8-5-2019

Laboratory evaluation of cold in-place recycling asphalt mixtures using a balanced mix design

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LABORATORY EVALUATION OF COLD IN-PLACE RECYCLING ASPHALT MIXTURES USING A BALANCED MIX DESIGN APPROACH

by

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A Thesis

Submitted to the
Department of Civil and Environmental Engineering
College of Engineering
In partial fulfillment of the requirement
For the degree of
Master of Science in Civil Engineering
at
Rowan University
June 16, 2019

Thesis Chair: Yusuf Mehta, Ph.D., P.E.

Dedications

I would like to dedicate this work to my father, my mother, my sisters and my brother. To my grandma and all the people for their support in all my academic endeavors.

Acknowledgements

This work would not have been possible without the guidance and assistance of Dr. Yusuf Mehta, professor and graduate coordinator in the department of civil and environmental engineering, for the opportunity he offered me to work on this project. He has been a great advisor, supportive of my career goals, and always worked with me to make this research complete on time.

I am grateful to the entire faculty I had the pleasure to work with during this project. A special thanks to my thesis committee: Dr. Douglas Cleary and Dr. Gilson Lomboy from Rowan University Civil and Environmental Engineering Department for their insightful comments, time, support, and assistance. I would also like to extend a special thanks to Dr. Ayman Ali, CREATEs manager, who has advised and assisted me throughout my research.

I would also like to thank my family and friends for their continuous support throughout my graduate career thus far. Many thanks to Caitlin Purdy, CREATEs lab manager, and all the undergraduate students who worked alongside me and were behind the completion of this research. I wish them hard luck in their future endeavors.

Finally, I would like to thank the US Department of Transportation (DoD) for their continued support, assistance, and for the research grant which made this research possible.

Abstract

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2018-2019
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The objective of this research study is to present a procedure for designing Cold-In Place Recycling (CIR) mixtures through balancing cracking and rutting for these mixtures. Eight CIR mixtures were prepared using two recycling agents (foamed and emulsified asphalts), then cured for three days at two temperatures (140^{o}F and 50^{o}F), and compacted at two gyration levels (30 and 70 gyrations). The CIR mixtures were prepared at constant dosages of water and cement, 3% and 1%, respectively. Air void of each CIR performance test specimen was determined using the CoreLok device. The rutting susceptibility of these mixtures was then evaluated using the Asphalt Pavement Analyzer (APA) and Dynamic Complex Modulus ($|E^*|$) while resistance to cracking was evaluated using the Indirect Tensile Strength (ITS) test and Fracture Energy was determined using the Semi-Circular Bend (SCB-FE) test. The developed balanced mix design approach was used successfully in selecting the optimum binder content for each CIR mixture. Experimental and statistical evaluations were also conducted on CIR mixtures prepared with optimum binder contents. The results showed that using a higher compaction level or higher temperature of curing leads to increasing both foamed and emulsified asphalt CIR mixtures' ability to resist rutting. In terms of cracking, SCB-FE results showed that emulsified asphalt CIR mixtures were better at resisting cracking than foamed asphalt CIR mixtures.

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Chapter 1

Introduction

Background

Cold In Place Recycling (CIR) is a rehabilitation technique that involves milling an existing asphalt pavement surface layer, processing millings through particle size screening and reduction; introduction of a binding material (i.e., asphalt emulsion or foamed asphalt); and introduction of additional aggregates (i.e. virgin aggregates) if necessary. Finally, the cold recycled asphalt mix is placed and compacted using standard paving equipment. The placed cold recycled asphalt mix is then allowed to cure for a period of time (up to a week) depending on the binding agent utilized. Once cured, the pavement is overlaid with a wearing surface course layer that is about 1.5-inch (38.1 mm) thick.

CIR rehabilitation technique has shown success in extending the service life of pavements up to 15 years through improving structural strength of rehabilitated pavements (Kim et al, 2011). The main cold recycling techniques that have been successfully used to treat distressed pavements are presented below:

- Full-depth Reclamation FDR (depth from 4.9 to 11.8 in. (125 to 300 mm)) known as full-depth reclamation, using a pulverizer to eventually obtain a mixture of recycled asphalt pavement, and a considerable portion of the underlying layer (base material and asphalt binder) (Morian et al., 2012; Cox and Howard, 2013).

- Partial-depth CIR (depth from 2.55 to 4.9 in. (65 to 125 mm)) reuses only the existing asphalt concrete layer. This process is generally performed on thicker, uniform asphalt pavements. The recycling is carried out with multi-functional recycling equipment (Cox and Howard, 2013).

Rehabilitating deteriorated pavements using CIR has a number of construction, environmental, and economic benefits. This technique will be the best choice to construct pavements in remote locations such as the Arctic where the construction materials are obtained from the existing pavement. As a result, CIR will provide substantial savings regarding fuel consumption and the number of trucks needed to haul materials. Further, CIR is regarded as an ecofriendly technique since it does not require any heating and does not release carbon dioxide (CO_2) in the air. Also, traffic disruption is remarkably minimized when using CIR, compared to other conventional techniques, which improves the construction conditions (Kim et al., 2011; Kit Black, 2013; Turk et al., 2016; Sanger et al., 2017).

Problem Statement

Researchers have conducted extensive studies to enhance mechanical and engineering properties of cold in-place recycling mixtures. Different mix designs were developed and utilized by researchers, agencies and state DOTs on CIR projects. However, the following points have not been considered in previous CIR-related studies:

- CIR rehabilitation technique was generally performed on asphalt pavements with low to medium traffic conditions.

- CIR mix design procedures did not account for air void measurements of the prepared CIR mixtures.
- Performance based mix design developed for CIR consisted of selecting optimum binder contents of CIR mixtures based only on cracking performance measures (i.e. indirect tensile strength).
- Studies investigating the curing process of CIR mixtures focused on high temperatures (i.e. 77^{o}F and above)

Therefore, additional research should be conducted to extend the use of CIR in different regions in the world (i.e., remote locations) and seasons (i.e., autumn – winter). In addition, different compaction levels of CIPR mixtures representing the level of traffic subjected on roadways should also be considered.

Research Hypothesis

This study was conducted to investigate the hypothesis that a balanced mix design approach can be followed to successfully design CIR mixtures with optimal rutting and cracking performances. Rutting measures (i.e., APA rut depth and dynamic modulus |E*| at high temperatures) and cracking measures (i.e., indirect tensile strength ITS and semi-circular bend fracture energy SCB-FE) can be used to select optimum binder contents of foamed and emulsified asphalt CIR mixtures.

Significance of Study

This study is conducted to evaluate the impact of recycling agent (emulsion and foamed asphalt), compaction level (30 and 70 gyrations), and curing process (50^{o}F (10^{o}C) and 140^{o}F (60^{o}C), for three days) on CIR laboratory performance, in terms of the rutting and cracking. The CIR mixture is designed using a balanced mix design (BMD) approach to meet heavy loading generally subjected to airfield pavements. If CIR balanced mix design is found to be successful, the following benefits will be offered to US Department of Defense (DoD):

- Improved service life of airfield pavements,
- Update current specifications related to cold in-place recycling,
- Feasible construction in remote locations (i.e. Arctic region),
- Extension of construction season: CIR construction is possible in relatively cold temperatures,
- Expedite construction time,
- Environmental and economic benefits (less gas emission and reuse of existing material).

Goal & Objectives

The goal of this study is to utilize a balanced mix design (BMD) approach to select optimum binder contents for emulsified and foamed asphalt CIR mixtures. The BMD method was used to prepare CIR mixtures capable of withstanding heavy traffic levels and cold curing conditions (i.e. arctic region). In fact, the focus was on balancing the cracking and rutting performances when selecting optimum binder contents of CIR mixtures. This study involved the following objectives to accomplish the overall goal of this study:

- Developing a design procedure for CIR asphalt mixtures using a balanced mix design approach to select optimum binder contents of these mixtures.

- Evaluating, experimentally and statistically, the impact of binding agent type, compaction level, and curing process on rutting and cracking performances of CIR mixtures.
- Comparing rutting and cracking performances of CIR mixtures prepared at optimum binder contents and selecting three CIR mixtures: (1) cracking resistant mixture, (2) rutting resistant mixture, and (3) and BMD mixture.

Research Approach

The approach utilized to meet the overall goal of this study consisted of the following tasks:

Task 1: Conduct a comprehensive literature review pertaining to CIR by reviewing domestic and international previous CIR-related studies. This task will present the currently available mix design procedures for designing CIR asphalt mixtures in the lab and in the field. In addition, the best practices typically implemented for rehabilitating asphalt pavements using CIR will be discussed. This task will also cover the main distresses and challenges that have been identified for CIR rehabilitated pavements, as well as the major factors affecting the long-term performance of these pavements.

Task 2: Identify and select representative materials that will be used in preparing mixtures for the laboratory mix design of CIR mixtures. RAP is obtained from Rowan University Accelerated Pavement Testing Facility (RUAPTF) and characterized in terms of gradation, maximum specific gravity, and existing binder content. Types and contents of binding agents and recycling additives are selected based on literature.

Task 3: Develop an experimental program utilized in this study to prepare eight CIR mixtures: combination of two types of recycling/binding agents, two compaction levels, and two curing processes. These mixtures are designed using a balanced mix design approach in which cracking and rutting performance measures are used to select an optimum binder content of each CIR mixture. This task also discusses the cracking and rutting performance tests that will be used to characterize the prepared mixtures.

Task 4: Conduct performance tests on CIR mixtures and analyze the results of each test. Correlation between binder contents and cracking and rutting performance measures is evaluated prior to selecting optimum binder contents of CIR mixtures. This task also investigates the impact of recycling agent type, compaction level, and curing process on rutting and cracking performance of CIR mixtures. The significance of the effects of these factors also statistically evaluated using Analyses of Variances (ANOVA) on performance measures results.

Chapter 2

Literature Review

Introduction

Cold In-Place Recycling (CIR) is a rehabilitation technique that involves processing and treating deteriorated Hot Mix Asphalt (HMA) pavements using recycling agents (asphalt-based) and/or chemical additives. As the name implies CIR does not require heat when restoring a damaged pavement layer (AASHTO, 1998) because the CIR mix is produced at ambient site temperatures. CIR has been successfully used to rehabilitate all kinds of pavements such as city and county roads, and highways with different traffic volumes (Lewis and Collings, 1999; Forsberg et al., 2001; Fiser and Varaus, 2004; Mondares et al., 2014). The use of CIR offers several construction, economic, and environmental advantages over other conventional rehabilitation techniques (Kim et al., 2009; Chen et al., 2010). For instance, CIR involves milling the existing deteriorated pavement and reusing the reclaimed millings in producing a stabilized base pavement layer. This leads to shortening construction time and eliminates the need to use virgin aggregates; thus, persevering resources.

In this chapter, the results of a comprehensive literature review pertaining to CIR asphalt mixtures are presented. The following subsections provide information relevant to the CIR process, the various CIR mix design methodologies, the best CIR field construction practices, and the reported laboratory and field performance of CIR mixtures and pavements.

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General Cold In-Place Recycling Process

Overall, CIR consists of milling the existing pavement to a certain depth, width, and length, then sizing the RAP material to an evenly graded aggregate mix with a maximum size of 25 mm. Recycling agents such as emulsified asphalt and foamed asphalt are then added to the graded RAP to obtain a homogeneous and uniformly coated recycled pavement mixture. This material must be put in place, then compacted in conformance with the plans and specifications. The construction procedure steps are illustrated in Figure 1 (Davidson and Croteau, 2013; ARRA, 1992; Hicks et al., 1987). The CIR construction and practice guidelines are discussed in the following subsections providing information pertaining to the successful construction of a CIR pavement layer (Lane and Kazmierowski, 2014).

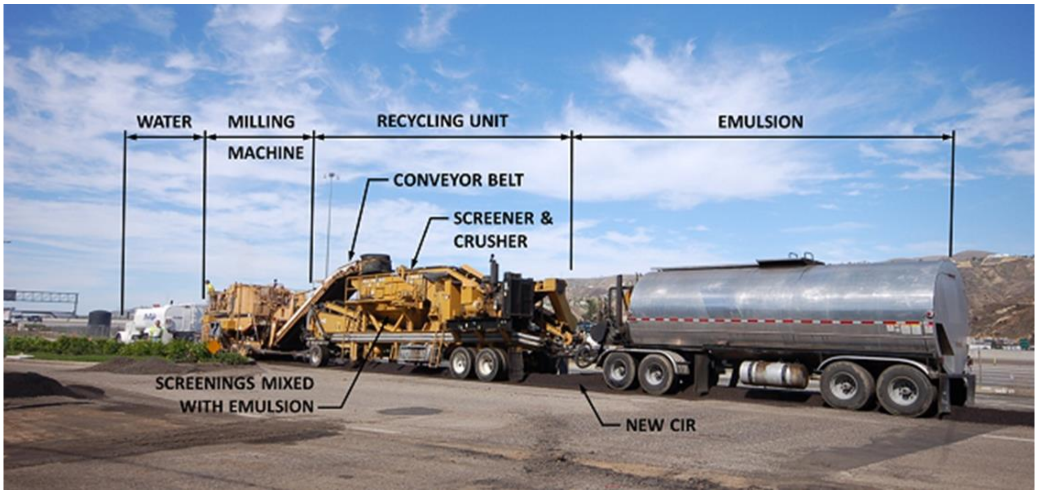


Figure 1. Cold in-place recycling equipment (LA Department of Public Works, 2018)

Step 1: Project selection and CIR requirements. Prior to selecting CIR as the method for repairing a deteriorated pavement, a field survey is required to examine the degree of existing distresses and identify their exact locations. This facilitates determining if CIR is the appropriate technique for this project. In general, the following information is collected during a field survey aiming to repair a deteriorated pavement structure (Stroup-Gardiner, 2012):

- Records review: assessment of construction/maintenance information and review of past condition surveys;
- Visual inspection: determine mode and severity of pavement distresses; and,
- Pavement investigation: additional information on the nature and condition of the asphalt pavement and the extent of the distresses.

CIR technique is generally performed on cracked asphalt pavements with sound structure and well-drained bases. CIR technique is also applicable on pavements featuring the following load and non-load associated distresses: transverse cracks, longitudinal cracks, fatigue cracks, rutting, raveling, potholes, and polished surface. It is important to note that deteriorated asphalt pavement layer should be treated at early stages (i.e., when ruts and cracks begin to appear) using CIR technique to ensure a satisfactory service life of CIR rehabilitated pavement (FHWA, 2018).

Step 2: Mix design of Cold In-Place Recycling. The second major step in the general CIR process is the design of CIR mixture by determining the optimum binder content. For this purpose, a portion of the pavement section is milled with the reclaimed asphalt pavement (RAP) collected for further analysis. The millings (or RAP) are then used in design methods suggested by researchers (Kim and Lee, 2011). The mix design process also involves determining the percentages of water and chemical additives to be used in the mixture. For additional details about the various methods of designing CIR mixtures the reader is referred to Section 2.4 of this chapter.

Step 3: Milling of deteriorated surface pavement layer. The field portion of the CIR process begins after having finalized the mix design. For this purpose a train of equipment (Figure 1) is used to complete the process in site (or In-Place). A milling is machine is the first piece of equipment used for milling the deteriorated surface pavement layer, as shown in Figure 2. The milling machine mills from 2 to 4 in. of the top surface layers of deteriorated pavements.

Figure 2. CIR Milling Process (Roadtec, 2019)

Step 4: Millings sizing and mixing with recycling agent. Milling and screening equipment are then utilized to reduce the RAP size to desired sizes (maximum size of 1 in. (25 mm)) (Kim and Lee, 2011; Wirtgen, 2016). After crushing and sizing, the RAP millings are treated in a mixing unit using a selected recycling agent (e.g., emulsified recycling agent) with water/additives added into the mix (Figure 3). It is also noted that certain CIR practices call for spreading the chemical additives (e.g., Portland cement) on top of the existing pavement and before milling.

Figure 3. CIR Mixing Process (Suit-Kote, 2019)

Step 5: Placement of the CIR mix. The CIR mixture is then placed over the milled pavement and graded to the desired thickness. Conventional asphalt paver or self-propelled pavers are then used to place the CIR mixture (Figure 4). It important to note that the lift thickness for CIR mixture is typically 2 in. (50 mm) minimum especially when millings present relatively large maximum aggregate size.. The paver wings are also emptied regularly to avoid accumulation and reduce the segregation (Wirtgen, 2012).

Figure 4. CIR Mix Placement (Suit-Kote, 2019)

Step 6: Compaction. Once the CIR mix is placed, a primary compaction is applied on the CIR layer using traditional compaction equipment such as self-propelled rollers, vibratory-steel drum and pneumatic tired rollers (Figure 5). In general, compaction operations should start 15 minutes after placement of CIR layer, when the ambient temperature is above 60°F (15.6°C). In case the ambient temperature is below 60°F, a waiting time of 10 minutes is recommended for each 5°F below 60°F (15.6°C). Nuclear density testing (ASTM D 2950) is regularly conducted throughout the compaction process until achieving a desired density (Wirtgen, 2012).

Figure 5. Compaction Process (ForConstructionPros.com, 2019)

Step 7: Cure and maintenance. The compacted CIR layer is open to traffic when this layer is sufficiently cured. Prior to placing the surface layer (i.e. HMA overlay), the CIR layer must remain in-place: (a) at least for 2 days and until there is no more than 2.0 % moisture in the recycled pavement mix, or (b) at least for 10 days without rainfall (Tario, 2010). A fog seal is also applied on top of the CIR layer so as to coat, protect, enrich, and rejuvenate the existing asphalt binder (emulsion or foamed, as shown in Figure 6 (Davidson and Croteau, 2013). Additional compaction can be performed on CIR layer when the curing and maintenance processes are completed. Density of the recycled pavement must be carefully checked using nuclear density gauge (nuclear density test ASTM D 2950).

Figure 6. Fog Sealing (The Gourman Group, 2019)

Step 8: Secondary compaction. Additional compaction can be performed on CIR rehabilitated pavement when the curing and maintenance processes are completed. The secondary compaction is generally performed using pneumatic or/and steel drum rollers (Wirtgen, 2012). Density of the recycled pavement must be carefully checked by the means of nuclear density gauge (nuclear density test ASTM D 2950). Similarly to primary compaction (section 2.2.5), this test is repeated to check if a maximum density was attained. It is important to avoid over-compacting the recycled mat to prevent rutting formation (Wirtgen, 2012).

General Laboratory CIR Mixture Design Approach

Prior to treating deteriorated asphalt pavements using CIR technology, it is necessary to determine the optimum contents of the recycling agents/additives used in preparing CIR mixtures. The goal of a mix design is to prepare a mixture of aggregates and binder that can achieve desired levels of performance in the field performance.

Laboratory mix designs are generally developed following CIR construction practices. It is also important to mention that there is no standard for designing CIR asphalt mix (Ozer, 2015). Prior to preparing CIR mixtures, CIR materials should be selected and characterized, and then the performance of the prepared mixtures is evaluated. This section discusses the materials generally used in previous CIR projects and detail a general laboratory procedure for designing and evaluating CIR mixtures.

Overview of CIR mix design methods. Several mix design procedures were developed by various researchers, agencies, and state departments of transportation (DOTs) to select the optimal binder content and/or optimal water content for CIR projects (Berenice, 2017, Ozer, 2015, Buss et al., 2017). The process of designing a CIR mix involves obtaining representative RAP materials from existing pavements, which would then be mixed, at ambient temperatures, with a binding agent (either asphalt emulsion or foamed asphalt) at varying binder contents, and/or water contents. For each binder content, test specimens are prepared to conduct performance testing (e.g., indirect tensile strength, ITS, or semi-circular bend, SCB). The optimum CIR binder content (and/or the optimum water content) could then be determined as the binder content (and/or the water content) at which the highest ITS (or fracture energy) is obtained (Kim and Lee, 2011). Additional details are provided in the following subsections.

Step 1. Collect samples from field. Reclaimed asphalt Pavement (RAP) samples are collected from the milled pavement surface to be analyzed and characterized in the laboratory before use in CIR mix. A CIR milling machine is used to mill deteriorated asphalt pavement surfaces (i.e., from 2 to 4 in. (50 to 100 mm). Random sampling techniques (AASHTO T2) are generally used to collect representative samples from the pavement to be rehabilitated. The collected millings are then dried, at room temperature, for ten days until the moisture contents of RAP millings was below 0.3% (Epps, 1998; Kim and Lee, 2011).

Step 2: Determine RAP properties. Several studies focused on determining the characteristics of RAP materials to be used in preparing CIR mixtures. These characteristics included the existing asphalt content of RAP (i.e., penetration and viscosity of the recover asphalt content), gradation, moisture content, and density measurements (i.e., Maximum specific gravity). Additional RAP properties were assessed such as permeability and abrasion resistance of RAP. It is important to note that both RAP gradation and extracted aggregates gradation are two of the main properties in deciding whether virgin aggregates are needed (Kandhal and Mallick, 1997; Bennet and Maher, 2005; Alam et al., 2010; Bleakley and Cosentino, 2013). A brief summary of the quality assessment and performance requirement of materials followed by different state DOTs (i.e., WSDOT, NYSDOT) is presented in Table 1 (ARRA, 2016).

Step 3: Add aggregate (optional). In general, virgin aggregate are added to CIR mixtures in order to improve the strength of CIR mixtures, and minimize the creep of RAP (Bleakley and Cosentino, 2013). In fact, the RAP gradation is usually affected by the fines generated during the milling process or due to contamination from the underlying layers. Therefore, the gradation of RAP (as received from milling) may not be suitable for the intended recycled base course. In this case, virgin aggregates are added to satisfy the graduation requirement or structural improvement of the recycled mix (Epps, 1980, ARRA, 2016).

Table 1

Example of Main Specifications for CIR asphalt mix design (ARRA, 2016).

Test	Properties	Requirements
AASHTO T308	Existing binder content of RAP	• Maintain binder ± 0.2% (i.e. WSDOT), or ± 0.3% (i.e. ADOT) (Tario, 2010).
AASHTO T11-T27	Gradation of RAP	• 1.25 inch maximum • Passing 1.5 inch (i.e. NYSDOT) (Tario, 2010)
AASHTO T209	Bulk Specific gravity of compacted cured specimen	• 1.4-inch diameter mold compaction based on either 75 blows Marshall each side or gyratory compactor at 30 gyrations
AASHTO T269	Maximum Theoretical Specific Gravity	• Measurement on specimens after 140°F (60°C) curing to constant weight for no less than 16 hours and no more than 48 hours.
AASHTO T283	Air Voids of Compacted, Cured Specimens	• Recycling agent content should not be adjusted to meet an air void content.
AASHTO T245	Indirect Tensile Strength	• Minimum 45 psi
AASHTO T283	Marshall Stability	• Minimum 1,250 lbs
ASTM D7196	Tensile Strength Ratio/Retained Marshall Stability based on Moisture Conditioning	• Minimum 0.70
ASTM D7196	Tensile Strength Ratio/Retained Marshall Stability based on Moisture Conditioning	• Minimum 0.70

Step 4: Select type, amount, and grade of recycling agents/additives. The most commonly used recycling agents are: emulsified asphalt and foamed asphalt. Various types of polymer are also utilized to reduce rutting, increase early strength, and reduce thermal cracking of CIR mixtures. Recycling additives can also be added to CIR mixtures such as Portland cement and lime slurry. These additives are used at small amounts so as to enhance mix cohesion, shorten the curing time, and increase the moisture susceptibility of the CIR materials. The commonly used recycling agents in CIR are: asphalt emulsions and foamed asphalt description of CIR recycling agents and additives is provided below (ARRA, 2016):

Asphalt emulsions. Cationic and anionic are the most commonly considered asphalt emulsions in CIR. Dense-graded aggregate (or RAP) gradation containing fines require slow setting emulsions. The asphalt emulsion is also selected based on compatibility with the RAP milling. Emulsions are also selected based on other properties such as the binding properties, coating, initial strength, and breaking time of emulsion. It is important to note that field coating test (AASHTO T 59) is highly recommended to determine whether asphalt emulsions (anionic or cationic emulsified asphalt) are compatible with the RAP and new aggregate (Division of Construction, 2009; Mitchell, 2009). A summary of the recommended combinations is presented in Table 2 (Asphalt Institute, 1986

Table 2

Guidelines for Selection of Emulsified Asphalt Binders for CIR.

Emulsion	Type	Aggregates
Anionic (AASHTO M140)	MS-2, MS2h	Open-graded aggregates
	HFMS-2, HFMS-2h HFMS-2s SS-1, SS-1h	Dense-graded aggregate, sand, and sandy soil
Cationic (AASHTO M208)	CMS-2, CMS-2h	Open-graded aggregate
	CSS-1, CSS-1h	Dense-graded aggregate, sand, and sandy soil

Foamed Asphalt. The use of CIR foamed asphalt is increasing because it offers several economic and construction benefits. As the name indicates, foamed asphalts are produced using a foaming machine by injecting hot asphalt binder (e.g., PG 64-22) with cold water. The expansion ratio and half-time values are determined to characterize foamed asphalts and determine optimum foaming water content (Kim et al., 2011; Kuna et al., 2014). The water content resulting in highest values of expansion rate and half-time is used in production of foamed asphalt for CIR mixtures.

Recycling additives. Portland cement and lime slurry have showed effectiveness when used as additives in preparing CIR mixtures. These chemical additives provide improved early strength, enhanced rutting resistance, and improved moisture damage protection. Cement and lime have been used very successful in combination with asphalt emulsions (Division of Construction, 2009; Mitchell, 2009; Kim et al., 2011).

Step 5. Determine the moisture content required for mixing. Water is regarded as a key element in CIR mixes since it contributes to coating RAP millings with the recycling agents, and also, facilitates compaction in the field (Anderson et al., 1985). In general, the typical water content for standard CIR is in the range of 2 to 5% (Scholz et al., 1991; Kim et al., 2011; ARRA, 2016). Optimum moisture content of CIR mix is determined using Proctor compaction which can produce a very high moisture content. Other methods (e.g., 75 blows Marshall Compaction at room temperature, or gyratory compaction via the Superpave Gyratory Compactor (SGC)) can also be used to select the optimum moisture content of CIR mixtures (Carter et al., 2010; Bang et al., 2011; Cox and Howard, 2015).

Step 6. Determine bulk and rice specific gravity. CIR mixtures consisting of emulsions or foamed asphalt, and sometimes low dosage of cement or lime (e.g., 1%), are allowed to cure in an oven for a given period of time (e.g., seven days at 140°F). (Cox and Howard, 2015). Table 3 presents compaction and curing procedures adopted by different agencies and DOTs (Apeagyei and Diefenderfer, 2013). Once the curing process of CIR specimens is completed, these test specimens are tested for bulk specific gravity (G_{mb}) and the theoretical maximum specific gravity (G_{mm}) for each CIR emulsion specimen using ASHTOO T331 (CoreLok Method). Cox and Howard (2016) determined the G_{mm} of RAP in accordance with ASTM D6857 (AASHO T209). The tested CIR specimens consisted of a mixture of RAP and cement (4.5%), 2% emulsions with 2.3% cement, or 4% emulsions with 1% hydrated lime of total mix weight.

Table 3

Examples of Compaction and Curing Procedures for CIR Mixes

Compaction Method	Description	References
Marshall	75 blows	Wirtgen, 2006 Fu et al. 2010
Gyratory	25 gyrations	Buss et al. 2017 Kim et al. 2011
	30 gyrations	Kim and Lee, 2006
	300 gyrations	Martinez et al., 2007
Curing Temperature	**Curing Time**	**References**
104ºF (40ºC)	2 days	Kansas DOT, New Mexico DOT
113ºF (45ºC)	7 days	Kim et al. 2011
160ºF (71ºC)	3 days	Wirtgen, 2006 Buss et al., 2017
77ºF (25ºC)	7 days	Saleh, 2006
77ºF (25ºC)	14 days	Kim et al. 2011
77ºF (25ºC)	28 days	Bessa et al. 2016

Step 7: Determine the optimum binder content. A set of test trial mixtures with different properties (initial curing properties, final curing properties, and moisture sensitivity) are prepared in order to determine an optimum content for CIR recycling agents/additives. the indirect tensile strength (ITS) test is generally used to determine the optimum binder content for CIR test specimens prepared (compacted at 30 gyrations in SGC or 75 blows by Marshall hammer) at various binder contents (i.e., 0.5 through 3% with 0.5% increments) and using a constant moisture content (e.g., 4%) (Kim et al., 2007). Previous studies showed that the optimum binder content varies from 1.5% to 3%, the optimum water content varies from 1.5% to 4%, and optimum cement content from 0.5% to 2% (Niazi and Jalili, 2009; Brovelli and Crispino, 2012; Berthelot et al., 2013;

Gao et al., 2014; Bessa et al., 2016; Graziani et al., 2018). It is important to note that when CIR mixtures are prepared using virgin aggregates, higher ranges of recycling agents/additives contents are recommended (Cox and Howard, 2015; ARRA, 1996; Lee et al., 2016). Finally, a job mix formula can be established and used to reproduce CIR mixtures in the field.

Best Practices of CIR Field Construction

CIR technology has the ability to increase the service life of asphalt pavements by approximately 11 years, provided that certain best practices are employed (Chen et al., 2010; Warren et al., 2011). When CIR technology is performed on pavements with light deterioration, the service life of such pavements is approximately extended by 50% more than damaged pavements rehabilitated with CIR technology (Warren et al., 2011). Several construction factors affect the long-term CIR performance as well as the service life of rehabilitated pavements (Chen et al., 2010; Cross et al., 2010). The following subsections provide details of best CIR construction practices.

Best practices for CIR mix production

- The type and amount of binder, recycling additives: Anionic and cationic emulsions, recycling additives, and water should not be added to CIR mixtures in excessive amounts. Excessive amount of binder, additives, or water cause asphalt bleeding or flushing before compaction (ARRA, 2016).
- Mixing of the materials: When there is an inadequate mixing of RAP with binder and additives, or there is insufficient asphalt coating of the RAP, a mix segregation can occur. In order to prevent this, all CIR materials should be sufficiently held in

the mixing chamber until the mixture is homogenous (up to 2 minutes) (ARRA, 2016).

- RAP gradation: When CIR is operating and there is a variation in depth of the milled materials (some of the subbase is also milled), RAP behind the recycling unit is likely different and poorly graded. Therefore, depth of milling should be regularly checked and adjusted (ARRA, 2016).
- Size of RAP: During CIR milling process, RAP materials can be oversize if the screen bar (or breaker) is not properly operating. Therefore, the screen bar as well as all the equipment should be carefully checked prior to CIR construction (ARRA, 2016).
- Emulsion content: After compaction, raveling can occur to the surface of the CIR rehabilitated pavement when low emulsion content (e.g., 0.5%) is added to the mix. While a shiny black mat can appear after compaction when high emulsion content is added (e.g., 5%). In this case, virgin aggregates can be added to the mix to reduce the amount of emulsions.

Environmental and other considerations: Additional challenges can be encountered by road engineers during the early implementation of CIR technique with respect to the design approach and construction methodology (Harun et al, 2010; ARRA, 2016). The main challenges are:

- Weather: Rain during CIR operations or during the curing process can have multiple effect on CIR mixture.
- Equipment Failure: At least one of the contractor's equipment fails to meet the

requirements.

- Storage of recycling agents/additives: Maintaining additives (i.e. cement) in suspension inside the slurry feed tank.
- Fabric/Geosynthetic incorporation into CIR layer: Presence of foreign materials in the existing pavements (e.g. rubberized crack filler, pavement markers, loop wires, thermoplastic markers…) can affect the performance of CIR pavement by inhibiting its placing and its compaction.
- Curing time: Slow curing problems may occur when work takes place in damp or cold weather conditions (Tabakovic et al., 2015)..
- Moisture: Some CIR materials are susceptible to moisture which make them more likely to crack. These materials can also be shoved to the sides causing a breakdown of the pavement under heavy trafficking (Tabakovic et al., 2015).
- Drainage system: Inadequate/poor drainage system can also aggravate failure of rehabilitated pavement.

There are ways to prevent the above-mentioned challenges regarding the construction of CIR rehabilitated pavement:

- Weather: CIR operations is performed when the pavement temperature is above 50°F (10 °C) with overnight ambient temperatures above 35 °F (2°C) (Tario, 2010).
- Equipment Failure: Prior to construction: all CIR construction equipment is checked. In addition, pavements to be rehabilitated are evaluated in order to identify areas where materials properties are not uniform. This can cause damage

to construction equipment (ARRA, 2016)

- Storage of recycling agents/additives: Cement/lime slurry storage need to have agitators or similar equipment to keep the recycling additives in suspension when held in the slurry feed tank as well as during transport (ARRA, 2016).
- Fabric/Geosynthetic incorporation into CIR layer: Contractor should conduct field investigations and prevent the incorporation of shredded materials into CIR materials (ARRA, 2016).
- Curing time: In addition to the ambient temperature being above 50ºF, 3% of moisture content, or less, is recommended for faster curing (ARRA, 2016).
- Moisture: Portland cement and/or lime slurry are added to CIR mix so as to provide an enhanced moisture damage protection (ARRA, 2016; Tabakovic et al., 2015).
- Drainage system: It is important to strengthen the drainage system of the rehabilitated pavement by selection the appropriate CIR material prior to the mix design (ARRA, 2016).

Laboratory CIR Mix Design Methods

Several agencies and departments of transportation have successfully established mix design procedures for CIR technology. For example, Asphalt Recycling and Reclaiming Association (ARRA) proposed three methods to design mixtures for CIR projects: Modified Marshall mix design, Modified Hveem mix design, and Oregon mix design (ARRA, 2016). Other agencies (i.e. Wirtgen, Asphalt Institute), Departments of Transportation (i.e. Rhode Island, Pennsylvania, New Jersey, and Florida), and the US department of defense have developed their own mix design procedures which have many similarities with certain differences (i.e. Number of gyrations, type of binder, RAP gradation). This section presents the available mix design procedures utilized by several agencies and DOTs for preparing CIR mixtures.

Unified Facilities Guide Specifications (UFGS) mix design procedure for CIR. The current mix design procedure developed by US DoD (Unified Facilities Guide Specifications UFGS-32-01-17, 2018) consists of obtaining RAP from milling existing asphalt concrete pavement. UFGS specifies that the maximum particle size of RAP millings should be less than half the thickness of the compacted CIR pavement (maximum of 1-1/2 inch and a minimum of 90% of the RAP passing 1 inch (25 mm) sieve) (UFGC, 2008). UFGS-32-01-17 focuses on determining the properties of RAP millings and existing asphalt in the RAP. RAP is then mixed with Asphalt cement such as recycling agents: cationic emulsions of type CSS-1h or SS-1h conforming to ASTM D977. The military mix design presents the amount of asphalt binder (tolerance of 0.3%) and specifies the amount of water (0.5 % intervals, from 0 to 2.5 %) to add to CIR mixture. This design procedure should guarantee an optimum compaction condition. Once the optimum contents of asphalt binder and water are determined using indirect tensile strength test, samples are compacted at 250°F (121°C) with 75 blows of typical Marshall Hammer according to COE CRD-C 649 and COE CRD-C 650 (UFGC, 2008). The compacted CIR specimens are then placed in an oven at 140°F (60°C) for 96 hours. Then, dry density of samples is determined. It is also worth mentioning that (UFGC, 2008) specifies that CIR construction should not happen in bad weather conditions (rain, storms, fog…etc.) or on a layer containing free water. CIR projects should be employed when the ambient air temperature is above 50°F (10°C). Nevertheless, these specifications for CIR mix design are considered outdated and should be revised and ameliorated.

Modified Marshall mix design. This mix design procedure was developed for CIR mixtures using 3% of moisture content (including: emulsion water, water remaining in RAP, and water added into mixture). Emulsions are added to the mixtures at desired contents in 0.5 % increments. CIR Mixtures are then compacted with 50 blows (per face) of the Marshall compacting hammer and, afterwards, allowed to cure in an oven at 140°F for 6 hours. The cured CIR specimens are tested for bulk specific gravity, stability at 140°F (60°C), and flow at 140°F (60°C). The maximum specific gravity for each binder content is also determined using equation (1) below. CIR specimens' properties (air voids (AV), volume of asphalt binder (VB), voids in mineral aggregate (VMA), and voids filled with asphalt binder (VFB)) are determined using the following equations (2) through (5) (Epps, 1986; Asphalt Institute, 1986). Marshall Stability test is then used to determine the optimum binder content of the produced CIR mixtures. When CIR mixtures present high stability and low flow value, this will have negative impact on CIR rehabilitated pavements (likely to develop cracks under heavy moving loads).

$$G_{mm} = \frac{W_m}{W_m - W_w} \qquad (1)$$

$$AV = \frac{(G_{mm} - G_{mb}) \times 100}{G_{mm}} \qquad (2)$$

$$VB = \frac{\frac{W_b}{G_{mb}}}{\frac{W1+W2+W3+Wb}{G_{mm}}} \qquad (3)$$

$$VMA = AV + VB \qquad (4)$$

$$VFB = \frac{VB \times 100}{VMA} \quad (5)$$

Where:

G_{mm} = Maximum specific gravity of mix
W_m= Weight of mix in air, g
W_w= Weight of mix in water, g
W_1= Weight of coarse aggregate, g
W_2= Weight of fine aggregate, g
W_3= Weight of filler in the total mix, g
W_b= Weight of bitumen in the total mix, g
G_{mb}= Specific gravity of bitumen

Modified Marshall mix-design used for Superpave mix design. Lee and al. (2016) developed a new mix design using RAP obtained from different locations in the United States. The purpose of their study was to evaluate the effectiveness of CIR materials compaction using the SGC instead of the Marshall hammer (Lee et al., 2016). This new mix design procedure consists, approximately, of same steps discussed in Modified Marshall mix design. However, the cured CIR specimens are compacted with 52 gyrations at 77°F (25ºC), and then allowed to cure for 6 hours at 140°F (60ºC). Finally, one can determine the optimum emulsion content OEC or OWC (if the water content was not considered constant prior to mixing) (Lee et al., 2016).

Modified Hveem mix design. This method of specimen preparation is same as in Modified Marshall Method. In this method, the Marshall compactor is replaced by kneading compactor, applying around 20 tamping blows at 1.725 MPa pressure to achieve a semi-compacted condition. Afterwards, the compaction pressure is raised to 3.45 MPa and 150 tamping blows are applied to complete the compaction. Then, the specimen is subjected to a leveling-off load with a testing machine at 5.6 kN at a head speed of 1 mm/minute. All the parameters (RAP properties, optimum binder/water contents) described in Modified Marshall Method are also determined in this method (Epps, 1986, Asphalt Institute, 1986).

Mix Design developed for Oregon State. This method aims to select an initial asphalt emulsion content to be added into the recycled mix containing 100 % RAP (no virgin aggregates are required). The procedure consists of adjusting a base emulsion content of 1.2% (by weight of RAP) on the basis of properties of aggregate and asphalt binder recovered from RAP. The method is applicable only when the recycling agent is either a cationic medium setting or anionic high float medium setting type (HFE-150) emulsion (Asphalt Institute, 1986). The gradation of RAP millings is determined only for ½-in., ¼-in., and 5/64-in. sieves. Next, the estimated asphalt emulsion content is determined using equation (6).

$$\text{ECEST} = 1.2 + AG + AAC + AP/V \qquad (6)$$

Where:

ECEST = Estimated added emulsion content

1.2 = Base emulsion content

AG = Adjustment for milling gradations

AAC = Adjustment for milling residual asphalt content

AP/V = Adjustment for millings penetration or viscosity

In the Oregon mix design method, specimen is achieved gradually using a hydraulic compaction device with a load of 25,000 psi (172,400 kPa). In this process, the stress level is increased to achieve 20,000 psi (137, 900 kPa) for the first one minute, and then additional 5,000 psi (34,500 kPa) is applied for next thirty seconds to attain final load of 25,000 pai (172,400 kPa).

Wirtgen mix design. Wirtgen mix design procedure requires determining the engineering properties of RAP millings such as grading (sieves analysis), plasticity, and density in accordance with ASTM D422, D4318, and AASHTO T180, respectively. RAP gradation is as follows: 53.6% passing No.4 sieve (4.75 mm), 18.7% passing 0.5 in. sieve (13.2 mm) and retained on No.4 sieve (4.75 mm), and 27.7 % passing 3/4 in. sieve (19 mm) but retained on 0.5 in. sieve (13.2 mm). Afterwards, the Hygroscopic moisture content ($W_{air\text{-}dry}$) of selected RAP is determined by placing RAP samples in an oven at temperature rannging between 221 and 230°F (105 and 110ºC). $W_{air\text{-}dry}$ is determined using the equation (7) below (Wirtgen, 2012)

$$W_{air\text{-}dry} = \frac{(M_{air-dry} - M_{dry})}{M_{dry}} \tag{7}$$

Where:

W air-dry= hygroscopic moisture content (% by mass)
M air-dry= mass of air dried material (g)
M dry= mass of oven dried material (g)

The prepared CIR mixture is allowed to cure for 7 days in an oven at a temperature ranging between 60 and 70°F (21ºC). Also, an accelerated curing can be achieved by placing CIR mixtures in sealed bags and let them cure in an oven at 170 to 180°F (77 to 83ºF). However, when cement is added to the mix, the curing period is then to 45 hours and the oven temperature is dropped to 140°F (60ºC). The optimum binder content of CIR mixtures is generally determined by conducting ITS test on CIR specimens prepared with varied binder contents (Wirtgen, 2012).

Mix design developed for Rhode Island DOT. The university of Rhode Island (URI) developed mix design method that consists mainly of mixing RAP, obtained from milling a construction site of Route 3, Rhode Island, with emulsions (CSS-1h). The appropriate number of gyrations for compactions was investigated so as to better represent field conditions (Lee and Mueller, 2014). The URI procedure determines the appropriate number of gyration for field density reproduction (Lee and Mueller, 2014). CIR mixtures were compacted with 175 gyrations using a superpave gyratory compactor. The estimated bulk specific gravity was determined: (1) after each gyration, and (2) after 175 gyrations. CIR specimens were then allowed to cure in an over at 140ºF (60°C) to cure for one day (Lee and Mueller, 2014). Finally, CIR specimens were tested for indirect tensile strength and creep compliance, in accordance AASHTO T 322, at temperatures of -4, 14 and 32°F (-20, -10, and 0ºC, respectively).

Mix design developed for Iowa DOT. The Iowa DOT mix design procedure developed by Kim and Lee (2012) consisted of mixing 100% RAP, collected from different CIR projects in the state, with emulsions type CSS-1h and HFMS-2P at different contents (0.5%, 1%, 1.5%, 2%, and 2.5%), and with constant water content (3%). Prior to mixing, RAP is dried until obtaining a final RAP moisture content between 0.1 and 0.2%. Then, RAP gradations are designed through dividing, into six stockpiles, the materials retained from the following sieves: 25, 19, 9.5, 4.75, 1.18 mm and passing 1.18mm. Millngs with size bigger than 1 in. (25 mm) are discarded. After mixing the graded RAP with emulsions and water, the CIR mix will be compacted using SGC with 25 gyrations. Then, the compacted mix is then allowed to cure in an oven at 104°F (40ºC) for three days. The optimum binder content of CIR mixtures is determined using wet indirect tensile strength (Kim and Lee, 2011).

Other mix design procedures. Table. 4 presents a brief summary of mix design methods developed by other states in the US (i.e. Pennsylvania and Minnesota) and in Canada (i.e. Ontario). These procedures are different in the binder type (anionic or cationic emulsions), the binder content range, compaction method, curing time, and target volumetric (Salomon and Newcomb, 2000).

Table 4

Additional Examples of Mix Design Procedure.

State/Province	Pennsylvania	Minnesota	Ontario
Binder Type	CMF-2 or CSS-1h	CSS-1h, HFMS-2s, or HFMS-2p	HF-150
Binder Content	2 to 3.5%, with 0.5% increments at OWC.	[1, 1.5, 2, and 3%] and determine OEC	0.5 to 2.5%, with 0.5% increments
Water Content	3 to 7%, with 1% increments at 2.5% binder. Determine OWC.	Varying water content until obtaining 4% total liquid content	Varying water content until obtaining 4.5% total liquid content.
Compaction	75 blows with Marshall Hammer at 73°F.	40 or 150 gyrations using SGC, depending on experiments.	50 blows in the Marshall. Additional 25 blows after curing in the molds for 24h.
Curing	Up to 96h at 104°F	From 24h to 168h	72h at 140°F
Volumetrics	Resilient Modulus and Bulk Specific Gravity must be determined.	Resilient Modulus, Bulk Specific Gravity, and Maximum Specific gravity must be determined.	Air voids between 8 and 12%. Min Marshall Stability of 2000 lbs at 72°F.

Laboratory and Field Performance of CIR

The laboratory and field performance of CIR mixtures in terms of rutting susceptibility and cracking resistance have been investigated by several researchers like (Doyle and Howard, 2013; Buchanan et al., 2004; Cox and Howard, 2015b). This section presents an overall review of both laboratory and field performance of CIR mixtures in previous studies.

CIR Laboratory Performance Tests

Asphalt Pavement Analyzer test. The asphalt pavement analyzer (APA) test was conducted in accordance with AASHTO T340 "Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)", to determine the rutting potential of CIR mixes. A vertical load of 101 lbs (449.2 N) is applied with pressurized rubber hoses (pressure of 100 psi (689 kPa)) on top of CIR specimens. This test specifies whether a CIR mixture, subjected to 8,000 passes at 147°F (64°C), is susceptible to rutting. Each state specifies the maximum rut depth allowed in their pavements. For instance, New Jersey specs does not allow rut depth values above 0.2 in. (5 mm), while in Mississippi, rut depth values should range between 0.16 and 0.24 in. (4 and 6 mm) for high traffic (Doyle and Howard, 2013; Buchanan et al., 2004; Cox and Howard, 2015b).

Dynamic Modulus testing. The dynamic modulus |E*| test is commonly conducted according to AASHTO T62-03 "Determining Dynamic Modulus of Hot Mix Asphalt Concrete Mixtures", in order to evaluate the stiffness of CIR mixtures under different loading frequencies (e.g., 0.1 Hz, 10Hz, and 25Hz) and at various testing temperatures (e.g., 4ºC, 37ºC, and 54ºC). The dynamic modulus $|E^*|$ is determined by dividing the maximum dynamic stress by peak axial strain, obtained for CIR mixtures at given loading frequency and testing temperature. The result of dynamic modulus test is a $|E^*|$-master curve developed based on the time-temperature correspondence approach. The master curve for a CIR mixture help evaluate the rutting susceptibility (i.e. at high testing temperature and low loading frequency) and cracking resistance (i.e., low testing temperature and high loading frequency) of these mixtures (Kim et al., 2009; Diefenderfer, 2016).

Flow Number Testing. The flow number (FN) test is commonly conducted in accordance with AASHTO T79 "Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)". The FN test characterizes the rutting potential of asphalt mixtures subjected to haversine loading. The cumulative deformation is then determined as a function of load cycles. In this test, load is generally applied for 0.1 s, then released for 0.9 s, to form one cycle. This process is repeated up to 10,000 loading cycles. The results of the FN test are presented as a cumulative permanent deformation curve (El-Basyouny et al., 2005; Kim et al., 2009).

Indirect Tensile Test. The indirect tensile (ITS) test is generally conducted according to AASHTO T283 "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage". The IDT test is typically performed at 77ºF (25°C) with a loading rate of 50mm/min. When conducted at lower temperatures (i.e., 32ºF (0ºC)), the loading rate is reduced to 1in. /min. In this testing, a cylindrical CIR specimen is subjected to compressive loads creating a vertical stress (tensile) within the vertical plane causing the specimen to break in two halves. Different studies showed that the fracture energy obtained from the IDT stress-strain curve can characterize the cracking behavior and the cracking potential of CIR mixtures (Koh and Roque, 2010; Doyle and Howard, 2013; Cox and Howard, 2015b).

Semi-Circular Bend Test. The semi-circular bend (SCB) test is conducted on cut and notched CIR specimens, in accordance with AASHTO TP-105 "Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)". Similarly to ITS test, SCB test is performed at 77ºF (25ºC) or at 32ºF (0ºC), with loading rates of 2 and 1 in. /min (50 and 25 m/min), respectively. This test characterizes the cracking resistance of CIR mixtures to loading by evaluating the fracture energy of these mixtures. For instance, Charmot et al. (2017) evaluated the cracking behavior of CIR mixtures prepared with varying contents of emulsion and cement, at low temperature (32ºF (0ºC)) to optimize these mixtures (e.g., determining the optimum binder/water content that correspond to the maximum SCB fracture energy).

CIR laboratory performance evaluation

Asphalt Pavement Analyzer test: Cox and Howard (2015b) conducted APA testing on CIR specimens with different properties according to typical Mississippi specs for asphalt mixtures (i.e. at 147ºF for 8,000 cycles with a 100 lbs load applied by pressurized rubber hoses of 100 psi). Results showed that CIR specimens prepared with cement showed higher rutting resistance than those mixtures prepared with just emulsion. Therefore, APA test was recommended for evaluating rutting susceptibility of CIR rehabilitated pavements (Cox and Howard, 2015b).

Dynamic Modulus testing. Kim and Lee (2012) also conducted dynamic modulus test, in accordance with AASHTO T 79 on CIR emulsion mixes at 3 different temperatures (40°F, 70°F, and 100°F) and six different frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz). Similarly to FN testing, Kim and Lee (2012) reported that CIR cationic mixtures (i.e. CSS-1h) presented higher dynamic modulus values than CIR anionic mixes (i.e. HFMS-2P). Kim and Lee (2012) also stated that |E*| of CIR emulsion mixtures was not affected by temperature or loading frequency. Thus, the dynamic complex modulus was recommended by the authors to evaluate the stiffness of CIR mixtures at high and low temperatures (Kim and Lee, 2012).

Flow Number testing: Previous studies conducted the flow number test on CIR mixtures with different properties (i.e., binder type and content, curing process) to assess CIR rutting resistance (Kim and Lee, 2012; Rodezno et al., 2015). Kim and Lee (2012) conducted a flow number test on CIR mixtures prepared with emulsions (CSS-1h and HFMS-2P) to evaluate rutting susceptibility of asphalt emulsion CIR mixtures. The FN test consisted of applying a 20.3 psi (140 kPa) loading stress on CIR emulsion mixtures at 104°F up to 20,000 passes until 5% of cumulative permanent strain is achieved. The results of the FN test conducted by Kim and Lee (2012) showed that CSS-1h emulsion CIR specimens presented higher FN values than those of HFMS-2P emulsion CIR specimens. In addition, an increase in emulsion content from 0.5% to 1.5% caused CIR specimens to fail. Therefore, the FN test was recommended by Kim and Lee (2012) to select optimum binder content (typically emulsions) to be used when designing CIR mixtures.

Indirect Tensile test: The indirect tensile (IDT) testing is generally conducted at 77ºF (25°C) with a load rate of 2 in. /min (50mm/min) in accordance with AASHTO T283. Different studies showed that the fracture energy obtained from the IDT stress-strain curve can characterize the cracking behavior and the cracking potential of CIR mixtures (Koh and Roque, 2010; Doyle and Howard, 2013; Cox and Howard, 2015b). Recently, Lee et al., (2016) developed a volumetric-based CIR mix design procedure using the Superpave gyratory compactor. In this study, CIR specimens were prepared using RAP obtained from different geographic locations and emulsified asphalt. The CIR mixtures were then compacted to densities similar to those obtained in the field. The tensile strength (ITS) and creep compliance of CIR specimens were then determined using the indirect tensile (IDT) strength test. This study also focused on testing a full-scale CIR test section located in Arizona. Lee et al. (2016) reported that the IDT results were satisfactory and, therefore, this test was recommended for cracking characterization of CIR mixtures.

Semi-Circular Bend test: Charmot et al. (2017) evaluated the cracking behavior of CIR mixtures prepared with varying contents of emulsion and cement, at low temperature (32ºF (0ºC)). Results of SCB low temperature fracture test showed that there is a strong correlation between fracture energy and emulsion contents (positive trend), and fracture energy and cement content (negative trend). In addition, SCB fracture energy measure was efficient in predicting CIR cracking performance and determining optimum contents of emulsion and cement. Therefore, Charmot et al., (2017) reported that SCB test, conducted at low temperature, was successfully used to evaluate CIR cracking performance as well as to select optimum contents for recycling agents/additives.

Field performance evaluation

The laboratory experimental program helps establish a job mix formula (JMF) to follow when producing CIR mixtures. This JMF needs to be validated when constructing CIR rehabilitated pavements, in the field, through evaluating the resistance of these pavements to various distresses (i.e. cracks, rut, raveling…). In fact, CIR pavements are generally monitored with respect to functional and structural performances after the completion of construction. The functional performance of pavements is evaluated using the International Roughness Index (IRI) (percentage of cracks and rut depth), while the structural performance is measured using non-destructive methods (i.e. falling weight deflectometer (FWD)) (Harun et al., 2009; Kevin, 2015; Buss et al., 2017). A discussion of CIR pavements' performance evaluation is provided next.

General pavement surveys. A study conducted by (Buss et al., 2017) aimed to investigate all the factors that can affect the long-term performance of CIR rehabilitated pavements, to estimate the viability and the effectiveness of CIR technique on pavements with different levels of deterioration. The pavement management information system (PMIS) of Iowa DOT provided the pavement performance data of approximately 100 CIR projects previously conducted in different pavements within the state of Iowa. Buss et al., (2017) carried out statistical analysis to investigate the different types of pavement distresses likely occurring on CIR rehabilitated pavements. The study of Buss et al., (2017) focused on the following distresses:

Transverse Cracks: A previous study of (Huang, 2004) revealed that the variation of temperature (from hot summer to very cold winter) is one of the reasons of transverse cracking formation in asphalt pavements. In general, three types of transverse cracking can be seen on asphalt pavements' surfaces, depending on the width of cracks (Miller and Bellinger, 2003):

- Low transverse cracks: when the mean width of a crack is less than 6 mm;
- Medium transverse cracks: when the mean width of a crack is between 6 and 19 mm), and;
- High transverse cracks: when a mean width of a crack is higher than 19 width.

Buss et al., (2017) reported that, a year after construction, there was no visible transverse cracks in any of the cold recycled pavements. Twelve years after construction, low to medium transverse cracks were observed in several CIR pavements.

Longitudinal Cracks: This type of cracks is generally found under one of the following levels of severity (Miller and Bellinger 2003):

- Low-severity longitudinal cracks: when the mean width of a crack is less than 0.23 in. (6 mm);
- Moderate-severity longitudinal cracks: when the mean width of a crack is between 0.23 and 0.75 in (6 and 19 mm), and;
- High-severity longitudinal cracks: when a mean width of a crack is higher than 0.75 in. (19 mm) width.

Buss et al., (2017) investigated longitudinal cracks present in two levels: non-wheel path and wheel path. Analysis conducted on Iowa CIR rehabilitated pavements showed that only low-severity cracks were present in non-wheel path throughout the analysis period. Eight years after construction, low-severity cracks appeared and tended to increase in the following years, while medium to high-severity longitudinal cracks were found in significant amounts in the wheel path (Buss et al., 2017).

Fatigue cracks: Also known as alligator cracks. This pavement distress is generally generated when pavements are subjected to heavy load (Huang 2004). Cold recycled pavements in Iowa showed a significant decrease in alligator cracking rate, which started to appear as low-severity cracking, 9 years after CIR construction (Buss et al., 2017).

Rutting: This type of pavement distress is generally created in the wheel path as a longitudinal depression on the pavement surface (Huang, 2004). Prior to constructing CIR pavement, rutting was observed in constant rates. After construction, the rutting did not start to increase progressively to the original rutting depth until the year 12 (same condition as before constructing CIR) (Buss et al., 2017). Buss et al., (2017) concluded that CIR technology significantly improved rutting in most of CIR rehabilitated pavements, 10 years after construction.

Pavement functional performance. In general, the International Roughness Index (IRI) indicates the riding quality of roadways. Harun et al., (2009) conducted a study to evaluate the riding quality of different Malaysian roadways constructed via CIR technology. Sixty months after construction, IRI testing was performed on several locations of the CIR rehabilitated roadways. Harun et al., (2009) found that the IRI values were ranging from 2.5 m/km to 3.5 m/km, indicating a poor riding quality of the tested roadways. Table 5 presents brief guidelines for evaluating the performance of CIR rehabilitated pavements using IRI values, Cracks' rate and rut depth (Harun et al., 2009).

Table 5

Pavement Functional Performance criteria (Harun et al., 2009)

IRI (m/km)	Rut Depth (mm)	Crack (%)	Performance
< 2	< 5	< 5	Good
2 – 3	5 – 10	5 – 10	Fair
> 3	> 10	> 10	Poor

Pavement Structural Performance. The structural performance of CIR rehabilitated pavements is generally evaluated by means of central deflection data measured by Falling Weigh Deflectometer (FWD). The outcomes of this test help determine the quality of structural condition of CIR rehabilitated pavements. In addition, the elastic modulus of CIR pavements can also be determined using FWD so as to evaluate pavement's resistance to deformation under traffic load (Harun et al., 2009). In a recent study, da Silva et al., (2013) conducted FWD test on CIR test section during rainy and dry seasons, for two years (2009 and 2010) to study both seasonal and traffic effects. da Silva et al., (2013) reported that a significant difference in deflections was observed between rainy and dry seasons (around 20%). With regard to traffic effects, deflections also increased up to 15% per year, then continued increasing during the rainy season and the following dry season (da Silva et al., 2013).

Marshall Stability testing (strength and durability tests). A trial section of full-scale pavement, subjected to low volume traffic, was constructed in Israel via CIR technology using emulsions type HFMS-1 (high floating anionic emulsion). The CIR mix was designed in the lab following the modified Marshall Mix design procedure while it was modified so as to meet the climate conditions in Israel (140°F). The CIR mix consisted of 70% RAP, 20% Virgin aggregates, and 10% quarry sand and HFMS-1. Twelve months after the construction of the CIR section, strength test (Marshall stability test) at 140°F and durability tests were performed on cores obtained from the cold recycled section, in accordance with ASTM D1559 (Cohen et al., 1987). Cohen et al. (1987) reported that the CIR layer showed a satisfactory performance by attaining an acceptable resistance to deformation, cracking, and rutting after one year of service. Furthermore, the results of durability tests showed a high durability potential as well as a high resistance of the cold recycled layer to the damaging effects of high/low temperature and water (Cohen et al., 1987).

Summary

Overall, CIR technique has been used successfully to treat deteriorated asphalt pavements in a short period of time, with low cost, and without harming the environment. The use of CIR method was generally confined to low and moderate trafficked pavements, while no case of heavy trafficked pavements (i.e. airfields) was reported. For instance, some agencies restricted the use of CIR technique when rehabilitating pavements with traffic is greater than 4,000 ADT, while in few cases, CIR was performed on pavements with significantly higher traffic (around 16,000 ADT) (Tario, 2010). In addition, mix design procedures developed for CIR mixtures often considered the cracking parameters (i.e. ITS, fracture energy, fracture index) when selecting optimum contents of binding agents, recycling additives, and/or water of CIR mixtures. The rutting performance of CIR mixtures was generally disregarded.

Therefore, there is a need to extend the CIR practice on heavy traffic loading / aircraft loading pavements with a concurrent consideration of appropriate materials' selection and modified construction process. Since the performance at the post-construction stage is the most important consideration of CIR practice from low and medium to heavy traffic condition, a preliminary study of materials is required that should include a comparison between the structural requirements for heavy traffic condition and the structural properties achieved by CIR technique. The deficits of structural strength of CIR for heavy traffic loading will be identified and compensated by the materials selections and construction procedure developed using a balanced mix design approach. Thus, considering both cracking and rutting performance measures when selecting optimum binder contents of CIR mixtures. It is envisioned that this study will deliver a comprehensive information of CIR balanced mix design for heavy traffic conditions with the quality control and quality insurance of materials and performance tests.

Chapter 3

Description of Cold In-Place Recycling (CIR) Materials Used

In this study, a hundred percent of reclaimed asphalt pavement was used in preparing cold in-place recycling mixtures, without adding virgin aggregates. Two recycling agents were used in this study such as CSS-1h emulsified asphalt and neat PG 64-22 foamed asphalt. With regard to additives, Portland cement was added to CIR mixtures to increase the strength of these mixtures. Water was also added to CIR mixtures to enhance the process of coating RAP with Portland cement as well as to facilitate the compaction process of these mixtures. Prior to mixing, the characteristics of RAP, recycling agents and additives were identified to meet the requirements specified by AASHTO/ASTM standards when preparing CIR mixtures. This section discusses the materials acquired for this study and presents the characteristics for each one of them.

Reclaimed Asphalt Pavement (RAP)

In this study, a portion of a HMA pavement section, located at Rowan University Accelerated Pavement Testing Facility (RUAPTF), was milled using a standard milling machine typically used in CIR projects, to collect RAP needed for preparing CIR mixtures (12 ft. wide by 15 ft. long by 4 in. deep) (Figure 7). It is important to mention that the millings were collected from an HMA section in RUAPTF because, once the laboratory analysis of CIR mixtures are completed, this section will be rehabilitated using CIR technology, thus, facilitating field validation of the developed Balanced Mix Design (BMD) procedure in the near future. In order to characterize the millings obtained for this study, a number of tests were performed on dry RAP to gather more information regarding the gradation, the maximum specific gravity, and the existing binder content.

Figure 7. RAP obtained from RUAPTF

Sieve analysis. Dry sieve analysis was conducted in accordance with AASHTO T27 to determine the gradation of the RAP to be used in this study. It is also worthy to note that a significant quantity of CIR millings (approximately 450 Kg) was sieved to obtain a more representative gradation of the obtained RAP. A large sieve shaker was used to sieve RAP millings. Figure 8 shows the general gradation of the obtained RAP.

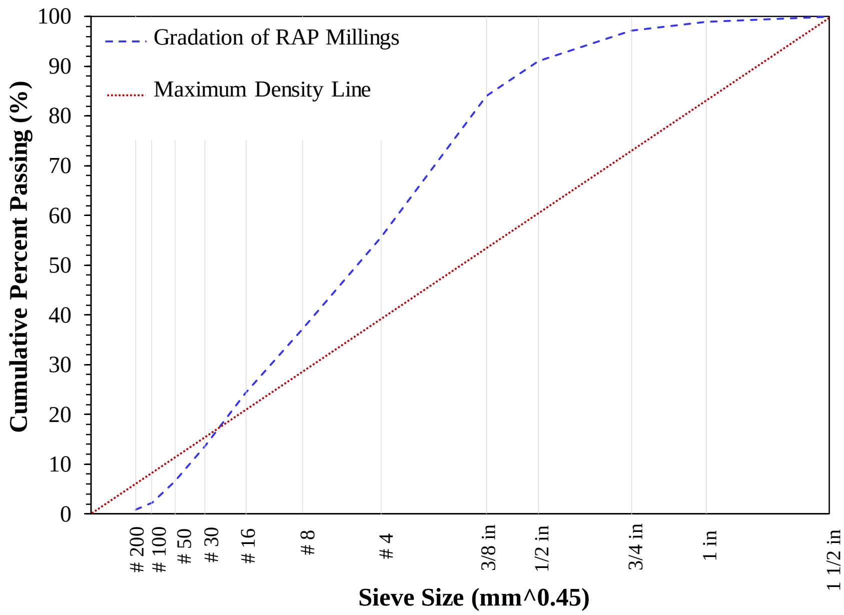


Figure 8. General Gradation of RAP materials

In addition, washed sieve analysis was also performed on two replicates of the obtained RAP, in accordance with AASHTO T11, to determine the fine materials passing sieve no.200 (75 µm). The results, summarized in Figure 9, showed that the RAP millings collected for this study contained an average of 2.5% of particles passing sieve no.200, which is a good indicator of the permeability of the RAP. The CIR mixture will serve as a base layer.

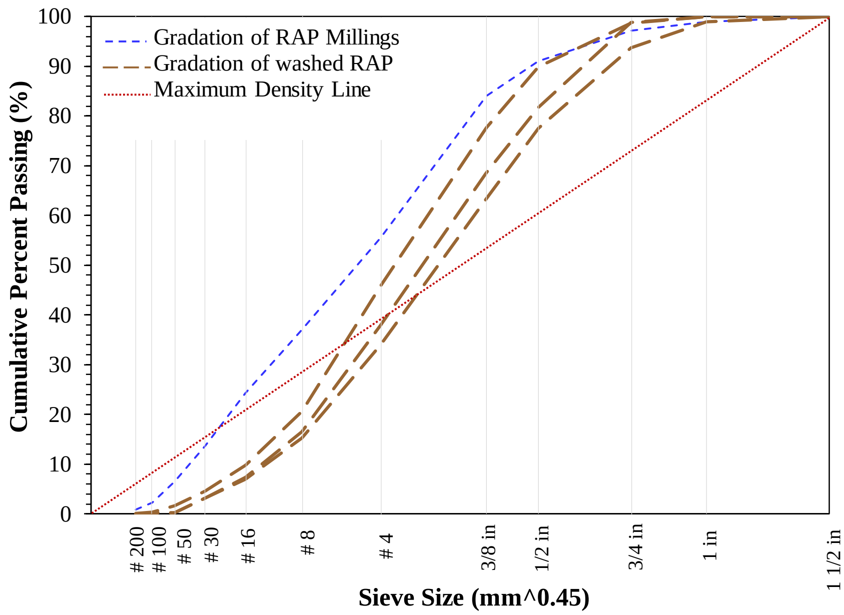


Figure 9. Gradation of washed RAP materials

Maximum specific gravity. The maximum theoretical specific gravity (G_{mm}) of sampled RAP was also determined using the CoreLok device, shown in Figure 10, in accordance with ASTM D6857. Three replicates of RAP batched to the general gradation (Figure 8), were allowed to dry overnight in an oven at 80°C to ensure that the moisture content of RAP is significantly reduced. The results of G_{mm} are presented in Table 6.

Figure 10. CoreLok Device Used to Determine Volumetric of CIR mixtures

Table 6

Maximum Specific Gravity Results of RAP

Sample	G_{mm}	Average G_{mm}	Standard Dev.
RAP-1	2.525	2.527	0.002
RAP-2	2.529		
RAP-3	2.528		

Existing binder content. In order to quantify and characterize the binder content utilized to construct the milled HMA pavement section, an extraction and recovery of the existing binder content of RAP was performed in accordance with AASHTO T319. Prior to initiating the extraction of the binder, three samples of RAP were blended to the general gradation and dried in an oven at 176°F (80°C) overnight. The results of the aged asphalt binder content, presented in Table 7, show that the average content of the binder existing in RAP is approximately 5.5%.

Table 7

Existing Binder Content of RAP

Samples	RAP Weight before (g)	RAP Weight after (g)	Weigh of Aged Binder (g)	Binder Content (%)
RAP-1	1881.6	1771.8	63.3	5.65
RAP-2	1870.6	1761.45	55.5	5.66
RAP-3	1788.1	1692.36	60.2	5.22

Recycling Agent

One of this study's focuses was on evaluating the impact of different recycling agents on the laboratory performance of CIR mixtures. Two re-cycling agents were selected for this study based on the literature. These binders are: CSS-1h emulsified asphalt and neat PG 64-22 foamed asphalt.

Emulsified asphalt. A slow setting cationic asphalt emulsion (CSS-1h) was used in this study. This emulsion was manufactured by the New Jersey-based Asphalt Paving Systems, Inc. and supplied in small quantities as required. The obtained emulsion was stored in 1-gallon plastic containers at room temperature to prevent emulsion from breaking. Before every use, these containers were gently agitated to prevent the settlement/separation of emulsion. Table 8 presents the main properties of CSS-1h emulsion used to prepare emulsified asphalt CIR mixtures.

Table 8

Properties of CSS-1h Emulsified Asphalt

Properties	Results
Sieve (%)	0.00
25ºC SF Viscosity (sec)	22.0
25ºC, 100G, 5 sec Penetration	29.0
pH	5.0
Residue (%)	63.15

Foamed asphalt. A neat PG 64-22 asphalt binder was used in this study to produce foamed asphalt. This asphalt binder was manufactured by Asphalt Paving Systems, Inc. and supplied in five-gallon buckets. Prior to preparing foamed asphalt CIR mixtures, the asphalt foaming process was tested at different contents of process water (2% - 3.5%, with increments of 0.5% of total foamed asphalt weight) so as to determine the optimum water content (OWC) required to create foam. At OWC, foamed asphalt exhibits maximum values of half-life and expansion ratio. Table 9 presents the properties of neat PG 64-22 foamed asphalt determined at three temperatures: 311, 329, 347ºF (155ºC, 165ºC, and 175ºC).

Table 9

Foaming Properties Test Results

Temperature	Half-Life (s)	Expansion Ratio	OWC (%)
155	8	8	2.5
165	10.5	10	2.5
175	7.5	9	3

As can be seen in Table 9, when the process temperature is increased from 155 to 165°C, a significant increase can be observed in the values of expansion ratio and half-life. However, these values are reduced when the process temperature is increased from 165 to 175°C. This shows that, at 165ºC, neat PG 64-22 foamed asphalt presented the highest half-life and the best expansion ratio values (10 seconds for half-life and 10.5 for expansion ratio). Therefore, foamed asphalt, to be used in this study, should be produced at 165ºC using a process water content of 2.5% of total foamed asphalt weight, to ensure high quality foamed asphalt CIR mixtures. A Wirtgen WLB 2S foamed asphalt machine (laboratory –scale) was used to produce foamed asphalt by introducing cold water and air to hot asphalt binder of PG 64-22 (Figure 11).

Figure 11. Laboratory-Scale Foaming Machine

Additives: Portland Cement

In this study, a Type I Portland cement was used to improve the strength of the CIR mixtures to be prepared, as well as to achieve a rapid curing for these mixtures. The amount of Portland cement to be added to CIR mixtures was selected as 1.0% of total mix weight, based on literature (section 2.2.4). It is important to mention that: (1) 3.0 % (total mix weight) of water content was added to CIR mixtures to facilitate the process of mixing RAP with Portland cement, and (2) no virgin aggregates were used to prepare these CIR mixtures.

Chapter 4

Balanced Mix Design Approach

Overview of the Laboratory Experimental Program

The Laboratory experimental program was established evaluate rutting susceptibility and cracking resistance of emulsified and foamed asphalt CIR mixtures compacted with different gyration levels and subjected to different curing processes. The goal of performance testing was to develop a CIR design using a BMD approach to select optimum binder contents of CIR mixtures with different design properties. This section discusses CIR specimen production methodology and performance evaluation program.

CIR Samples Production using Balanced Mix Design Method

The mix design method used in this study was developed based on the concept of balancing between cracking and rutting performances of CIR mixtures in order to select a relevant optimum binder content. The developed design method consisted of five steps (Figure 12). A discussion of each step is provided in the following:

Step 1: Obtaining CIR materials. The obtained RAP material was allowed to dry, overnight, in an oven at 80^{o}C. Prior to mixing, RAP was blended to the general gradation, as shown in Figure 8, to eliminate materials' variability. It is important to produce CIR mixtures with representative RAP from the pavement structure to be treated using CIR technology. A portion of the pavement, to be rehabilitated, was milled using a CIR milling machine to obtain representative RAP millings for CIR production in the lab. RAP was then characterized in terms of gradation, maximum specific gravity, and aged binder content (see section 3.1). In addition, CSS-1h emulsion and neat PG 64-22 foamed asphalt were selected as the recycling agents to be used in preparing CIR mixtures in the laboratory. Portland cement was also selected because, besides lime, it is the most commonly used additive for producing CIR mixtures. Water was also required to facilitate the compaction process of CIR mixtures.

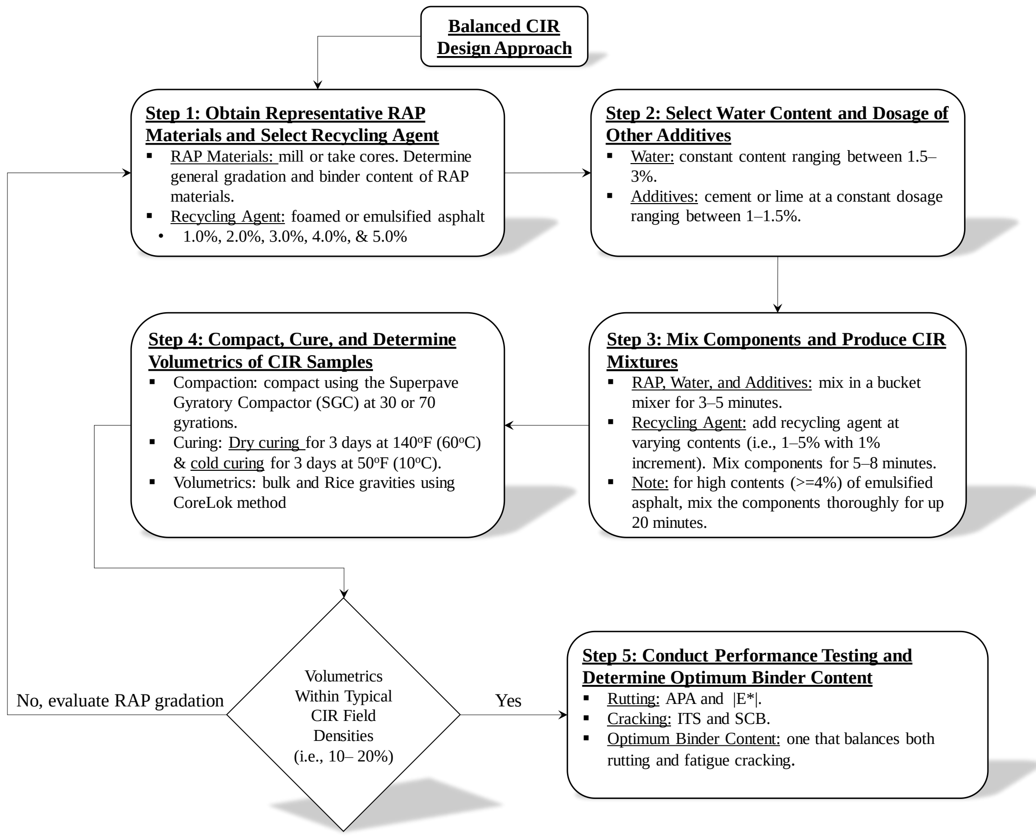


Figure 12. BMD design approach of CIR mixtures

Step 2: Select contents of recycling additives and water. The water content selected for this study was 3%, based on previous studies reporting that the optimum water content was generally ranging between 1.5 to 3%. With regards to recycling additives, the amount of Portland cement needed for CIR mixtures production was 1%, selected based on previous studies (Scholz et al., 1991; Cox and Howard, 2015; Kim and Lee, 2011; Lee et al, 2016).

Step 3: Mix CIR components. To prepare CIR mixtures, batches of RAP were mixed with Portland cement and water, at the selected dosages, for up to 5 minutes using a stand mixer. Afterwards, one of the selected recycling agents (step 1) was added to CIR mix at varying amounts (1–5% of total mix with increments of 1%), and allowed to mix for up to 8 minutes. When emulsion was used at higher dosages (e.g., 4% and 5% of total mix), a longer mixing period was needed (up to 20 minutes) so as the emulsion is completely absorbed by RAP and to avoid having “watery” CIR specimens.

Step 4: Compact CIR mixtures. Immediately after mixing, the CIR mixtures were compacted at one of the following compaction levels: 30 gyrations and 70 gyrations, using the Superpave Gyratory Compactor (Figure 13). In fact, all CIR mixtures were compacted targeting different heights, depending on the performance test to be conducted on each test specimen. It is important to note that the gyrations levels used in this study were selected to simulate the level of traffic subjected on the roadway to be rehabilitated. For instance, roadways with low to medium traffic levels are generally compacted at 30 gyrations, while heavy trafficked pavements, such as airfields, can be compacted with 70 gyrations (Rushing et al., 2012). Therefore, the reason behind compacting the CIR mixtures with a higher number of gyrations (i.e., 70 gyrations) was to model the use of CIR on pavements under heavy traffic conditions.

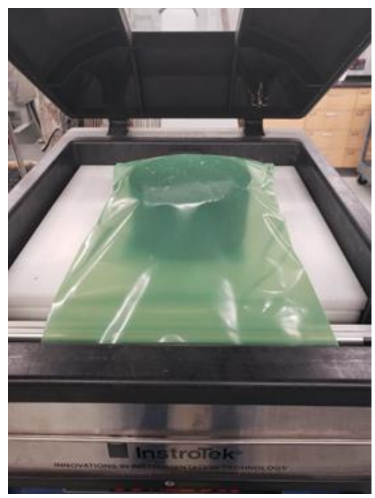
Figure 13. Superpave Gyratory Compactor (SGC)

Step 5: Cure CIR mixtures. hot and dry condition, that is placing CIR specimens in an oven at 140^{o}F for three days, and (2) cold condition, that is placing CIR specimens in a fridge at 50^{o}F for three days. These curing conditions were selected in order to represent most of the environmental conditions during which the CIR process can be performed in the field.

Step 6: Measure density of CIR Mixtures. In this step, the air void of each cured CIR mix was determined. In addition to the compacted samples, three replicates of loose CIR mixtures were also allowed to cure at one of the temperatures presented in Step 5. The maximum theoretical specific gravity (G_{mm}) of the loose mix and the bulk specific gravity (G_{mb}) of the compacted samples were then determined using CoreLok device so as to estimate the air voids of each CIR mixture (Figure 14). Air voids of CIR mixes should be similar to typical field CIR densities (i.e., up to 20% air voids; depending on binder content used). If CIR air voids does not meet these requirements, additional testing should be conducted on multiple samples of RAP materials to better determine the gradation of the RAP millings (Step 1). Mineral filler (<0.075 mm) can also be added to ameliorate the gradation if a similar gradation if obtained after conducting the additional testing.

In total, eight CIR mixtures were prepared using a combination of two recycling agents, two compaction levels, and two curing processes. Table 10 presents the designation of each CIR mixture based on design properties. For instance, if a mixture was prepared using emulsion, compacted at 30 gyrations, and allowed to cure in an oven at 140°F for three days, the mixture will be designated as CIR-E30H, where "E" stands for emulsion, "30" stands for 30 gyrations, and "H" stands for hot curing.

(a)



(b)

Figure 14. Density Measurements using CoreLok: (a) Rice Specific Gravity; (b) Bulk Specific Gravity

Table 10

CIR mixtures' properties and designation

Mixture	Recycling Agent	Gyrations	Curing Process
CIR-E30H	CSS-1h emulsion	30	3 days at 140°F
CIR-E30C	CSS-1h emulsion	30	3 days at 140°F
CIR-E70H	CSS-1h emulsion	70	3 days at 140°F
CIR-E70C	CSS-1h emulsion	70	3 days at 140°F
CIR-F30H	PG 64-22 Foamed Asphalt	30	3 days at 50°F
CIR-F30C	PG 64-22 Foamed Asphalt	30	3 days at 50°F
CIR-F70H	PG 64-22 Foamed Asphalt	70	3 days at 50°F
CIR-F70C	PG 64-22 Foamed Asphalt	70	3 days at 50°F

CIR Test Methods

The purpose of conducting performance tests on CIR specimens was to utilize the performance measures (rutting and cracking), determined for each CIR mixture, to select optimum binder contents of these mixtures. In this step, Asphalt Pavement Analyzer (APA) rut depth and the Dynamic Complex Modulus (|E*|) were selected to quantify rutting in accordance with AASHTO T 340 and AASHTO T 342, respectively; while Indirect Tensile Strength (IDT) and Semi-Circular Bend Fracture Energy (SCB-FE) were used to quantify cracking resistance in accordance with ASTM D6931 and AASHTO TP124, respectively.

Asphalt Pavement Analyzer (APA) test. The APA is a wheel tracking device that is typically used for evaluating the rutting potential of asphalt mixtures. This test was conducted in accordance with AASHTO T340 (Figure 15). It involves applying a 100-lb force, using a steel wheel, on top of a pressurized hose (100 psi) which then transfers the load to the test specimens. The wheel moves back and forth on top of the hose and each movement from one side of the specimen to the other is considered one pass (or loading cycle). In this study, the APA was utilized to determine the rut depth values of all four CIR mixtures discussed above. The test was conducted at 147^{o}F (64^{o}C) with the specimens allowed to condition for a minimum of 6 hours at that temperature before testing. A total of three APA replicates (i.e., 6 SGC compacted specimens) were tested and the average rut depth is reported. It is noted that all CIR samples were compacted to a height of 75 mm and the test was terminated after completion of 8000 loading cycles.

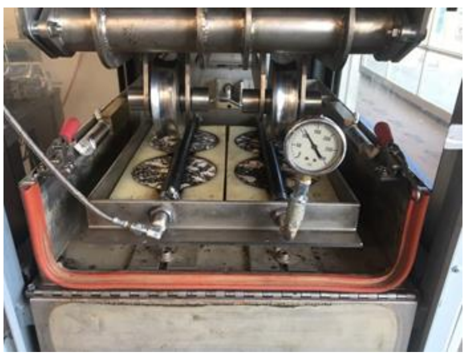



Figure 15. Asphalt Pavement Analyzer (APA) Test

Dynamic Complex Modulus. The dynamic complex modulus (|E*|) is a test used to evaluate the performance of asphalt mixtures over a spectrum of temperatures and loading frequencies. As a result, this test provides a general overview of asphalt mixture stiffness under a range of traffic speeds and environmental conditions (Figure 16). At high temperatures and low loading frequencies, rutting is the predominant failure mode of asphalt mixtures (including CIR mixtures). In this study, the |E*| was conducted at the standard temperature range of 4, 21, 37, and 54^{o}C while also applying loading at frequencies 0.1Hz, 0.5Hz, 1Hz, 5Hz, 10Hz, and 25Hz. The dynamic modulus values obtained for high temperatures (37.8 and 54^{o}C for this study) and at low frequencies (10 Hz) were selected to determine the rutting potential of CIR mixtures. The frequency of 10 Hz is used by researchers when interpreting |E*| results as it represents the speed at which traffic travels.

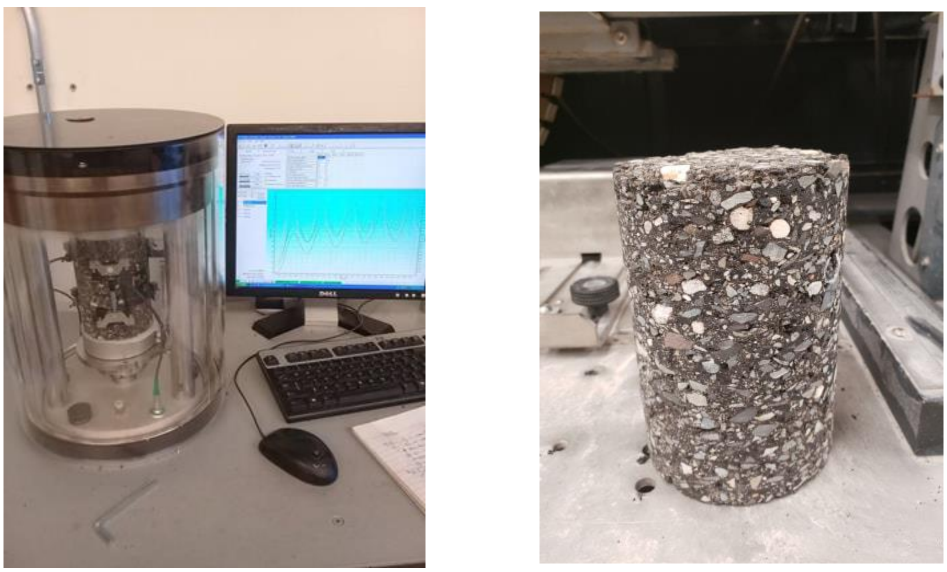


Figure 16. Dynamic Complex Modulus Test

All samples were first compacted to a height of 180 mm, dry cured, and then cored and cut to obtain cylindrical specimens having a diameter of 100 mm (4 in.) and a height of 150 mm (6 in.). Three replicates were tested for each mix.

Indirect Tensile Strength. The ITS is a measure of asphalt mixtures' tensile strength. Thus, it is a good indicator of asphalt mixtures' ability to resist cracking. This test involves diametrically loading asphalt specimens at a rate of 50 mm/min (room temperature or higher) or 12.5 mm/min (cold temperatures; 0°C and lower) and determining the stress at which a specimen breaks (using peak load). Higher ITS values are desirable as they indicate that the tested asphalt mixture is more resistant to cracking than lower ITS values. For this study, samples of all four CIR mixtures (previous section) were compacted to a height of 63 mm and tested at 0°C to determine the ITS of the mixtures. Three replicates were tested for each mix.

Figure 17. Indirect Tensile Strength Test

Semi-Circular Bend. The SCB is another test used for characterizing the cracking susceptibility of asphalt mixtures (Figure 18). Similar to the ITS, notched semi-circular specimens are loaded diametrically, while being simply supported, using a loading rate of 50 mm/min. Using the recorded load versus displacement SCB curve, the fracture energy (FE) is computed as the area under that curve. The FE parameter is an indicator of an asphalt mixture's ability to resist cracking; the higher FE is the more resistant is the mix. In this study, SCB specimens were notched, to simulate a crack in the test specimen, using a 12.5 mm long and 1 mm wide notch. Testing was conducted at 0^oC and three replicates per mix were tested according to the SCB protocol. A testing temperature of 0^oC was selected, for both ITS and SCB, because it represents a more conservative temperature at which cracking will be more pronounced. This also falls in line with what was reported in literature by Charmot et al. (2018).

Figure 18. Semi-Circular Bend Test Setup

Determination of Optimum Binder Content

Using rutting and cracking data obtained through conducting performance tests on CIR specimens, the optimum binder content of each mixture can be determined using the balanced mix design (BMD) approach. At optimum binder contents, CIR mixtures should present a maximum cracking resistance and a minimum rutting susceptibility. Figure 19 (a) explains the method of determining optimum range of binder content balancing between rutting and cracking performances of CIR mixtures. Two cases are generally seen when optimizing CIR mixtures using the BMD approach: (1) when the binder content resulting in a maximum cracking resistance (i.e., at peak ITS or SCB-FE) is lower than that resulting in minimum rutting susceptibility (i.e., APA rut depth threshold), the optimum binder content is selected as the binder content maximizing the cracking performance. (2) When the binder content resulting in a highest cracking resistance is greater than that resulting in lowest rutting susceptibility, the optimum binder content corresponds, in this case, to the mid-point of the shaded area (between both binder contents), as shown in Figure 19 (b).

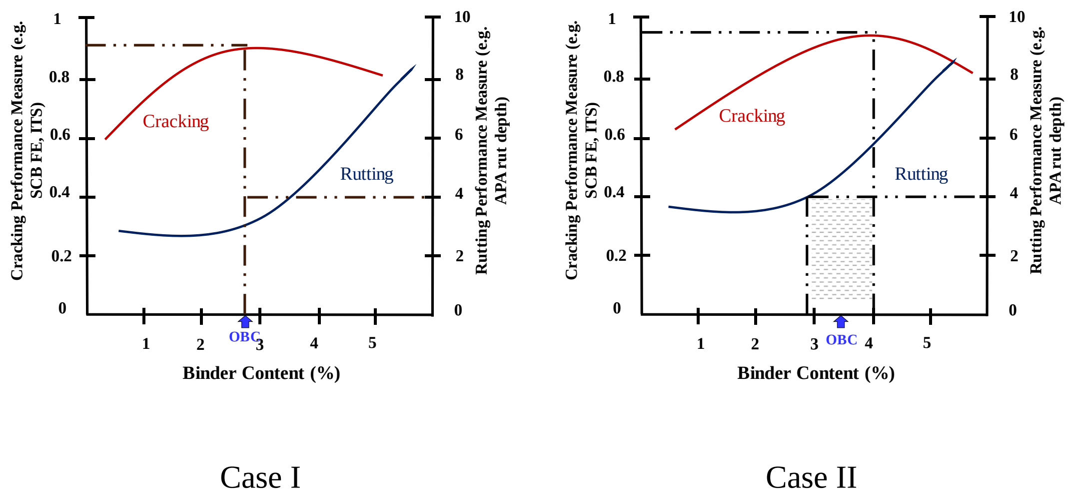


Figure 19. Example of how to select an OBC using CIR rutting and cracking performance measures.

Chapter 5

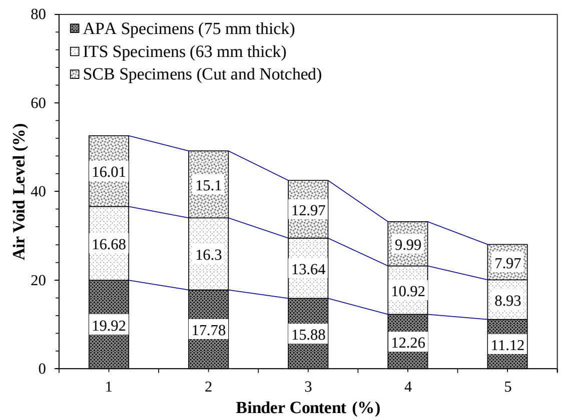
CIR Balanced Mix Design: Results, Analysis, and Discussion

Overview of CIR Balanced Mix Design Results

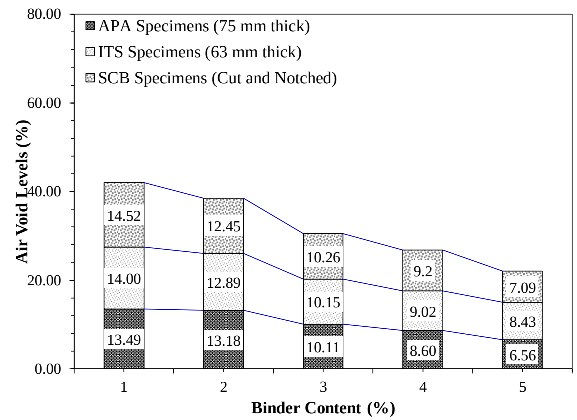
One of the goals of this study was to evidence the practicality and applicability of the introduced CIR balanced mix design method. Therefore, a thorough understanding of the performance tests, to be conducted on CIR test specimens, was required. These performance tests should be able to capture the effect of the variation of CIR binder content on rutting and cracking performance measures. If a strong correlation is found between performance measures and the binder content, then the selected performance tests can be used to determine an optimum range of binder content of CIR mixtures using the BMD approach. Finally, the impact of recycling agent type, compaction level, and curing process on CIR rutting and cracking performance measures was evaluated at optimum binder contents. The significance of this impact was then validated using statistical analyses (i.e. ANOVA).

Volumetric Results

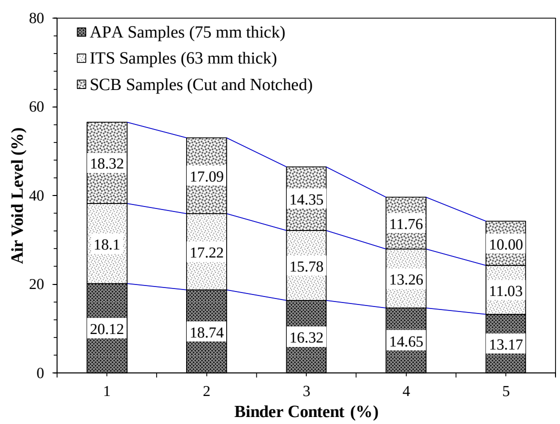
Prior to conducting performance testing on CIR test specimens, density measurements were determined for all CIR mixtures so as to evaluate the impact of binder content on CIR volumetrics. In addition, the results of CIR laboratory densities were also used to evaluate the effect of recycling agent type, compaction level, and curing process on CIR air voids.



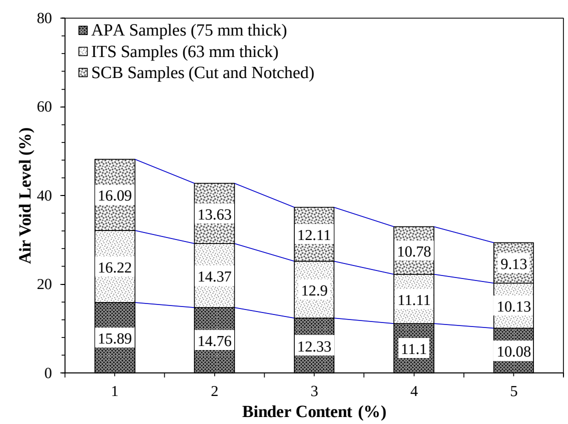
(a) CIR-E30H



(b) CIR-E70H

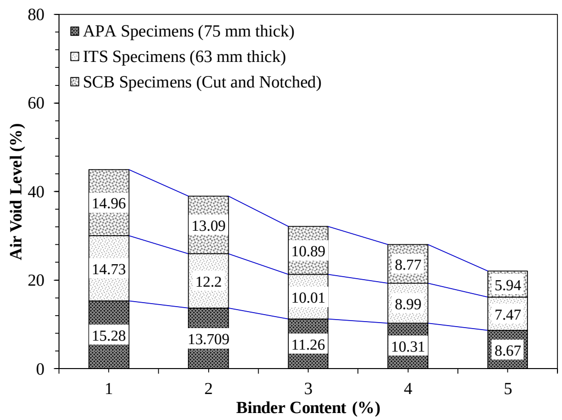


(c) CIR-E30C

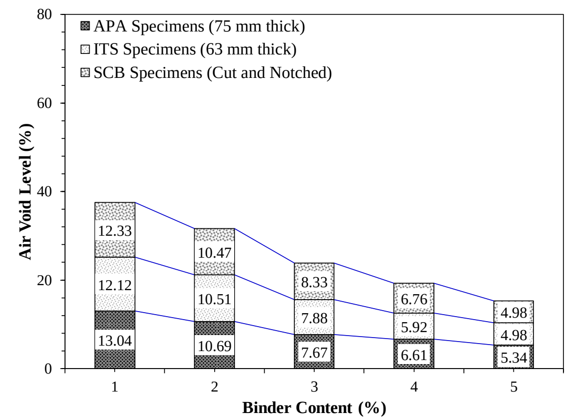


(d) CIR-E70C

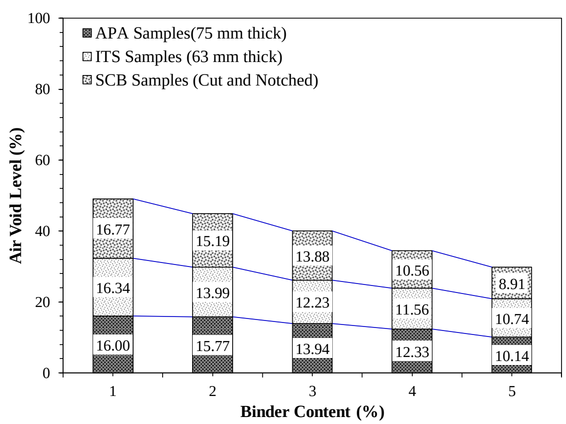
Figure 20. Volumetric analyses of Emulsified Asphalt CIR mixtures



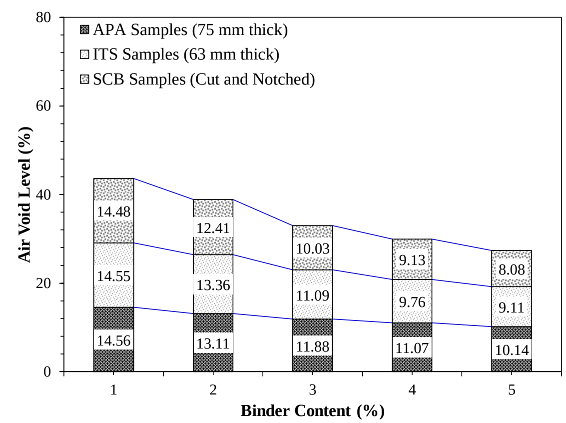
(a) CIR-F30H



(b) CIR-F70H



(c) CIR-F30C



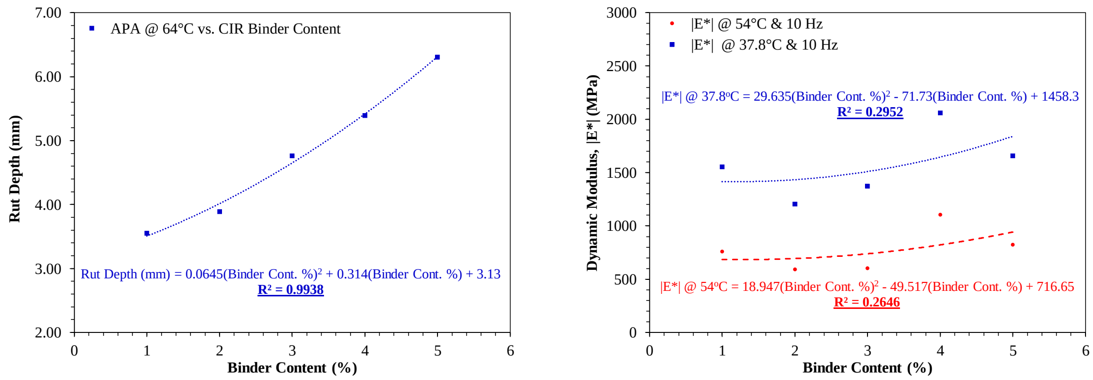
(d) CIR-F70C

Figure 21. Volumetric analyses of Foamed Asphalt CIR mixtures

Thus, CoreLok method was selected to determine both maximum and bulk specific gravities for all CIR specimens, in accordance with ASTM D6857 and AASHTO T331, respectively. Figures 20 and 21 summarize the air void levels obtained for emulsified and foamed asphalt CIR specimens with different design properties in terms of gyration level and curing temperature. As can be seen from Figures 20 and 21, an increase in the binder content of CIR mixtures resulted in a decrease in air voids of these mixtures (drop by up to 4% for every increase of 1% of binder). In terms of recycling agent type, emulsified asphalt CIR mixtures presented slightly higher air voids than foamed asphalt (up to 2% difference for same binder content). Compaction level also presented a significant effect on CIR volumetrics. In fact, CIR mixtures compacted with 70 gyrations presented lower by up to 4% air voids than those compacted with 30 gyrations. With regard to the effect of curing temperature, CIR mixtures subjected to hot curing (three days at 140°F) presented lower air void levels than those subjected to cold curing. The results of volumetric analyses were expected because adding more binder to a mixture would fill more voids within the RAP matrix and also increase lubrication to facilitate compaction causing measured air voids to drop. In addition, increasing the compaction level and the curing temperature enhances the process of asphalt coating of RAP, and thus, reduces the air void. In summary, the results of volumetric analysis showed that all CIR samples presented air void levels similar to those typically found in CIR layer in the field.

Binder Content as a Predictor of CIR Performance Measures

In order to select performance measures capable of determining optimum binder contents of CIR mixtures with satisfactory accuracy, the correlation between rutting and cracking measures and binder content was evaluated using regression analysis method. Figure 22 and 23 present the relationships developed between rutting measures (i.e., rut depth, |E*|) and cracking measures (i.e., ITS, and SCB-FE) and binder content of CIR mixtures (i.e., CIR-E30H). As can be seen from the figures, the effect of varying the binder content on CIR performance can be identified. In terms of rutting, as illustrated in Figure 22 (a), an increase in the binder content resulted in increasing the CIR rut depth values; therefore, indicating the ability of APA rut depth measure to seize the impact of CIR binder content on CIR rutting performance. In addition, a strong correlation (R^2 = 99%) was found between APA rut depth measure and CIR binder content, signifying that CIR binder content can be a strong predictor of CIR rutting performance. Figure 22 (b) presents the relationship between dynamic modulus (|E*|), obtained at high temperatures (i.e., 37ºC and 54ºC) and 10 Hz loading frequency, and CIR binder content. A weak correlation was found between dynamic modulus rutting measure and CIR binder content (constant tend; R2 = 26.46% and R2 = 29.52%). Based on these observations, the dynamic modulus $|E^*|$ measure of CIR was discarded and only APA rut depth measure was considered for developing a balanced mix design procedure for CIR mixtures.



(a) (b)

Figure 22. Correlation between Rutting Measures and Binder Content (CIR-E30H)

In this study, CIR binder content presented a significant impact on APA rut depth while had little to no impact on $|E^*|$ of CIR mixtures. The reason that lies behind these observations is that in the case of APA test, CIR specimens are conditioned for at least 8 hours and tested at 147°F (64°C) for 8,000 loading cycles. While for $|E^*|$, specimens are only conditioned for two hours (98°F (37°C) or 129°F (54°C)) and tested with only 550 cycles. In addition, $|E^*|$ test is a non-destructive test (both stress and strain levels are low) and is generally sensitive to binder content changes when performed on hot mix asphalt (HMA) mixtures. However, emulsified asphalt is only made of 65% residual binder (for example, if emulsified content is 1% of total mix weight than the residual binder content is 0.65% of total mix weight), which makes $|E^*|$ unable to capture the binder content change in the case of CIR mixtures.

With regards to cracking performance measures, Figure 23 (a) and Figure 23 (b) show that both ITS and SCB fracture energy increased as CIR binder content increased until reaching a peak, generally corresponding to highest cracking resistance of CIR mixtures. Once the peak is attained, any increase in CIR binder resulted in a decrease of ITS and SCB-FE values. The reason behind the decrease of cracking measures after reaching the peak was that CIR mixtures tend to become softer with the increase of binder (becoming more lubricant). This resulted in a drop in the strength of CIR mixtures. Furthermore, a strong correlation was found between cracking measures and CIR binder content (ITS vs Binder content: R^2 = 92%; SCB-FE vs binder content: R^2 = 80%). Based on these observations, both cracking measures (ITS and SCB-FE) were able to capture the effect of varying the binder content on CIR mixtures' resistance to cracking. It is also important to note that the obtained trends of cracking measures were similar to previous studies that aimed to select an optimum binder content of CIR mixtures using only ITS/SCB-FE peaks. Therefore, both ITS and SCB-FE measures were considered for developing a balanced mix design procedure for CIR mixtures.

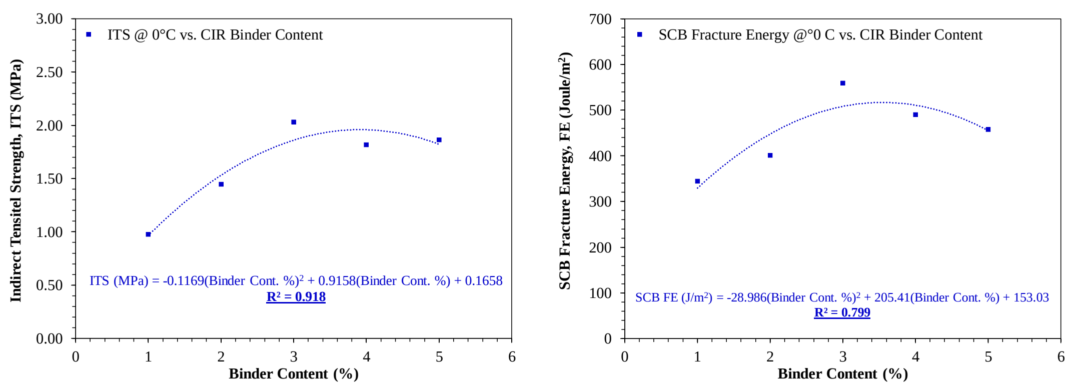


Figure 23. Correlation between Cracking Measures and Binder Content (CIR-E30H)

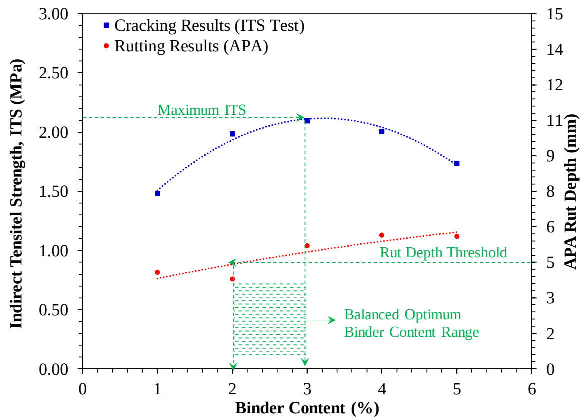
Demonstration of the CIR Balanced Mix Design Approach

After selecting rutting and cracking performance measures (in the previous section), balanced optimum binder contents of CIR mixtures can be selected using the

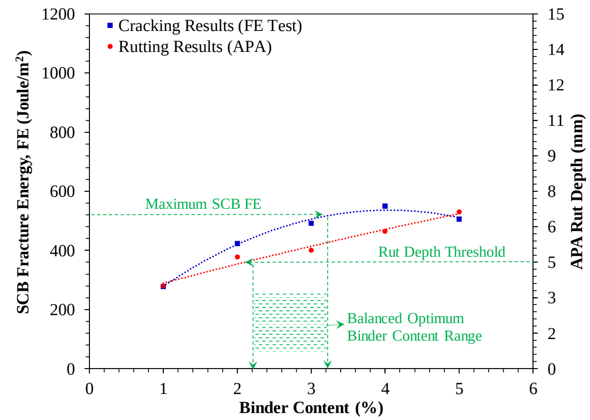
BMD approach. Figure 24 through 26 illustrate the relationships between CIR binder contents, and CIR rutting measures (i.e., APA rut depth) and both cracking measures (i.e., ITS, and SCB-FE). This relationship will help establish a range for selecting an optimum binder content using two main parameters: (1) maximum CIR cracking resistance (peak of either ITS or SCB-FE), and (2) CIR rut depth threshold (5 mm). Based on CIR BMD results, three main cases, demonstrated in Figures 24 through 26, for selecting balanced optimum ranges of binder contents can be identified depending on the rutting and cracking measures' trends. A discussion of each case is provided in the following subsections.

Case I: Both performance measures are relevant. This case is presented in Figure 24 for mixtures CIR-E30H and CIR-F70H. As illustrated in these figures, the trend for rutting performance measure (APA rut depth) is constantly increasing while cracking performance measures (ITS and SCB-FE) presented peaking trends, as CIR binder increases. Therefore, both performance measures were considered relevant for determining optimum ranges of CIR binder content. In this study, the APA rut depth threshold was considered as 5 mm (maximum rut depth allowed in New Jersey asphalt pavements). The binder content optimizing rutting resistance of CIR mixtures can be determined as illustrated in Figure 24 (i.e., 2.0% and 2.2% for CIR-E30H, shown in Figures 24 (a) and (b); and 3.8% for CIR-F30H, as shown in Figures 24 (c) and (d)). In the other hand, both peak values of ITS and SCB-FE were also used to determine the optimum binder content corresponding to a maximum cracking resistance of CIR mixtures. As can be seen from Figure 24, the optimum binder contents of CIR-E30H can be selected as 3.0% (using ITS peak) and 3.2% (using SCB-FE peak), while regarding

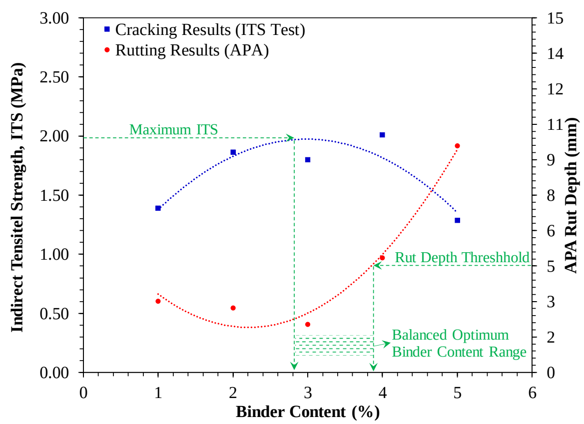
CIR-F70H, the optimum binder contents can be selected as 2.8% (using ITS peak) and 2.9% (using SCB-FE peak). Based on these observations, ranges of optimum binder contents, balancing between rutting and cracking performances, can be established for both CIR mixtures, using both cracking measures (ITS and SCB-FE). As mentioned chapter 4, there are two ways of selecting an optimum binder content of CIR mixtures. The first case is illustrated in Figures 24 (a) and (b): the optimum binder content of CIR0-E30H can be selected as the average of mid-point of CIR binder content ranges, established using APA rut depth vs. both cracking measures (ITS and SCB-FE). Therefore, the balanced optimum binder content of CIR-E30H was found to be 2.7%. The second case of selecting a balanced optimum binder content of CIR mixtures is illustrated in Figures 24 (c) and (d). The binder content maximizing the cracking resistance of CIR-F70H was lower than that minimizing the rutting susceptibility of this mixture. Thus, the balanced optimum binder content of CIR-F70H is the same as the average binder content resulting in the peaks of ITS and SCB-FE (2.85%).



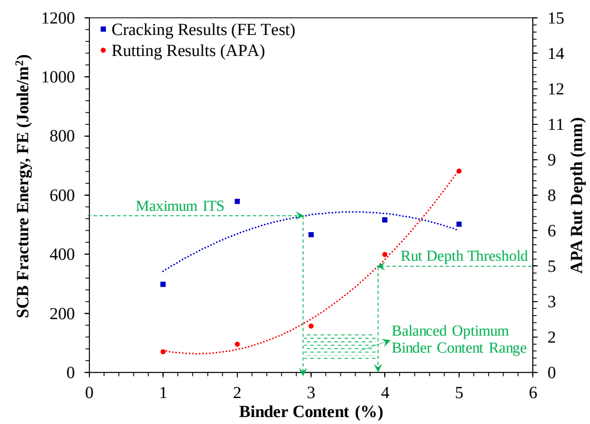
(a) CIR-E30H: APA rut depth vs ITS



(b) CIR-E30H: APA rut depth vs SCB-FE



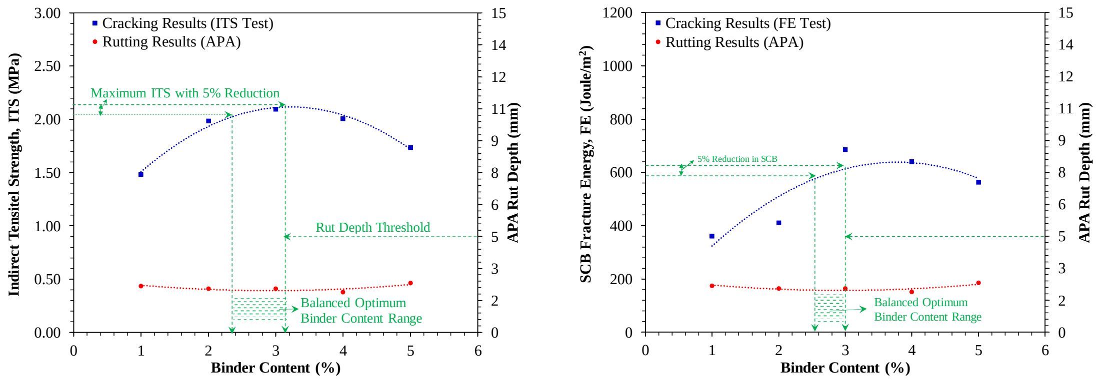
(c) CIR-F70H: APA rut depth vs ITS



(d) CIR-F70H: APA rut depth vs SCB-FE

Figure 24. Balanced Mix Design Results for CIR mixtures (case 1)

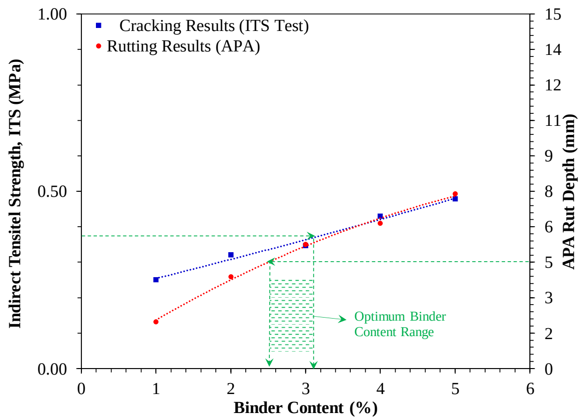
Case II: Only cracking measures are relevant. Another case was observed in some CIR mixtures (i.e. CIR-E70H) when using the BMD approach to select optimum binder contents for these mixtures. In fact, the APA rut depth values measured for CIR-E70H mix presented a relatively constant trend indicating that the increase in CIR content had no impact on APA rut depth of CIR-E70H. With regards to cracking performance, both ITS and SCB-FE of CIR-E70H presented peaking trends indicating that the increase in CIR binder content has impact on the cracking performance of CIR-E70H mix. Therefore, only the cracking performance is relevant and considered for selecting a balanced optimum binder content for this CIR mixture. Figure 25 presents the BMD results for CIR-E70 mix, as an example. The balanced optimum binder content is based on both peaks ITS and SCB-FE values as well as a slight 5% percent reduction in these peak values. It is important to note that this 5%reduction was proposed to select CIR optimum binder content because there would not be any significant change in cracking measures of CIR mixtures (For example: CIR-E70H peak ITS is 2.15 MPa while the 5% reduction is at 2.04 MPa). Thus, the balanced optimum binder content of CIR-E70H mix is selected at 2.88% (average of binder contents corresponding to maximum ITS and SCB-FE values.



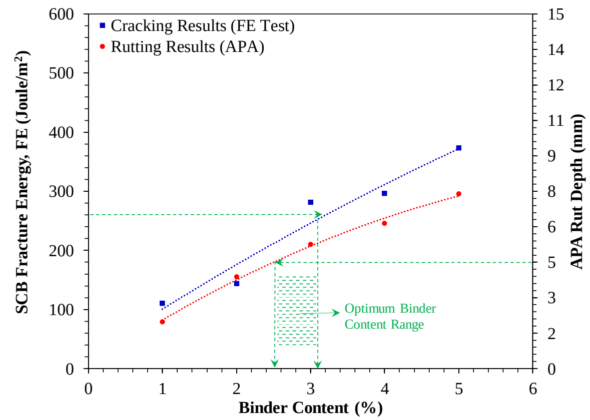
(a) CIR-E70H: APA rut depth vs ITS (b) CIR-E70H: APA rut depth vs SCB-FE

Figure 25. Balanced Mix Design Results for CIR mixtures (case 2)

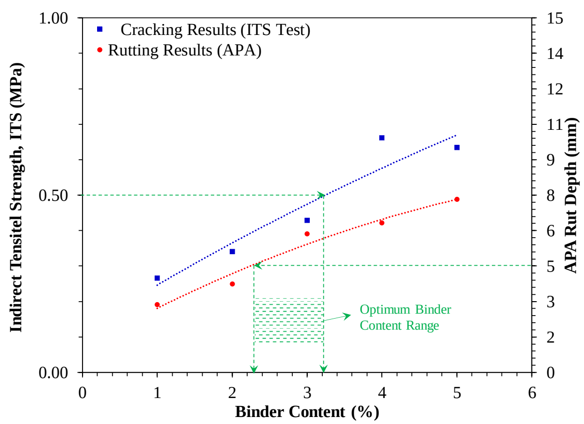
Case III: Both performance measures are showing increasing trend. In this case is illustrated in Figure 26, at least one of the cracking measures' values presents an increasing trend (with no peak) with the increase in CIR binder content. The APA rut depth values also show increasing trend as CIR binder content increases. In order to optimize each CIR mixture belonging to case III, CIR optimum binder content ranges were established using APA rut depth threshold of 5 mm and maximum cracking performance. For instance, the balanced optimum binder content of CIR-E30C can be selected as the average of the mid-point of the CIR binder contents range established using SCB-FE vs. APA rut depth (i.e. 2.75%) and ITS vs. APA rut depth (i.e. 2.85%), as shown in Figures 26 (a) and (b). The balanced optimum binder content of CIR-E30C is 2.8%. Additional examples of case III, presented in Figures 26 (c) and (d), show that CIR-F30C and CIR-F70C presents balanced optimum binder contents of 2.9% and 3.2%, respectively.



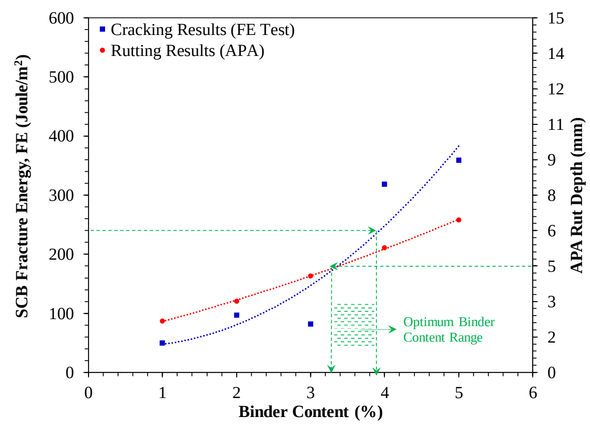
(a) CIR-E30C: APA rut depth vs ITS



(b) CIR-E30C: APA rut depth vs SCB-FE



(c) CIR-F30C: APA rut depth vs ITS



(d) CIR-F70C: APA rut depth vs SCB-FE

Figure 26. Balanced Mix Design Results for CIR mixtures (case 3)

No clear peak was observed from cracking measure results of CIR mixtures subjected to cold curing (10°C (50°F) for three days). This means that the curing process at cold temperature was not sufficient for the samples to gain maximum strength even when increasing the binder content which falls in line with the findings of the study of Kim and Lee (2011). This can be proven by looking at the results of similar mixtures subjected to hot curing where a clear peak can be observed in cracking measures (Figure 27).

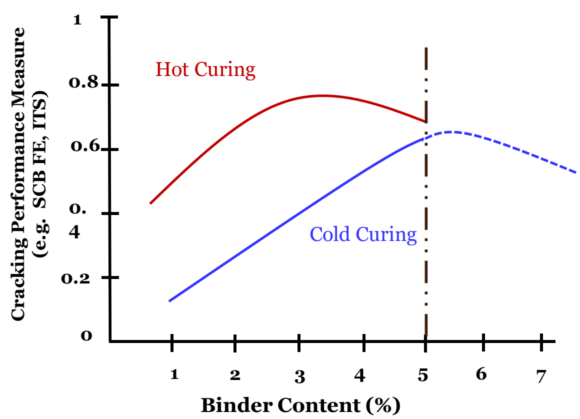


Figure 27. Impact of Curing Process Type on Cracking Performance

In summary, the results presented in Figure 24 through 26 indicate that CIR mixtures can be successfully designed following the BMD approach utilized as part of this study. This design method was found efficient since it yielded balanced optimum binder contents, ranging between 2.5% and 3.2%, that are similar to those typically found in literature (Kim and Lee, 2011). Table 11 presents a summary of the balanced optimum binder content results for emulsified and foamed asphalt CIR mixtures with different gyration levels and curing processes. As this table shows, the variability of the selected balanced optimum binder contents varied for the eight CIR mixes. The lowest coefficient of variation within the data was 1.34% (CIR-F70C) while the highest coefficient of variation was 19.77% (CIR-F70H) indicating that the variability in the selected optimum binder contents is low.

Table 11

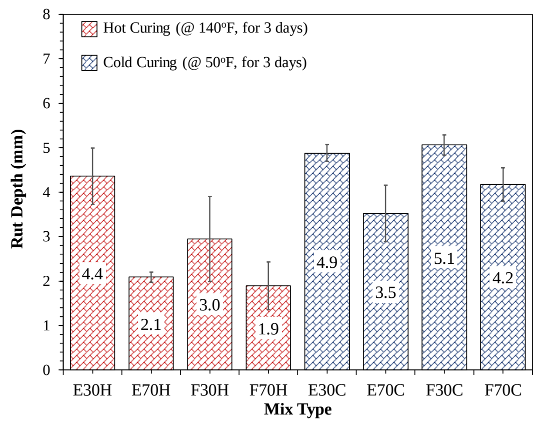
Optimum Binder Contents of CIR Mixtures

Mixture	OBC (%)			Average	STDEV.	COV (%)
CIR-E30H	3.20	2.40	2.50	2.70	0.44	16.14
CIR-E70H	2.93	2.93	2.78	2.88	0.09	3.01
CIR-F30H	2.70	2.55	2.60	2.62	0.08	2.92
CIR-F70H	2.00	2.80	2.95	2.58	0.51	19.77
CIR-E30C	2.80	2.95	2.70	2.82	0.13	4.47
CIR-E70C	3.20	2.60	3.15	2.98	0.33	11.16
CIR-F30C	2.95	2.75	3.00	2.90	0.13	4.56
CIR-F70C	3.20	3.28	3.20	3.23	0.04	1.34

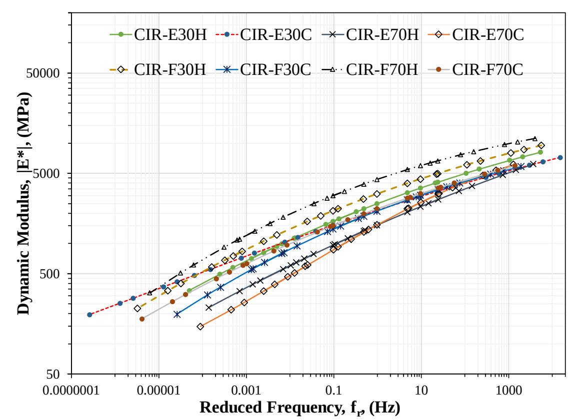
Overall, the results of the balanced mix design developed for CIR mixtures presented similar results of optimum binder contents than those found in literature. However, foamed asphalt CIR mixtures optimum binder contents, ranging between 2.8 and 3.2%, were relatively higher than those typically found when using CIR mix design methods focusing just on cracking performance. This can be related to RAP millings properties (RAP binder content, binder PG grade, and gradation), presence of virgin aggregates, types and dosages of additives present in CIR mixture. For instance, a study conducted by Berthelot et al (2013) reported optimum binder contents of 2%, however, Portland cement was used in 2% of total mix weight.

Performance Comparisons among All CIR Mixtures

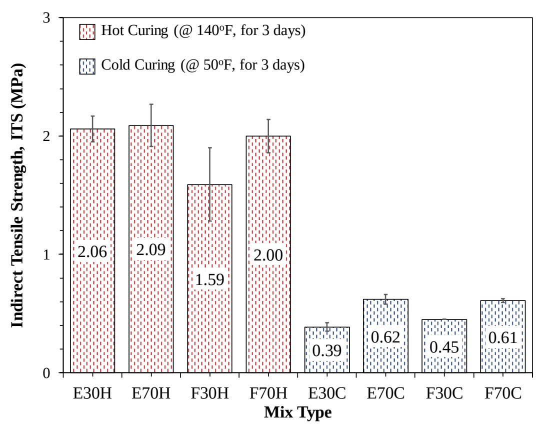
To better understand the impact of recycling agent type, compaction level, and curing process on the CIR laboratory performance, Figures 27 (a) and (b) present the overall results of rutting measures (APA rut depth and |E*| at 54^{o}C and 10 Hz) and cracking measures (ITS and SCB-FE at 0^{o}C) determined at optimum binder contents of CIR mixtures. As can be seen from the figures, the rutting and cracking performance varied for the different mixtures. For instance, the range of APA rut depth values were between 1.89 mm (CIR-F70H) and 5.08 mm (CIR-F30C), which indicates a satisfactory performance of CIR mixtures in terms of rutting (APA rut depth threshold is 5 mm). In addition, all CIR mixtures subjected to hot curing presented relatively lower APA rut depth values than those subjected to cold curing. In the other hand, all CIR mixtures presented similar moduli at high temperature (54^{o}C) and low frequency (10Hz). The sigmoidal master curves developed for the eight CIR mixtures at optimum binder contents showed that, recycling agent type, compaction level, and curing process had no to little impact on CIR rutting performance. In fact, all CIR mixtures subjected to hot curing presented slightly higher |E*|values than those subjected to cold curing.



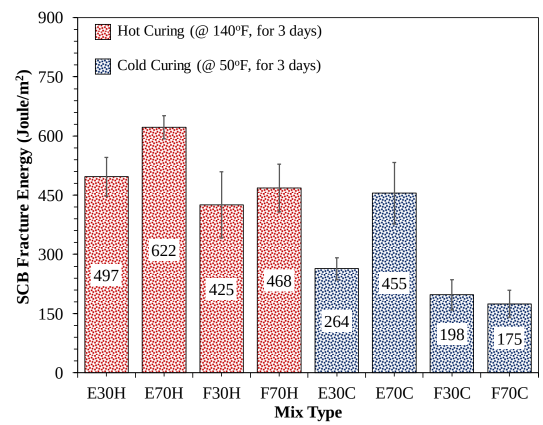
(a) APA results



(b) Dynamic Complex Modulus results



(c) ITS results



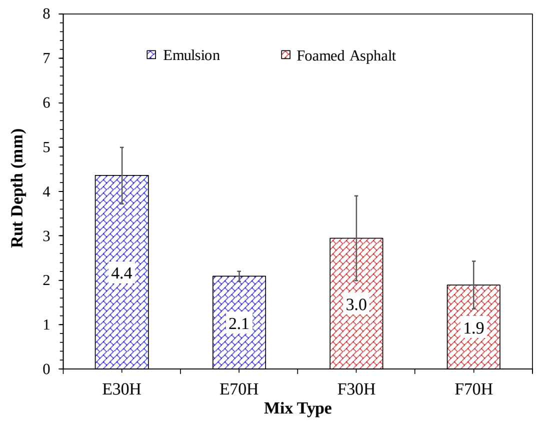
(d) SCB-FE results

Figure 28. General Comparison of CIR mixtures

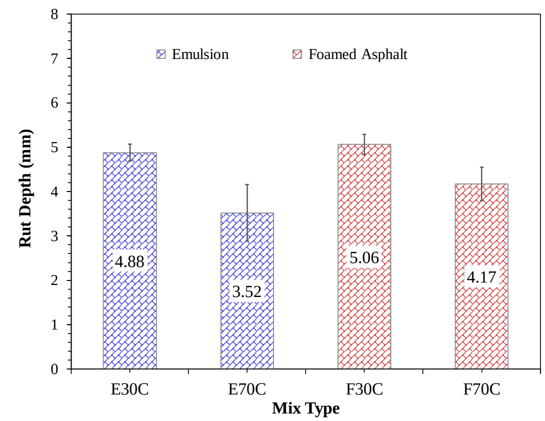
In terms of cracking, the tensile strength values (at 0°C) of CIR mixtures ranged between 0.39 MPa (CIR-E30C) and 2.09 MPa (CIR-E70H), while SCB fracture energy values (at 0°C) ranged between 174.8 and 622.3 $J.m^{-2}$. Figure 27 (c) shows that CIR mixtures subjected to hot curing exhibited significantly higher tensile strength and SCB fracture energy than those with cold curing. In summary, CIR mixtures prepared with different types and levels of recycling agent types, gyration levels, and curing processes did not have similar performances in terms of rutting and cracking. Thus, there is a need to evaluate the impact of each factor (binding agent, compaction level, and curing process) on CIR rutting susceptibility and cracking resistance.

Impact of binding agent on CIR performance (rutting and cracking). Figure 28 and 29 presents the rutting and cracking performance measures determined at optimum binder content of emulsified and foamed asphalt CIR mixtures. In terms of rutting, both emulsion and foamed CIR mixtures presented similar APA rut depth values (within 1 mm) given the same gyration level and curing temperature, as shown in Figures 28 (a) and (b). In addition, the results of complex dynamic modulus performed at high temperature (i.e., 54°C) and loading frequency of 10 Hz, as illustrated in Figures 28 (c) and (d), shows that emulsion and foamed asphalt presented similar rutting performances when these mixtures are subjected to hot curing (at 140°F for three days), as illustrated in Figure 28 (c). However, when allowed to cure at 50°F for three days, CIR mixtures prepared with foamed asphalt exhibited higher |E*| values than those prepared with emulsified, highlighting a better rutting resistance of foamed asphalt CIR mixtures at low temperatures of curing. Overall, emulsified and foamed asphalt presented similar effect on CIR rutting performance given the same gyration level and at high temperature of curing (i.e. 140°F), while CIR mixtures, subjected to cold curing, presented lower rutting susceptibility when prepared with foamed asphalt.

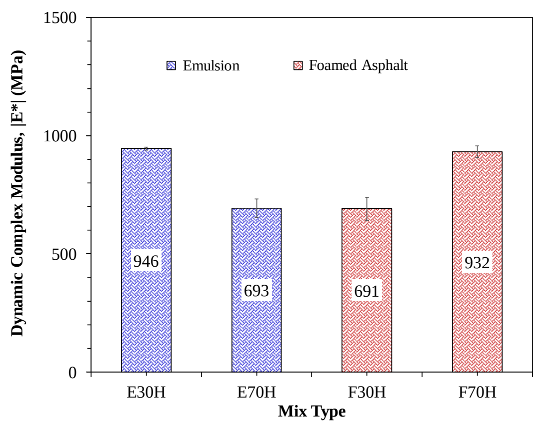
With regards to cracking performance, Figure 29 presents the results of ITS and SCB-FE of CIR mixtures. In fact, both emulsified and foamed asphalt CIR mixtures presented similar tensile strength results, when compacted with same gyration level and subjected to the same curing process. However, emulsified CIR mixtures presented higher SCB-FE values, by over 20%, than those prepared with foamed asphalt, when compacted at same gyration level and subjected at hot curing. However, at low curing temperatures (i.e. 50°F), emulsified CIR mixtures present significantly higher cracking resistance, by over 100%, than that of foamed asphalt CIR mixtures (Figure 29 (d)). In summary, CIR mixtures prepared with emulsified or foamed asphalt exhibited similar rutting performance, while emulsified asphalt CIR mixtures presented better cracking performance, given the same gyration level and curing temperature. In addition, SCB-FE measure highlighted efficiently the impact of recycling agent type on CIR cracking performance.



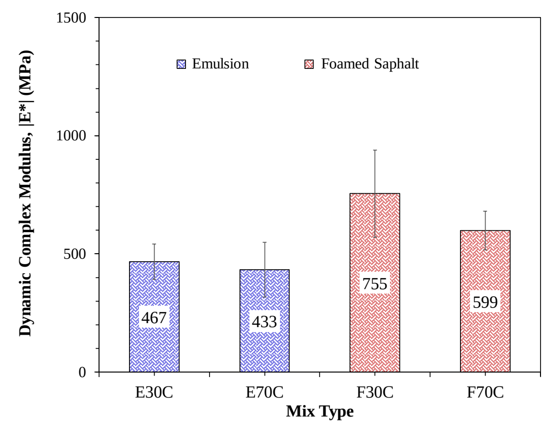
(a) APA rut depth measure at hot curing



(b) APA rut depth measure at cold curing

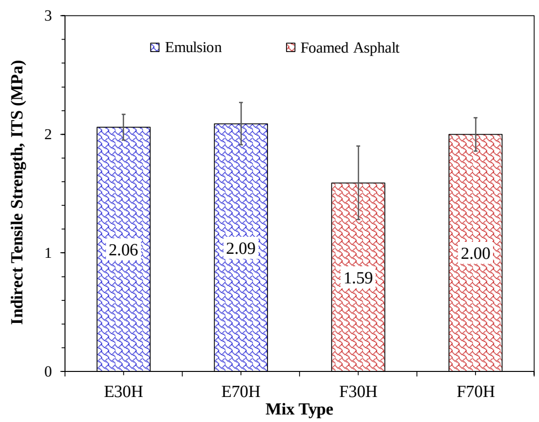


(c) |E*| measure at hot curing

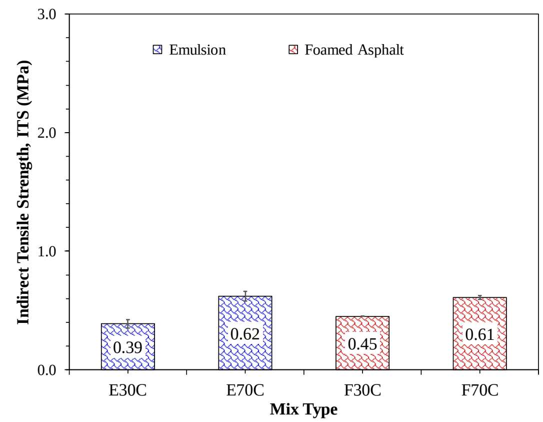


(d) |E*| measure at cold curing

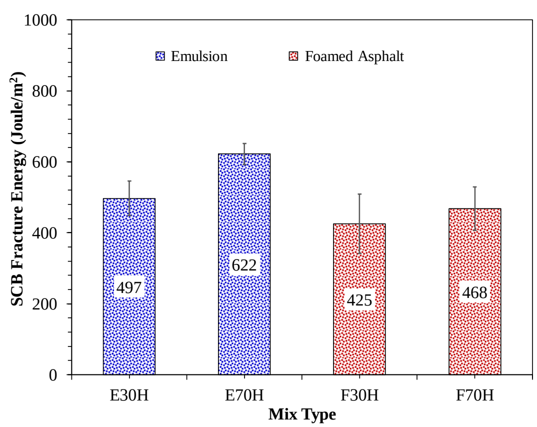
Figure 29. Effect of Recycling Agent Type on CIR Rutting Performance



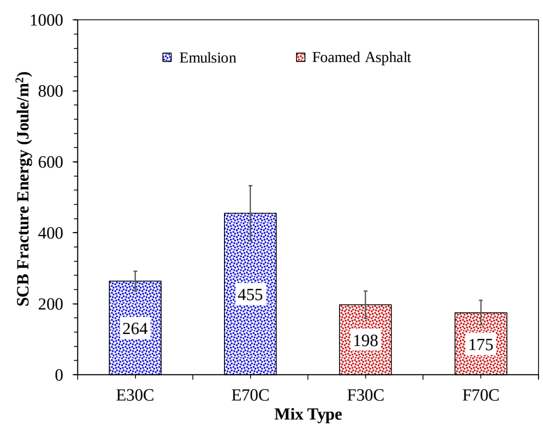
(a) ITS measure at hot curing



(b) ITS measure at cold curing



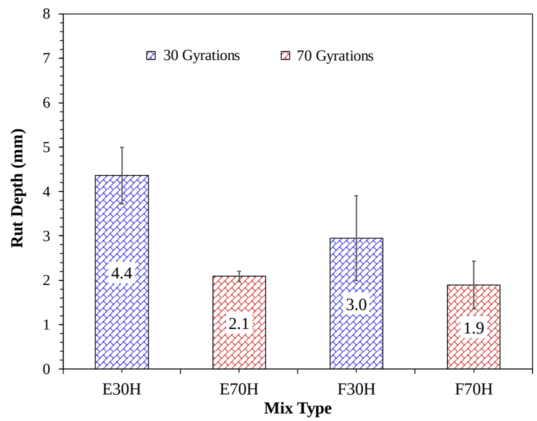
(c) SCB-FE measure at hot curing



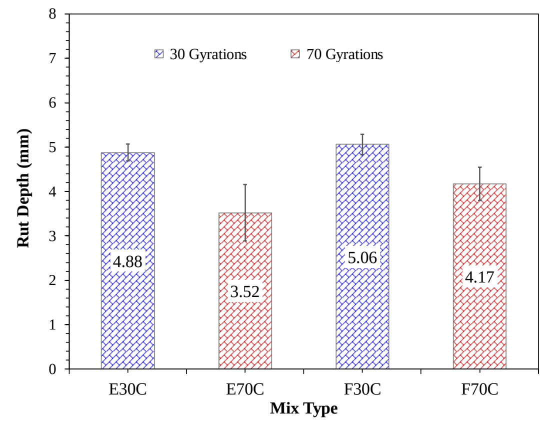
(d) SCB-FE measure at cold curing

Figure 30. Effect of Recycling Agent Type on CIR Cracking Performance

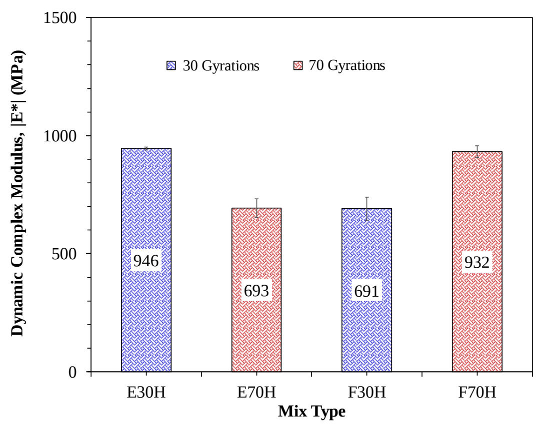
Impact of compaction level on CIR performance (rutting and cracking). Figures 30 and 31 illustrates the impact of compaction level on CIR rutting and cracking performance, given the same binder type and curing process. With regards to rutting, both emulsified and foamed asphalt CIR mixtures compacted with 30 gyrations presented higher APA rut depth values than those compacted with 70 gyrations, as shown in Figures 30 (a) and (b). Therefore, higher compaction level (i.e. 70 gyrations) of CIR mixtures can increase CIR rutting resistance by giving more stiffness to these mixtures and by reducing their air void levels. In the other hand, Figures 30 (c) and (d) presents the the results of dynamic modulus (|E*|) performed at 54ºC and a loading frequency of 10 Hz. As can be seen in the figures, both gyration levels (30 and 70) presented similar impact on the rutting performance of CIR mixtures subjected to the same curing process. Thus, only APA rut depth measure was efficiently able to seize the impact of gyration level on CIR rutting performance. In terms of cracking, both emulsified and foamed asphalt CIR mixtures compacted with 70 gyrations presented slightly higher ITS values than those compacted with 30 gyrations, as shown in Figures 31 (a) and (b). This indicates that ITS measure was not capable of capturing the impact of compaction level on CIR cracking resistance. Figures 31 (c) and (d) illustrates the SCB-FE results of CIR mixtures compacted with different gyration levels. In fact, both emulsified and foamed asphalt compacted with 70 gyrations exhibited significantly higher fracture energy than CIR mixtures compacted with 30 gyrations, giving the same curing process.



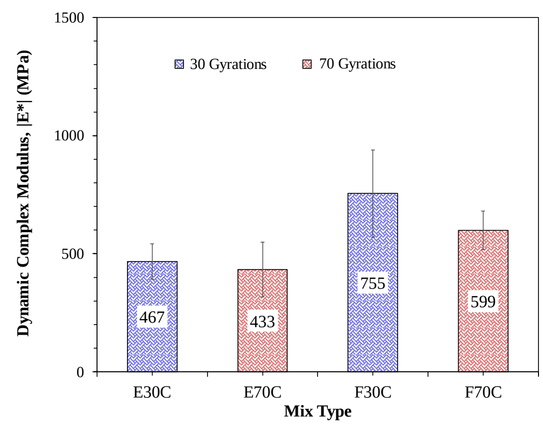
(a) APA rut depth measure at hot curing



(b) APA rut depth measure at cold curing

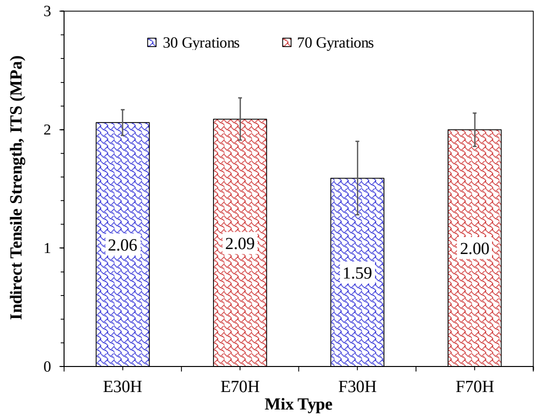


(c) |E*| measure at hot curing

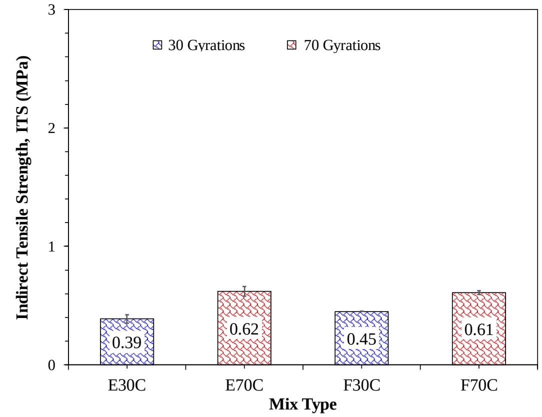


(d) |E*| measure at cold curing

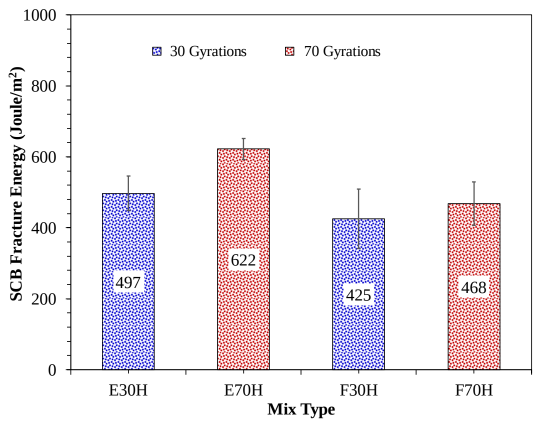
Figure 31. Effect of Compaction level on CIR Rutting Performance



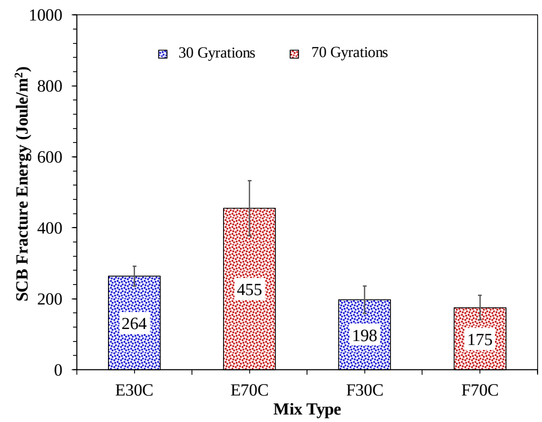
(a) ITS measure at hot curing



(b) ITS measure at cold curing



(c) SCB-FE measure at hot curing



(d) SCB-FE measure at cold curing

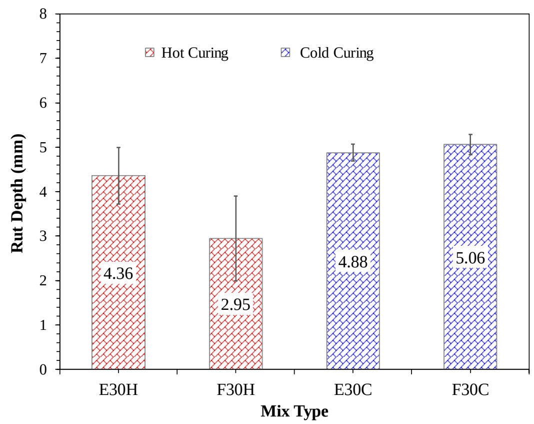
Figure 32. Effect of Compaction level on CIR Cracking Performance

Therefore, an increase in compaction level of CIR mixtures can considerably improve the resistance of CIR mixtures to cracking. In addition, SCB-FE energy was capable of capturing the impact of compaction level on CIR cracking performance.

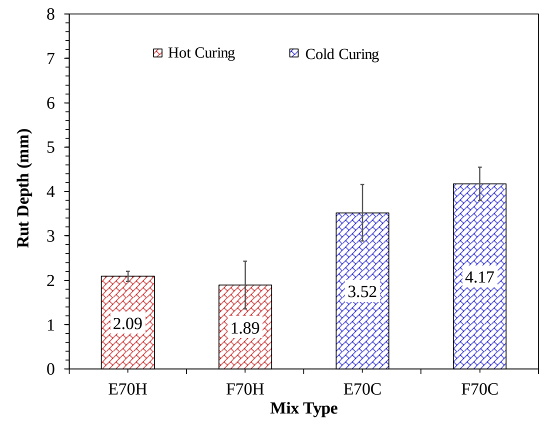
Impact of curing process on CIR performance (rutting and cracking). Figures 32 and 33 below present the impact of curing process on the rutting and cracking performance of CIR mixtures prepared with the same binding agent (emulsion or foamed asphalt) and compacted with same gyration level (30 or 70). As can be seen from Figure 32 (a), CIR mixtures subjected to hot curing (at 140^{o}F for three days) exhibited slightly better rut depth values than CIR mixtures subjected to cold curing (at 50^{o}F for three days).

When the gyration level increases from 30 to 70 (Figure 32 (b), the impact of curing process significantly increase. In fact, APA rut depth results of emulsified and foamed asphalt CIR mixtures subjected to hot curing exhibited almost 80% lower rut depth values than CIR mixtures cured at 50^{o}F for three days. Therefore, higher curing temperature, associated with higher gyration level, improves the rutting resistance of CIR mixtures. In the other hand, the effect of curing process on CIR dynamic modulus was also evaluated. Figures 32 (c) and (d) present the effect of curing process on |E*| of CIR mixtures compacted at 30 gyrations and 70 gyrations, respectively. As can be seen from Figure 32(c), both emulsified and foamed asphalt CIR mixtures exhibited relatively similar |E*| values at both curing conditions. However, when compacted at 70 gyrations, CIR mixtures subjected to hot curing presented significantly higher |E*| than those mixtures subjected to cold curing. Based on these observations, the curing process had a significant impact on CIR rutting performance, when generally compacted with higher level of gyrations.

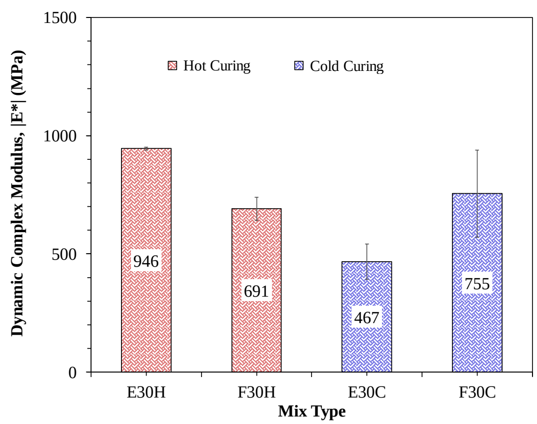
With regards to CIR cracking performance, the effect of curing process on CIR cracking measures (ITS and SCB-FE) was also evaluated, as presented in Figure 33. Given the same binding agent and compaction level, the ITS values of CIR mixtures subjected to hot curing were significantly higher (by above 300%) than the ITS values of CIR mixtures subjected to cold curing (Figure 33 (c)). Similarly, emulsified and foamed asphalt CIR subjected to hot curing exhibited significantly higher fracture energy than that of CIR mixtures subjected to cold curing. These results indicate that the curing process of CIR mixtures present a significant impact on CIR cracking measures (ITS and SCB-FE). Therefore, both CIR cracking measures were successfully capable of capturing the impact of curing process on CIR cracking resistance. In fact, the reason behind the significant increase in cracking measures' values when increasing the curing temperature (from 50 to 140^{o}F), is that CIR mixtures have sufficiently cured and hardened at higher temperature (less moisture content remaining), thus increasing the strength of these mixtures.



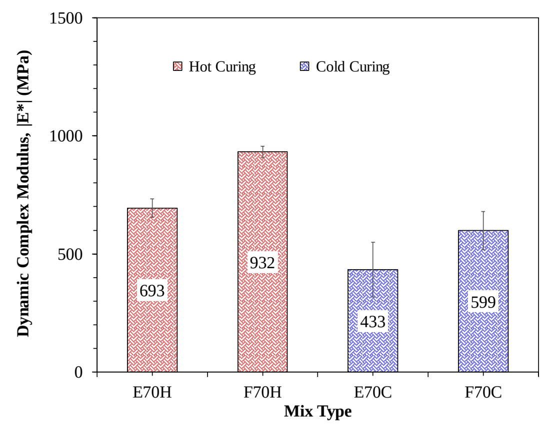
(a) APA rut depth measure at 30 gyrations



(b) APA rut depth measure at 70 gyrations

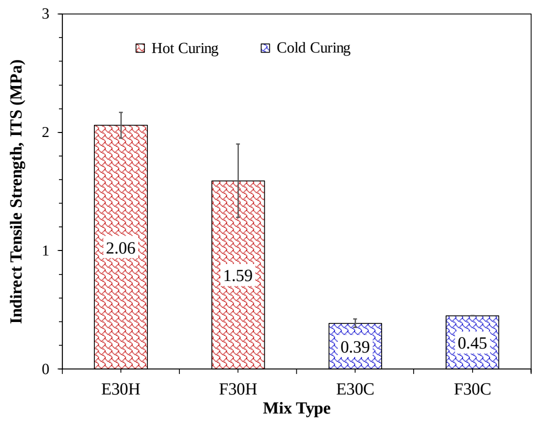


(c) |E*| measure at 30 gyrations

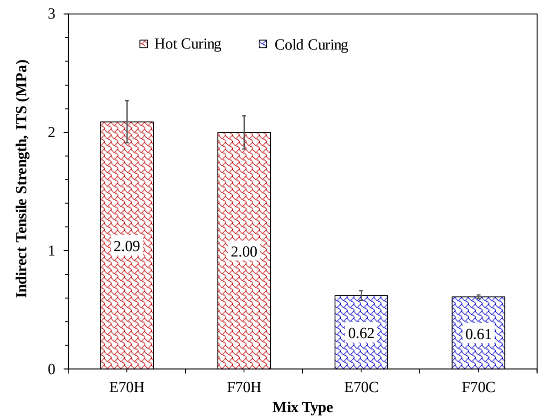


(d) |E*| measure at 70 gyrations

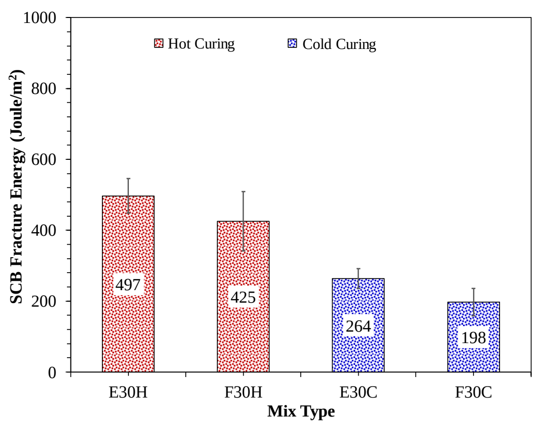
Figure 33. Effect of Curing Process on CIR Rutting Performance



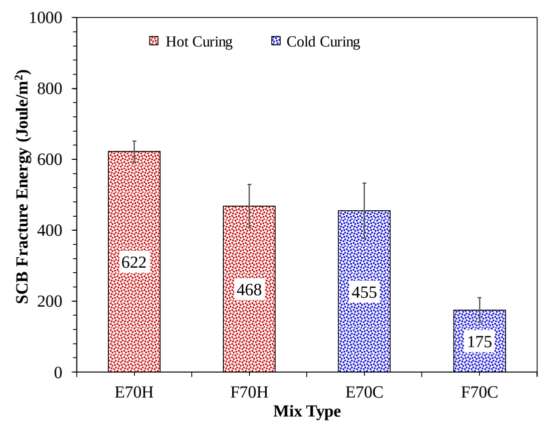
(a) ITS measure at 30 gyrations



(b) ITS measure at 70 gyrations



(c) SCB-FE measure at 30 gyrations



(d) SCB-FE measure at 70 gyrations

Figure 34. Effect of Curing Process on CIR Cracking Performance

Statistical Analyses

Analysis of variance (ANOVA) were conducted on rutting and cracking measures results of emulsified and foamed asphalt CIR mixtures to statistically evaluate the effect of binding agent type, compaction level, and curing process on CIR performance. The interaction between these three factors (binder type, compaction level, and curing process) was also assessed to investigate if these interactions would have a significant impact on rutting and cracking performance of CIR mixtures. The results of univariate ANOVA for each performance measures are discussed in the following subsections.

Effect on APA rut depth measure. ANOVA analysis was conducted on three replicates of each balanced CIR mixture to statistically evaluate the effect of the binding agent, gyration level, and curing temperature on the CIR rut depth. As can be seen from Table 12, the results of univariate ANOVA performed on APA rut depth data showed that "binder type" presented p-value > $\alpha = 0.05$, indicating that the recycling agent type (emulsion or foamed asphalt) did not have significant impact on CIR rutting susceptibility. Similarly, the curing process also had a minor impact on CIR rutting performance, presenting a p-value of 0.29. However, the compaction level of CIR mixtures presented a significant impact on APA rut depth values (p-value = 0.017). Therefore, compacting CIR mixtures with different gyration level would have an impact on CIR rutting performance. This observation validates, in fact, the findings presented in this chapter, that there is a strong dependence of the relationship between APA rut depth and CIR compaction level. In addition, the results of univariate ANOVA analysis showed that none of the interactions between the factors had significant effect on APA rut depth.

Table 12

ANOVA analysis on APA Rut Depth Measure

Source	F	p-value	Significant(Yes/No)
Binder (Bind)	.449	.509	No
Gyration (Gyr)	6.563	.017	Yes
Curing (Cur)	1.177	.289	No
Bind * Gyr	.814	.376	No
Bind * Cur	.002	.969	No
Gyr * Cur	.131	.721	No
Bind * Gyr * Cur	.250	.622	No

Effect on Dynamic Complex Modulus measure. ANOVA analysis was also performed sample obtained at high temperatures (37°C and 54°C) and loading frequency of 10 Hz, as presented in Table 13. The result of univariate ANOVA showed that both binding agent type (emulsion and foamed asphalt) and compaction level (30 and 70 gyrations) had minor effect, at both temperatures of 37°C and 54°C, on CIR rutting performance. However, the curing temperature factor presented a significant effect on the rutting susceptibility of CIR mixtures, presenting p-values of 0.012 and 0.033 at 37°C and 54°C, respectively. In addition, ANOVA results showed that all the interactions between recycling agent type, compaction level, and curing process, did not have any significant impact on CIR rutting performance except for one interaction, between CIR binder type and the curing process, at testing temperature of 37°C, presenting a p-value of 0.027.

Table 13

ANOVA analysis on |E| Measure*

Source	Temp	F	p-value	Significant (Yes/No)
Binder (Bind)	54C	.90	.371	No
	37C	5.19	.052	No
Gyration (Gyr)	54C	.6	.813	No
	37C	.00	.998	No
Curing (Cur)	54C	6.58	.033	Yes
	37C	10.46	.012	Yes
Bind * Gyr	54C	.33	.577	No
	37C	.59	.465	No
Bind * Cur	54C	.49	.501	No
	37C	7.26	.027	Yes
Gyr * Cur	54C	.69	.428	No
	37C	.292	.604	No
Bind * Gyr * Cur	54C	1.437	.265	No
	37C	2.99	.122	No

Effect on Indirect Tensile Strength Measure. Table 14 presents the results of ANOVA analysis conducted on ITS measure data of CIR mixtures. As can be seen from the table below, only the gyration level and the curing process had significant effect on CIR tensile strength (i.e., p-values of 0.002 for gyration level; and 0.0001 for curing temperature). The interaction between the different factors was also investigated. The results of p-values showed that none of the interactions presented significant effect on CIR cracking resistance. In summary, the binder type (emulsion or foamed asphalt) had no impact on the strength of CIR mixtures while gyration level and curing temperature had significant effect on the cracking performance of CIR mixtures. An increase or the gyration level or in the curing temperature would yield significant increase in CIR strength, as discussed in this chapter.

Table 14

ANOVA analysis on ITS Measure

Source	F	p-value	Significant?
Binder (Bind)	.037	.849	No
Gyration (Gyr)	11.660	.002	Yes
Curing (Cur)	220.54	.000	Yes
Bind * Gyr	.001	.981	No
Bind * Cur	.596	.448	No
Gyr * Cur	1.958	.175	No
Bind * Gyr * Cur	.082	.777	No

Effect on Semi-Circular Bend fracture energy measure. Table 15 presents the results of ANOVA analysis conducted on SCB-FE measure data of emulsified and foamed asphalt CIR mixtures. As can be seen from the table below, the results of ANOVA showed that all the factors, recycling agent type, compaction level, curing process, had a significant effect on SCB-FE of CIR mixtures presenting p-values of 0.011, 0.027, and 0.0001, respectively. However, ANOVA analyses showed that the interactions between these factors had no significant effect on CIR cracking performance. In fact, these observations are supported with the findings presented in this chapter: emulsion CIR mixtures presented higher cracking resistance than CIR mixtures prepared with foamed asphalt. An increase in the gyration level or the curing temperature resulted in an increase in SCB fracture energy of CIR mixtures.

Table 15

ANOVA analysis on SCB-FE Measure

Source	F	p-value	Significant?
Binder (Bind)	7.620	.011	Yes
Gyration (Gyr)	5.561	.027	Yes
Curing (Cur)	25.942	.000	Yes
Bind * Gyr	1.284	.268	No
Bind * Cur	2.094	.161	No
Gyr * Cur	.001	.974	No
Bind * Gyr * Cur	.775	.387	No

Chapter 6

Summary of Findings, Conclusions & Future Work

Summary of Findings and Conclusions

This study presented a method for designing emulsified and foamed asphalt CIR mixtures, through balancing between cracking and rutting performance of these mixtures. In order to evaluate the feasibility and practicality of the balanced mix design method, eight CIR mixtures were produced in the lab using a combination of two recycling agents (foamed asphalt and emulsion), two compaction levels (30 and 70), and two curing processes temperatures (50° F and 140°F). All the CIR mixtures were prepared constant dosages of Portland cement and water, 1% and 3%, respectively. Air void levels were then determined for each mixture using CoreLok device to ensure that these mixtures presented similar air voids to those typically found in CIR layer in the field. APA rut depth and |E*| measures were determined to evaluate the rutting susceptibility of CIR mixtures while ITS and SCB-FE measures were determined to assess the cracking resistance of these mixtures. Regression analysis was then conducted on rutting and cracking performance measures to evaluate the ability of CIR binder contents in predicting the rutting and cracking performances of CIR mixes. All performance measures presenting strong correlations with CIR binder content were then used to select optimum binder content of the eight CIR mixes. The process of selecting optimum binder contents was demonstrated for all CIR mixes and presented as part of this study.

Rutting and cracking performances were evaluated for CIR balanced mix design (BMD) mixtures in order to assess the impact of the factors on CIR performance measures (i.e. APA rut depth, ITS, and SCB-FE) at optimum binder contents.

Summary of Findings. The summary of the findings from this study were:

- The volumetric analysis conducted using CoreLok showed that increasing the binder content of foamed and emulsified asphalt CIR mixtures resulted in a decrease in air void level by up to 4%, for every increase of 1% of binder.
- The air void level of emulsified asphalt CIR mixtures was 2% higher than that of foamed asphalt, given the same binder content.
- When the same binding agent was used, CIR mixtures compacted with 30 gyrations presented higher air void, by up to 4% at the same binder content, than CIR mixtures compacted with 70 gyrations.
- The air void level of CIR mixtures subjected to hot curing (three days at 140°F) presented lower air void, by up to 3% at the same binder content, than CIR mixtures subjected to cold curing (three days at 50°F).
- Regression Analysis conducted on CIR cracking measures (ITS and SCB) and rutting measures (APA rut depth and $|E^*|$) showed a strong correlation between both cracking measure (ITS vs Binder content: R^2 = 92%; SCB-FE vs binder content: R^2 = 80%), only one rutting measure (APA rut depth vs Binder content: R^2 = 99%) and CIR binder content. A weak correlation was found between dynamic modulus rutting measure and CIR binder content (constant tend; R2 = 26.46% and R2 = 29.52%).

- Using the BMD design approach, a balanced optimum binder content was determined for each of the eight CIR mixtures. The balanced optimum binder content of both foamed and emulsified CIR mixtures ranged between 2.6 and 3.2%.
- CIR performance measures were determined at optimum binder contents. The results showed that the range of APA rut depth values were between 1.89 mm (CIR-F70H) and 5.08 mm (CIR-F30C), while all CIR mixtures presented similar $|E^*|$ values at high and low temperatures. In terms of cracking performance, the tensile strength values (at 0^oC) of CIR mixtures ranged between 0.39 MPa (CIR-E30C) and 2.09 MPa (CIR-E70H), while SCB fracture energy values (at 0^oC) ranged between 174.8 and 622.3 $J.m^{-2}$.
- ANOVA analysis conducted on CIR performance measures at optimum binder contents showed that the recycling agent type had significant impact only on SC-FE (p-value = 0.011). Compaction level had impact on APA rut depth, ITS, and SCB-FE, presenting p-values of 0.17, 0.02, and 0.027, respectively. Curing process presented a significant impact $|E^*|$ at 37 and 54^oC, ITS, and SCB-FE, presenting p-values of 0.012, 0.033, 0.000, and 0.000, respectively. It is also important to mention that only the interaction between the recycling agent type and curing process had significant impact on $|E^*|$ at 37^oC (p-value = 0.027).

Conclusions. Based on performance testing results and the ANOVA analyses conducted on all rutting and cracking data of CIR mixtures, the following conclusions were drawn:

- The balanced mix design approach was used successfully in designing eight CIR mixtures. This was evidenced with performance testing results that highlighted the importance of rutting measures, which generally was not considered in previous mix design methods for CIR mixtures, as well as its dependence on the binder content of emulsified and foamed asphalt binder content. Therefore, the developed balanced mix design method ensures a better design of CIR mixtures.
- Three of the four rutting and cracking measures (i.e., APA rut depth, ITS, and SCB-FE) presented a strong dependence on CIR binder contents. Regression analysis conducted on CIR performance measures showed that there is a strong correlations between these measures (i.e., APA rut depth, ITS, and SCB-FE) and CIR binder content; therefore, indicating that these measures can be used successfully for developing a balanced mix design method for CIR mixtures.
- The dynamic complex modulus, |E*|, conducted at high temperature (i.e., 54°C) and a loading frequency of 10Hz was relatively constant for all CIR mixtures. This rutting measure was, in fact, unable to capture the change in CIR binder content; thus, |E*| measure was not considered when the balanced mix design for CIR mixtures.
- Three cases for determining ranges of balanced optimum binder contents for CIR mixtures were observed. These cases were dependent on the type of trends obtained using the three performance measures (i.e. APA rut depth, ITS, and

SCB-FE) and CIR binder content. The BMD results also indicated that these cases can be dependent on the type of CIR binding agent, compaction level, and curing process used in designing CIR mixtures.

- The recycling agent type (emulsion or foamed asphalt) showed a minor effect on rutting performance of CIR mixtures. This can be explained by the fact that, when compacted using the same compaction level, both foamed and emulsified CIR mixtures have similar ability to resist rutting. However, the SCB results at optimum binder contents showed that emulsion CIR mixtures presented higher fracture energy values than those of foamed asphalt CIR mixtures; indicating that emulsion CIR mixtures are better at resisting cracking than those prepared using foamed asphalt as the recycling agent.
- The compaction level of both foamed and emulsified asphalt CIR mixtures showed a significant impact on both rutting and cracking performance of these mixtures. APA rut depth results at optimum binder contents showed that CIR mixtures compacted at 70 gyrations had lower rutting susceptibly and higher cracking resistance than those of CIR mixtures compacted at 30 gyrations.
- The curing process also had a significant impact on rutting and cracking performance of both foamed and emulsified asphalt CIR mixtures. Performance tests' results showed that CIR mixtures submitted to hot curing (i.e. 140°F for three days) had relatively lower rutting susceptibly (i.e., lower APA rut depths and higher |E*|) and higher cracking resistance (i.e., higher ITS and SCB-FE) than those submitted to cold curing (i.e. 50°F for three days).

- The outcomes of this study showed that the BMD developed for CIR mixtures can be implemented for both hot and cold regions. However, more studies should be conducted to investigate ways to improve rutting and cracking performance of CIR mixtures in cold regions.

Future Work. This study focused on developing a mix design for cold in-place recycling mixtures prepared with emulsions or foamed asphalt, compacted at different gyration levels, and subjected to cure at high and low temperatures. The laboratory performance of these mixtures was evaluated in terms of rutting and cracking to select optimum binder contents using the BMD approach. The rutting and cracking performance results of the balanced CIR mixtures were considered satisfactory. Therefore, there is a need to validate the laboratory results in the field by conducting full-scale accelerated testing on pavement sections constructed using the CIR mix design developed as part of this study. This will be executed as follows:

- Investigate the impact of different curing ages on the performance of CIR mixtures (e.g., 10, 20, and 30 days), mainly those subjected to cold curing. Extending the curing process will likely improve the strength of CIR mixtures by ensuring a complete reaction of the elements existing in Portland cement, thus, achieving a maximum strength of CIR mixtures.

- Compare mix design methods typically used for CIR technique by certain agencies (i.e., Pennsylvania mix design, Military mix design, and Modified Marshal mix design) to the CIR mix design developed as part of this study following the BMD design approach.

- Prepare three CIR pavement sections using the laboratory results: (1) rutting resistant section, (2) cracking resistant section and (3) and balanced mix design section. All the section will be constructed at Rowan University Accelerated Pavement Testing Facility (RUAPTF) because the millings used to prepare CIR mixtures in the lab were obtained from this pavement. If the RAP used in APT and RAP used in preparing CIR mixtures in the lab do not have a similar source, the results cannot be comparable. RAP millings with different sources may present different properties: aggregate type, gradation, binder content, binder PG grade and presence of additives. In this project, samples will be taken from each CIR full-scale section to be tested in the lab. Each sample will be tested for air void level, binder content by performing extraction and recovery and mineral matter, APA rut depth, and ITS. This will make it possible to compare full-scale testing results to laboratory testing results.

- Apply Heavy Vehicle simulator on each CIR pavement section at different loading frequencies (truck tire, aircraft tire). As loading progresses, the condition of each CIR pavement section will be characterized through several tests and visual inspections.

- Instrument each CIR section with asphalt gauges, thermocouples, and pressure cells to evaluate stress and strain responses of CIR pavement section to determine threshold values for rutting and cracking performance measures. Air temperature will be controlled to ensure testing each section at low temperature (e.g., 32^{o}F (0^{o}C)), so as to simulate cold regions.

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