, construction situations, loading capacity, and productivity. Figure 5 and Figure 6 show milling machines available on the market. Cold milling machines can be equipped with bolt-on packages that allow them to be used for CIR as well. An additive spray bar is mounted on the cutter housing to inject foamed or emulsified asphalt into the cutter housing. The additive is then thoroughly blended with the milled materials by the cutter drum and can be left in a window or fed by the conveyor directly into the paver (from Wirtgen and Roadtec websites). Table 1 and Table 2 summarize the main features of the milling machines made by Wirtgen and Roadtec, respectively. Also, Caterpillar provides six different cold milling machines (cold planers).

(a) Wirtgen small milling machine (b) Wirtgen large milling machine

(c) Wirtgen milling unit

Source: Wirtgen website.

Figure 5. Cold Milling Machines of Wirtgen.

(a) Roadtec RX-700e/ex (b) Roadtec RX-900e/ex

Source: Roadtec website.

Figure 6. Cold Milling Machines of Roadtec.

Table 1. Summary of Main Features of Wirtgen Milling Machines.

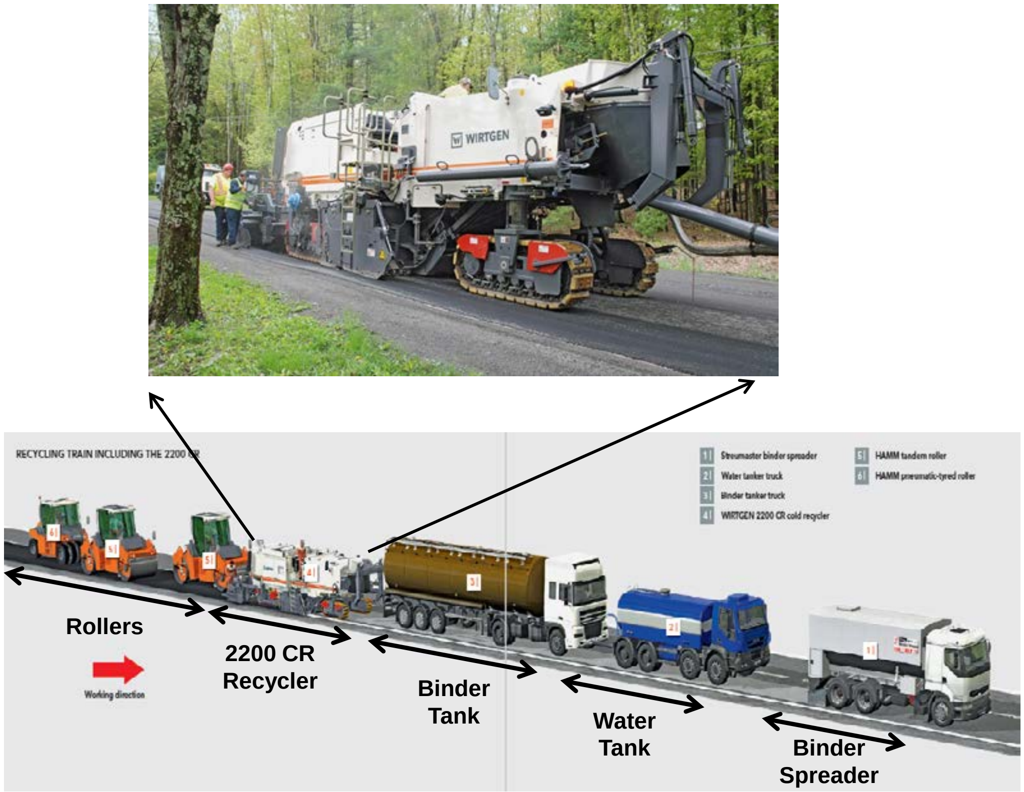
Wirtgen Milling Machines	**Models**	**Milling Width**	**Milling Depth**	**Features**
Small milling machines	W-35-Ri	14"	0–4"	- Partial repairs of roadways. - Milling around road fixtures. - Cutting slots and milling tie-ins. - Removal of road markings. - Renovation of industrial areas and indoor facilities. - Rumble strip millings.
	W-50-Ri	20"	0–8"	
	W-60-Ri	23"	0–8"	
	W-100-i	39"	0–12"	
	W-100-Ri	39"	0–12"	
	W-120-Ri	3' 11"	0–12"	
Compact milling machines	W-100-CFi	39"	0–13"	- Milling works under cramped conditions. - Partial repairs of roadways. - Layer-by-layer removal of road pavements. - Production of specified surface textures (fine milling). - Leveling irregularities in the surface course.
	W-120-CFi	48"	0–13"	
	W-130-CFi	51"	0–13"	
	W-150-CFi	51"	0–13"	
Large milling machines	W-200-i	6' 7"	0–13"	- Layer-by-layer removal of road pavements. - Removal of complete road pavements up to a milling depth of 13 inches. - Production of specified surface textures (fine milling). - Leveling irregularities in the surface course. - Improving the skid resistance.
	W-200-Hi	6' 9"	0–12"	
	W-210-i	6' 7"	0–13"	
	W-220	7' 3"	0–14"	
	W-220-i	7' 3"	0–14"	
	W-250-i	7' 3"	0–14"	

Table 2. Summary of Main Features of Roadtec Milling Machines.

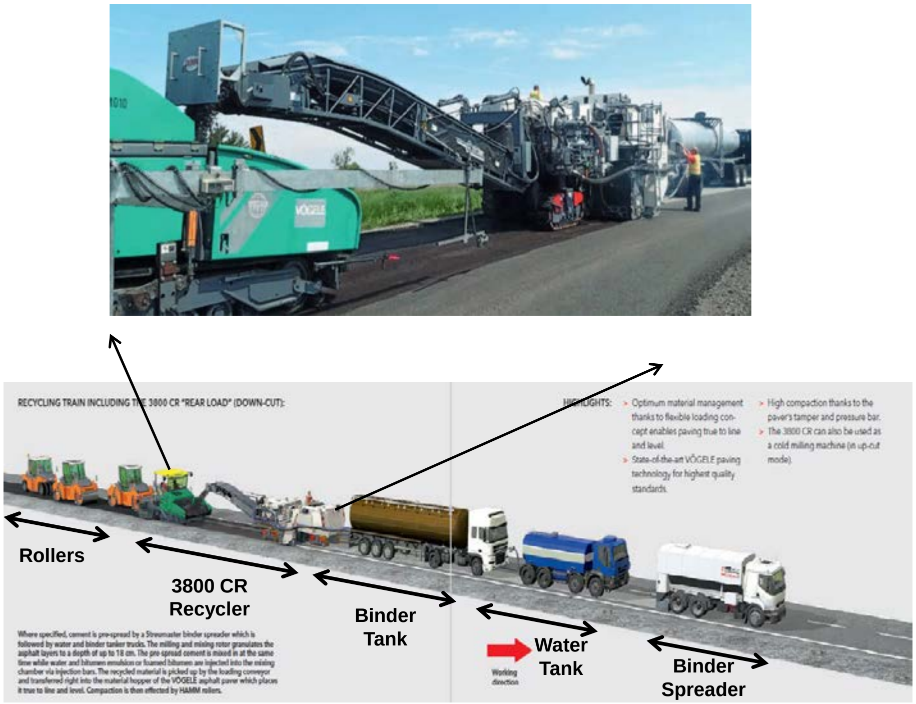
Roadtec Milling Machines	Milling Width	Milling Depth	Features
RX-100e	20"	8"	- Highly efficient for small areas. - Easy to cut around manhole covers and other obstructions.
RX-300e/ex	47.25"	12"	- Compact milling machine. - For both commercial applications and narrow milling projects. - 100° load-out conveyor swing capability.
RX-600e/ex	86"	13"	- Available with four-track assemblies. - Light and maneuverable for urban situations. - Ample loading capacity.
RX-700e/ex	126"	13"	- Heavy-duty machine. - Available with four-track or three-track assemblies. - 60° front load-out conveyor swing.
RX-900e/ex	150"	14"	- The most productive machine. - Available with four-track or three-track assemblies. - 60° front load-out conveyor swing. - Additional custom width can be supplied.

Wirtgen In-Situ Cold Recyclers

Wirtgen provides two different in-situ cold recyclers, as shown in Figure 7: (a) Wirtgen 2200 CR (track-mounted recycler), and (b) Wirtgen 3800 CR (rear load type). The Wirtgen 2200 CR is equipped with injection systems that convey the liquid binding agents, via hose connections, from the tanker trucks coupled to the machine for precise injection into the mixing chamber. The heavy-duty milling and mixing rotor granulates the existing damaged asphalt pavement to a depth of up to 10 inches (250 mm). The granulated material is then mixed with the pre-spread cement and injected water and emulsion or foamed asphalt in the machine’s mixing chamber, thus creating a new mix in an in-situ process. The recycled mix is then deposited between the rear track units via a material guide plate system. The Wirtgen 3800 CR has the same process as the Wirtgen 2200 CR, including the fact that the recycled material can be picked up by the loading conveyor and transferred right into the material hopper of an asphalt paver (VÖGELE paver), which places it true to line and level (from the Wirtgen website).



(a) Wirtgen 2200 CR: track-mounted recycler



HIGHLIGHTS:

- Optimum material management thanks to flexible loading concept enables paving true to line and level.
- State-of-the-art VÖGELE paving technology for highest quality standards.
- High compaction thanks to the paver's tamper and pressure bar.
- The 3800 CR can also be used as a cold milling machine (in up-cut mode).

Where specified, cement is pre-spread by a Streumaster binder spreader which is followed by water and binder tanker trucks. The milling and mixing rotor granulates the asphalt layers to a depth of up to 18 cm. The pre-spread cement is mixed in at the same time while water and bitumen emulsion or foamed bitumen are injected into the mixing chamber via injection bars. The recycled material is picked up by the loading conveyor and transferred right into the material hopper of the VÖGELE asphalt paver which places it true to line and level. Compaction is then effected by HAMM rollers.

(b) Wirtgen 3800 CR: rear load type

Source: Wirtgen website.

Figure 7. Cold Recycling Process with Cold Recyclers.

Roadtec In-Situ Cold Recycler

The Roadtec RT-500 is a mobile recycling trailer that can either be fed or pulled by an RX-900 (Figure 6[b]) for in-place recycling, as shown in Figure 8. With a rating of 500 tons/hour (tph), it is capable of recycling miles of road in a short amount of time. Table 3 summarizes the main features of the in-situ recyclers made by Wirtgen and Roadtec.

Source: Roadtec website.

Figure 8. Roadtec RT-500 Cold Recycler.

Table 3. Summary of Main Features of In-Situ Cold Recyclers.

In-Situ Cold Recycler	Model	Working Width	Recycling Depth	Features
Wirtgen	2200-CR	7' 3"	0–10"	- Recycling with the customary up-cut milling process against the direction of travel. - Recycling with the customary down-cut milling process in the direction of travel.
	3800-CR	12' 6"	0–6"	
Roadtec	RT-500	—	—	- Pushed by RX-900 cold planer. - Materials are discharged directly into paver. - Can be set up to make cold mix from a RAP stockpile using emulsion or foam.

Cold Central-Plant Recycling Plants

In-plant operations for the asphalt mix production can be feasible for the CCPR process. A mobile mix plant is one good option for the CCPR process since the mixing plant can come to the vicinity of the project site. The mobile plant allows for time and cost savings, reducing expensive truck travel and fuel consumption. Both Wirtgen and Roadtec provide a mobile mix plant, as shown in Figure 9. The KMA-220i from Wirtgen can mix 246 tph of cold mix asphalt, while the RT-500 from Roadtec can also be set up on a site as a cold mobile mix plant that can produce cold mix asphalt of 500 tph.

(a) Wirtgen: mobile cold recycling mixing plant

(b) Roadtec: mobile cold recycling mixing plant

Figure 9. Mobile Cold Recycling Mixing Plants.

CIR/CCPR SPECIFICATIONS

Table 4, Table 5, and Table 6 summarize CIR and/or CCPR specifications of several agencies in terms of weather limitations, pulverizing (RAP gradation), and equipment capacities. Table 7 summarizes the curing criteria for CIR in the United States; the information came from 42 states that were surveyed on CIR guidelines by the Federal Highway Administration (FHWA). The curing criteria are either moisture content in percentage or curing time in hours or days.

Table 4. Weather Limitation Specifications.

Organization	Specification
Asphalt Recycling and Reclaiming Association (ARRA) (CIR/CCPR)	• Shall be performed when the RAP temperature is above 50°F (10°C) with overnight ambient temperatures above 35°F (2°C). • Some emulsified asphalt may require a higher operating ambient and/or RAP temperature, such as 60°F (16°C) and rising.
FHWA FP-14 (CIR)	• Do not begin work when fogs, showers, rain, frost, or temperatures below 35°F (2°C) are anticipated within 24 hours. • Place cold in-place recycled asphalt base on a dry, unfrozen surface when the air temperature in the shade and the road surface temperature are 50°F (10°C) and rising.
American Association of State Highway and Transportation Officials (AASHTO) Section 411 (CIR)	• Work when the atmospheric temperature is at least (60°F) and when there is no precipitation.
Virginia Department of Transportation (DOT) (CIR/CCPR)	• Shall be completed when both the atmospheric temperature and material to be processed (measured in the shade and away from artificial heat) is a minimum 50°F. (The weather forecast shall not call for freezing temperatures within 48 hours after placement of CIR on any portion of the project.)
Texas DOT (CIR/CCPR)	• Perform work when roadway surface temperature is 60°F and rising. CIR work will not be allowed during foggy or rainy weather, and the forecast shall not call for freezing temperatures within 48 hours after placement.

Source: (*3*–*9*).

Table 5. Pulverizing Specifications.

<table>
<tr><th>Organization</th><th>Specification</th></tr>
<tr><td>ARRA
(CIR/CCPR)</td><td>The gradation of the RAP shall have 100% passing the 1.25-inch (31.5 mm) sieve.</td></tr>
<tr><td>FHWA FP-14
(CIR)</td><td>Mill the existing pavement to the required depth and width. Reduce oversize particles to a maximum size of 1.5 inches (37.5 mm).</td></tr>
<tr><td>AASHTO Section 411
(CIR)</td><td>Mill and pulverize existing asphalt pavement to the specified depth. Use a self-propelling pulverizing machine capable of maintaining a uniform grade and cross-slope. Ensure pulverized material meets the following gradation:
<table>
<tr><th>Sieve Size</th><th>% Passing</th></tr>
<tr><td>2.0 inches</td><td>100</td></tr>
<tr><td>1.5 inches</td><td>90–100</td></tr>
</table></td></tr>
<tr><td>Virginia DOT
(CIR/CCPR)</td><td>Maximum sieve size, 1.5 inches (37 mm) and 100% passing limit (AASHTO T27).</td></tr>
<tr><td>Texas DOT
(CIR/CCPR)</td><td>Crush or break the reclaimed asphalt material such that 100% will pass the 1.0-inch sieve prior to the addition of the asphalt emulsion.</td></tr>
</table>

Source: (*3*–*9*).

Table 6. Equipment Capability Specifications.

Organization	Specification
ARRA (CIR/CCPR)	• A minimum 12.5 ft (3.9 m) cutter capable of removing the existing pavement to the depths. • Cutting depth to within 0.25 inch (6 mm) of the desired depth. • An effective means for controlling cross-slope.
FHWA FP-14 (CIR)	• Automatic depth controls to maintain the cutting depth to within plus or minus 0.25 inch. • Positive means cross-slope elevation control. • Capability of milling the existing asphalt pavement material to the required depth in a single path. • 12.5 ft minimum cutter width.
TxDOT (CIR)	• Can cut in one continuous pass to the depth shown on the plans and to a minimum width of not less than 12 ft. • Has automatic depth controls to maintain the cutting depth to within 0.25 inch of that shown on the plans. • Use transverse controls with an automatic system to control cross-slope at a given rate. (The use of a heating device to soften the pavement will not be permitted.)

Source: (*3*–*5*, *9*).

Table 7. Summary of Curing Criteria for CIR in the United States.

State	Standard	State	Standard
Alabama	—	Nevada	10~45 days
Arizona	1.5% or less	New Hampshire	14 days
Arkansas	—	New Jersey	—
Colorado	Below 1%	New Mexico	Minimum of 2 hours
Connecticut	2 hours	New York	7 days
Delaware	7 days	North Carolina	—
Florida	—	Ohio	10~14 days
Hawaii	—	Oklahoma	—
Idaho	10 days	Ontario	14 days
Illinois	—	Pennsylvania	At least 1 week Max 2%
Iowa	1.5%	South Carolina	—
Kansas	2% or less	South Dakota	1.5% or less
Kentucky	—	Tennessee	—
Louisiana	—	Texas	—
Maine	4 days	Utah	—
Maryland	—	Vermont	1.5% or less
Massachusetts	—	Virginia	—
Mississippi	—	Washington	1%, 7 days
Missouri	—	West Virginia	—
Montana	—	Wisconsin	—
Nebraska	7 days or longer	Wyoming	—
TxDOT	No traffic, including construction traffic, will be allowed on completed recycled asphalt pavement for a period of at least 2 hours. Pavement may be opened to all traffic after 2-hour period. This time may be adjusted by the engineer to allow establishment of sufficient cure so traffic will not initiate raveling.		

Source: (*10*).

MIX DESIGN SPECIFICATIONS OF CIR/CCPR

Laboratory mix designs should be performed with representative samples taken from the roadway for CIR or from a stockpile for CCPR. It is crucial to verify the suitability of selected materials including stabilizing agents that will be produced on site. Mix design procedures can be used for emulsified asphalt or foamed asphalt as the primary stabilizing agent. Additional additives such as cement and lime may be used to meet the requirements if necessary. Generally, mix design procedures for both CIR and CCPR incorporate five basic steps as follows:

- Step 1: Preparation of sample.
    - Field sampling.
    - Soil tests (gradation and moisture content).

- Step 2: Determination of stabilizing agent amount including optimum moisture content (OMC).
- Step 3: Fabrication of testing specimens.
- Step 4: Curing of the specimens.
- Step 5: Engineering property tests.

The mix design requirements of CIR and CCPR in Texas are summarized in Table 8 and Table 9, respectively. Also, other agencies' mix design requirements are presented in Table 10 through Table 13 for comparison and review purposes.

Table 8. CIR Mix Design Requirements of Texas.

<table>
<tr><td colspan="3">150 mm specimens shall be prepared in a Superpave gyratory compactor. The mixture should meet the following criteria at the selected design asphalt emulsion content.</td></tr>
<tr><th>Property</th><th>Criteria</th><th>Purpose</th></tr>
<tr><td>Compaction effort, Superpave gyratory compactor</td><td>1.25° angle, 600 kPa stress, 35 gyrations</td><td>Density indicator</td></tr>
<tr><td>Density, Tex-207-F, Part I</td><td>Report</td><td>Compaction indicator</td></tr>
<tr><td>Hamburg Wheel Test*, Tex-242-F</td><td>5,000 passes (min)
15,000 passes (max)</td><td>Rutting resistance</td></tr>
<tr><td>Gradation for design millings, Tex-200-F, Part I</td><td>Report</td><td>—</td></tr>
<tr><td>Marshall stability, ASTM D1559 Part 5, 40°C</td><td>2500 lb min</td><td>Stability indicator</td></tr>
<tr><td>Retained stability based on cured stability**</td><td>70% min</td><td>Ability to withstand moisture damage</td></tr>
<tr><td>Tensile strength, psi; Tex-226-F</td><td>40 min</td><td>Cracking resistance</td></tr>
<tr><td>Raveling test, 4-hour cure @ 10°C and 50% humidity, ASTM D7196 and Appendix B</td><td>2% max</td><td>Raveling resistance</td></tr>
</table>

* Tested on compacted specimens after 60°C (140°F) curing to constant weight. Specimen must obtain minimum number of passes prior to reaching 0.5-inch rut depth. Specimen must obtain at least 0.5-inch rut depth prior to maximum number of passes.

** Vacuum saturation of 55 to 75 percent; water bath at 25°C for 23 hours, with last hour at 40°C.

Source: (*9*).

Table 9. CCPR Mix Design Target Values and Requirements of Texas.

Material	Target Range (%) by weight
RAP	90–92
Field Sand	4–5
Emulsion (short-term mix)	2.5 ± 0.25
Emulsion (long-term mix)	3.0 ± 0.25
Water	2.0

Property	Test Method	Requirement
Compaction, Texas Gyratory Compactor	Tex-206-F	NA
Moisture Content, %	Tex-212-F	Report
Theoretical Maximum Specific (Rice) Gravity	Tex-227-F	Report
Laboratory Molded Bulk Specific Gravity	Tex-207-F	Report
Laboratory Molded Density, %	Tex-207-F	Report
Unconditioned Hveem Stability, min*	Tex-208-F	15
Conditioned Hveem Stability Ratio, % min**	Tex-208-F	80

* Long-term stabilities tested on compacted specimens after curing to constant weight in a 140°F oven.
** 23-hour soak at 77°F, followed by 1-hour soak at 104°F.
Source: (*8*).

Table 10. CIR/CCPR Mix Design Requirements for Emulsified Asphalt, ARRA.

Test Method	Criteria	Property
Asphalt content of RAP AASHTO T308 (ASTM D6307)	Report only	Quantity of existing binder
Gradation of unextracted RAP AASHTO T11 and T27 (ASTM C117 and C136)	1.25-inch (31.5 mm) maximum	Maximum particle size
Bulk specific gravity of compacted, cured specimens AASHTO T166 (ASTM D2726)	Report only	Density as compacted
Maximum theoretical specific gravity AASHTO T209 (ASTM D2041)	Report only	Maximum specific gravity
Air voids of compacted, cured specimens AASHTO T269 (ASTM D3203)	Report only—recycling agent content should not be adjusted to meet an air void content	Compacted air voids
Either		
Indirect tensile strength AASHTO T283 (ASTM D4867)	Minimum 45 psi (310 kPa)	Cured strength
Or		
Marshall stability AASHTO T245 (ASTM D6927)	Minimum 1,250 lb (5,560 N)	Cured stability
Tensile strength ratio/retained Marshall stability based on moisture conditioning AASHTO T283 (ASTM D4867) AASHTO T245 (ASTM D6927)	Minimum 0.7	Resistance to moisture-induced damage
Raveling test of cold mixed bituminous mixtures ASTM D7196	**Maximum 7.0% loss**	Resistance to raveling
Ratio of residual asphalt to cement	Minimum 3:1	Prevent rigid behavior
RAP coating test AASHTO T59	Minimum good	Coating of binder
Maximum emulsified asphalt heating temperature	Report only (obtained from supplier)	Maximum heating temperature
PG grade of recycling agent AASHTO M320	Select low-temperature PG grade of recycling agent to meet or be one grade higher than the requirements for location of project and depth in pavement structure	Resistance to low-temperature cracking

Source: (*3*, *4*).

Table 11. CIR/CCPR Mix Design Requirements with Emulsified Asphalt in Virginia.

Item	Test Method	Criteria	Fabrication/Conditioning Procedure
Emulsified Asphalt Stabilized Materials			
1	Moisture Density Relations AASHTO T180, Method D	Determined by design; used to establish target field density	
2	Marshall Stability Test ASTM 5581 (6-inch specimens), AASHTO T245 (4-inch specimens)	2500 lb minimum (6-inch [150 mm] diameter specimen), or 1250 lb minimum (4-inch [100 mm] diameter specimen)	Three specimens shall be produced at 75 blows per side (or 30 gyrations per AASHTO T312) and cured at 140ºF (60°C) to constant mass; hold specimens at 104°F (40°C) for 2 hours in a forced draft oven immediately prior to testing.
3	Retained Stability ASTM 5581 (6-inch specimens), AASHTO T245 (4-inch specimens)	Minimum 70% of results of #2	An additional three specimens shall be produced and cured at 140°F (60°C) to constant mass. Specimens shall then be vacuum saturated to 55–65% moisture content, 77°F (25°C) water bath for 23 hours and 104°F (40°C) water bath for an additional hour immediately prior to testing.
4	Raveling Stability (ASTM D7196)	Maximum 2%	Specimens shall be produced using a gyratory at 20 gyrations and cured at 50°F (10°C) for 4 hours at 50% humidity.
5	Thermal Cracking (Indirect Tensile Test, AASHTO T322)	The critical cracking temperature must be less than or equal to the pavement temperature given for the project climate area and pavement depth by LTPPBind	See Notes 1 through 7 in Table 12.

Source: (*7*).

Table 12. CIR/CCPR Mix Design Requirements with Foamed Asphalt in Virginia.

Item	Test Method	Criteria	Fabrication/Conditioning Procedure
Foamed Asphalt Stabilized Materials			
1	Moisture Density Relations, AASHTO T180, Method D	Determined by design; used to establish target field density	
2	Dry Indirect Tensile Strength (ITS), AASHTO T283 Section 11	45 psi min	Three specimens shall be produced using 75 blows per side (or 30 gyrations per AASHTO T312) compacted at or below OMC and cured as follows: 4-inch (100 mm) diameter specimens—oven dry at 104°F (40°C) for 72 hours and cool to ambient temperature for 24 hours; 6-inch (150 mm) diameter specimens—air dried for 24 hours, then an additional 48 hours at 104°F (40°C) in sealed plastic bag, cool to ambient temperature for 24 hours.
3	Retained Indirect Tensile Strength, AASHTO T283 Section 11	Minimum, 70% of the dry ITS from Item 9	An additional three specimens shall be produced and cured according to Item 9, and then submerged in 77°F (25°C) water bath for 24 hours prior to testing.
4	Expansion Ratio, Wirtgen 2012 Cold Recycling Manual	10 times when aggregate temperature is 50°F to 77°F (10°C to 25°C); 8 times when aggregate temperature is greater than 77°F (25°C)	
5	Half-Life—Wirtgen 2012 Cold Recycling Manual	6 second min	
All materials (emulsified asphalt and foamed asphalt) shall be controlled following Item 1.			
1	Materials Gradation Test (AASHTO T27), prior to stabilization	Gradation to control field production	

Notes:

1. Specification temperature shall be chosen using current FHWA LTPPBind software, using the weather station closest to the project. The required temperature shall be the coldest temperature at the top of the recycled layer, using 98 percent reliability.
2. Samples shall be compacted to 150 mm (6-inch) diameter and at least 115 mm height, compacted to within 1 percent of design air voids at the design stabilizing agent content. Compacted samples shall be cured at 140ºF (60ºC) no less than 48 hours. Before testing, sample mass shall be checked every 2 hours until change in mass between successive checks does not exceed 0.05 percent. After curing, two specimens shall be saw-cut from each compacted sample to 50 mm (2 inches) in height. Perform bulk density testing after saw-cutting.
3. Three specimens are required at each of the three testing temperatures.
4. Select two testing temperatures that bracket the specification temperature above. For example, if the specification temperature is −13ºF (−25ºC), then two of the selected testing temperatures shall be −4ºF and −22ºF (−20ºC and −30ºC). A temperature of 14ºF or −40ºF (−10ºC or −40ºC) shall be used as the third testing temperature.
5. The tensile strength test shall be performed on each specimen directly after the tensile creep test (at the same temperature as the creep test).
6. The critical cracking temperature is defined as the temperature at the intersection of the thermal stress curve (derived from the creep data) and the tensile strength line (the line connecting the average tensile strengths at the three testing temperatures).
7. To meet this specification, the critical cracking temperature predicted by the Indirect Tensile Test must be less than or equal to the pavement temperature given for the project climate area and pavement depth by LTPPBind.

Source: (*7*).

Table 13. CIR Mix Design Parameters of FHWA Section 310.

Material or Property	Requirement
Indirect tensile strength, AASHTO T283* Tensile strength dry Tensile strength ratio	70 psi (480 kPa) minimum 70% minimum
Raveling test, ASTM D7196, 4-hour cure at 50°F (10°C), 50% humidity** Average mass loss	5% maximum

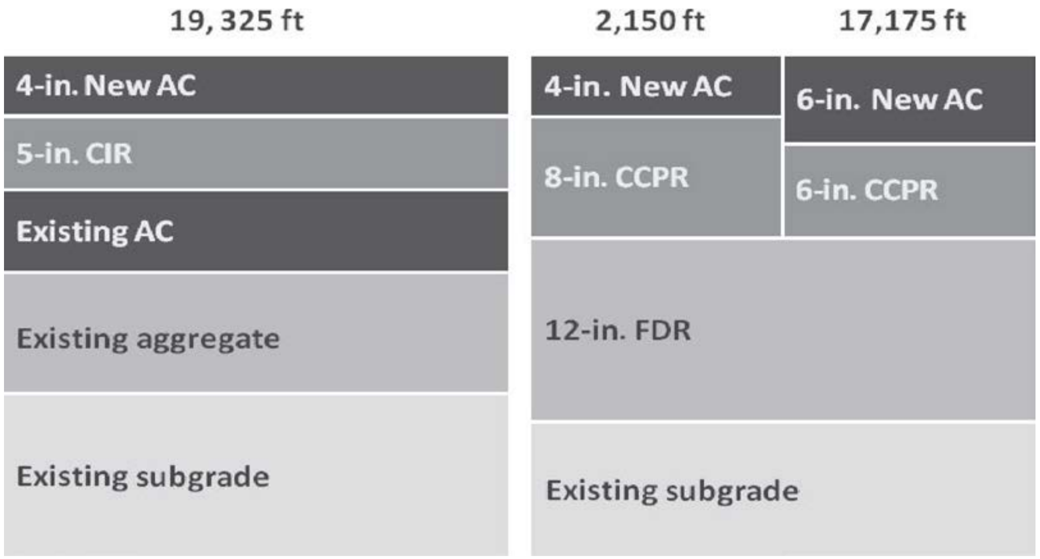
* Follow the modified AASHTO T283 procedures as indicated in Federal Lands Highway T 524.
** Use the listed testing conditions for the raveling test, unless otherwise directed by the CO.
Source: (*5*).

FIELD PERFORMANCE OF CIR AND CCPR NATIONWIDE

Field performance is ultimately the key interest to pavement engineers and road users. It is critical to identify the real performance of CIR/CCPR pavements. Detailed information on field performance of CIR/CCPR pavements in several states in the United States including the limited experience in Texas is described in this section.

Virginia

In 2011, Virginia DOT constructed a 3.66 mi section on southbound I-81 near Staunton, Virginia, using full-depth reclamation (FDR), CCPR, and CIR. Prior to the construction, this section showed structurally related deterioration at the pavement surface, had a low structural capacity, and had a history of frequently recurring maintenance. According to Virginia DOT records in 2008, the directional traffic volume was 23,000 vehicles per day with 28 percent being trucks. Figure 10 shows the completed cross-section of the pavement structure. A combination of CIR and asphalt concrete (AC) overlay was constructed on the left lane, while the right lane was constructed with a combination of FDR, CCPR, and AC overlay. A hydraulic cement content of 1.0 percent and a foamed asphalt content of 2.0 percent were used to produce the CIR and CCPR materials. A combination of hydraulic cement and lime kiln dust was used to stabilize the base layer with use of the FDR. The initial 3-year performance of the 3.66-mi section of I-81 was assessed for rut depth, ride quality, and structural capacity. To date, approximately 6 million equivalent single-axle loads (ESALs) have been applied, and both lanes performed well after 3 years of service (*11*, *12*, *13*).



(a) (b)

Figure 10. Cross-Section of Pavement Structure: (a) Left Lane and (b) Right Lane.

Mississippi

The Mississippi DOT constructed a segment on high-traffic (average annual daily traffic [AADT] of 12,000) US 49 in 2010 using FDR, CIR, and traditional construction. The US 49 project was an approximately 14.8-km section of a four-lane divided highway with 14 percent trucks at the time of construction. The pavement structures exhibited distresses such as longitudinal cracking, transverse cracking with spalling, rutting, potholes, and patching. Figure 11 shows the six pavement sections of US 49 and their locations. Detailed information on the pavement sections is summarized in Table 14. After 53 months open to traffic, three data sets were measured: pavement distress survey, in-place core laboratory-measured properties, and falling weight deflectometer (FWD) data. Overall, all US 49 sections performed well, and the cement FDR and emulsion CIR sections performed the best based on the survey results. Laboratory-measured properties of in-place cores demonstrated distinct differences between cement and emulsion stabilization; however, trends did not manifest in overall distress survey results. FWD data indicated that most sections showed good structural capacity, except Section 5 (cement CIR), which may result in more rapid fatigue damage (*14*, *15*).

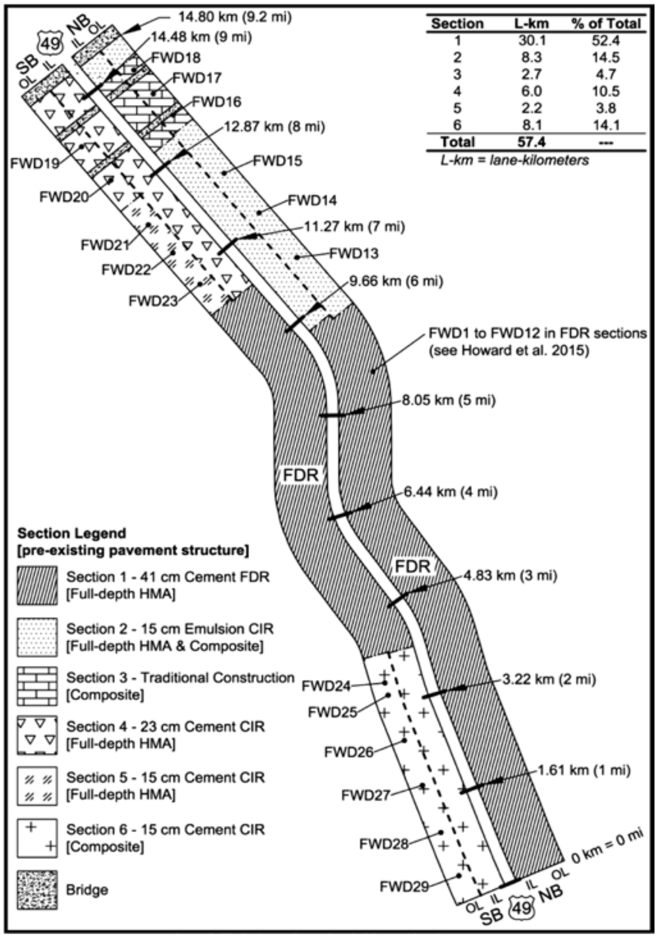


Figure 11. US 49 Map Showing Six Pavement Sections.

Table 14. Information on US 49 Pavement Sections.

Pavement Layers	Property	Section					
		1	2	3	4	5	6
9.5 mm NMAS HMA	Thickness	3.8 cm	3.8 cm	3.8 cm	3.8 cm	3.8 cm	3.8 cm
	Grade	PG 76-22	PG 76-22	PG 76-22	PG 76-22	PG 76-22	PG 76-22
19 mm NMAS HMA	Thickness	7.6 cm	7.6 cm	18.9 cm	7.6 cm	7.6 cm	7.6 cm
	Grade	PG 76-22	PG 76-22	Varied[a]	PG 76-22	PG 76-22	PG 76-22
Base	Thickness	41 cm	15 cm	15 cm	23 cm	15 cm	15 cm
	Type	FDR	CIR	Crushed stone	CIR	CIR	CIR
	Binder and dosage[b]	4.8% cement	4% emulsion and 1% hydrated lime	Not applicable	4.4% cement	4.4% cement	4.4% cement
Preexisting structure[c]	—	Full-depth HMA	Full-depth HMA and composite	Composite	Full-depth HMA	Full-depth HMA	Composite

Note: Emulsion was a cationic engineered emulsion classified as a CSS-1h with 63% residue (i.e., 4% emulsion yielded a 2.5% residual asphalt content); thickness = nominal targeted thickness; NMAS = nominal maximum aggregate size; cement was a Type I Portland cement.

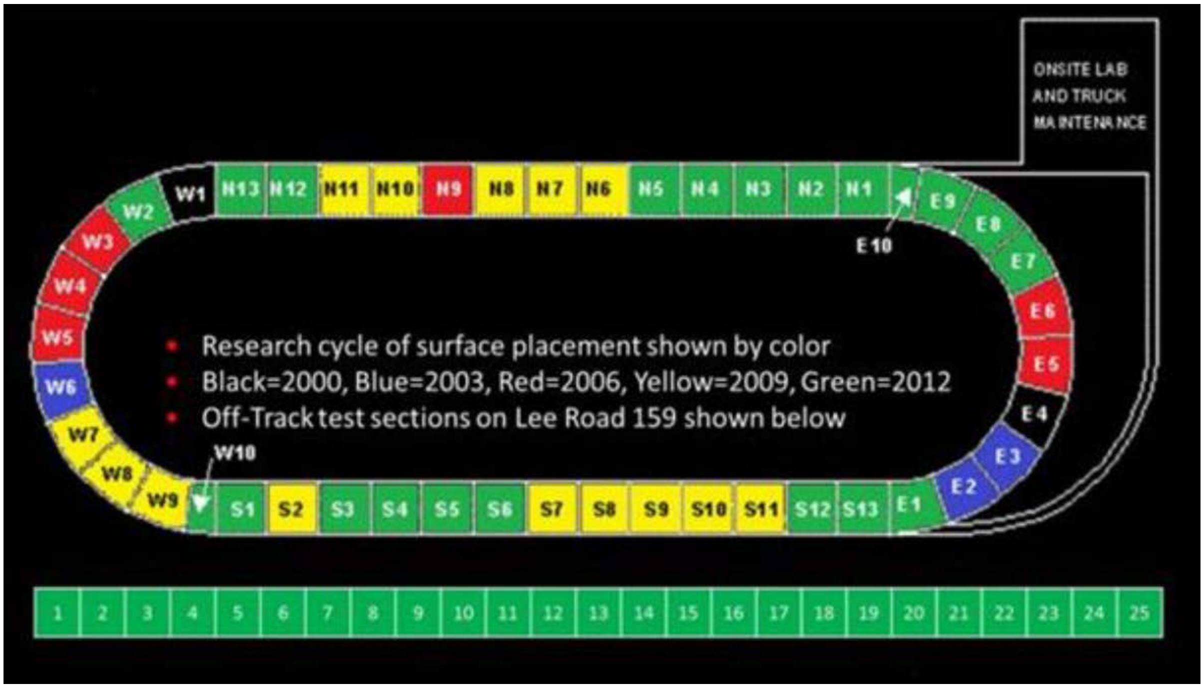
[a] The lowest 6.3 cm of the total 18.9-cm layer used PG 67-22 binder; the upper 12.6 cm used PG 76-22 binder.

[b] Binder dosages are by mass of RAP.

[c] Preexisting structure refers to the general pavement structure present prior to rehabilitation.

Alabama and Virginia

In 2012, Virginia DOT contracted with the National Center for Asphalt Technology (NCAT) in Alabama to evaluate the performance of three test sections using CCPR. The three test sections were subjected to heavily loaded trucks until approximately 10 million 18-kip ESALs during the 2012–2014 track cycle at the NCAT Test Track. The initial 2-year performance was investigated by analyzing the results of laboratory testing from collected cores, as well as deflection testing from FWD, temperature, pressure, and strain measurements from embedded instruments, and surface-observable deterioration of the pavement sections. Figure 12 and Figure 13 show the three sections constructed at the NCAT Test Track and the average as-built thickness of each test section including material types, respectively. During the 2-year test cycle with 10 million 18-kip ESALs applied, no observable surface distresses were found, the ride quality changed very little, and the rutting was less than 0.3 inch in all three sections. Other results and findings can be found in the related report (*16*).



Note: Virginia DOT sections are N3, N4, and S12.

Figure 12. NCAT Test Track Diagram.

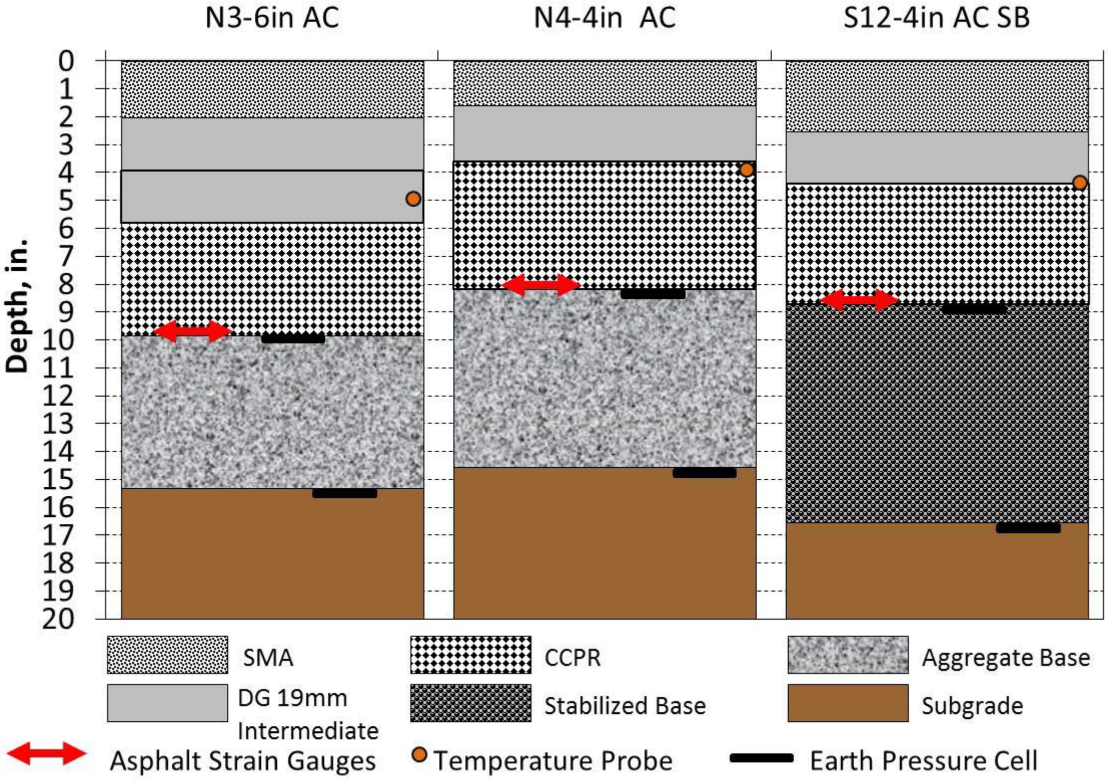


Figure 13. Pavement Structure (As-Built) of Each Test Section.

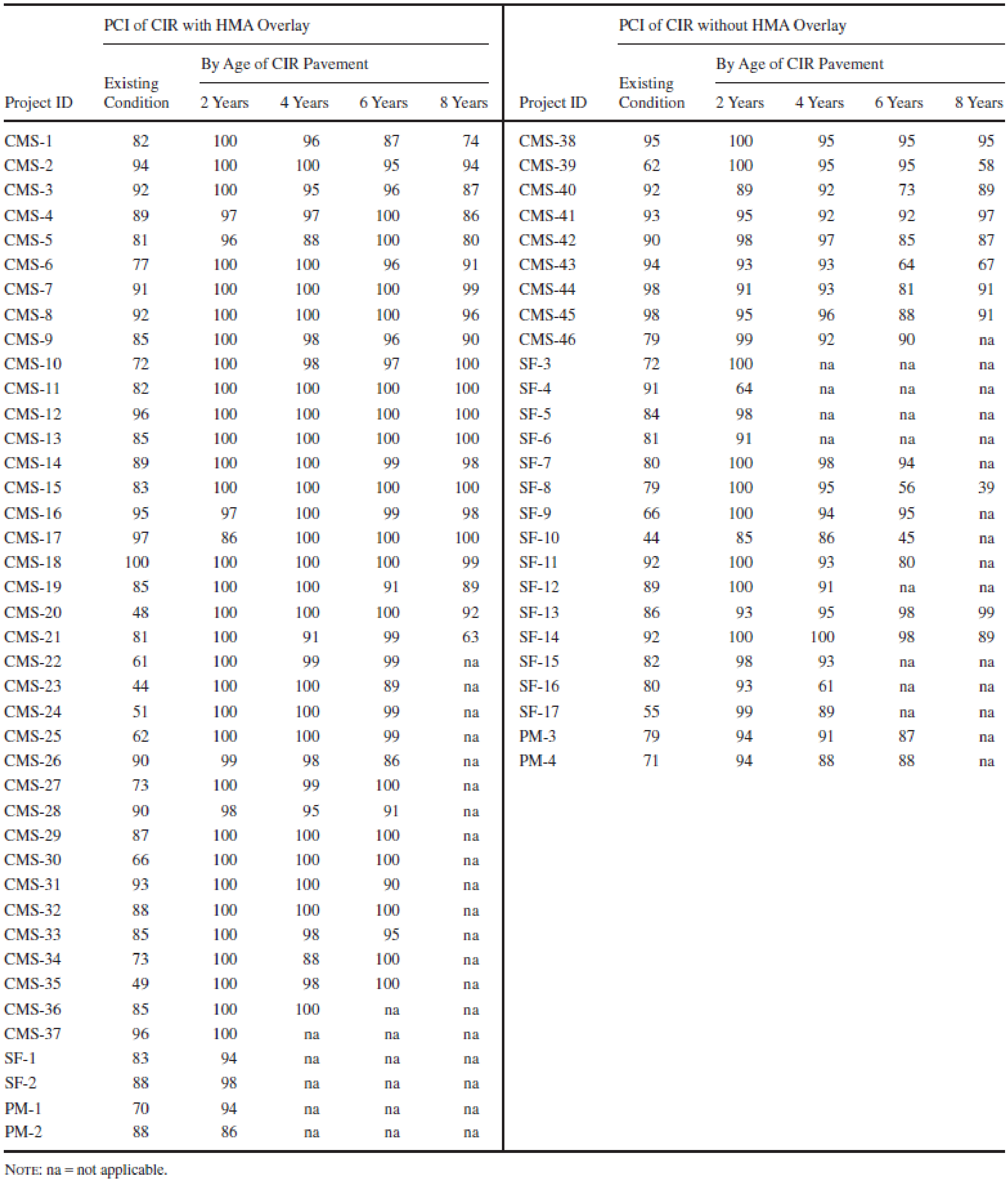
Nevada

Nevada DOT constructed more than 50 CIR projects between 2001 and 2009. Nevada DOT has been constructing two types of CIR projects: for high-volume roads, CIR is covered by an HMA overlay and a surface treatment; and for low-volume roads, CIR is followed by just a surface treatment. Sanjeevan et al. (*17*) evaluated the long-term performance of CIR pavements (both types mentioned) and three emulsion technologies (CMS-2S, solvent-free [Reflex], and polymerized asphalt surface sealer) based on the concept of the pavement condition index (PCI). They measured the pavement distresses of CIR pavements according to Nevada DOT specifications and calculated the PCI values for CIR pavements. The PCI decision matrix is as follows:

- Excellent condition: if PCI is greater than 85.
- Very good condition: 70–85.
- Good condition: 55–69.
- Fair condition: 40–54.
- Poor condition: if less than 40.

Table 15 presents the calculated PCI values of CIR pavements with and without HMA overlay at different ages of CIR pavements. The CIR pavements with HMA overlay had significantly reduced rutting and roughness, whereas those reductions in the CIR pavements without HMA overlay were not as significant. In terms of cracking, half of the CIR with HMA overlay pavements and most of the CIR without HMA overlay pavements experienced transverse cracking, while one-third of the CIR pavements with HMA overlay and two-thirds of the CIR without HMA overlay experienced longitudinal cracking during their in-service periods. Overall, roads constructed with CIR followed by an HMA overlay plus surface treatment performed much better than low-volume roads constructed with CIR followed by just a surface treatment.

Table 15. Performance Data of CIR Pavements Based on PCI.



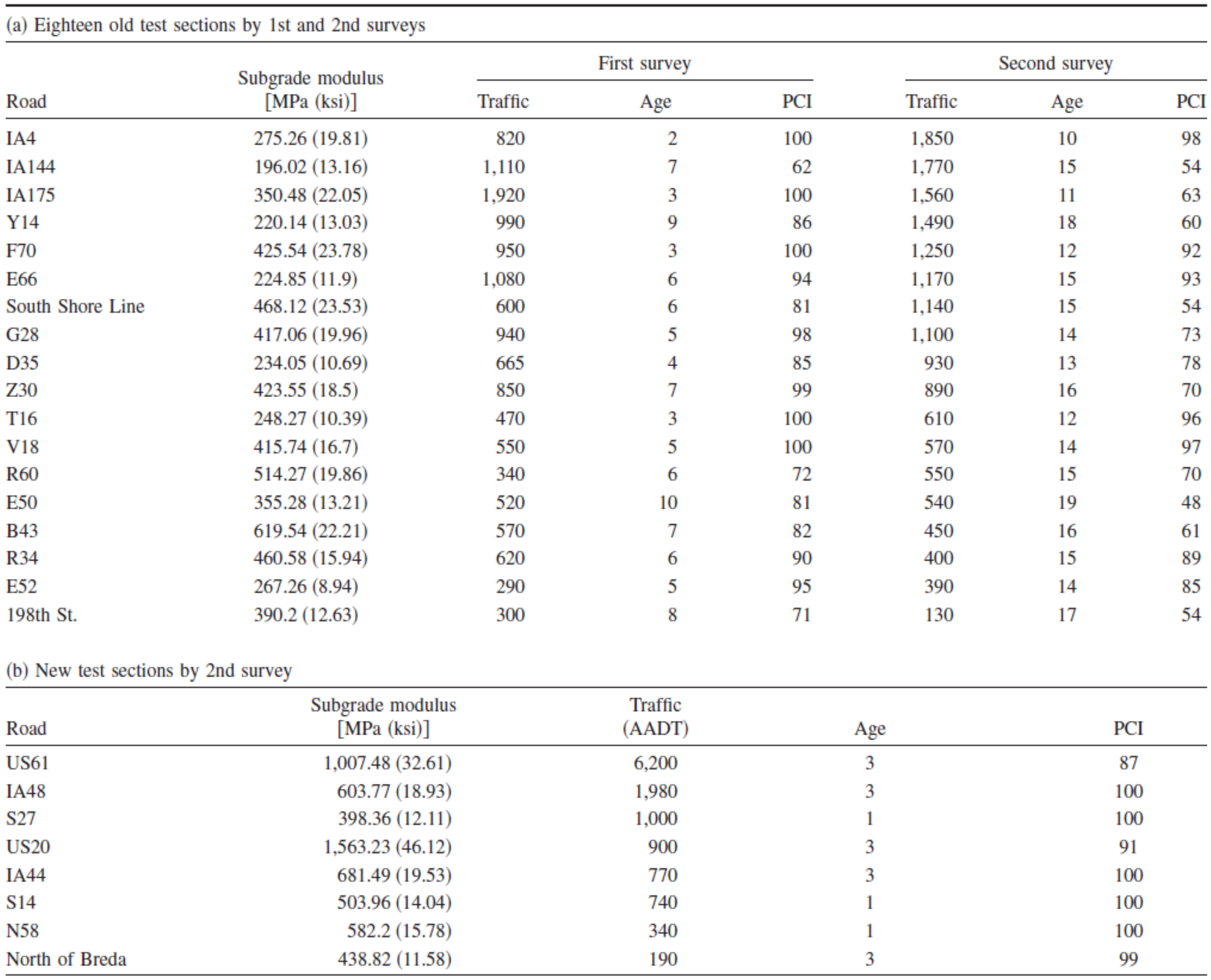
	PCI of CIR with HMA Overlay						PCI of CIR without HMA Overlay				
		By Age of CIR Pavement						By Age of CIR Pavement			
Project ID	Existing Condition	2 Years	4 Years	6 Years	8 Years	Project ID	Existing Condition	2 Years	4 Years	6 Years	8 Years
CMS-1	82	100	96	87	74	CMS-38	95	100	95	95	95
CMS-2	94	100	100	95	94	CMS-39	62	100	95	95	58
CMS-3	92	100	95	96	87	CMS-40	92	89	92	73	89
CMS-4	89	97	97	100	86	CMS-41	93	95	92	92	97
CMS-5	81	96	88	100	80	CMS-42	90	98	97	85	87
CMS-6	77	100	100	96	91	CMS-43	94	93	93	64	67
CMS-7	91	100	100	100	99	CMS-44	98	91	93	81	91
CMS-8	92	100	100	100	96	CMS-45	98	95	96	88	91
CMS-9	85	100	98	96	90	CMS-46	79	99	92	90	na
CMS-10	72	100	98	97	100	SF-3	72	100	na	na	na
CMS-11	82	100	100	100	100	SF-4	91	64	na	na	na
CMS-12	96	100	100	100	100	SF-5	84	98	na	na	na
CMS-13	85	100	100	100	100	SF-6	81	91	na	na	na
CMS-14	89	100	100	99	98	SF-7	80	100	98	94	na
CMS-15	83	100	100	100	100	SF-8	79	100	95	56	39
CMS-16	95	97	100	99	98	SF-9	66	100	94	95	na
CMS-17	97	86	100	100	100	SF-10	44	85	86	45	na
CMS-18	100	100	100	100	99	SF-11	92	100	93	80	na
CMS-19	85	100	100	91	89	SF-12	89	100	91	na	na
CMS-20	48	100	100	100	92	SF-13	86	93	95	98	99
CMS-21	81	100	91	99	63	SF-14	92	100	100	98	89
CMS-22	61	100	99	99	na	SF-15	82	98	93	na	na
CMS-23	44	100	100	89	na	SF-16	80	93	61	na	na
CMS-24	51	100	100	99	na	SF-17	55	99	89	na	na
CMS-25	62	100	100	99	na	PM-3	79	94	91	87	na
CMS-26	90	99	98	86	na	PM-4	71	94	88	88	na
CMS-27	73	100	99	100	na						
CMS-28	90	98	95	91	na						
CMS-29	87	100	100	100	na						
CMS-30	66	100	100	100	na						
CMS-31	93	100	100	90	na						
CMS-32	88	100	100	100	na						
CMS-33	85	100	98	95	na						
CMS-34	73	100	88	100	na						
CMS-35	49	100	98	100	na						
CMS-36	85	100	100	na	na						
CMS-37	96	100	na	na	na						
SF-1	83	94	na	na	na						
SF-2	88	98	na	na	na						
PM-1	70	94	na	na	na						
PM-2	88	86	na	na	na						

NOTE: na = not applicable.

Iowa

Kim et al. (*18*) conducted pavement surface distress surveys on 26 CIR test sections in Iowa. The pavement surface distresses were collected using an automated image collection system, and collected data were then compiled to compute PCI for each test section to determine the long-term performance of the CIR sections. Table 16 summarizes the information and performance data of the 26 CIR test sections. Researchers concluded that overall, the CIR test sections in Iowa performed well and as predicted, with up to 34 years with good subgrade support and 22 years with poor subgrade support until reaching the poor condition (PCI=40).

Table 16. Performance Data and Information for 26 CIR Test Sections in Iowa.



(a) Eighteen old test sections by 1st and 2nd surveys

Road	Subgrade modulus [MPa (ksi)]	First survey Traffic	First survey Age	First survey PCI	Second survey Traffic	Second survey Age	Second survey PCI
IA4	275.26 (19.81)	820	2	100	1,850	10	98
IA144	196.02 (13.16)	1,110	7	62	1,770	15	54
IA175	350.48 (22.05)	1,920	3	100	1,560	11	63
Y14	220.14 (13.03)	990	9	86	1,490	18	60
F70	425.54 (23.78)	950	3	100	1,250	12	92
E66	224.85 (11.9)	1,080	6	94	1,170	15	93
South Shore Line	468.12 (23.53)	600	6	81	1,140	15	54
G28	417.06 (19.96)	940	5	98	1,100	14	73
D35	234.05 (10.69)	665	4	85	930	13	78
Z30	423.55 (18.5)	850	7	99	890	16	70
T16	248.27 (10.39)	470	3	100	610	12	96
V18	415.74 (16.7)	550	5	100	570	14	97
R60	514.27 (19.86)	340	6	72	550	15	70
E50	355.28 (13.21)	520	10	81	540	19	48
B43	619.54 (22.21)	570	7	82	450	16	61
R34	460.58 (15.94)	620	6	90	400	15	89
E52	267.26 (8.94)	290	5	95	390	14	85
198th St.	390.2 (12.63)	300	8	71	130	17	54

(b) New test sections by 2nd survey

Road	Subgrade modulus [MPa (ksi)]	Traffic (AADT)	Age	PCI
US61	1,007.48 (32.61)	6,200	3	87
IA48	603.77 (18.93)	1,980	3	100
S27	398.36 (12.11)	1,000	1	100
US20	1,563.23 (46.12)	900	3	91
IA44	681.49 (19.53)	770	3	100
S14	503.96 (14.04)	740	1	100
N58	582.2 (15.78)	340	1	100
North of Breda	438.82 (11.58)	190	3	99

Texas

The CIR technology is rarely used in Texas. However, the Amarillo District has used CIR successfully as a pavement rehabilitation strategy. The Amarillo District constructed CIR on high-traffic US 83 (AADT of 7,000 with 65 percent heavy trucks) from September to October in 2010. The project started at the Oklahoma border and ran south 6.1 mi. The project had two distinct pavement sections that required slightly different construction methods. Outside of town, which is a two-lane rural highway, the solution included recycling the top 5 inches with the CIR process, using fog sealing, and adding an under-seal and a surface course of 1.5 inches of dense-graded HMA-Type D/70-28. In town, which is a four-lane urban highway, the treatment plan specified recycling the top 3 inches with the CIR process, fog sealing, and then adding the underseal followed by the same HMA surface course. Figure 14 shows before construction and after 3 years of service, showing that the section had performed well (*19*).

(a) Condition before CIR construction

(b) After 3 years of service

Figure 14. Before and after CIR Construction on US 83 in Texas.

Modulus of Cold Recycling Pavements

The modulus of a pavement layer is the key input for the pavement structural design process. Also, it is typically used to predict the pavement performance using distress models. Thus, it is important to use a reasonable design modulus for pavement layers. Many researchers have made great efforts to measure the modulus of cold recycling layers in both the field and laboratory.

Chan et al. (*20*) conducted the FWD test to measure the resilient modulus of a CIR foam layer and CIR emulsion layer prior to HMA overlay. The average resilient modulus values of the CIR foam layer and CIR emulsion layer were 1,173 MPa (170 ksi) and 1,059 MPa (154 ksi), respectively. Researchers reported that the two mixes had been performing similarly over the past 5 years.

Cox et al. (*14*) measured the modulus of three different CIR sections on US 49 after 53 months open to traffic, the detailed information for which was presented in Table 14. The laboratory-measured modulus values of CIR Section 2, Section 5, and Section 6 were 3.2 GPa (460 ksi), 13.9 GPa (2,016 ksi), and 11.8 GPa (1,711 ksi), respectively.

Diefenderfer et al. (*16*) conducted the dynamic modulus test on a laboratory-produced CCPR mixture fabricated from materials produced during construction. Figure 15 shows the results of the dynamic modulus testing at the four test temperatures and at frequencies of 10, 1, and 0.1 Hz. As shown, the trend was similar for asphalt materials: the dynamic modulus of the CCPR materials decreased with increasing temperature at each test frequency and increased with increasing test frequency at each temperature. The modulus of the CCPR mixture at 21.1°C and 10 Hz was about 600 ksi.

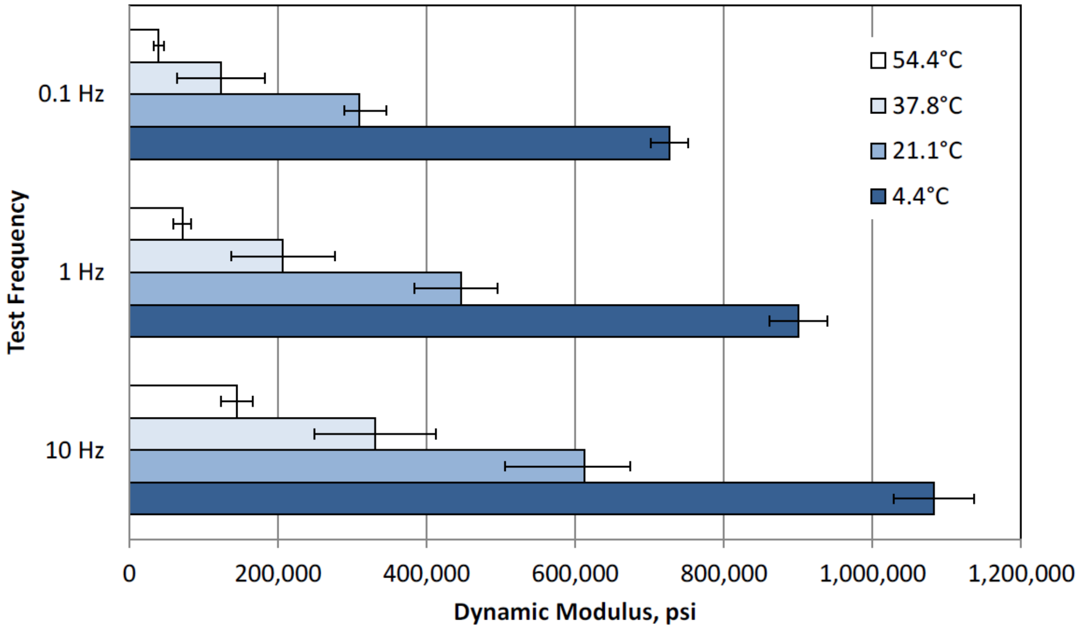


Figure 15. Dynamic Modulus Test Results of CCPR Mixture.

Schwartz (*21*) presented dynamic modulus values of various cold recycling mixtures. Field cores were taken for testing from 25 projects in 13 locations. The field cores were treated to small-scale cylindrical testing specimens, as shown in Figure 16. Then, the typical dynamic modulus testing procedure was followed, and the dynamic modulus values measured are shown in Figure

17. As seen, the range of the dynamic modulus values of cold recycling mixtures at 20°C is between 300 ksi and 940 ksi.

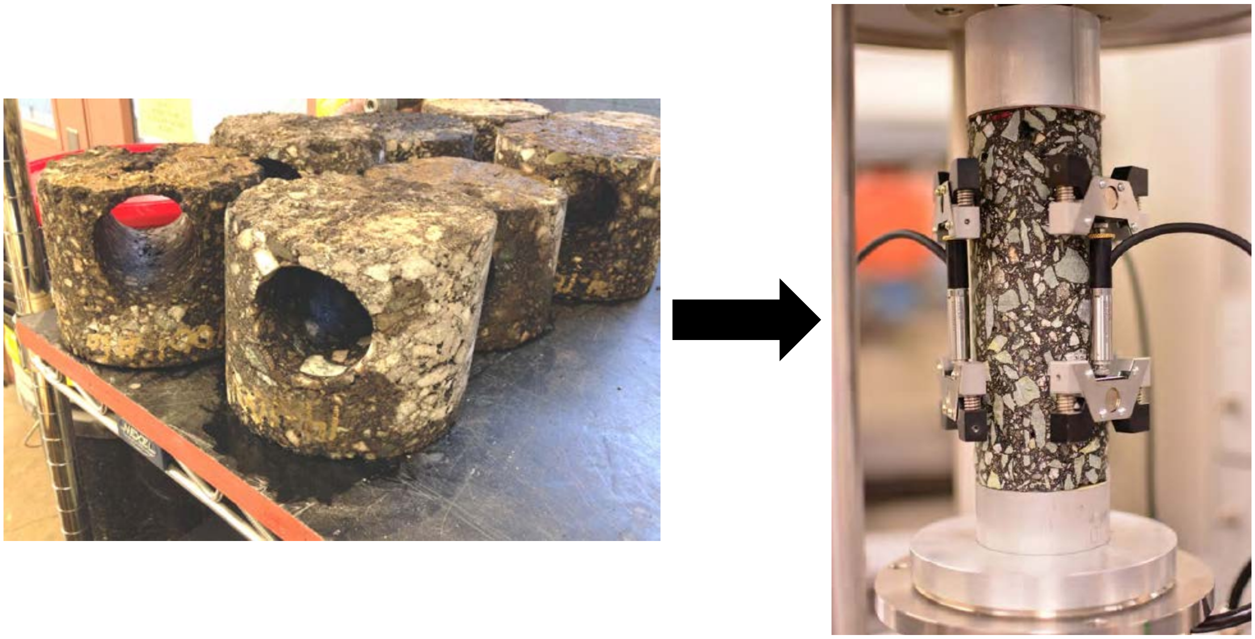


Figure 16. Small-Scale Dynamic Modulus Test Method for Cold Recycling Field Cores.

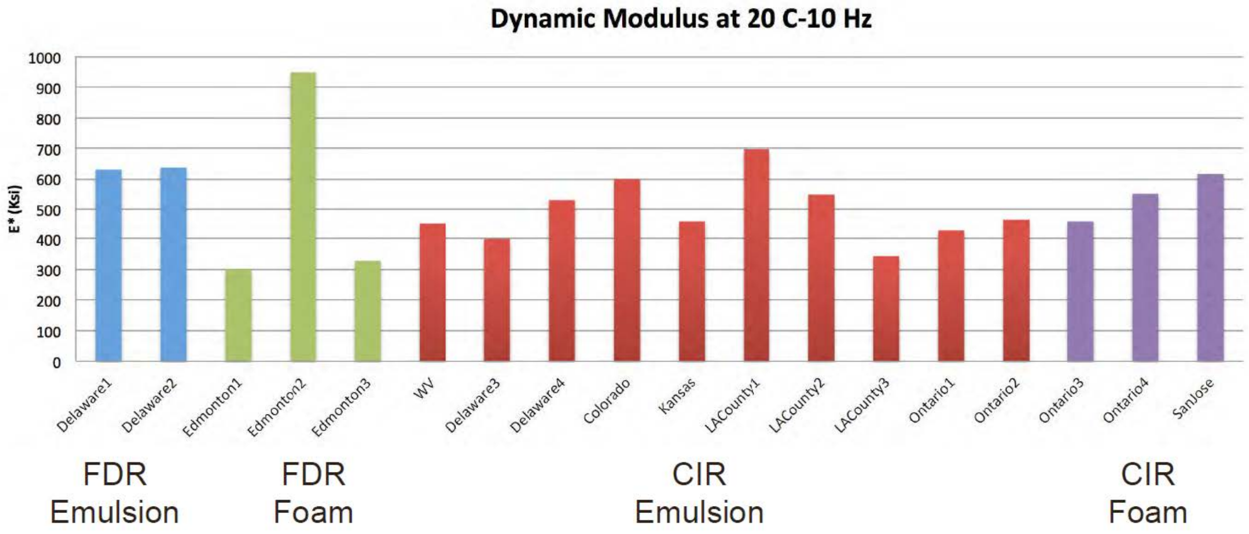


Figure 17. Dynamic Modulus Test Results of Cold Recycling Field Cores.

CIR EXPERIENCE IN TEXAS

Staff from AMA, ATL, BRY, LFK, and CST were contacted for input on how they identify moisture damage, what types of pavement rehabilitation strategies they use for pavements with moisture damage, limits of any existing sections that have been rehabilitated using CIR or

CCPR, and locations of current pavement sections that may have moisture damage. The following summarize the inputs received:

- Field observations and/or forensic analysis generally are used to determine if moisture damage exists. To a lesser extent, ground-penetrating radar (GPR) is used if those data are available. Inspection of pavement cores serves as the validation of the presence or lack of moisture damage.
- In general, districts report mixes with gravel aggregate experience more moisture damage.
- The most common strategy for rehabilitation is to mill out the moisture damaged material and inlay new HMA. The RAP from the milling operation generally is used by adding back into HMA.
- The only known sections of CIR or CCPR in Texas are in AMA on US 83:
    - US 83, from Oklahoma State Line to Perryton (CIR).
    - US 83, from Lipscomb County Line to Horse Creek (CIR).
- Six potential candidate sections were identified. Chapter 3 will present these candidates.

CONCLUSIONS

The literature review leads to the following conclusions:

- Equipment: Various equipment and options are available from industry. Depending on work areas, construction situations, loading capacity, and productivity, CIR and CCPR processes can be customized for best practices.
- Specifications: Existing relevant specifications of several agencies were reviewed. General information on such things as weather limitations, RAP gradation, and equipment capacities was similar among agencies. However, the mix design requirements were quite different. Also, each state agency has different curing criteria for CIR in terms of either moisture content or curing time. It is believed that the CIR/CCPR specifications need to be improved for best practices.
- Field performance: CIR and CCPR are becoming popular methods for rehabilitating existing asphalt pavements, and they have been successfully used for even high-traffic-volume roadways (i.e., I-81). Many researchers have reported that CIR/CCPR pavements have performed well. It seems that cold recycling technology will continue to be used as a rehabilitation method in the future.

CHAPTER 3. PROJECT INVESTIGATIONS AND SAMPLING

Sections considered possible candidates for recycling strategies were identified, and researchers performed GPR on candidate pavement sections as an initial screening. After evaluating these data, Table 17 summarizes the sections used for further work in this research project.

Table 17. Sections Used for Evaluating Cold Recycling Options.

District	Roadway	Extents
AMA	US 60	Panhandle to 3.8 mi. West – EB direction only
AMA	I-40	TRM 98.57 – 110.006 – EB direction only
BMT	FM 92	CR 4130 to US 190

Note: Cores also collected from existing CIR on both US 83 sections in AMA for lab testing.

Figure 18 illustrates general field strategies employed for sampling. Figure 19 shows FWD collection and pavement coring on an existing CIR section for further field performance analysis.

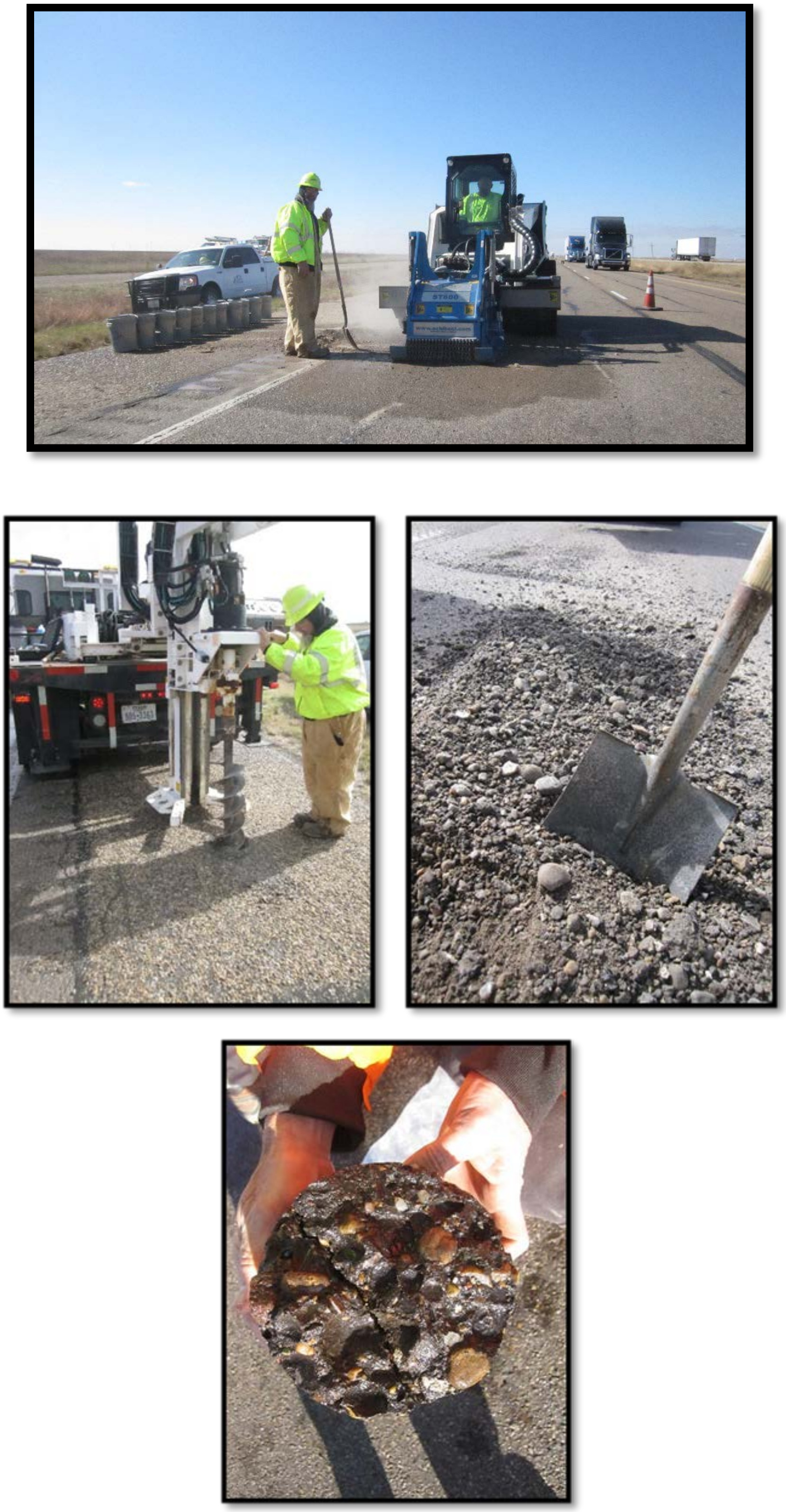


Figure 18. Example Field Sampling Activities.

Figure 19. FWD and Coring of existing CIR Section.

US 60 SUMMARY

Figure 20 presents an example GPR scan and core from US 60. Figure 21 illustrates the typical existing structure and observations from field drilling. The data suggest deterioration exists in the asphalt layer. The district indicated interest in exploring recycling solutions for this section, so field materials were returned to the lab for further analysis.

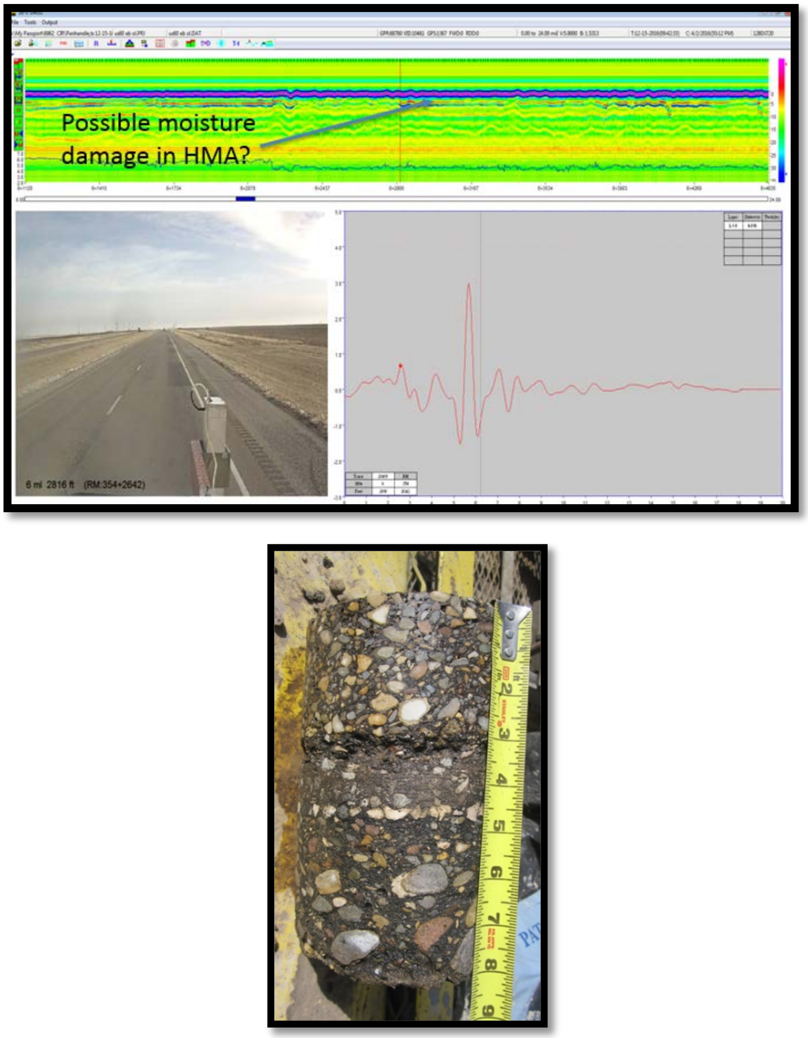
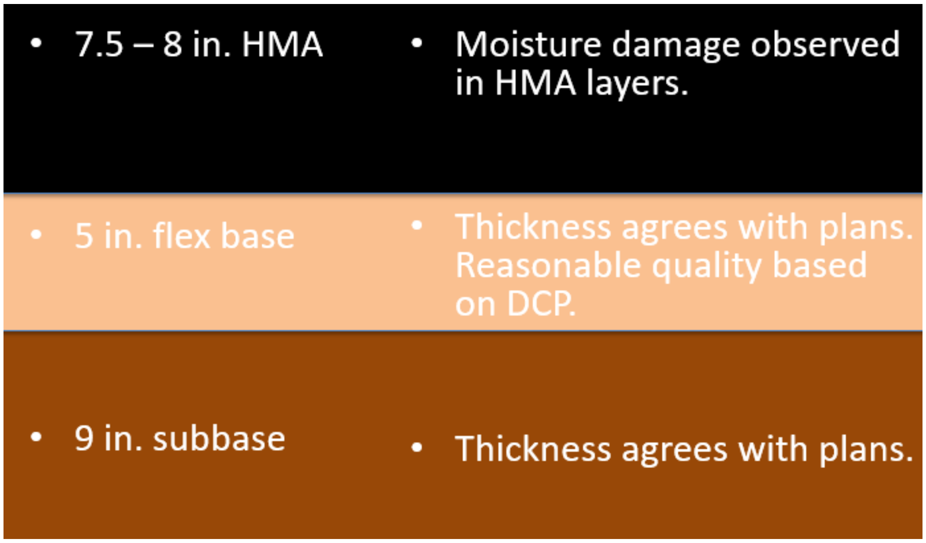


Figure 20. Example GPR and Core from US 60.



- 7.5 – 8 in. HMA
- Moisture damage observed in HMA layers.
- 5 in. flex base
- Thickness agrees with plans. Reasonable quality based on DCP.
- 9 in. subbase
- Thickness agrees with plans.

Figure 21. Typical Structure and Observations from US 60.

I-40 SUMMARY

Figure 22 shows example GPR data and a representative core from this section. While the GPR data do not show traces indicating moisture damage, coring revealed the asphalt layer was deteriorated through the entire depth. Figure 23 shows the drill logs from the section. The district expressed interest in exploring recycling solutions for this section, so field materials were returned to the lab for further analysis.

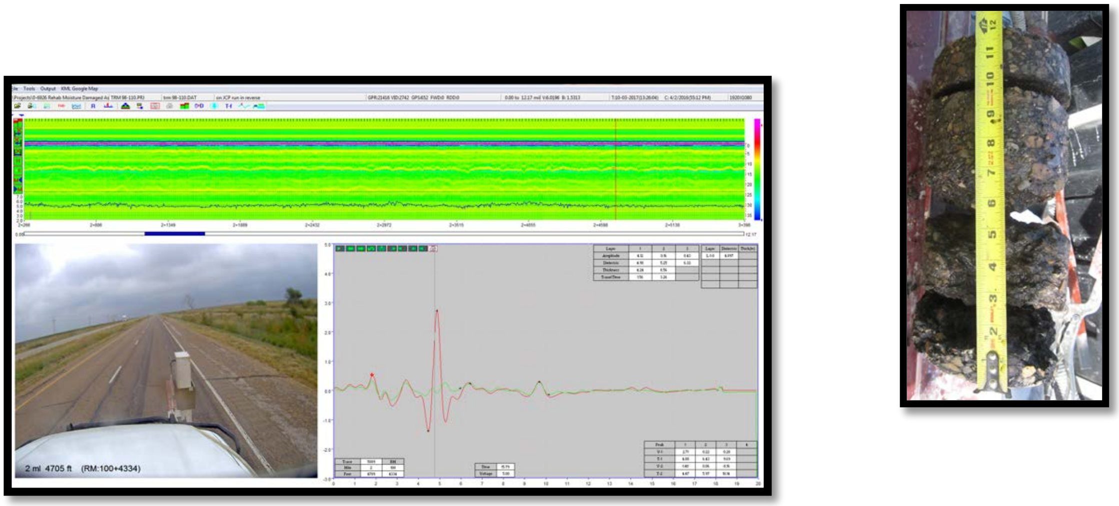


Figure 22. Example GPR from I-40.

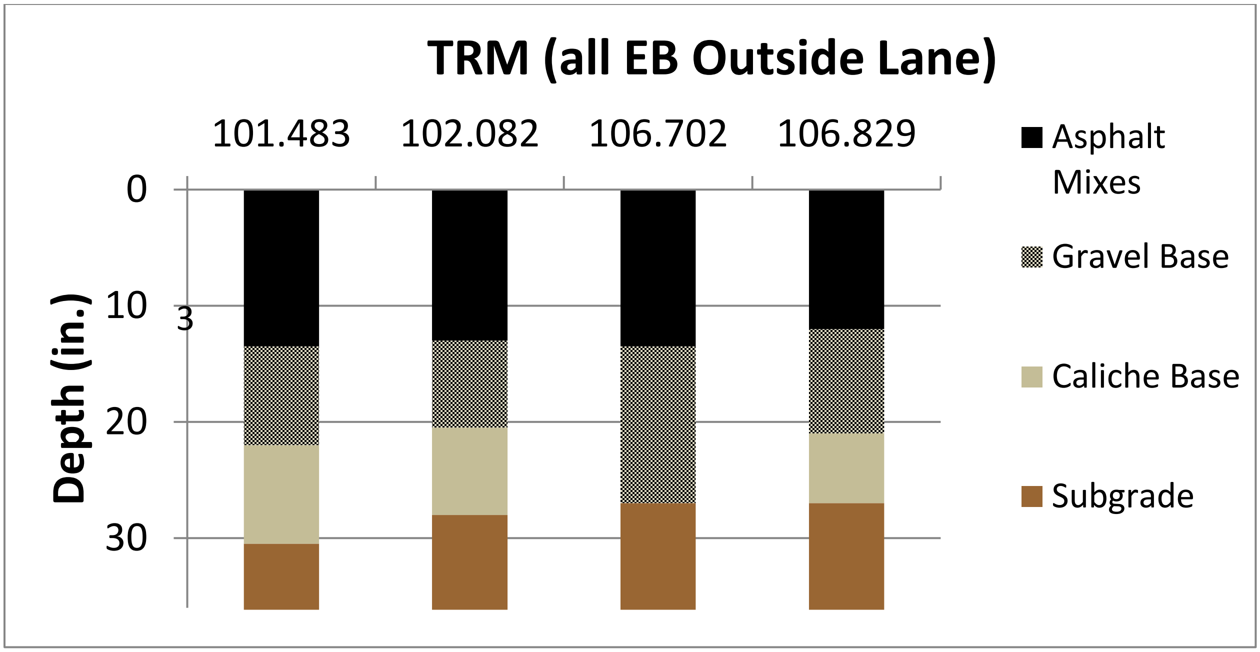


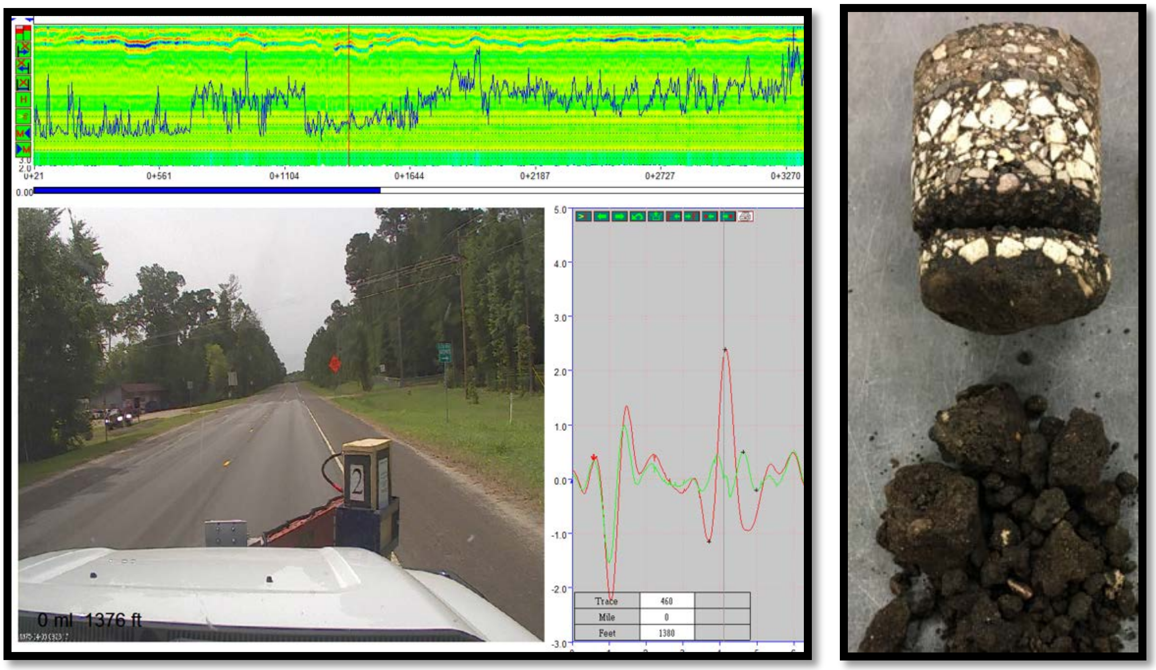
Figure 23. Drill Logs from I-40.

FM 92 SUMMARY

Figure 24 illustrates negative subsurface reflections in the GPR from this section along with a representative core. Coring showed significant deterioration in the oil sand layer; the lower layer was often not recoverable when coring. The Maintenance Section reported that when performing spot repairs, the material was often wet. Researchers sampled materials from the roadway and found the layering to consist of:

- 4–5 in. of asphalt (several thin lifts plus seals).
- 7–8 in. of oil sand.
- 12 in. of sandy select fill.
- Moderate-PI subgrade.

The district expressed interest in exploring recycling options for this section, so field materials were returned to the lab for further analysis.



Trace 460
Mile 0
Feet 1380

Figure 24. Example GPR and Core from FM 92.

CHAPTER 4. PERFORMANCE OF LAB AND FIELD MIXTURES

Researchers performed a laboratory study to determine suitable mixture designs and characteristics of the recycled mixture using materials sampled from the sections shown in Table 18. The collected RAP materials were dried, and gradation analysis was performed. The sieve analysis results are plotted on a 0.45 power chart in Figure 25.

Table 18. Sections Sampled for Lab Testing.

District	Roadway	Extents
AMA	US 60	Panhandle to 3.8 mi. West – EB direction only
AMA	I-40	TRM 98.57 – 110.006 – EB direction only
BMT	FM 92	CR 4130 to US 190

Note: Cores also collected from existing CIR on both US 83 sections in AMA for lab testing.

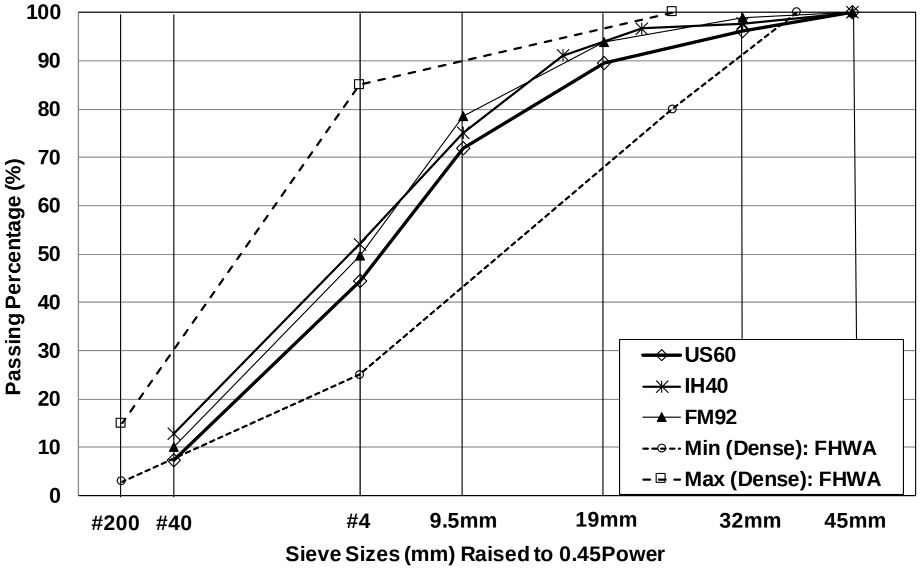


Figure 25. Gradation Plots from Three Different RAP Sources.

The laboratory study included the following phases:

- Perform mixture design.
- Conduct performance-related tests for rutting and cracking potential of CIR mixture.
- Conduct a performance review of existing CIR sections on US 83.

CIR MIX DESIGN

Fixed moisture contents for CIR mixtures are commonly documented and generally range from 2 to 5 percent (*22*). Based on the literature review, a moisture content of 4 percent was selected for CIR mix production in this study.

Three treatment options were considered to produce different CIR mixes for each RAP source:

- CSS-1H emulsion to produce CIR-emulsion mix.
- PG58-28 asphalt binder for CIR-foam mix.
- PG64-22 asphalt binder for another CIR-foam mix.

For each treatment option, three different asphalt contents were used to determine the optimum asphalt content. For CIR-emulsion mix, emulsion contents of 1 percent, 2 percent, and 3 percent were selected, while foamed asphalt contents of 2 percent, 2.5 percent, and 3 percent were used for both PG58-28 and PG64-22 asphalt binders. This combination made a total of nine CIR mixes for each RAP source.

Following the literature, the design procedure used indirect tension (IDT) tests on both moisture conditioned and dry specimens (*2*). These IDT test results were used to determine the optimum asphalt content based on the TxDOT Spec 3279, which calls for achieving a dry IDT strength of 45 psi and a wet IDT strength of 30 psi. Six specimens in 4 inches diameter and 2 inches high were prepared for each asphalt content, and these specimens were then oven cured for 3 days at 40°C. After curing, three of the specimens were submerged in water for 24 hours. On the fourth day, the IDT test was run on both the dry and wet specimens at 25°C. Figure 26 shows the equipment used and representative CIR specimens manufactured in this study.

Figure 26. Lab Foaming Equipment and CIR Specimens after IDT Test.

Figure 27 shows the results of CIR mix designs. Based on the IDT strength results in Figure 27, it was decided to treat each RAP source with 1.0 percent CSS-1H emulsion, 2.5 percent foamed asphalt with PG58-28 asphalt binder, and 2.5 percent foamed asphalt with PG64-24 asphalt binder, respectively. Although not all the mixtures met IDT strength criteria with foamed asphalt, work continued with both binder grades at the 2.5 percent treatment rate to study possible binder grade influences on expected field performance. Thus, these three CIR mixes for each RAP source were selected to perform advanced material tests to evaluate their rutting and cracking potential.

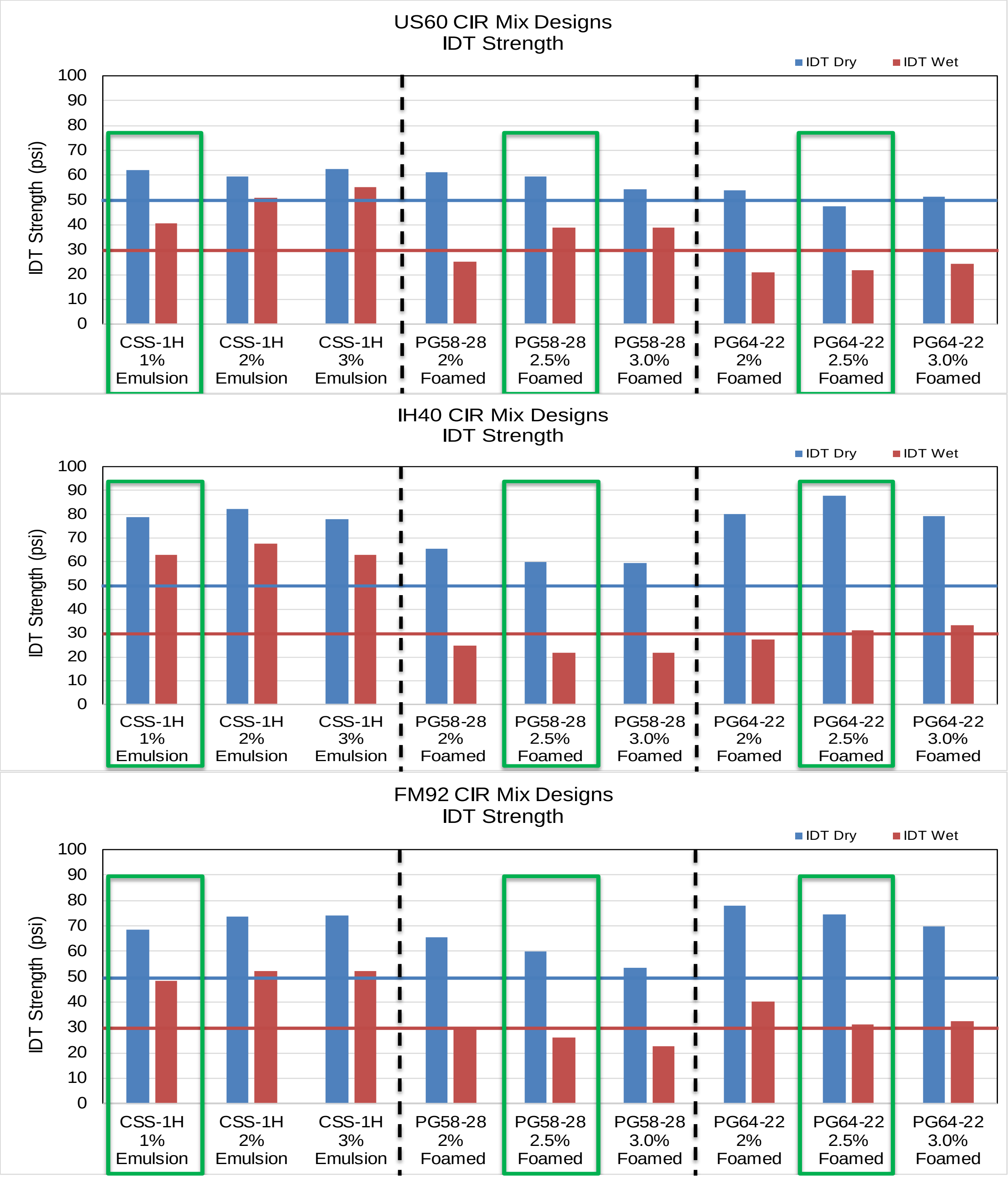


Figure 27. IDT Strength Results of CIR Mixes.

PERFORMANCE TEST ON CIR MIXES

A series of laboratory tests was performed to determine rutting and cracking potential of selected CIR mixes. These tests included the Hamburg wheel track test, Illinois flexibility index test (I-FIT), indirect tensile asphalt cracking test (IDEAL-CT), resilient modulus test, dynamic modulus (E*) test, and repeated load test as shown in Figure 28.

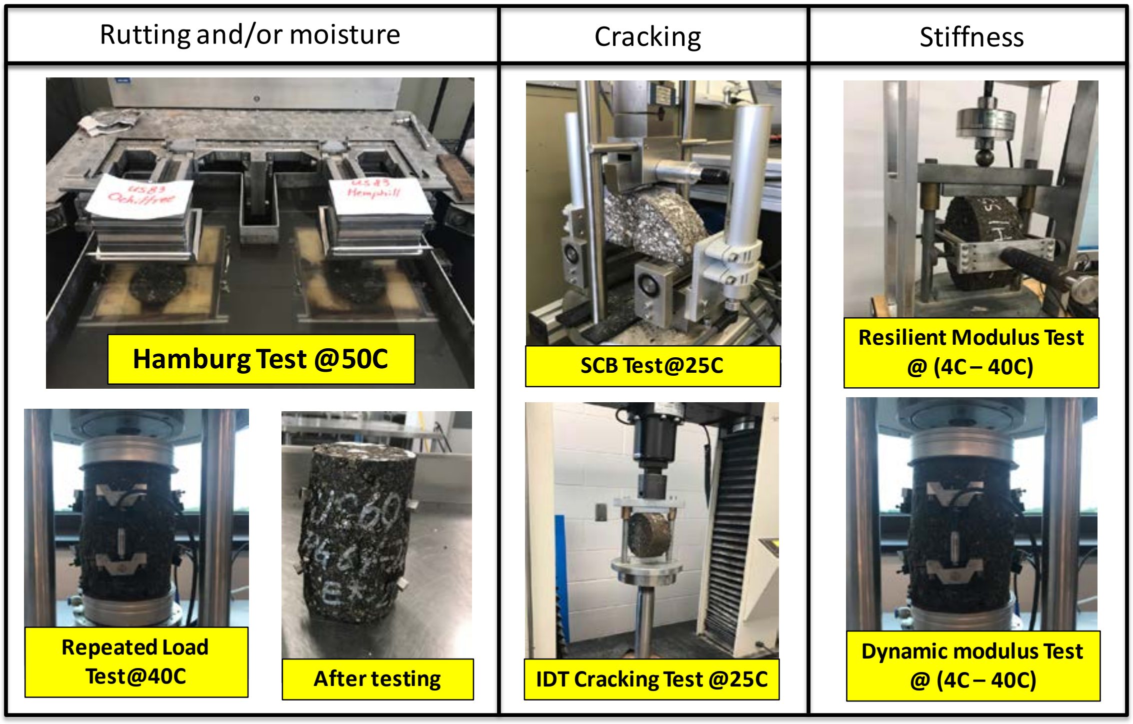


Figure 28. Performance Tests Used for CIR Mixtures.

Hamburg Wheel Track Test

The Hamburg wheel tracking test was conducted at a temperature of 50°C in accordance with TEX-242-F (*23*). A Superpave gyratory compactor was used to produce cylindrical specimens with a diameter of 150 mm (6 inches) and a height of 62 mm (2.4 inches). A masonry saw was used to cut along the edge of the cylindrical specimens. The stop criterion was rut depth of 12.5 mm (0.5 inches) or 20,000 passes.

Figure 29 shows the failure cycles of each CIR mix. All CIR mixes showed very poor rutting resistance and moisture susceptibility. Observations from the test results include:

- The binder type significantly affected the rutting performance and moisture susceptibility of CIR mixes.
- Given the same RAP source, the performance of CIR-emulsion mixes (CSS-1H) was better than CIR-foam mixes (PG58-28 and PG64-22 binders).

- The results suggest that CSS-1H makes CIR mixes stiffer than PG58-28 and PG64-22 foamed asphalt treatments.
- The RAP source also significantly affected the rutting performance and moisture susceptibility of CIR mixes. Given the same treatment option, the results show that RAP materials from FM 92 seem stiffer than others. This observation indicates that gradations, aging history, residual binder content of RAP, and variability of RAP would affect performance results.

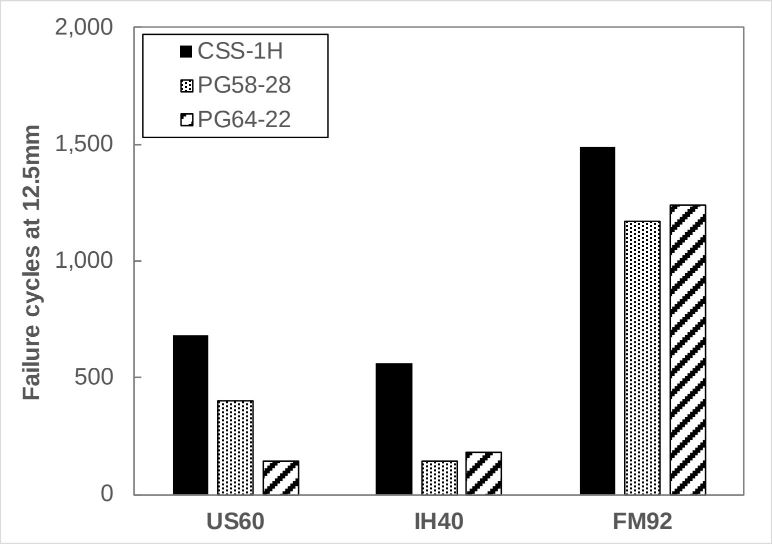


Figure 29. Results of Hamburg Wheel Track Test.

Illinois Flexibility Index Test

The I-FIT has been recently developed to quantify cracking potential of asphalt mixtures (*24*). This test suggests a test temperature of 25°C with a loading rate of 50 mm/min (2 inches/min). The key of this test method is to use a flexibility index (FI) to characterize cracking resistance of asphalt mixes. The FI is derived from a load-displacement curve obtained from the I-FIT test with two different parameters: fracture energy (G_f) and the slope ($|m|$) at the post-peak inflection point, as demonstrated in Eq (1). Typically, the FI values vary from 1 to 30 for the poorest to best performing asphalt mixes.

$$FI = \frac{G_f}{|m|} \times A \tag{1}$$

where, G_f = fracture energy (J/m^2).

$|m|$ = absolute value of post-peak load slope (kN/mm).

A = unit conversion and scaling factor equal to 0.01.

Figure 30 shows the I-FIT results by plotting the average FI of each CIR mix. Overall, the cracking resistance of all CIR mixes showed a FI less than 7. This means these CIR mixes would be expected to be very susceptible to cracking.

In general, the cracking resistance of asphalt mixtures is sensitive to their stiffness. The stiffer the mix, the worse is the cracking resistance. Figure 29 along with Figure 30 illustrate that softer mixes (i.e., fewer cycles to failure in the Hamburg test) had more crack resistance (i.e., a higher FI). The binder type also affected the cracking resistance of CIR mixes. Given the same RAP source, CSS-1H made CIR mixes stiffer than PG58-28 and PG64-22 foamed asphalt treatments. Correspondingly, CIR-emulsion mixes showed the lowest the FI number.

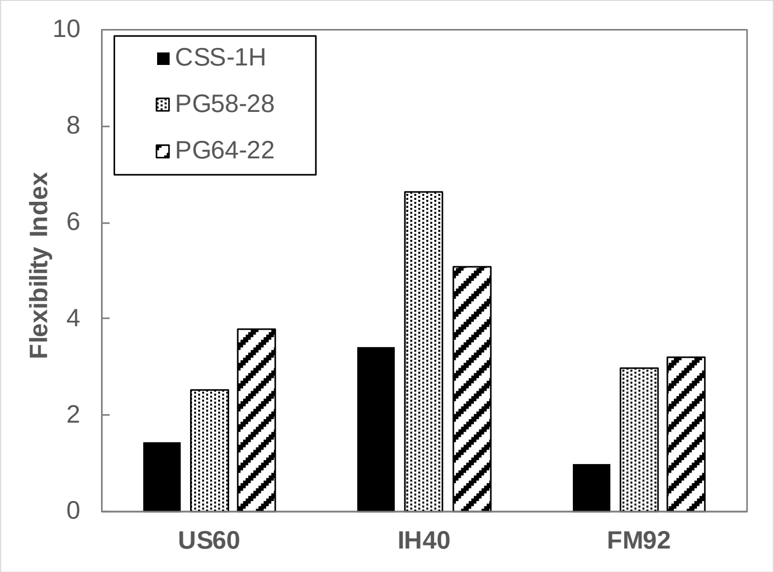


Figure 30. Results of Illinois Flexibility Index Test.

Indirect Tensile Asphalt Cracking Test

The IDEAL-CT, similar to the traditional indirect tensile strength (IDT) test, recently has been developed to identify the cracking behavior of asphalt mixtures and routine asphalt mix designs (*25, 26*). The testing specimen is subjected to a loading rate of 50 mm/min at a temperature of 25°C. Three cylindrical specimens with a diameter of 150 mm (6 inches) and a height of 62 mm (2.4 inches) were prepared and tested for each CIR mix.

The IDEAL-CT test determines a performance-related cracking parameter from the measured load versus displacement curve (*27*). The unitless cracking test (CT) index calculated according to Eq. (2) or (3) is used to quantify the cracking resistance of asphalt mixes. Typically, the CT values vary from 1 to 800 for the poorest to best performing asphalt mixes.

For those specimens with different thickness:

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \mathrm{FI} = \frac{\mathrm{t}}{62} \times \frac{\mathrm{G_f}}{|\mathrm{m}_{50}|} \times \left(\frac{\mathrm{l}_{50}}{\mathrm{D}}\right)^2 \mathrm{FI} = \frac{\mathrm{t}}{62} \times \frac{\mathrm{G_f}}{|\mathrm{m}_{75}|} \times \left(\frac{\mathrm{l}_{75}}{\mathrm{D}}\right) \mathrm{FI} = \frac{\mathrm{t}}{62} \times \frac{\mathrm{G_f}}{|\mathrm{m}_{75}|} \times \left(\frac{\mathrm{l}_{75}}{\mathrm{D}}\right)$$
(2)

For those specimens with 62 mm thickness:

$$\mathrm{FI} = \frac{\mathrm{G_f}}{|\mathrm{m}_{75}|} \times \left(\frac{\mathrm{l}_{75}}{\mathrm{D}}\right)\ CT_{Index} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \qquad (3)$$

where, t = specimen thickness (mm).
D = specimen diameter (mm).
G_f = fracture energy (J/m^2).
$|m_{75}|$ = absolute tangent slope where the load is reduced to 75 percent the peak load (kN/mm).
l_{75} = displacement until the load is reduced to 75 percent the peak load.

Figure 31 shows the IDEAL-CT results by plotting the average CT$_{\text{Index}}$ of each CIR mix. Overall, the IDEAL-CT results showed a similar trend as the I-FIT results. Given the same RAP source, both the IDEAL-CT and the I-FIT results showed exactly the same rankings. This means the cracking resistance of CIR mixes were properly characterized, and both cracking test methods are appropriate methods for CIR mixes.

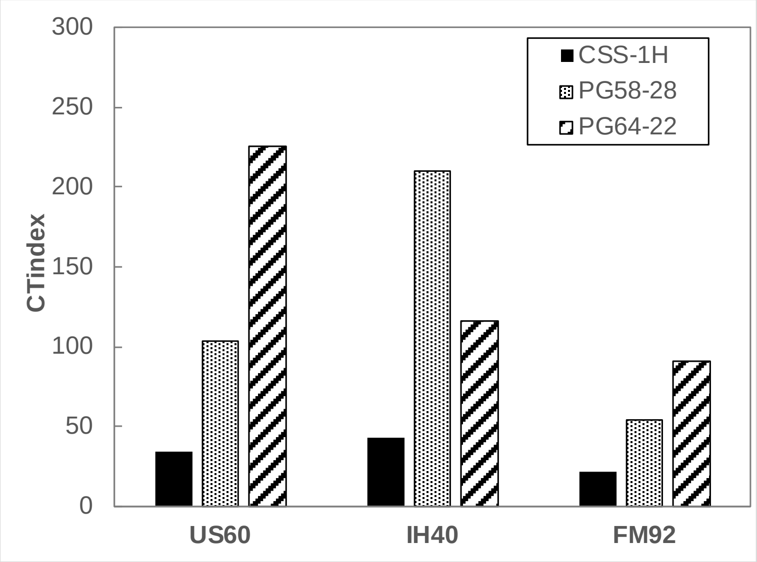


Figure 31. Results of IDEAL-CT.

Resilient Modulus Test

The resilient modulus test was used to determine the elastic modulus of CIR mixes. The resilient modulus values were calculated based on AASHTO TP31-96 (*28*). The CIR specimens were placed in the constant temperature apparatus to ensure a consistent temperature of 25 ± 1°C before testing. The repeated load in the indirect tension mode was applied in the form of a haversine curve with a loading time of 0.1 second and a rest period of 0.9 second in one cycle, and up to 106 cycles. The horizontal recoverable deformations were measured and average resilient modulus values from two replicates were obtained.

Figure 32 shows the resilient modulus of the CIR mixes. Given the same treatment option, the RAP materials from FM 92 exhibited higher resilient modulus values than those of others. Also, given the same RAP source, the resilient modulus of CIR-emulsion mixes (CSS-1H) showed higher than those of CIR-foam mixes (PG58-28 and PG64-22 binders). These results are consistent with findings previously discussed from the Hamburg and cracking tests.

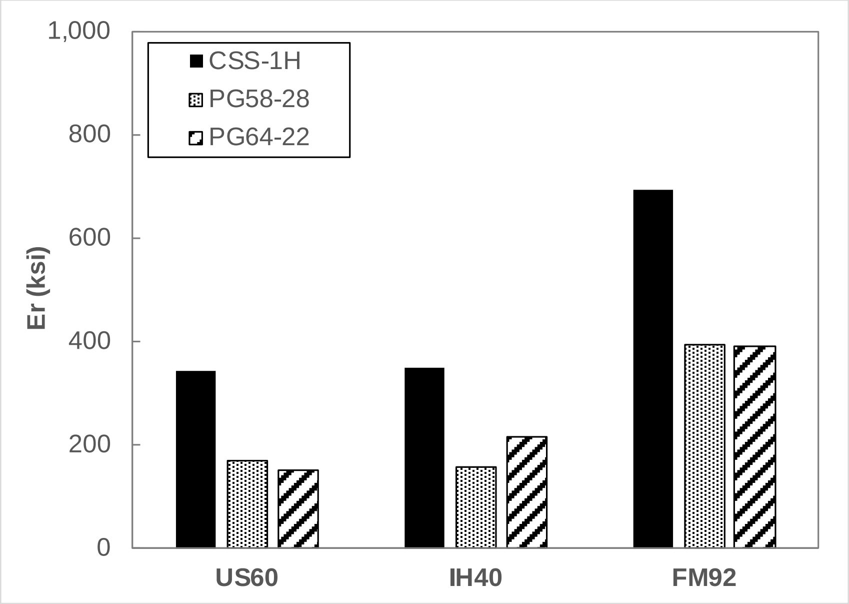
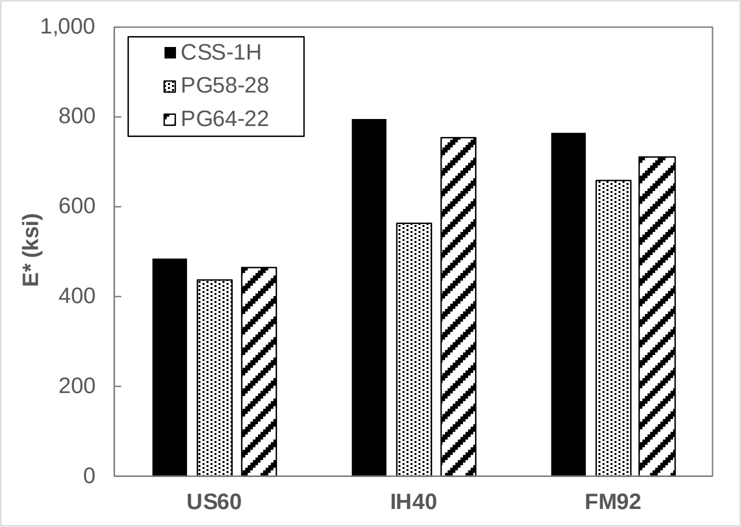


Figure 32. Results of Resilient Modulus Test.

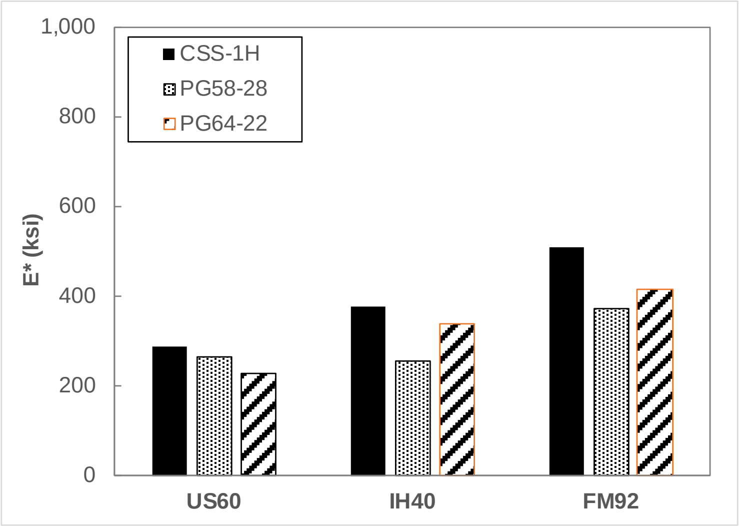
Dynamic Modulus (E*) Test

The dynamic modulus test was conducted to measure changes of the viscoelastic stiffness of CIR mixes. The test was conducted following AASHTO TP79-11 (*29*). The Superpave gyratory compactor was used to produce cylindrical specimens with a diameter of 100 mm (4 inches) and a height of 150 mm (6 inches). To measure the axial displacement of the testing specimens, mounting studs were glued to the surface of the specimens so that three linear variable differential transformers could be installed on the surface of the specimens through the studs at 120° radial intervals with a 70 mm (2.75 inches) gauge length. Temperatures of 4, 20, and 40°C and six and/or seven loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz (40°C only) were used. Two replicates were tested and average values of dynamic modulus at each different test temperature over the range of loading frequencies were obtained.

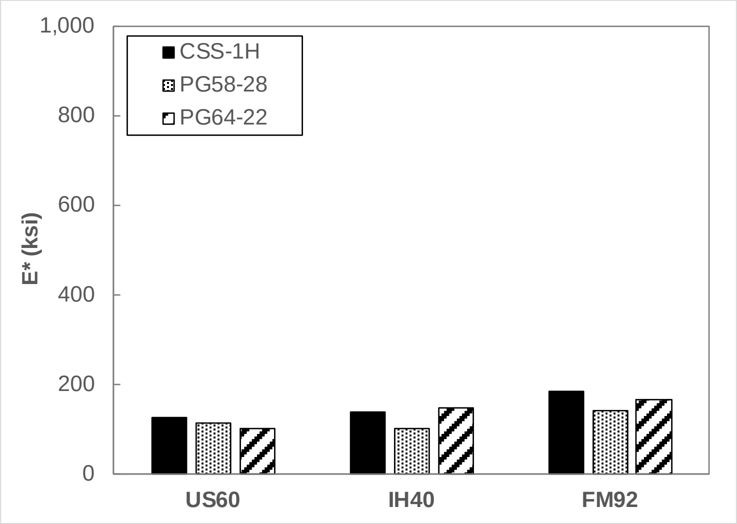
In general, the frequency-temperature superposition concept is applied to obtain the linear viscoelastic master curves at a target reference temperature. For comparison purposes, however, dynamic modulus values measured at 10 Hz and at each testing temperature are plotted on bar charts as shown in Figure 33. As expected, the dynamic modulus test results exhibited similar trends as the resilient modulus results. Additional findings from the dynamic modulus testing is that these CIR mixes clearly showed temperature-dependent behavior.



(a) at 4°C



(b) at 20°C



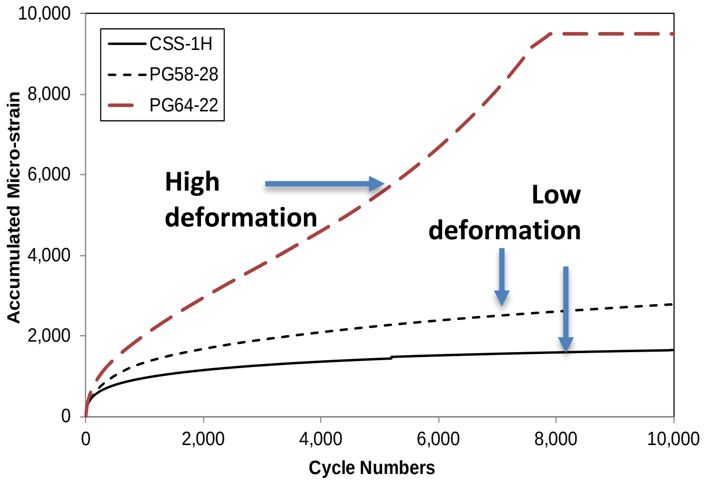
(c) at 40°C

Figure 33. Dynamic Modulus Values Measured at 10 Hz and at Each Temperature.

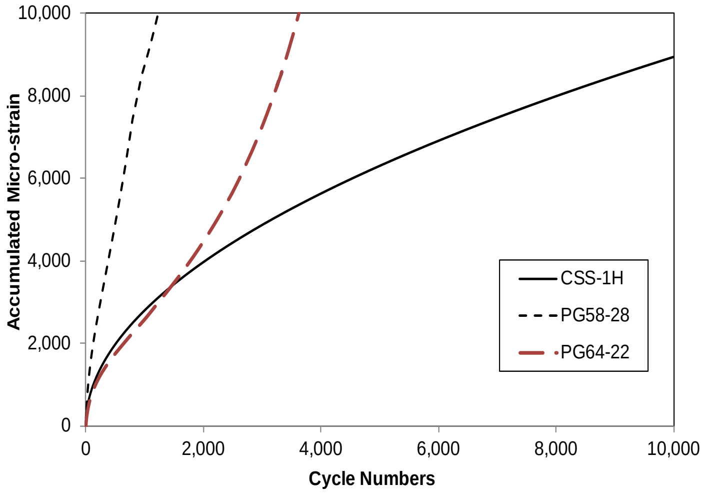
Repeated Load Test

Two replicates from each CIR mix were prepared as with the dynamic modulus test specimens. The unconfined, repeated load test was performed under a deviator stress level of 138 kPa (20 psi) at 40°C. A loading stress level of 138 kPa was selected based on the studies performed by Zhou et al. (*30*, *31*). The loading stress is applied in the form of a haversine curve with a loading time of 0.1 second with a rest period of 0.9 second in one cycle. Loading stress is repeatedly applied on the specimens until it exhibits a tertiary flow and reaches 5 percent permanent strain level or the number of loading cycles reaches 10,000.

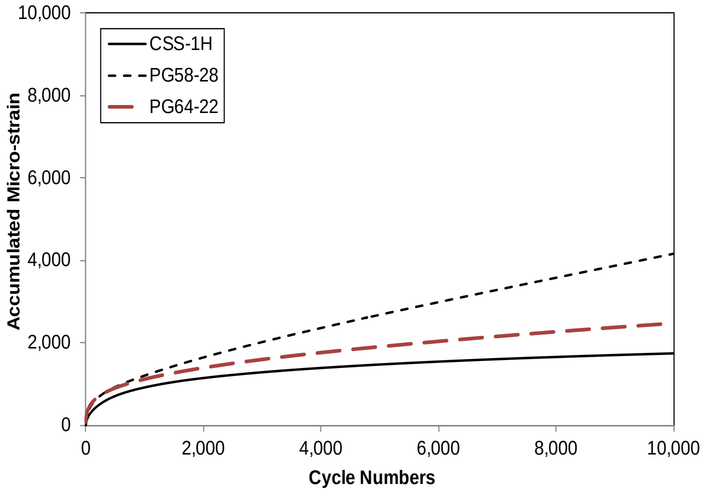
Figure 34 presents plots of the measured accumulative permanent strain against the number of loading cycles. The repeated load test results showed exactly the same trends and rankings. Given the same RAP source, the CIR-emulsion mixes (CSS-1H) exhibited lower accumulative permanent strains than those of CIR-foam mixes (PG58-28 and PG64-22 binders). The RAP source significantly affected the expected rutting performance of CIR mixes. Given the same treatment, the RAP materials from FM 92 showed the lowest accumulated permanent strain.



(a) US 60



(b) I-40



(c) FM 92

Figure 34. Results of Repeated Load Test for Each RAP Source.

PERFORMANCE ON EXISTING CIR SECTIONS IN TEXAS

The CIR technology is rarely used in Texas. However, the Amarillo District has used CIR, and they have been successful with it as a pavement rehabilitation strategy. The Amarillo District constructed two different CIR sections on US-83. The first CIR section was constructed in Ochiltree County from September to October 2010. This project started from Oklahoma border to south 9.8 km (6.1 miles). The other CIR section was constructed in Hemphill County from Lipscomb County line to south 9.8 km (6.1 miles) in fall 2013.

To evaluate the field performance of these CIR pavements, cores were collected from existing CIR on both sections for lab testing. Field cores were returned to the lab for laboratory testing, which included visual observation, Hamburg wheel track test, I-FIT, IDEAL-CT, and resilient modulus test.

Visual Observation

Figure 35 shows representative field cores from existing CIR on both US 83 sections. Fifteen cores were taken from each section. Most cores from both sections showed very good condition. The average thickness of each layer of Ochiltree County section was 43 mm (1.7 inches) for the top surface layer (HMA) and 147 mm (5.8 inches) for the CIR layer, while Hemphill County section had 42 mm (1.65 inches) for the HMA layer and 109 mm (4.3 inches) for the CIR layer, respectively.

Core #1
AC surface: 1.5″
CIR: 5.5″

Core #2
AC surface: 1.4″
CIR: 5.7″

Core #3
AC surface: 1.5″
CIR: 5.7″

(a) Ochiltree County

Core #1
AC surface: 1.5″
CIR: 4.5″

Core #2
AC surface: 1.5″
CIR: 4.0″

Core #3
AC surface: 1.5″
CIR: 4.0″

(b) Hemphill County

Figure 35. Visual Observation and Cores' Thickness Measurements.

Results of Hamburg Wheel Track Test

In order to perform the wheel tracking test, field cores were cut into individual HMA and CIR test specimens. For the CIR layer, cores were cut into 62 mm (2.4 inches) in height, which is required testing specimen size. On the other hand, the HMA layer was cut into 38 mm (1.5 inches) in height and was patched with a plaster to meet the required test specimen size. Table 19 summarizes the rut depth measured from both HMA and CIR cores of each section. The rutting resistance of CIR cores showed very good performance. The CIR layer of Hemphill County showed even better performance than that of the HMA layer.

Table 19. Results of Hamburg Wheel Track Test (mm).

Location	Layer	No. of passes				Failure cycles
		5,000	10,000	15,000	20,000	
Ochiltree Co.	HMA	1.77	2.45	5.26	12.52	17,800
	CIR	2.98	4.73	10.15	12.67	15,750
Hemphill Co.	HMA	3.29	7.40	10.82	12.64	17,100
	CIR	5.49	7.16	9.03	10.61	-

Results of Cracking Tests

Field cores were cut to make test specimens for the I-FIT and IDEAL-CT. Table 20 and Table 21 summarize the results of I-FIT and IDEAL-CT, respectively, on the field cores. Both cracking tests showed the same trend. As expected, the cracking resistance of the HMA layers exhibited better performance than that of the CIR layers. Based on the test results, both HMA and CIR cores of each section seem susceptible to cracking.

Table 20. Results of I-FIT Test: Flexibility Index (No Unit).

Location	Layer	#1	#2	#3	#4	#5	#6	AVG
Ochiltree Co.	HMA	5.6	3.5	1.6	4.7	6.2	5.1	**4.5**
	CIR	0.17	0.12	0.42	0.77	0.2	0.16	**0.3**
Hemphill Co.	HMA	2.6	1.1	7.3	4.1	9.5	7.8	**5.4**
	CIR	0.49	0.28	0.66	0.44	0.56	1.05	**0.6**

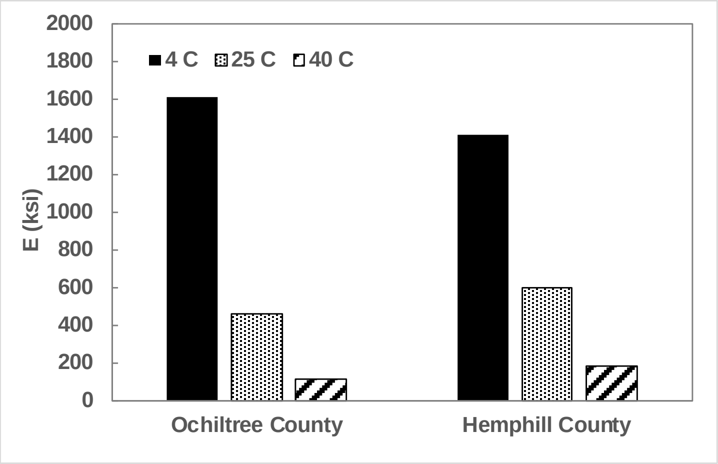
Table 21. Results of IDEAL-CT Test: CT_{Index} (No Unit).

Location	Layer	#1	#2	#3	AVG
Ochiltree Co.	HMA	76.2	91.1	112.3	**93.2**
	CIR	11.7	9.6	6.8	**9.4**
Hemphill Co.	HMA	34.6	35.9	27.9	**32.8**
	CIR	10.4	15.8	15.6	**13.9**

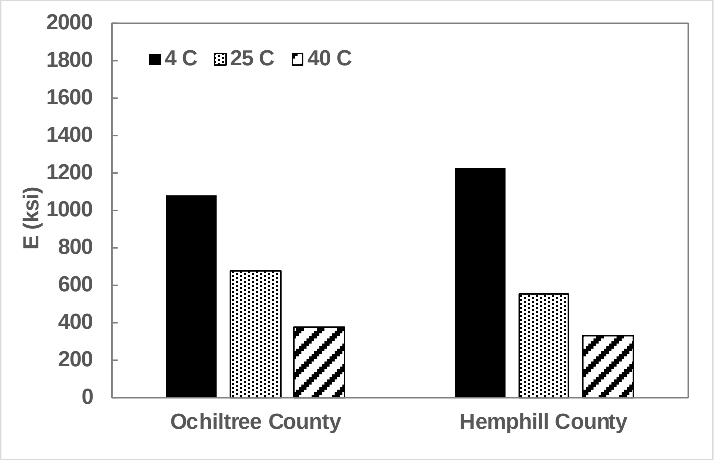
Results of Resilient Modulus Test

The resilient modulus test was performed at three different temperatures of 4, 20, and 40°C. Figure 36 presents the resilient modulus measured from both HMA and CIR cores of each section. Consistent with other findings in this research project, temperature-dependent behavior from both HMA and CIR cores was observed in these resilient modulus test results. As the temperature increased, the resilient modulus decreased. Given the same testing temperature of 4°C, the resilient modulus of HMA cores showed higher values than those of CIR cores.

However, CIR cores showed higher resilient modulus than those of HMA at 40°C. This observation is consistent with the CIR cores showing similar or better rutting performance than HMA cores in the Hamburg test, which uses a 50°C test temperature.



(a) HMA cores



(b) CIR cores

Figure 36. Results of Resilient Modulus.

CONCLUSIONS

Based on mix designs and lab performance-related results of CIR mixes and performance results of existing CIR pavement sections in Texas, the data support the following conclusions:

- Treatment options for CIR mixes can be identified. Binder type affects the CIR mix performance. The mixture properties are temperature dependent.
- For the materials evaluated in the lab, although stiffness and modulus values were reasonable, lab results suggest rutting performance may be a concern.
- Rutting performance on field CIR cores was similar to HMA, but cracking performance showed poorer results.

- If cracking resistance of CIR mixes is a concern, additional additives may be considered to improve crack resistance.
- Lab tests in this research used multiple approaches to characterize rutting, cracking, and stiffness of CIR mixes. These tests showed the same trends and made sense in context of the expected tradeoffs and interdependencies of rutting, cracking, and mix stiffness. This observation indicates the series of laboratory tests used in this research project are appropriate to characterize CIR mixes.

CHAPTER 5. DESIGN AND CONSTRUCTION RECOMMENDATION

INTRODUCTION

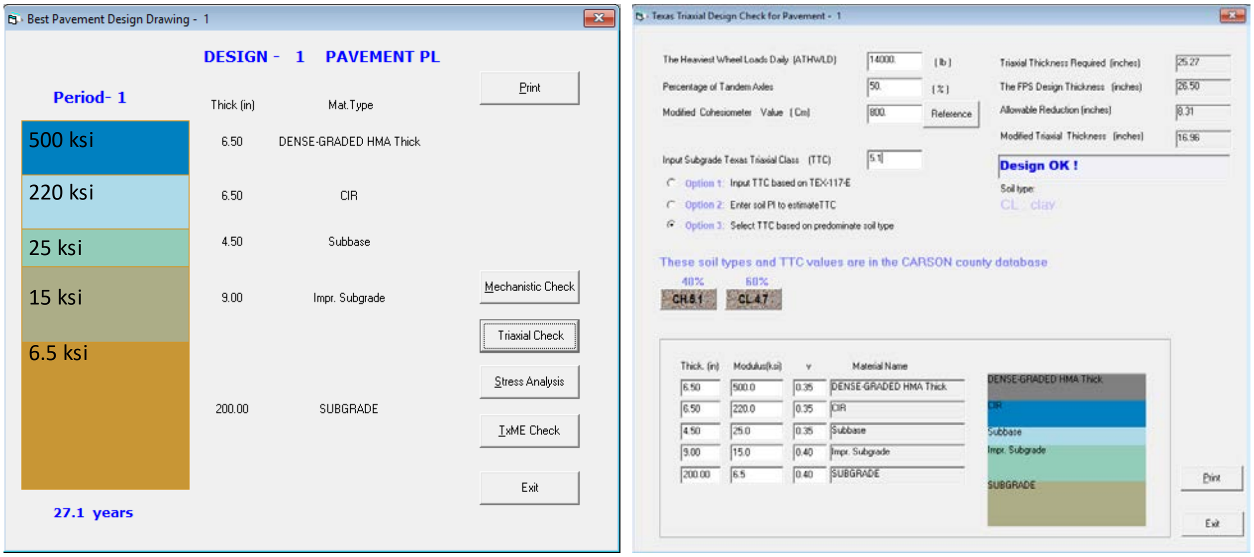
Field sections from US 60, I-40, and FM 92 were sampled and then characterized for their modulus, rutting, and cracking properties in the laboratory. The characterized material properties of CIR mixtures were used to analyze the expected performance of pavement design options using Flexible Pavement System (FPS21) and the Texas Mechanistic-Empirical (TxME) flexible pavement design software.

PAVEMENT DESIGNS USING FPS21

For each field section, possible pavement structures were designed using FPS21. Based on inputs of traffic and layer moduli as summarized in Table 18, the thickness design for each section was performed until it passed the triaxial check. Figure 37 shows developed pavement structures.

Table 22. Key FPS21 Design Inputs for Field Sections.

	US 60	**I-40**	**FM 92**
Beginning ADT	4,920	14,000	2,300
Ending ADT	9,150	19,200	3,200
Truck Percent (%)	23.5	52.3	10.0
18-kip ESAL for 20 Years (millions)	9.79	35.7	0.774
Subgrade Modulus (ksi)	6.5	7.2	10



DESIGN - 1 PAVEMENT PL

Period- 1

Thick (in)	Mat.Type
6.50	DENSE-GRADED HMA Thick
6.50	CIR
4.50	Subbase
9.00	Impr. Subgrade
200.00	SUBGRADE

27.1 years

The Heaviest Wheel Loads Daily (ATHWLD) 14000. (lb)
Percentage of Tandem Axles 50. (%)
Modified Cohesiometer Value (Cm) 800.
Input Subgrade Texas Triaxial Class (TTC) 5.1
○ Option 1: Input TTC based on TEX-117-E
○ Option 2: Enter soil PI to estimateTTC
● Option 3: Select TTC based on predominate soil type

Triaxial Thickness Required (inches) 25.27
The FPS Design Thickness (inches) 26.50
Allowable Reduction (inches) 8.31
Modified Triaxial Thickness (inches) 16.96

Design OK !

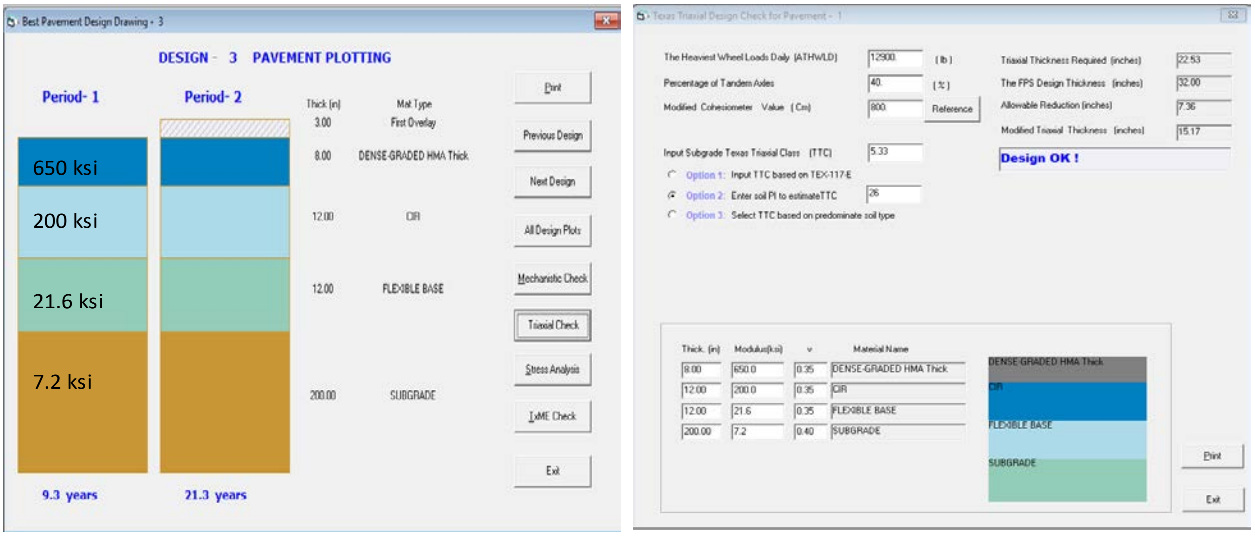
Soil type:
CL clay

These soil types and TTC values are in the CARSON county database

40%	60%
CH 5.1	CL 4.7

Thick. (in)	Modulus(ksi)	v	Material Name
6.50	500.0	0.35	DENSE-GRADED HMA Thick
6.50	220.0	0.35	CIR
4.50	25.0	0.35	Subbase
9.00	15.0	0.40	Impr. Subgrade
200.00	6.5	0.40	SUBGRADE

(a) US 60



DESIGN - 3 PAVEMENT PLOTTING

Period- 1 9.3 years

Period- 2 21.3 years

Thick (in)	Mat.Type
3.00	First Overlay
8.00	DENSE-GRADED HMA Thick
12.00	CIR
12.00	FLEXIBLE BASE
200.00	SUBGRADE

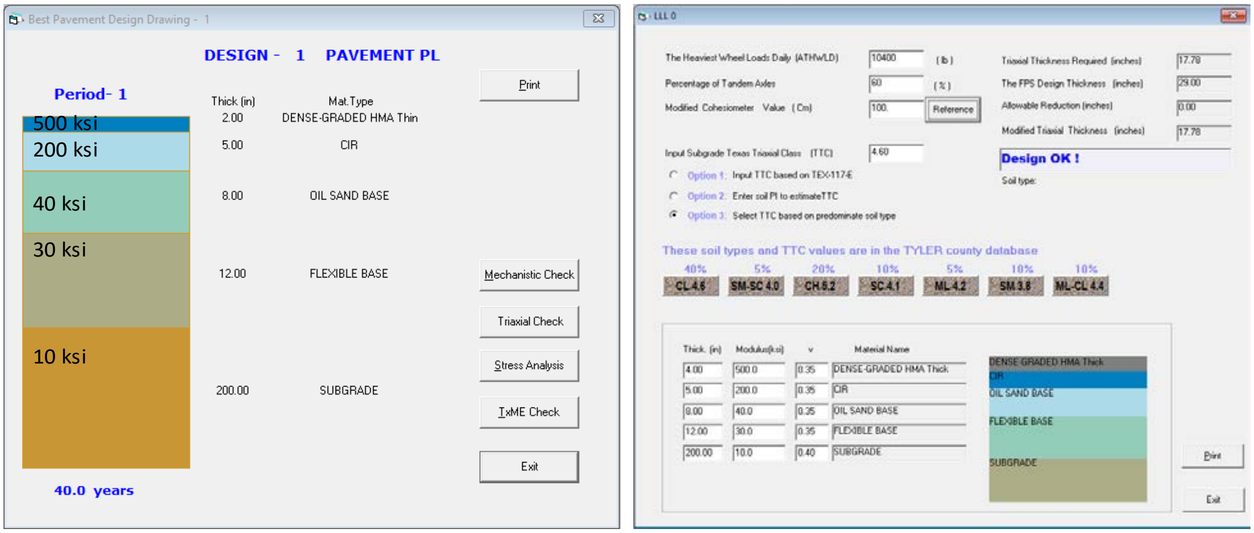
The Heaviest Wheel Loads Daily (ATHWLD) 12900. (lb)
Percentage of Tandem Axles 40. (%)
Modified Cohesiometer Value (Cm) 800.
Input Subgrade Texas Triaxial Class (TTC) 5.33
○ Option 1: Input TTC based on TEX-117-E
● Option 2: Enter soil PI to estimateTTC 26
○ Option 3: Select TTC based on predominate soil type

Triaxial Thickness Required (inches) 22.53
The FPS Design Thickness (inches) 32.00
Allowable Reduction (inches) 7.36
Modified Triaxial Thickness (inches) 15.17

Design OK !

Thick. (in)	Modulus(ksi)	v	Material Name
8.00	650.0	0.35	DENSE-GRADED HMA Thick
12.00	200.0	0.35	CIR
12.00	21.6	0.35	FLEXIBLE BASE
200.00	7.2	0.40	SUBGRADE

(b) I-40



Best Pavement Design Drawing - 1

DESIGN - 1 PAVEMENT PL

Period- 1

Thick (in)	Mat.Type
2.00	DENSE-GRADED HMA Thin
5.00	CIR
8.00	OIL SAND BASE
12.00	FLEXIBLE BASE
200.00	SUBGRADE

40.0 years

LLL 0

The Heaviest Wheel Loads Daily (ATHWLD): 10400 (lb)

Percentage of Tandem Axles: 60 (%)

Modified Cohesiometer Value (Cm): 100.

Input Subgrade Texas Triaxial Class (TTC): 4.60

○ Option 1: Input TTC based on TEX-117-E

○ Option 2: Enter soil PI to estimateTTC

● Option 3: Select TTC based on predominate soil type

Triaxial Thickness Required (inches): 17.78

The FPS Design Thickness (inches): 29.00

Allowable Reduction (inches): 0.00

Modified Triaxial Thickness (inches): 17.78

Design OK !

Soil type:

These soil types and TTC values are in the TYLER county database

40%	5%	20%	10%	5%	10%	10%
CL 4.6	SM-SC 4.0	CH 5.2	SC 4.1	ML 4.2	SM 3.8	ML-CL 4.4

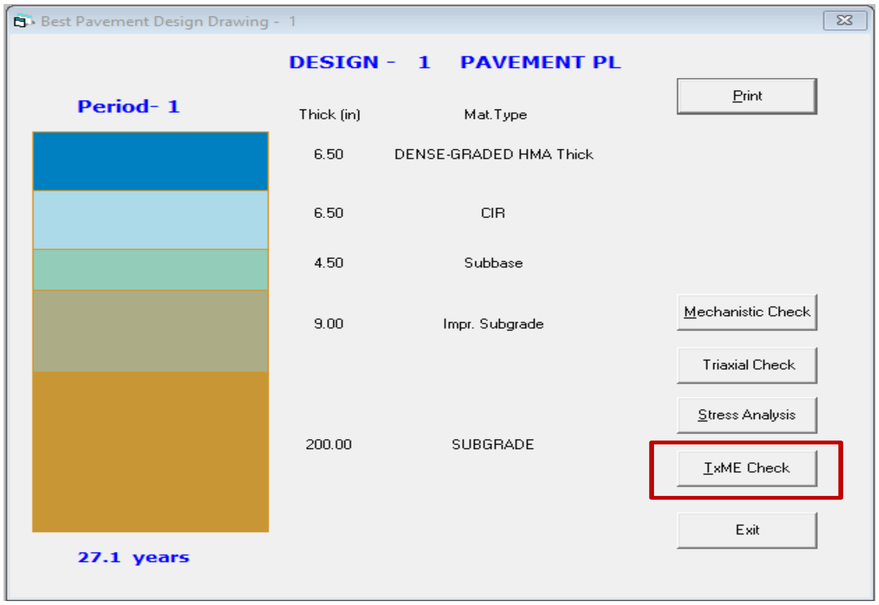
Thick. (in)	Modulus(ksi)	v	Material Name
4.00	500.0	0.35	DENSE-GRADED HMA Thick
5.00	200.0	0.35	CIR
8.00	40.0	0.35	OIL SAND BASE
12.00	30.0	0.35	FLEXIBLE BASE
200.00	10.0	0.40	SUBGRADE

(c) FM 92

Figure 37. Possible CIR Design Options for Field Sections.

PAVEMENT PERFORMANCE PREDICTION USING TXME

FPS 21 can connect to the TxME, thus allowing users to predict performance of each design option generated by FPS 21, as shown in Figure 38. The TxME flexible pavement design system was developed to generate more economical, reliable designs based on mechanistic-empirical modeling and performance-based material characterization.



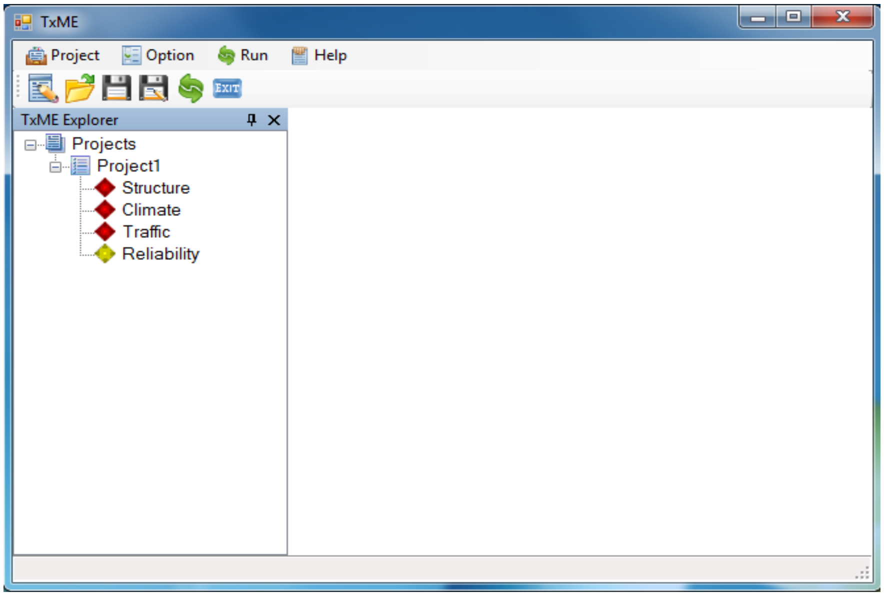
DESIGN - 1 PAVEMENT PL

Period- 1

Thick (in)	Mat.Type
6.50	DENSE-GRADED HMA Thick
6.50	CIR
4.50	Subbase
9.00	Impr. Subgrade
200.00	SUBGRADE

27.1 years

(a) Connection button to TxME program



(b) Main screen of TxME program

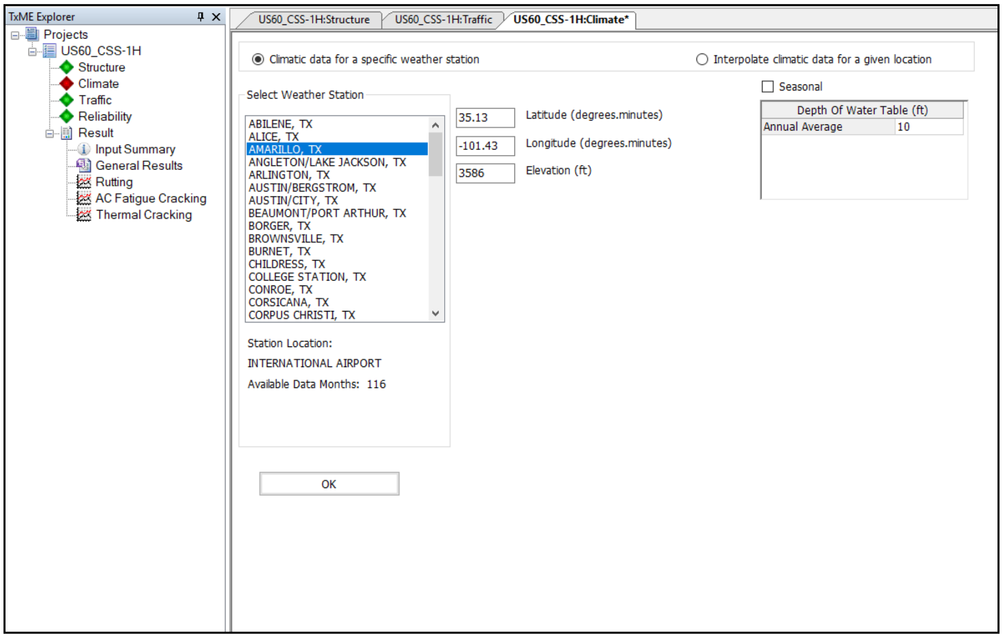
Figure 38. Performance Check Feature Connecting FPS 21 with TxME.

Simulation Inputs for TxME

TxME can consider environmental conditions (e.g., temperature, precipitation, and depth to water table) at the project site when predicting pavement performance. For example, Figure 39 shows the selected climate data input for US 60. In this example, the weather station in Amarillo, Texas, was selected.

With regard to traffic input, FPS 21 pavement design is based on ESALs, while TxME has two options: ESALs and load spectra. Load spectra provide a more realistic representation than

ESALs; however, no traffic load spectra data were available for these field sections. Thus, ESALs-based traffic input data were used for TxME simulations as shown in Figure 40.



● Climatic data for a specific weather station ○ Interpolate climatic data for a given location

☐ Seasonal

Select Weather Station

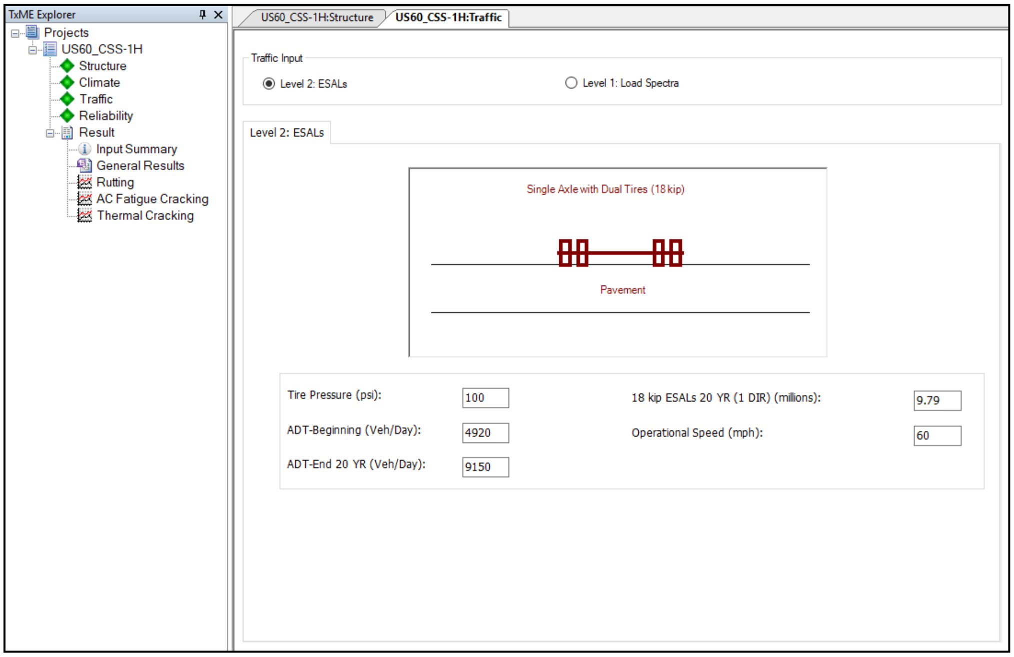
ABILENE, TX
ALICE, TX
AMARILLO, TX
ANGLETON/LAKE JACKSON, TX
ARLINGTON, TX
AUSTIN/BERGSTROM, TX
AUSTIN/CITY, TX
BEAUMONT/PORT ARTHUR, TX
BORGER, TX
BROWNSVILLE, TX
BURNET, TX
CHILDRESS, TX
COLLEGE STATION, TX
CONROE, TX
CORSICANA, TX
CORPUS CHRISTI, TX

Latitude (degrees.minutes): 35.13
Longitude (degrees.minutes): -101.43
Elevation (ft): 3586

	Depth Of Water Table (ft)
Annual Average	10

Station Location:
INTERNATIONAL AIRPORT
Available Data Months: 116

Figure 39. Climate Data Selection for US 60.



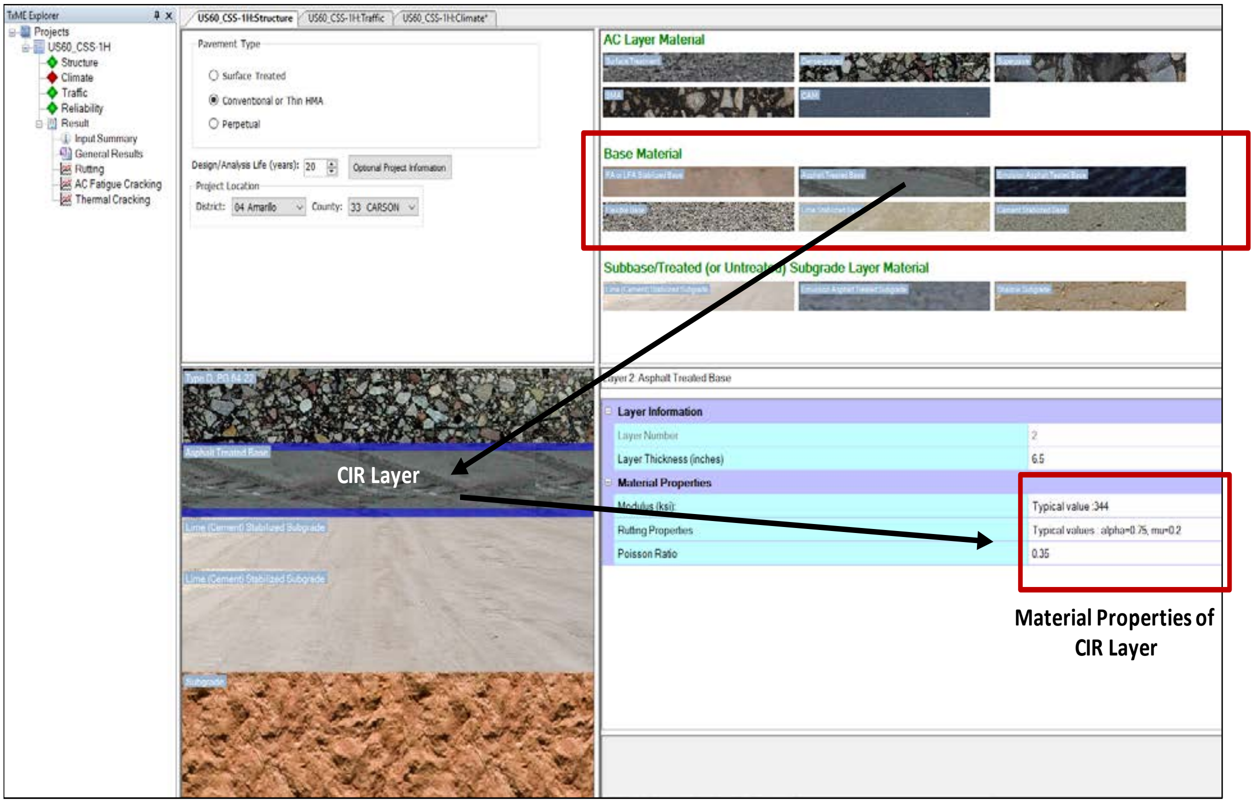
Traffic Input
● Level 2: ESALs ○ Level 1: Load Spectra

Tire Pressure (psi): 100
ADT-Beginning (Veh/Day): 4920
ADT-End 20 YR (Veh/Day): 9150
18 kip ESALs 20 YR (1 DIR) (millions): 9.79
Operational Speed (mph): 60

Figure 40. ESAL-Based Traffic Input for US 60 Entered in TxME.

Once representative traffic data are obtained, selecting appropriate material properties for pavement layers is the main concern when designing pavements. It is important to investigate how pavement performance is influenced by material properties. Figure 41 shows the material property data input screen of TxME, and there are six different base material options. Among them, the asphalt treated base was chosen to represent the CIR layer of the field sections. In order to evaluate CIR mixture design options, the characterized material properties of CIR mixtures were used as shown in Figure 41, while other layers used some of the TxME default values along with modulus values presented in Figure 37. The material properties used for the CIR layer included:

- Layer modulus: the resilient modulus test was performed, and Figure 42 presents the modulus values.
- Poisson ratio: a typical value of 0.35 was used for all CIR mixtures.
- Rutting properties (e.g., alpha and mu): the repeated load test was performed, and Figure 34 presents the test results. Alpha and mu values of each CIR mixture were determined based on the study performed by Hu et al. (*32*). Table 23 summarizes the measured alpha and mu values of each CIR mixture.



Pavement Type
○ Surface Treated
● Conventional or Thin HMA
○ Perpetual

Design/Analysis Life (years): 20

Optional Project Information

Project Location

District: 04 Amarillo

County: 33 CARSON

Layer 2: Asphalt Treated Base

Layer Information	
Layer Number	2
Layer Thickness (inches)	6.5
Material Properties	
Modulus (ksi)	Typical value :344
Rutting Properties	Typical values : alpha=0.75, mu=0.2
Poisson Ratio	0.35

Figure 41. Material Property Inputs of CIR Layer for US 60.

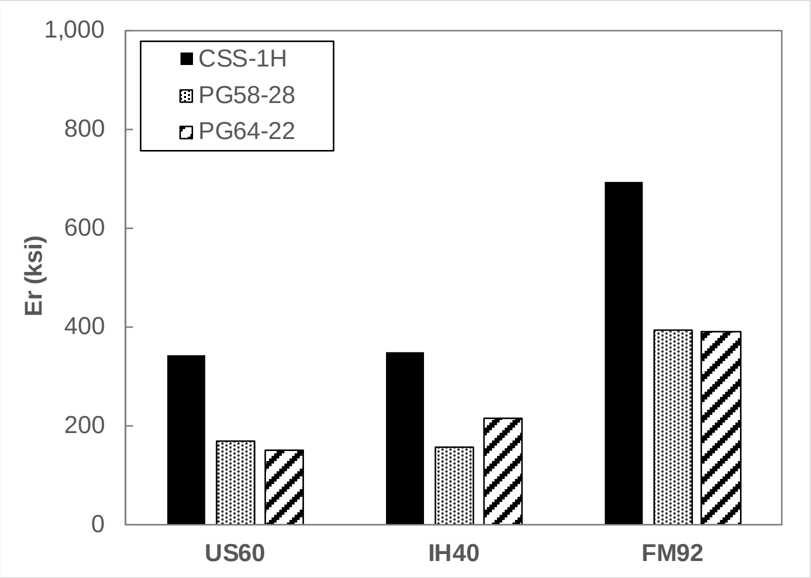
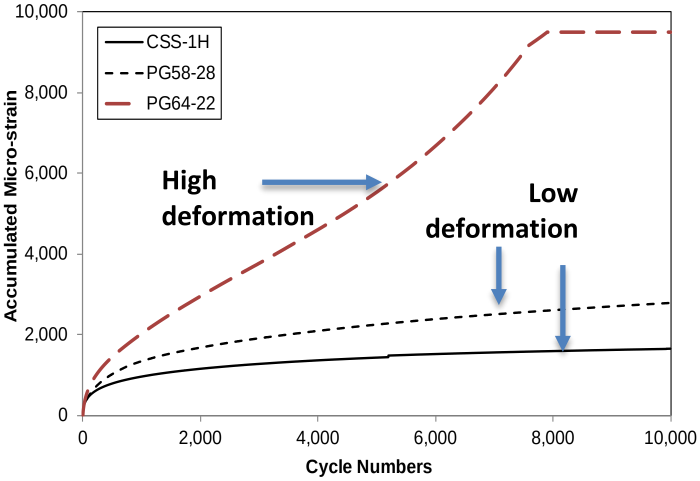
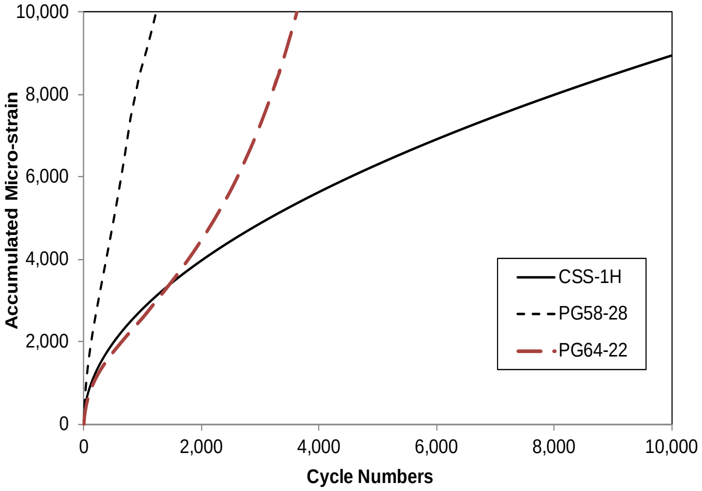


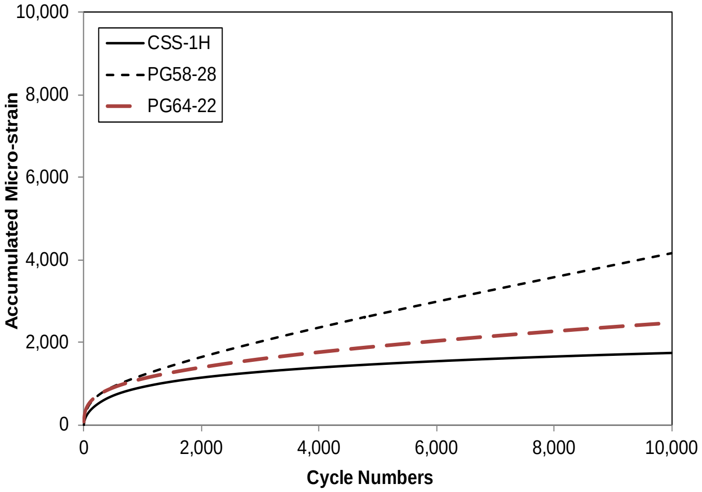
Figure 42. Resilient Modulus of Each CIR Mix for Field Sections.



(a) US 60



(b) I-40



(c) FM 92

Figure 43. Results of Repeated Load Test for Each CIR Mix of Field Sections.

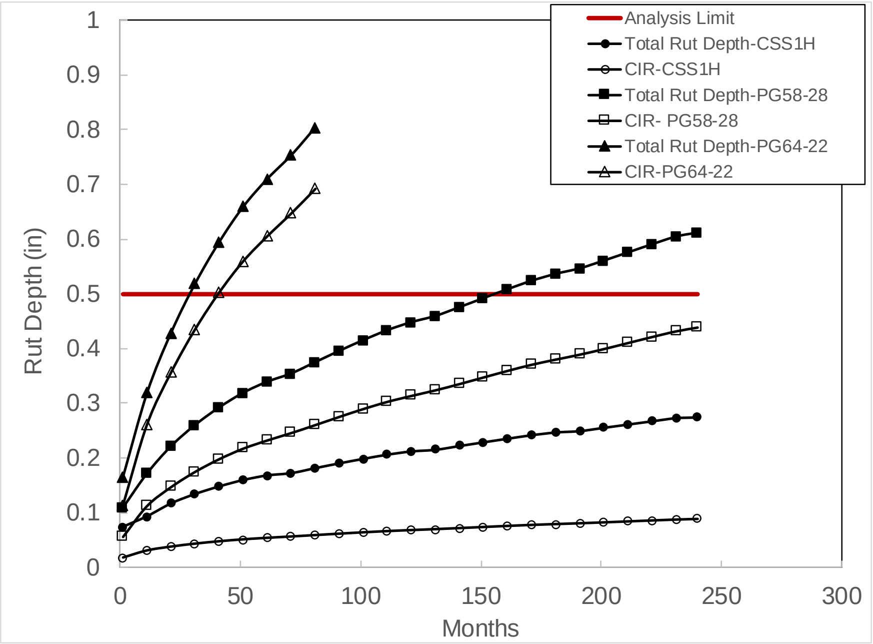
Table 23. Alpha and Mu Values for Each CIR Mix of Field Sections.

Field Sections	**CSS-1H**		**PG58-28**		**PG64-22**	
	alpha	**mu**	**alpha**	**mu**	**alpha**	**mu**
US 60	0.75	0.20	0.66	0.23	0.59	0.26
I-40	0.46	0.14	0.34	0.16	0.45	0.12
FM 92	0.70	0.23	0.57	0.21	0.64	0.25

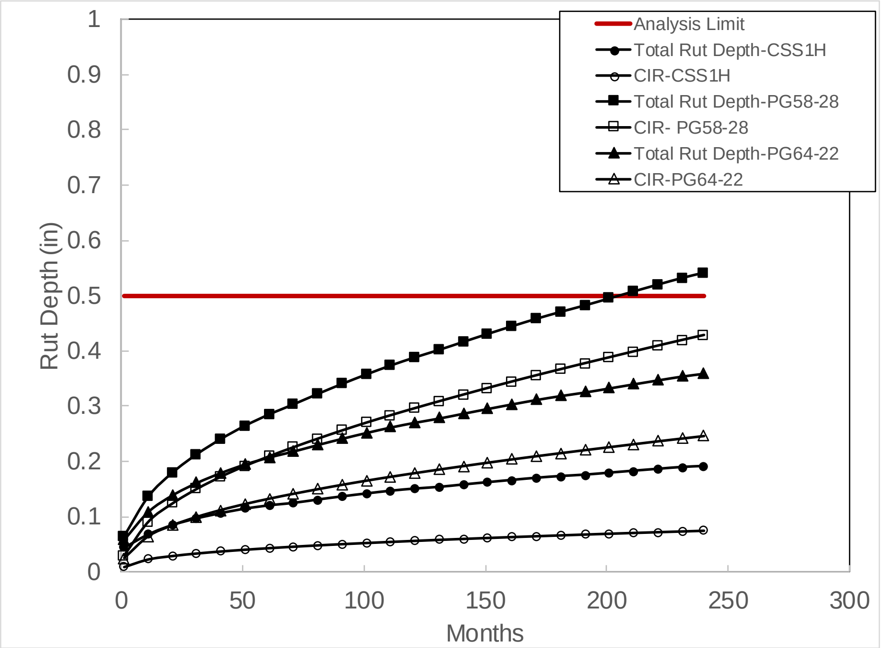
Prediction Results

Three different treatment options for the CIR layer were considered for each field section, which resulted in a total of nine TxME run files. The total rut depth of the pavement structure and the rut depth of the CIR layer from each TxME run were compared as shown in Figure 44.

Consistent with the results in Figure 34, the binder type and treatment option for the CIR layer significantly affected the predicted rutting performance of the pavements. The CIR layer treated with CSS-1H of both US 60 and FM 92 sections showed best performance compared to others treated with PG58-28 or PG64-22 binders. The simulation results for I-40 are not included in Figure 44, because in the TxME all cases for I-40 failed by rutting within only three months due to very high traffic and poor rutting resistance of the CIR mixtures.



(a) US 60



(b) FM 92

Figure 44. Predicted Rutting Performance of Field Sections.

CONSTRUCTION RECOMMENDATIONS

For each field section, pavement thickness designs using FPS 21 were performed and presented in Figure 37. The performance of these design options was further predicted using the TxME. The TxME simulation results indicate:

- For US 60, the CSS-1H treatment option was the only CIR layer option that passed.
- None of the treatment options for I-40 passed the TxME. The CIR mixtures of I-40 showed very weak rutting resistance, and the I-40 section has very high traffic conditions. The CIR layer for I-40 seems to not be a good option. Thus, it is recommended using different type of base materials such as a full depth reclamation mixture.
- Both CSS-1H and PG 64-22 treatment options for FM 92 passed. Although the PG 58-28 treatment option failed, the expected service life was 205 months.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Buried moisture damage in asphalt layers can often go undetected, resulting in new overlays not reaching their design life. Use of non-destructive testing like GPR can help detect these buried moisture damage problems. Recent developments for CIR and CCPR technologies can be considered for addressing moisture-damaged asphalt layers by recycling the existing material in place to create a structurally sound asphalt treated base layer.

CONCLUSIONS

Through a thorough literature review, field sampling and testing, a comprehensive lab study, and evaluation of pavement design alternatives, researchers determined the following conclusions and recommendations:

- Various equipment and options are available from industry. Depending on work areas, construction situations, and production rates, CIR and CCPR processes can be customized.
- Existing relevant specifications of several agencies were reviewed. General information on weather limitations, RAP gradation, and equipment capacities was similar among agencies. However, the mix design requirements were different. Also, each state agency has different curing criteria for CIR in either moisture content or curing time. Applicable specifications need to be updated for best practices.
- CIR and CCPR are becoming popular methods in rehabilitating existing asphalt pavements, and they have been successfully used for even higher traffic volume roadways. Many researchers have reported that CIR/CCPR pavements have performed well.
- Treatment options for CIR and CCPR mixes can be identified through the lab. Binder type affects the CIR mix performance. The mixture properties are temperature dependent.
- For the materials evaluated in the lab, although stiffness and modulus values were reasonable, lab results suggest rutting performance may be a concern.
- Rutting performance on field CIR cores was similar to HMA, but cracking performance showed poorer results.

RECOMMENDATIONS

Researchers recommend:

- The most significant recommendation for mix design requirements is to use the IDT rather than the Marshall Stability test to determine the design binder content. Appendix A provides laboratory guidelines.
- Additives may be considered to improve crack resistance if cracking is a concern.

- Lab tests in this research project used multiple approaches to characterize rutting, cracking, and stiffness of CIR mixes. These tests showed the same trends and made sense in context of the expected tradeoffs and interdependencies of rutting, cracking, and mix stiffness. This observation indicates the series of laboratory tests used in this research project are appropriate to characterize cold-recycled mixes.
- The special specification updates in Appendix B should be used for developing CIR/CCPR projects in Texas.

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APPENDIX A. LABORATORY GUIDELINES FOR MIXTURE DESIGN

INTRODUCTION

This guideline describes procedures for selecting and obtaining representative samples and the laboratory mix design procedures for cold in-place recycling (CIR) using the indirect tensile strength (IDT) test.

SAMPLING AND PROCESSING

Follow Tex-400-A for sampling stockpiled reclaimed asphalt pavement (RAP) materials. Follow the guidelines in Table 24 for sampling roadway materials.

Table 24. Sampling Roadway Materials.

Step	Recommended Approach	Acceptable Approach
1	Obtain historic plans. Conduct ground penetrating radar (GPR) survey.	Obtain plans and maintenance history.
2	Using plans and GPR survey, determine critical locations for sampling. Cover expected range of different types and thicknesses of asphalt concrete pavement.	Unless otherwise determined from plans and maintenance history, perform coring at 1 mi. spacing. For short projects (< 1 mi.), perform coring at a minimum of three locations.
3	Perform drill logs at each location of the pavement structure including at least the top 10 in. of subgrade.	Review core logs. Select locations representing significantly different types and thicknesses of asphalt concrete pavement for follow-up bulk sampling.
4	At each location of significantly different asphalt concrete materials, use a small recycler, auger, or core drill to obtain samples of the materials expected in the depth of the CIR road-mix.	At each location of significantly different asphalt concrete materials, use a small recycler, auger, or core drill to obtain samples of materials expected in depth of the CIR road-mix.
5	Collect approximately 400 lb of sample for each set of different materials requiring a mixture design.	Collect approximately 400 lb of sample for each set of different materials requiring a mixture design.

Cores, when used for obtaining bulk roadway sample, shall be cut in the laboratory to the anticipated depth of CIR treatment. Cores shall be crushed in the laboratory.

Gradation of the millings shall be determined by Tex-200-F Part I (dried at no greater than 104°F). The gradation should fall into one of the categories in Table 25, and if significant field processing variability is expected, a mix design should be performed using the medium gradation and a minimum of one of the fine or coarse gradations. Samples can be prepared with a sample splitter, or dry screened and the millings recombined in the laboratory to target gradation. Scalp oversize aggregate with a 1.0-inch screen.

Table 25. Master Gradation of Crushed Millings.
(% passing by Weight or Volume)

Sieve Size	Fine	Medium	Coarse
1″	100.0	100.0	100.0
¾″	95.0–100.0	85.0–96.0	75.0–92.0
#4	55.0–75.0	40.0–55.0	30.0–45.0
#30	15.0–35.0	4.0–14.0	1.0–7.0
#200	1.0–7.0	0.6–3.0	0.1–3.0

MIX DESIGN PROCEDURE

1. RAP Preparation: Prepare an 8,000 gram sample of RAP materials recombined to the expected field gradation for a set of six gyratory specimens per asphalt content.

2. Mixing.
    a. Place RAP materials into a mixer and pour in 4 percent moisture. Start the mixer, add emulsified asphalt or foamed asphalt, and mix thoroughly for 60 seconds.
    b. For emulsified asphalt, recommended emulsion contents are 1.0 percent, 1.5 percent, 2.0 percent, 2.5 percent, 3.0 percent, and 3.5 percent. Choose a minimum of two emulsion contents for the mix design.
    c. For foamed asphalt, determine the optimum foaming characteristics for a given asphalt binder according to the lab foaming system manufacturer’s instructions. Recommended foamed asphalt contents are 1.5 percent, 2.0 percent, 2.5 percent, 3.0 percent, and 3.5 percent. Choose a minimum of two foamed asphalt contents for the mix design.

3. Compaction.
    a. Determine the weight of sample needed to fill a 100.0 mm by 50.8 mm (4.0 in. by 2.0 in.) cylindrical mold at the target density determined following Tex-113-E at 4 percent moisture content.
    b. Setup the SGC with an external angle of 1.25° and consolidation pressure of 600 kPa. Configure the SGC to compact to a specified height of 50.8 mm (2 in.).
    c. Weigh out and compact a test specimen using a Superpave gyratory compactor (SGC).
    d. Extrude the compacted specimen from the gyratory mold.
    e. Measure the height of the specimen. When the height does not meet the requirements of 2 ± 0.06 in., determine a corrected weight of material for a height of 2 in.
    f. Weigh the other samples from the mixed material and compact a total of six specimens.
    g. Measure the weight to the nearest 0.001 lb and the height to the nearest 0.01 in. of each compacted specimen.

4. Curing.
    a. Place the compacted CIR specimens in an oven or temperature chamber at 40°C.
    b. Cure the specimens for a minimum of 72 hours.

5. Volumetric Characteristics.
   a. Calculate bulk specific gravity of only the three CIR specimens that will be used for wet IDT following Tex-207-F.
   b. Measure theoretical maximum specific gravity following Tex-227-F.
   c. Calculate air void.

6. Indirect Tensile Strength Test.
   a. Submerge three specimens for wet IDT completely in a water bath at 25°C for 24±1 hours.
   b. Store the remaining three specimens at room temperature for 24±1 hours.
   c. Perform the IDT test at 25°C following Tex-226-F.
   d. Calculate the average IDT of three specimens for dry and wet conditions, respectively.

7. Optimum Asphalt Content Selection.
   a. Proceed to Step 8 when the IDT results meet the specification requirements.
   b. When the IDT results fail to meet the specification requirements, make modifications as deemed necessary and repeat steps 1–6.

8. Hamburg Wheel Test and Raveling Test.
   a. Perform the Hamburg test and Raveling test in accordance with Tex-242-F and ASTM D7196, respectively.
   b. When the results meet the specification requirements, report the minimum treatment rate to meet specification requirements.
   c. When the results fail to meet the specification requirements, make modifications as deemed necessary and repeat steps 1–7.

APPENDIX B. SPECIFICATION RECOMMENDATIONS FOR COLD-RECYCLED ASPHALT MIXTURES

An extensive literature review on cold in-place recycling (CIR) and cold central-plant (CCPR) mixture designs and requirements along with laboratory testing and pavement performance prediction was conducted in this project. Based on the findings and results from prior tasks, Table 26 shows the recommended mixture design requirements, and Table 27 shows the recommended mixture testing for quality control, respectively. The updates are in ***bold italics***. While this project's activities focused primarily on materials for CIR, based on the literature and the findings in this project, Table 26 and Table 27 should also be appropriate for CCPR mixtures.

Table 26. Recommended Mix Design Requirements.

Property	**Criteria**	**Purpose**
Maximum Density, Tex-113-E	***@ 4% Moisture content***	***Set Target Density***
Compaction effort, Superpave Gyratory Compactor	1.25° angle, 600 kPa stress, ***Target density-based***	Prepare mix design Specimens
Density*(1) (2) (3)*, Tex-207-F, Part I	Report	Compaction Indicator
Hamburg Wheel Tracking Test*(2) (3)*, Tex-242-F	5,000 passes (min.) *(4)* 15,000 passes (max.)	Rutting Resistance
Gradation for Design Millings, Tex-200-F, Part I	Report	
Indirect Tensile Strength (IDT) (1) (2) (3), Tex-226-F	***50 psi (min.)***	***Cracking Resistance***
Moisture Conditioned (IDT) (1) (2) (3) (5)	***30 psi (min.)***	***Moisture Resistance***
Raveling Test, 4-hour cure @ 10ºC and 50% humidity, ASTM D7196	2% (max.)	Raveling Resistance
(1) ***Specimens in 100 mm (4.0 in.) diameter and 50.8 mm (2.0 in.) height shall be prepared*** (2) ***Determine the weight of specimen needed to mold at target density*** (3) ***Tested on compacted specimens after 40°C (104°F) curing for 72 hours.*** (4) ***If results do not meet minimum requirements, consider using cement additive by 0.5% increment.*** (5) ***After curing, submerge specimens completely in water for 24±1 hours and run at 25°C (77°F)***		

Table 27. Recommended Quality Control Tests.

Description	**Test Method**	**Minimum Contractor Testing Frequency**	**Test Requirements**
Hamburg Wheel Test	Tex-242-F	1 per day of production	5,000 passes (min.) 15,000 passes (max.) @ 12.5 mm (0.5 in.) rut depth
Dry Tensile Strength	***Tex-226-F***	1 per day of production	***50 psi (min.)***
Wet Tensile Strength	***Tex-226-F***	1 per day of production	***30 psi (min.)***
Density	Tex-207-F, Part I	1 per day of production	***95%***

In the literature, moisture content or water is differently accounted for across agencies. Cox and Howard (*33*) suggested standardizing all moisture contents to total moisture content (i.e., added mixing moisture, water phase of asphalt emulsion, and existing moisture) for consistency. The moisture content referred herein is the total moisture content. Across agencies, there is no standard method to determine the optimum moisture content for CIR mixtures, and multiple methods have been used in practice and research.

The Proctor test is one of methods used. However, this method generally yields high optimum moisture contents (i.e., 6 to 8 percent), which cause moisture drainage during compaction. This project also observed this phenomenon during compaction. Alternately, fixed moisture contents for cold-recycled mixtures are commonly documented and generally range from 2 to 5 percent. A moisture content of 4 percent is widely used in the literature. Thus, researchers recommend conducting the Proctor-style test to determine the target density at the fixed moisture content of 4 percent. Correspondingly, the weight of sample needed to fill cylindrical molds for mixture design is determined based on the target density. This requires target density-based compaction rather than 35-gyration compaction, which was the existing TxDOT requirement.

The Hamburg wheel tracking test is commonly used to evaluate the rutting potential and moisture susceptibility of asphalt concrete mixtures. In the literature, Hamburg wheel tracking testing on cold-recycled mixtures does not appear common; however, TxDOT used this test in SS3254. The requirement in SS3254 is for 12.5 mm (0.5 in.) of rut depth to occur between 5,000 and 15,000 passes. Based on the results in this project, all CIR mixtures when treated only with asphalt showed poor rutting resistance and moisture susceptibility in the Hamburg test and did not meet the requirement. For this reason, use of cement additive is generally recommended if asphalt-only treatment does not produce a mixture meeting the minimum Hamburg requirements. Cox and Howard (*22*) reported that 18 percent of CIR mixtures used a combination of binders. These blends are typically dominated by one binder with a small dosage of a secondary binder (e.g., 2.0 percent emulsion with 1 percent cement).

The most significant recommendation for mix design requirements is to use the indirect tensile strength (IDT) to determine the design binder content rather than the Marshall Stability test. Although many states still use the Marshall Stability test for the design purpose, the IDT test is recommended for the mix design because:

- It is a relatively simple procedure.
- It uses standard equipment available in typical TxDOT labs.
- Many recent recycling projects have documented successful use of the IDT test for binder content selection.
- Growing literature suggests the IDT test may also be useful in a performance-related context of predicting cracking performance.

Use of a raveling test in CIR mixture design is common practice across multiple agencies; the raveling test recommendation remains unchanged.