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LABORATORY ASSESSEMENT OF EMULSION-CEMENT PASTE AND COLD RECYCLED MIXTURES AT VARYING AMOUNTS OF EMULSION, CEMENT, AND WATER

Ahmed Saidi
Rowan University

LABORATORY ASSESSEMENT OF EMULSION-CEMENT PASTE AND COLD RECYCLED MIXTURES AT VARYING AMOUNTS OF EMULSION, CEMENT, AND WATER

by

Ahmed Saidi

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Dissertation Chair: Yusuf Mehta, Ph.D., P.E., Department of Civil and Environmental Engineering

Committee Members
Douglas Cleary, Ph.D., P.E., Civil and Environmental Engineering Department
Cheng Zhu, Ph.D., P.E., Civil and Environmental Engineering Department
Gilson Lomboy, Ph.D., P.E., Civil and Environmental Engineering Department
Umashanger Thayasivam, Ph.D., Mathematics Department

Dedications

I would like to dedicate this work to my parents who are my true role models for their sacrifices and their continuous support. To my sisters, my brother, my grandma, my aunt, and my friends for their support in all my academic endeavors.

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Abstract

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Yusuf Mehta, Ph.D., P.E.
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The main objective of this study was to assess the performance of cold recycled mixtures (CRMs) at: (1) binder level through evaluating the rheological and mechanical properties of emulsion-cement paste (ECP), and (2) mix level through characterizing the density and performance of CRMs. The testing program for ECPs included multiple stress creep recovery (MSCR), bending beam rheometer (BBR), linear amplitude sweep (LAS), penetration test, and isothermal calorimetry. For CRMs, a balanced mix design (BMD) approach was used to develop performance interaction charts to select optimum contents of emulsion, cement, and water maximizing the resistance of CRMs to rutting and cracking. Statistical and regression analyses were then conducted to assess the significance of the impact of ECP and CRM constituents on their performance and to evaluate the correlations between ECP and CRM testing parameters. Results showed that higher emulsion and cement contents led to lower air void level of CRMs. Further, greater cement contents improved rutting performance, but decreased the cracking resistance for both ECPs and CRMs. Performance interaction charts were also developed to select optimum contents of emulsion, cement, and water. Finally, the non-recoverable creep compliance and penetration at 40^{o}C of ECPs correlated well with CRM rutting performance, while low- and intermediate-temperature cracking measures of ECPs presented weaker correlation with CRM cracking resistance.

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Chapter 1

Introduction

Background

Cold recycled mixtures (CRM) technology is a sustainable method for constructing asphalt pavements using one of two techniques: cold in-place recycling (CIR) and cold in-plant recycling (CPR). CIR is an asphalt rehabilitation method that salvages the existing pavement and reuses the material for a stabilized base layer. Rehabilitating deteriorated pavements using CIR has a number of construction, environmental, and economic benefits (Pakes et al. 2018, Giani et al. 2015, Turl et al 2016, Sanger et al. 2017). While, in CPR, pavement millings are hauled to a mobile plant where they are processed, mixed with bituminous and cementitious additives, and water. The produced mixture is then brought to the jobsite to be paved back and compacted as a base layer.

CRM technologies improve construction conditions through minimizing traffic disruptions, shortening lane closures, and maintaining height clearances. CRM also conserves non-renewable resources (i.e., aggregates and asphalt binders) and reduces greenhouse gas emissions, fuel consumption, and number of haul trucks. These environmental benefits also result in reducing construction costs for contractors (Lewis and Collings, 1999; Forsberg et al., 2001; Fiser and Varaus, 2004; Mondares et al., 2014, Kim et al., 2009; Chen et al., 2010).

Several researchers recommended the use of CRM to treat asphalt pavements subjected to different traffic levels and various weather conditions (Kavussi and

Modarres 2010, Kim and Lee 2011, Kim and Lee 2012, Apeagyei and Diefenderfer 2013, Cox and Howard 2013, Saidi et al 2019a). Traditionally, state agencies developed unique mix designs for CRM to ensure sufficient performance. Recently, CRM mix design procedures have included performance testing protocols such as indirect tensile strength (IDT), semi-circular bend (SCB), and asphalt pavement analyzer (APA) tests.

Problem Statement

Although the first phase of this project, cold in place recycling (CIR) Phase I conducted in 2017-2019 (Saidi et al. 2019a, Saidi et al. 2019, Saidi et al. 2021), addressed the lack in literature about mix designs and full-scale testing, this study focuses on addressing the following points that might further improve the cold recycling technology of asphalt pavements:

- When selecting CRM materials and their respective optimal contents, most mix designs considered the cracking resistance and/or the strength of these mixtures over their rutting performance. Only a few studies optimized CRM mixtures in terms of both cracking and rutting performances as part of a balanced mix design (BMD) approach.

- Most BMDs were used to optimize one CRM component. No studies considered optimizing more than two CRM constituents (e.g., cement and water).

- The interactions between CRM materials during and after curing were not often considered in the reviewed studies. In fact, the interaction between emulsion and cement was only investigated as part of the CRMs using performance testing and microstructural analyses, and not as part of the emulsion-cement paste (ECP) using binder-scale performance testing.

Therefore, there is a need to expand the BMD approach for designing CRM mixtures to optimize not only bituminous additives, but also cementitious additives and water. Alternately, a comprehensive investigation of the interactions between bituminous, cementitious additives, and water is needed to understand the mechanisms, at ECP level, leading to an improved performance of CRM mixtures.

Research Hypotheses

This study investigated the influence of emulsion, cement, and water on the properties of emulsion-cement paste (ECP) and the performance and density of cold recycled mixtures (CRMs). Three hypotheses were behind conducting this dissertation, and are as follow:

1- There is lack in literature regarding the effect of varying the amounts of bituminous and cementitious additives (e.g., emulsion and Portland cement) and water of on the rheological and mechanical performance of ECPs. The amounts of emulsion, cement, and water might have a strong impact on the performance of ECP as well as on CRMs rutting and cracking performance.
2- A BMD approach can be used successfully to select the optimal contents of emulsion, cement, and water using asphalt pavement analyzer (APA) as a rutting test and semi-circular bend (SCB) as a cracking test.
3- There is a strong correlation between the properties of ECPs and CRMs at similar contents of emulsion, cement, and water.

Significance of Study

This study was conducted to evaluate the impact of varying the amounts of emulsion, cement, and water on (i) the rheological and mechanical properties of ECPs, and the performance and density of CRMs. A similar methodology for producing and testing ECPs and CRMs was adopted (e.g., equivalent amounts of emulsion, cement, and water; curing process of three days at 60°C). A BMD approach was followed to optimize the performance of CRMs, which allowed developing performance interaction charts. The findings from phase I (laboratory assessment of ECP properties) and phase II (laboratory assessment of the performance and density of CRMs) were then compared and their correlation was assessed. Several benefits can be reaped from this study if (i) the BMD approach is successfully used, and (ii) a strong correlation is found between ECP properties and CRM performance. These benefits include:

- Extending the service life of asphalt pavements using CRM technology.
- Encouraging agencies and state department of transportations (DOTs) to further implement this economical and environmentally friendly technology.
- Updating specifications related cold recycling technology (e.g., cold in-place recycling and cold in-plant recycling) with more cost-effective and timesaving approaches.

Goal & Objectives

The main goal of this study was to optimize the performance of CRMs using a BMD approach. Another goal is to gain a better understanding of the interaction between bituminous and cementitious additives leading to the formation of ECPs and ensuring the strength of CRMs. To address these goals, this study presents the following specific objectives:

a. Assess the rheological and mechanical properties of ECPs formed during the mixing process of CRM mixtures, at different proportions of emulsion, cement, and water;

b. Evaluate the laboratory density and performance of CRMs at varying contents of emulsion, cement, and water;

c. Develop performance interaction charts for CRMs using a BMD approach; and,

d. Evaluate the correlation of the performance of ECPs to that of CRMs.

Research Layout

The research study consists of seven chapters that aim to meet the overall goal of this dissertation. The first chapter presents a brief introduction and highlights the problem statement and goals of the study. Chapter 2 provides a summary of a comprehensive literature review pertaining to CRM technologies, the design processes developed for these mixtures, testing protocols, and summarizes previous attempts to characterize ECPs. Chapter 3 describes the materials and their corresponding proportions selected to prepare ECPs and CRMs and discusses the experimental program adopted to assess the properties of ECPs and the performance of CRMs.

Chapter 4 presents the findings from the binder-scale testing of ECPs at varying amounts of emulsion, cement, and water. Following Chapter 4, Chapter 5 discusses the results of laboratory testing of CRM at varying contents of emulsion, cement, and water. This chapter also presents the findings from the BMD approach including the performance interaction charts developed for low and intermediate temperatures. A description of the statistical analyses (multivariate MANOVA and regression analyses) performed on ECP and CRM testing results is provided in Chapter 6. This chapter also discusses the correlation between the rheological and mechanical properties of ECPs and the rutting and cracking performance of CRMs. Chapter 7 concludes this research study with a summary of findings, conclusions, limitations, and recommendations for future implementation of CRM.

Chapter 2

Literature Review

Introduction

In this chapter, a literature review that pertains to cold recycled mixtures (CRM) is presented. The following subsections discuss various CRM mixtures design methods, the impact of CRM mix constituents and design parameters on the performance of these mixtures, and materials selection. This chapter also reviews previous attempts to characterize the binding matrix of CRMs.

CRM Performance-Based Mix Design Methods

General CRM Mix Design Method

Several mix design methods were developed for CRM mixtures with the goal of improving their long-term performance through optimizing one or more mix constituents (e.g., added water, cement dosage, binder type and dosage, etc.). Although researchers used different design parameters, materials, and performance testing, the systematic method for designing CRM mixtures is still similar. This general approach consists of the following steps:

1. <u>Procuring and characterizing RAP millings, bituminous binders, and additives</u>: RAP millings are collected through milling asphalt pavements using a standard milling machine that is typically used in cold in-place recycling. Most mix design methods tend to use 100% RAP millings when producing CRM mixtures, while a few methods tolerate the addition of virgin aggregates in small amounts as a filler

(e.g., 3% mineral filler [Deng et al., 2018]; 10% of virgin fine aggregate [Stimilli et al., 2013]; and 15% virgin fine aggregates [Yan et al., 2010]). RAP millings are typically characterized to determine their gradation, binder content, and maximum theoretical specific gravity. These properties are determined using: a) dry sieve analysis procedure (AASHTO T27), b) RAP binder extraction and recovery test (AASHTO T319), and c) maximum theoretical specific gravity (G_{mm}) test using the CoreLok method (ASTM D6857) or traditional method (AASHTO T 209).

2. <u>Selecting dosages of bituminous and chemical additives, and water</u>: The next step consists of selecting the grade and dosages of emulsified or foamed asphalt binder, content of cement or lime slurry added into the mix, and determining how much water to add when producing a CRM mix.

3. <u>Mixing materials and producing CRM mixtures</u>: Once all materials are procured and characterized, CRM mixtures are produced by mixing batches of dry RAP millings with selected additives and water using a bucket mixer for at least two minutes. The selected bituminous binder is then added and mixed for at least two more minutes until the binder fully coats the RAP millings.

4. <u>Compacting and curing of CRM mixtures</u>: CRM mixtures are then compacted using either a Superpave gyratory compactor (SGC), vibratory compactor, or a Marshall hammer to produce test specimens with different heights and densities for performance testing (Table 1). The compacted samples are cured at dry or wet conditions; by placing them in an oven at a given temperature for a given period of time (Table 1).

5. Testing Volumetric and Performance of CIR: For each dosage combination (bituminous and cementitious additives, and water), maximum theoretical specific gravity (G_{mm}) and bulk specific densities (G_{mb}) of compacted specimens are determined using CoreLok as in the study of Cox and Howard (2015) and Saidi et al., (2019a). Using both G_{mm} and G_{mb} data, the air void levels (AV) are determined for each CRM mixture type using the following equation.

$$AV = \frac{(G_{mm} - G_{mb}) \times 100}{G_{mm}} \quad (1)$$

Where:

G_{mm} = Maximum specific gravity of mix;

G_{mb}= Specific gravity of bitumen

Determining air void level of CRM mixtures in the laboratory is very important since it helps in estimating the density of CRM layers in the field. In general, lower air void levels are desired when designing CRM mixtures. AASHTO Task Force No.38 recommended an air void level between 9% and 14% (Lee et al. 2016). Lin et al. (2020) found that CRM specimens prepared with emulsified asphalt (added at 3.5% by total mix weight) and compacted with 30 gyrations presented air void level of 11% on average. Flores et al. (2015) reported that air void of emulsified CRM mixtures ranged between 11% and 16%. Saidi et al. 2019a investigated the impact of varying emulsion contents (from 1% to 5%, with 1% increments) on CRM air voids. The authors found that the air void level of CRM mixtures compacted using 30 gyrations decreased from 19% (at 1% emulsion) to 8% (at 5% emulsion). Saidi et al. 2019a also recommended, when designing

CRM mixtures, to verify that air voids are less than 20% to ensure satisfactory field performance.

Table 1

Examples of Compaction Efforts for CRM Mixes

Compaction Method	Description	References
Marshall	75 blows	Wirtgen, 2006 Fu et al., 2010
Vertical Vibratory	Shaped for 60 seconds	Jiang et al. 2019
Gyratory	25 gyrations	Buss et al., 2017 Kim et al., 2011
	30 gyrations	Kim and Lee, 2006
	300 gyrations	Martinez et al., 2007

Table 2

Examples Curing Procedures for CRM Mixes

Curing Temperature	Curing Time	References
40°C	2 days	Kansas DOT, New Mexico DOT
45°C	7 days	Kim et al., 2011
71°C	3 days	Wirtgen, 2006 Buss et al., 2017
25°C	7 days	Saleh, 2006
25°C	14 days	Kim et al., 2011
25°C	28 days	Bessa et al., 2016

After measuring the air void level of CRM mixtures, laboratory performance testing can be conducted on compacted CRM specimens to assess the resistance of these mixtures to pavement distresses such as rutting and cracking. In most mix designs, performance tests are selected based on their ability to capture variations in the amount or type of CRM materials (e.g., cement, emulsion, etc…), and mix design parameters (e.g., compaction effort, curing process, etc…). Table 2 summarizes the CRM performance tests recommended in previous studies. Selection of the optimum binder content is also discussed in detail in the following section.

Table 3

Performance Characterization Tests for CRM Mixtures

Test	Standard Specification	Test Measure	Performance	Studies
Asphalt Pavement Analyzer (APA)	AASHTO T 340	APA rut depth (in./mm)	Rutting susceptibility	- Wang et al. 2018 - Gu et al. 2019 - Saidi et al. 2019a
Marshall Stability (MS)	ASTM D6927	Marshal Stability (MS) (lbs/kN) Retained MS (RMS) (%)	Strength	- Ghavibazoo et al. 2017 - Kim and Lee 2006
Hamburg Loaded Wheel Tester (HLWT)	AASHTO T 324	Maximum rut depth (RDHWLT) (mm)	Rutting and Moisture susceptibility	- Babagoli et al. 2016 - Sebaaly et al. 2021
Semi-Circular Bend (SCB)	ASTM D8044	Fracture energy (Joule/m2) And Flexibility Index	Thermal and fatigue cracking	- Charmot et al. 2017 - Saidi et al. 2019a
Indirect Tensile Strength (IDT)	ASTM D6931	IDT strength (ITS) Peak load (St) (psi/kPa)	Strength	- Ma et al. 2015 - Raschia et al. 2019 - Saidi et al. 2019a - Yan et al. 2010
Creep Compliance	AASHTO T322	Creep compliance (D(t))	Viscoelastic properties of CRM mixtures	- Thomas et al. 2000 - Lee et al. 2016
Resilient Modulus (Mr) test	ASTM D7369	Resilient Modulus (Mr) (psi/MPa)	Strength and Stiffness	- Kavussi et Modarres 2010 - Niazi et al. 2009

Selecting Optimum Binder Content for CRM Mix Constituents Using Cracking and Strength Tests

In general, CRM mix design methods focus on improving the performance of CRM mixtures by selecting the design yielding optimal strength and/or cracking performance. The selection process of the optimal contents of CRM constituents depends on: (1) performance test conducted on CRM specimens, (2) the selected range of CRM constituent contents, and (3) properties of CRM constituents. For instance, Kim and Lee (2016) assessed different mix design parameters for CRM mixtures prepared with foamed asphalt. Prior to CRM production, the properties of foamed asphalts were determined at different water contents and foaming temperatures. The authors reported that the optimum water content needed for foamed asphalt production was selected as the one leading to highest half-time ratio, which was 1.3% by total asphalt content at 170^{o}C. Kim and Lee (2016) used various foamed asphalt contents, water contents, and gradations to produce CRM mixtures, which were then tested using indirect tensile strength and Marshall Stability tests. Only foamed asphalt content and gradations had a significant impact on maximum stability and maximum bulk density of CRM mixtures. The authors selected the optimum contents of CRM as the one yielding the highest Marshall Stability and peak tensile strength, which was observed at 2.5% foamed asphalt content. In addition, Kim and Lee (2016) reported that the fine gradation presented the highest strength and cracking resistance. Therefore, the authors recommended the indirect tensile strength test to be used when optimizing CRM mixtures.

In a similar study, Diefenderfer et al. (2019) adopted a performance-based design approach for CRM mixtures that mirrors that used for hot mix asphalt. The authors investigated the capability of different cracking tests as well as analysis methods in capturing the change in the CRM design parameters and materials' type and contents. In this study, CRM mixtures were produced using different emulsion types and multiple cement contents. Once compacted and cured, each combination of CRM was subjected to the selected cracking characterization tests. The authors then assessed the ability of each test method to discern performance of CRM prepared using different emulsion types and cement contents. Diefenderfer et al. (2019) recommended using semi-circular bend and indirect tensile strength test when designing CRM mixtures as well as when selecting the optimum contents of emulsion and cement.

Charmot et al., (2017) found the semi-circular bend test, conducted at 0°C, could be used to evaluate CRM cracking resistance. In addition, the optimum contents of bituminous and chemical additives were selected as the ones resulting in peaks of SCB fracture energy or flexibility index. Different studies showed that the fracture energy obtained from the IDT stress-strain curve can also characterize the cracking potential of CRM mixtures (Cox and Howard 2015, Koh and Roque 2010, Doyle and Howard, 2013). A previous study conducted by Nassar et al. (2016) aimed to optimize the dosages of emulsion, pre-wetting water, and curing based on both volumetric and mechanical properties of CRM mixtures. The authors developed a central composite design with response surface methodology that focuses on conducting indirect tensile stiffness (20°C) and indirect tensile strength tests. The authors reported that the interaction of emulsion content, pre-wetting water content, and curing temperatures had different impacts on mechanical properties of CRM mixtures (Nassar et al., 2016). For instance, increasing the emulsion content or lowering the cutting temperature increased the rutting susceptibility of CRMs tested at high temperatures (Nassar et al., 2016). However, the air void levels of

CRM mixtures were only influenced by the pre-wetting water content followed by the emulsion content. The authors recommended the response surface methodology as a successful approach to design CRM mixtures and select the optimum contents of CRM constituents based on the maximum indirect tensile strength value. In a recent study, Lyu et al. (2019) investigated the influence of emulsion binder dosage, cement, and RAP content on fatigue, moisture stability, and high temperature properties of CRM mixtures. The authors used a multi-index weighted grey target theory to optimize the performance of CRM mixtures in terms of contents of emulsion, cement, and RAP based on the maximum fatigue resistance and moisture stability. Lyu et al. (2019) reported that both contents of emulsion and cement presented a significant impact on the performance of CRM at high temperatures and fatigue life, while water stability was sensitive mostly to the change of RAP content. The authors recommended a 3.8% emulsion, 2% cement, and 80% RAP for an optimal CRM performance.

In summary, most CRM mix design methods considered selecting the optimum contents of CRM constituents using cracking and strength tests. Although performance tests were not consistent between studies, the method for selecting optimum contents of CRM constituents was the same. The CRM constituents' content leading to peak cracking or strength measures were selected. Table 3 presents a summary of optimum contents of CRM constituents determined using cracking and strength tests.

Table 4

Optimum Contents of CRM Constituents Based on BMD Approach

Study	CRM Constituent	Optimum Content (%)	RAP Content (%)	Performance Test	Performance Measure
Lin et al. 2020	Emulsion	3.5	100	- IDT dry and wet	- Maximum ITS value
Li et al. 2016	Foamed Asphalt	3.0	100	- IDT dry	- Maximum ITS value
Armilli et al. 2016	Emulsion	5.5	80	- IDT dry	- Maximum ITS value
Wegman and Sabouri 2016	Emulsion	2.3%	100	- Intermediate SCB	- SCB fracture energy with a minimum requirement of 230 J/m2
Zhang et al. 2020	Emulsion	2.8	100	- Low-temperature SCB - Low-temperature IDT	- SCB fracture energy with a minimum requirement of 230 J/m2. No minimum requirement. - ITS with a minimum requirement of 0.6 MPa
Pi et al. 2020	Emulsion Cement	2.9 1.5	100	- IDT dry	- Maximum splitting strength value at 15^{o}C

Selecting Optimum Contents of CRM Constituents Using a Balanced Mix Design (BMD) Approach

Over the past few years, a new mix design method was developed for asphalt mixtures focusing on balancing mixtures' resistance to at least two pavement distresses, generally cracking and rutting. Although several balanced mix design methods were adopted for hot and warm mix asphalt mixtures (Diefenderfer et al. 2021; West et al. 2018; Sreedhar et al. 2021), a few were developed for CRM mixtures. In a recent study, Xu et al. (2021) reported that the technical requirements for designing pavements in China often consider either cracking resistance or rutting susceptibility, which affect considerably the service life of pavements in China. Therefore, the authors adopted a BMD approach for designing asphalt mixtures, including CRM mixtures, which accounts for both cracking and rutting resistance. Several tests were proposed by Xu et al. (2021) such as flexural strain, freeze-thaw cycles and splitting strength, and dynamic stability to assess the fatigue properties and rutting potential of CRM mixtures at different mixing proportions and conditions. An optimal asphalt to aggregate ratio between 4.5% and 6.5% for hot mix asphalt was selected as the one balancing both cracking and rutting performances. The authors also reported that the BMD approach did improve the performance of asphalt mixtures, including CRM mixtures, particularly at low temperature compared to traditional Marshall Mix design.

Dong and Charmot (2019) proposed a BMD approach for CRM mixtures prepared with emulsion at different contents and compacted at 50 gyrations. The cracking resistance of CRM mixtures was assessed using indirect tensile asphalt cracking test (IDEAL-CT) at 25°C at a loading rate of 50 mm/min, while the permanent deformation was assessed using wheel tracking test at 60°C. The authors recommended using both cracking and rutting tests when selecting the optimum contents of emulsion and cement to ensure a balanced performance of CRM mixtures. According to Dong and Charmot (2019), optimum contents of emulsion and cement are the ones leading to a cracking test index (CTI) higher than 100 and a dynamic stability (DS) higher than 1,000 passes. In a recent study, Saidi et al., (2019a) used a balanced mix design approach to select optimum contents of CRM as that content that maximizes the cracking resistance and minimizes the rutting susceptibility of CRM mixtures. Saidi et al. (2019a) used semi-circular bend (SCB) test to evaluate cracking and indirect tensile strength to measure the measure strength, the asphalt pavement analyzer (APA) test to assess rutting, and the dynamic complex modulus to determine the viscoelastic properties of CRM mixtures. Saidi et al. (2019a) recommended using the APA rut depth as a rutting measure and the SCB fracture energy or the tensile strength as a cracking measure. Rutting and cracking measures were then used to select optimum contents of bituminous additives (emulsion and foamed asphalt).

In summary, a number of researchers adopted a BMD approach for designing CRM mixtures. Using this method, CRM mixtures were optimized in terms of their resistance to more than one pavement distress (e.g., rutting and cracking are the most common). The optimum contents of CRM constituents are selected as the ones maximizing the cracking resistance and minimizing rutting susceptibility (Saidi et al. 2019a). In addition, some of the BMD designs presented performance thresholds that dictate whether a CRM mixture is balanced or not. Table 4 presents a summary of BMD design results adopted in previous studies when optimizing the performance CRM mixtures. As shown in this table, the optimum binder content for different CRM mixes ranged from 2.5 to 3.2%.

Table 5

Optimum Contents of CRM Constituents Based on Cracking and Strength Tests

Study	CRM Constituent	Optimum Content	Performance Test	Performance Threshold
Dong and Charmot 2019	Emulsion	2.5%	- Wheel Tracking - IDEAL-CT	- Cracking test index (CTI) higher than 100 - Dynamic Stability (DS) higher than 1,000 passes
Dong and Charmot 2019	Cement	0.75%	- Wheel Tracking - IDEAL-CT	- Cracking test index (CTI) higher than 100 - Dynamic Stability (DS) higher than 1,000 passes
Saidi et al. 2019a	Emulsified Asphalt	2.7 - 3%	- APA - SCB - IDT	- Rut depth lower than 5 mm
Saidi et al. 2019b	Foamed Asphalt	2.6 – 3.2%	- APA - SCB - IDT	- Rut depth lower than 5 mm

Impact of CRM Mix Constituents and Production Methods on Performance

Several research studies were conducted to improve the design of CRM mixtures by adopting different design approaches and methodologies (Saidi et al. 2019a, Kim et al. 2007; Brovelli and Crispino 2012; Lee et al. 2016; Ayala 2018; Wegman and Sabouri 2016; Cox and Howard 2018). Other studies investigated the impact of varying the type and/or dosages of binders and/or chemical additives (Kavussi and Modarres 2010, Berthelot et al. 2007; Graziane et al. 2018; Gao et al. 2014; Cox and Howard 2016; Niazi and Jalili 2009; Bessa et al. 2016). In addition, researchers studied the effect of using

RAP from different sources or different RAP gradations on CRM mixtures' performance (Ghavibazoo et al. 2017; Ma et al. 2015). The effect of CRM curing process and/or compaction effort on the CRM resistance to pavement distresses (Kavussi and Modarres 2010; Lee et al. 2016; Mallick et al. 2011; Cross 2003; Kim et al. 2011; Martinez et al. 2007) was also investigated. The following subsections present a summary of how these different factors influence the design and performance of CRM mixtures.

Impact of Binder Type, Chemical Additives, and Water on CRM Mixtures

The impact of binder type, chemical additives, and added water content on CRM mixtures was evaluated in literature. Ayala et al. (2021) assessed the performance of CRM mixtures prepared with different emulsion types (bituminous additive) and lime slurry dosages (chemical additives). Performance tests such as dynamic modulus and flexural beam fatigue were conducted at different temperatures and loading frequencies. The authors reported that the dosage of lime slurry, as well as the gradation of RAP millings, did not present a significant impact on the stiffness and viscoelastic properties of CRM mixtures. In addition, higher optimum emulsion contents improved the dynamic modulus of CRM mixtures, which is having a similar impact to that of binder content in hot asphalt mixtures (Ayala 2021).

Li et al. (2019) studied the impact of cement on the strength of CRM mixtures prepared with foamed asphalt. The results of performance tests, such as indirect tensile strength and simple triaxial tests, showed that increasing the cement content considerably improved the resistance to cracking, moisture damage, and permanent deformation of CRM mixtures. Graziani et al. (2018) evaluated the properties of CRM mixtures using indirect tensile strength and measuring water loss by evaporation during curing. The authors reported that water content did not influence the strength of CRM mixtures. This study also reported that a curing process of 28 days is sufficient for CRM mixtures to gain structural strength (i.e., cement hydration is complete) and for the water to evaporate.

Another study by Dolzicky et al. (2020) investigated the influence of different combinations of bituminous and chemical additives on the fatigue performance of CRM mixtures using indirect tensile fatigue test at 20°C (stress-controlled mode). The authors found that the combinations of the bituminous and chemical additives had a strong impact on CRM fatigue life. Increasing the cement content, given a constant emulsion content, led to an increase in CRM fatigue life. Dolzicky et al. (2020) reported that, at 2% emulsion content, fatigue life values were the highest even when varying cement contents. While when increasing emulsion content beyond 2%, the fatigue life of CRM mixtures started to decrease. Table 5 summarizes the contents of bituminous and chemical additives, and water at which CRM mixtures presented either optimal or satisfactory performance.

Table 6

Recommended Contents of Emulsion, Cement, and Water for CRM Mixtures

Author	Emulsion	Water	Cement
Saidi et al. 2019a	2.7%–3%	3%	1%
Issa et al. 2001	2.0%	2.0%	2.0%
Yan et al. 2017	4.3%	2.6%	1.5%
Du 2015	4.0%	0.9%	2.5%
Ma et al. 2015	2.0%	4.4%	1.5%
Grilli et al. 2016	3.0%	5.0%	2.0%
Kavussi et al. 2011	4.0%	4.4%	1.0%
	4.0%	4.9%	2.0%
	4.0%	5.3%	3.0%

Impact of RAP Gradation and Binder Content on CRM Performance

The size and shape of aggregates have a strong influence on the density and performance of asphalt mixtures. Thus, several researchers aimed to verify if these findings are still valid when using different RAP gradation in CRM mixtures. For instance, Ghavibazoo et al. (2017) studied the impact of gradation and binder content of RAP millings on the performance of CRM mixtures at varying dosages of bituminous and chemical additives, and water. The authors utilized multiple RAP sources presenting five asphalt contents and controlled gradations, which were then mixed at varying emulsion contents. Marshall Stability and moisture susceptibility tests were performed on each of the produced CRM mixtures. Ghavibazoo et al. (2017) reported that only RAP gradation influenced the performance of CRM mixtures. The authors also found that, regardless of the gradation and the binder content of RAP millings, increasing emulsion contents had a negative impact on moisture resistance and a positive impact on wet stability. In a different study, Ma et al. (2015) assessed the impact of RAP gradation, emulsion content, and cement dosage on the strength of CRM mixtures. The authors reported that RAP gradation presented a strong impact on the tensile strength and moisture stability of emulsified asphalt CRM mixtures. Conversely, Ma et al. (2015) suggested the addition of virgin aggregates and/or fine gradation to improve bonding between RAP and emulsion, and as a result, improving the performance of CRM mixtures.

More recently, Raschia et al. (2021) assessed the compactability of different RAP sources and their impact on the performance of CRM mixtures using dynamic complex modulus test and compressible packing model (CPM). Although CRM compactability was not influenced by RAP shape and gradation, the authors found that RAP binder properties as well as the chemical interaction between emulsion and RAP millings had an impact on CRM compactability. Another study conducted by Xie et al. (2021) focused on assessing the long-term performance of emulsified asphalt CRM mixtures at different aging properties of the asphalt contained in RAP millings. Prior to producing CRM mixtures, RAP was subjected to a long-term aging (up to 15 hours). The strength and cracking resistance of CRM mixtures, containing RAP with different aging processes, was then assessed using indirect tensile strength test and image processing. Xie et al. (2021) reported that the strength and cracking resistance of CRM mixtures increased with the increase of the dosage of aged RAP asphalt, while the strength and cracking resistance decreased with the increase of aging degree. This in turn suggests that the properties and amount of binder in the RAP millings have an impact on the mechanical properties of CRM mixtures.

Impact of Compaction Effort and Method on CRM Mixtures

When CRM mixtures are prepared, compaction is the step at which mixtures are compacted to a certain height or using a gyration level to a target height or density. Several studies were conducted to assess the impact of compaction level and method on the performance of CRM mixtures. Flores et al. (2021) assessed different compaction methods such as modified Proctor and Superpave gyratory compactor (SGC). Flores et al. (2021) found that, although modified proctor and gyratory compaction methods were used successfully to assess the compactability of CRM mixtures at different contents of water and emulsion. The gyratory compacted CRM specimens were more suitable for performance testing when higher bulk specific gravities (G_{mb}) are targeted. In a similar study, Wang et al. (2021) investigated the compaction characteristics of emulsified asphalt CRM mixtures compacted using a SGC. Different compaction efforts were considered in this study including: 0, 10, 30, 50, and 75 gyrations. Wang et al. (2021) found that CRM specimens presented a difference in air void of 8% when increasing gyrations from 0 to 10. Air voids decreased by up to 5% when increasing the gyration level from 10 to 30 gyrations, by 2% when increasing the gyration level from 30 to 50, and by 1.6% at 75 gyrations (Figure 1).

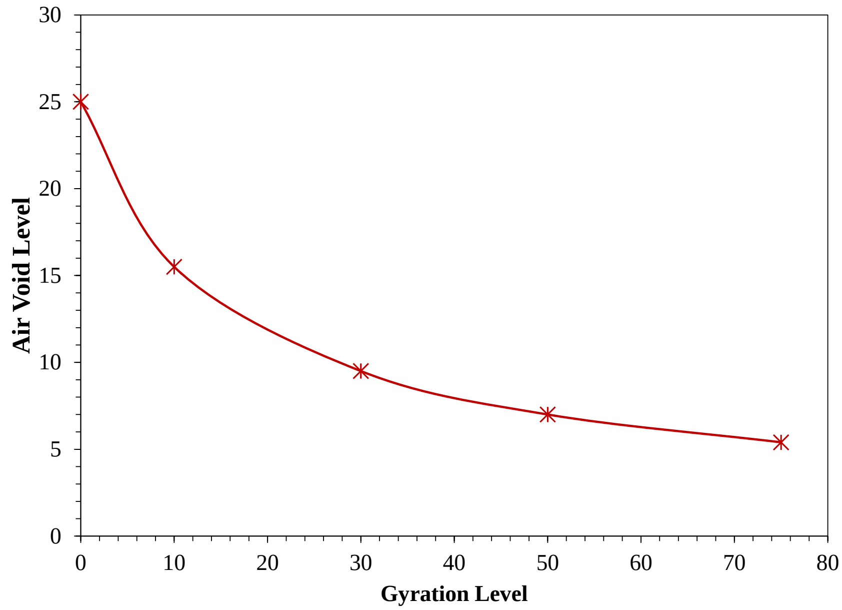


Figure 1. Impact of gyration level on the air void level of CRMs (Wang et al. 2021)

The authors also found that 50 gyrations applied on CRM mixtures was equivalent to 75 blows using the Marshall Hammer. The gyration level also had a significant impact on the selection of optimum contents of CRM constituents (binder, cement or other chemical additives, water, etc.). Wang et al. (2021) reported that the optimum water content of CRM mixtures reduced by 18% when increasing the gyration level up to 50 gyrations, while the optimum emulsion content increased from 3.0% to 3.5% at 50 gyrations. Another study by Watson et al. (2008) investigated the SGC gyration level at which the laboratory compaction effort of CRM mixtures would be representative of field compaction. The authors recommended compacting CRM specimens using 66 gyrations to attain similar field densities.

More recently, Saidi et al. (2019b) investigated the impact of gyration level on emulsified and foamed asphalt CRM mixtures. A Superpave gyratory compactor was used to compact CRM mixtures at one of two gyration levels: 30 and 70. The authors reported that CRM mixtures prepared with the same bituminous additive and subjected to the same curing process presented higher rutting susceptibility and lower cracking resistance when compacted at 30 gyrations. Increasing the gyration level to 70 caused an increase in CRM density, and therefore, improved the performance of these mixtures in terms of rutting and cracking (Saidi et al. 2019b).

Impact of Curing on CRM Mixtures

The selection of an optimal curing process when designing CRM mixtures is very important since, during this process, cement hydrates, the extra water in the mixture evaporates, and at the end, CRM mixtures gain their structural strength. Several studies were conducted to assess the impact of curing temperature and time period on the performance of CRM mixtures. For example, Bessa et al. (2016) studied the influence of curing process (ranging between 25°C and 100°C, for up 90 days) on CRM mixtures compacted with Marshall hammer and gyratory compactor. Bessa et al. (2016) found that the CRM mixtures cured at 60°C for one day presented similar strength to the ones cured at 25°C for 28 days. Based on the finding of this study, the authors recommended a curing process of 60°C for a short time period (up to 3 days) to ensure good mechanical properties for CRM mixtures. In a different study, Lin et al. (2018) cured CRM specimens in an oven at one of two conditions: 20°C for three days or 10°C for seven days. The authors also considered a humidity of 60% to simulate early-stage curing in the field. Lin et al. (2018) found that producing CRM mixtures with emulsion and cement contents of 3.8% and 2.0%, respectively, improved CRM mixes' early-stage strength and reduced their curing time.

Saidi et al. (2019b) evaluated the impact of curing on CRM mixtures prepared with one of two bituminous additives (emulsion or foamed asphalt) and compacted using one of two compaction efforts (30 or 70 gyrations) using a gyrator compactor. Two curing processes were selected for this study: 10°C and 60°C for 72 hours. Saidi et al. (2019b) reported that curing of both emulsified and foamed asphalt CRM mixtures had a strong impact on their performance. Mixtures subjected to a 72-hour curing at 60°C presented lower rutting susceptibly and higher cracking resistance than the mixtures subjected to a 72-hour curing at 10°C. The research team recommended a curing process of three days at 60°C.

Summary of Main Findings Related to CRM Mix Constituents Impacts

As demonstrated previously, several studies were conducted to assess the performance of CRM mixtures prepared at different binder and chemical additive dosages, using different binder types, varying water contents, curing methods, compaction methods. A summary of the main findings from literature pertaining to the impacts of each of these factors on CRM performance is given as follows:

- The performance of CRM mixtures is influenced by the type and content of bituminous additives, chemical additives, and water. In general, CSS-1h emulsion and portland cement were the most commonly used bituminous and chemical additives, respectively (Ayala et al. 2021; Li et al. 2019; Dolzicky et al. 2020). The range of CRM constituent contents recommended in previous studies varied as follows: 2% to 4% for emulsion contents, 1% to 3% for cement content, and 1% to 5% for water contents (Table 5).
- The properties of RAP millings (binder content and gradation) had different

impacts on the performance of CRM mixtures. For instance, the RAP's binder content and type did not influence the performance of CRM mixtures since RAP millings are considered black rocks (binder remains inactive during CRM mix production due to the absence of heat). However, CRM mixtures prepared using different RAP gradations behaved differently under performance testing. That is, a finer RAP gradation improved the resistance of CRM mixtures to rutting and cracking (Ghavibazoo et al. 2017; Ma et al. 2015; Raschia et al. 2021) when compared to a coarse RAP gradation.

- CIR's Compaction method and effort had an impact on performance. Specifically, the Superpave gyratory compactor (SGC) is recommended by most studies to be used when designing CRM mixtures. Higher gyrations tend to reduce air void level and improve the resistance of CRM mixes to rutting and cracking. The gyration level used in previous studies ranged between 30 and 100. The selection of compaction effort depends on the level of traffic a CRM mix is to be designed for (Flores et al. 2021; Wang et al. 2021; Saidi et al. 2019b).
- The curing process also influences the performance of CRM mixtures. Higher curing temperatures and longer curing times improve the resistance of CRM mixtures to rutting and cracking. Most studies recommended a curing temperature ranging between 40°C and 60°C, and a curing time from three days up to one week. A number of researchers found that CRM mixtures cured for three days at 60°C presented satisfactory performance (Bessa et al. 2016; Saidi et al. 2019a).

Based on the findings from literature, the selection of the optimum contents of CRM constituents depends on the design parameters of CRM mixtures. The recommendations from previous studies regarding design parameters (binder type and content range, compaction efforts, curing process, etc…) should be considered when using a BMD approach to optimize the performance of CRM mixtures.

Properties and Performance of Emulsion-Cement Paste (ECP)

The strength of CRM mixtures depends mainly on the properties of bituminous and cementitious additives mixed with RAP millings. Generally, emulsions are selected based on their binding properties, coating, initial strength, and breaking time, while the addition of portland cement improves the early strength of CRM mixes, enhances their rutting resistance, and offers better protection against moisture-induced damage. Different studies were conducted to gain a better understanding of the interactions between bituminous and chemical additives and their impacts on the performance of CRM mixtures (Pi et al. 2020; Du 2015; Ma et al. 2015; Garilli et al. 2019).

Pi et al., (2020) studied the effect of CRM materials' properties and dosages on the strength of emulsion CRM mixes. The morphological properties of these mixtures were determined through microscopic observations and aimed to evaluate the chemical reactions that occur within the mixture ensuring its strength. The authors investigated the impact of water and cement on the strength of emulsified asphalt cold recycled mixtures using indirect tensile strength. Pi et al., (2020) found that there is a positive interaction between cement, emulsion, and water when used in CRM mixtures. Increasing the dosages of cement and/or the emulsion improves the strength and moisture resistance of CRM mixtures. However, excessive dosages of emulsified asphalt and cement may reduce the strength of CRM mixtures. When the emulsion content increases, the rate of coating cement by asphalt increases as well. This slows the hydration process of cement and weakens the cold recycled mixture. Using indirect tensile strength data, optimal amounts of emulsified asphalt and cement were determined as 2.9% and 1.5%, respectively, according to Pi et al., (2020). Water dosage also presented a significant influence on the strength of CRM mixtures. In fact, increasing the water content caused an improvement in indirect tensile strength of CRMs.

Du (2015) focused on assessing the performance of emulsified asphalt CRM mixtures prepared with different chemical additives (portland cement, hydrated lime, and a mix of hydrated lime and ground-granulated blast-furnace slag). Several tests were conducted in order to evaluate the cracking resistance, rutting susceptibility, moisture damage, low temperature bending, and air void level on each CRM mixture. The microstructure of each mixture was also analyzed using environmental scanning electron microscope (ESEM) to assess the microstructure integrity of emulsion and each type of chemical additive. The author reported that portland cement and the combination of hydrated lime and ground-granulated blast-furnace slag reinforced the bonding of RAP within the mixture, and therefore, improved both cracking and rutting resistance of the CRM mixtures. As per the ESEM analysis, Du (2015) found that the hydration products obtained from all the chemical additives enhanced the cohesion and stiffness of the resulting asphalt mastic, which in turn improved the interface adhesion with RAP.

Similarly, Ma et al. (2015) evaluated the microstructure of ECP (Emulsion Cement Paste) as well as cement hydrates using SEM as part of CRM mixtures. The authors found that the hydration of cement was partially achieved by the water phase of emulsion, which may cause it to break. In fact, the cement hydration products such as columnar ettringite and hydrated calcium silicate form, with the emulsion's asphalt residue, a new strong binder within the CRM mix matrix. This cement-emulsion binder, also called emulsion-cement paste (ECP), provides CRM mixtures with semi-flexibility where the rigidity is created due to hydrated cement and flexibility is caused by emulsions. Ma et al. (2015) also reported that the interaction between cement and emulsion had a negative impact on the microstructure integrity of CRM mixtures through the formation of micro-pores resulting from water loss during cement hydration.

Garilli et al. (2019) investigated the versatility of the bending beam rheometer (BBR) test in assessing the performance of ECP specimens formed during CRM mixing. That was completed at different emulsion and cement combinations. The authors adopted a modified BBR testing protocol and a new sample preparation method for making ECP specimens. This method consisted of using glass microspheres to facilitate the production of ECP beams as well as to reduce the shrinkage and warpage of ECP beams during the curing process. Garilli et al. (2019) reported that the modified BBR test is a good approach to assess the performance of ECP at different design parameters (emulsion and cement contents, curing temperature, etc). Therefore, this method helps characterize the cracking performance of CRM mixtures from BBR test conducted on ECP beams. However, this approach needs to be further investigated before wider implementation, according to Garilli et al. (2019).

Summary and Findings from Literature

Several studies were conducted to develop mix design procedures that optimize the performance of CRM mixtures. The following points present the main findings from the comprehensive literature review conducted as part of this report:

- Most CRM mix design methods rely on performance tests to characterize the cracking resistance (e.g., SCB) of CRM mixtures when selecting optimum binder contents and other chemical additives. In these methods, optimum contents of CRM constituents (emulsion, cement, water, etc…) are generally selected as the ones maximizing cracking resistance.
- Few CRM mix design methods included the use of rutting when designing CRM mixtures. Those methods are known as balanced mix design methods of both emulsified and foamed CRM mixtures (e.g., Saidi et al., 2019a, Saidi et al., 2019b, Dong and Charmot, 2019). However, only one constituent (binder content or cement content) of CRM mixtures was optimized in these studies; keeping the dosages of the other CRM constituents constant.
- The interaction between CRM constituents were only considered as part of mixtures and not on the emulsion-cement paste (ECP) level. There is no literature regarding the interaction between emulsified asphalt and cement as well as the properties and performance of the resulting ECP. The impact of ECP on CRM performance was not previously evaluated.

Understanding the interactions between ECP constituents and evaluating the performance of ECP is very important since the performance of CRM mixtures is mostly governed by the properties of bituminous and chemical additives. Therefore, appropriate testing protocol should be considered to assess the rheological and mechanical performance of ECP specimens. Such assessment will help formulate a better understanding of the strengthening process of CRM mixtures, and to select the appropriate dosages of recycling agents and chemical additives ensuring a satisfactory CRM performance. In this study, a BMD approach is presented to select optimum contents of all the CRM constituents (i.e., bituminous and chemical additives, and water) to ensure an optimal resistance of CRM mixtures to pavement distresses (i.e., rutting and cracking). An investigation of the impacts of ECP on performance of CRM mixtures is also presented in this dissertation.

Chapter 3

Materials and Experimental Testing Program for ECP and CRM

In this study, CRM mixtures were prepared using RAP, emulsified asphalt, portland cement, and water. No virgin aggregates were used in preparing the CRM mixtures. The experimental testing program consisted of characterizing the properties and the performance of ECP, and evaluating the density and performance of CRM mixtures. A balanced-mix design (BMD) approach was then used to select optimum contents of all CRM constituents (emulsion, cement, and water) that maximize the cracking resistance and minimize the rutting susceptibility of CRM mixtures. The following subsections present more details regarding the characteristics of CRM materials and the experimental testing program adopted for this study.

RAP Millings

RAP for this study was obtained by milling a hot mix asphalt (HMA) pavement section, located at Rowan University Accelerated Pavement Testing Facility (RUAPTF), using a CRM milling machine. Several tests were performed on the dry RAP to assess the gradation, the maximum specific gravity, and the existing binder content of the RAP millings. The test results for the properties of RAP millings are provided in the following sections.

RAP Particle Size Distribution (Gradation)

Dry sieve analysis was performed on the collected RAP millings according to AASHTO T27 to determine the RAP gradation. At least 660 lbs (300 kg) of millings were sieved using a large-scale sieve shaker to obtain a representative gradation of the milled RAP (AASHTO 2020b). Figure 2 illustrates the general gradation for of the RAP millings as well as the average washed gradation of three samples, determined in accordance with AASHTO T11 (AASHTO 2020a). The gradation of RAP millings contains approximately 47% of particles passing sieve No.4 as seen in Figure 2, Additionally, the washed sieve analysis results (Figure 1) show that RAP millings had an average of 1.8% of particles passing sieve No.200.

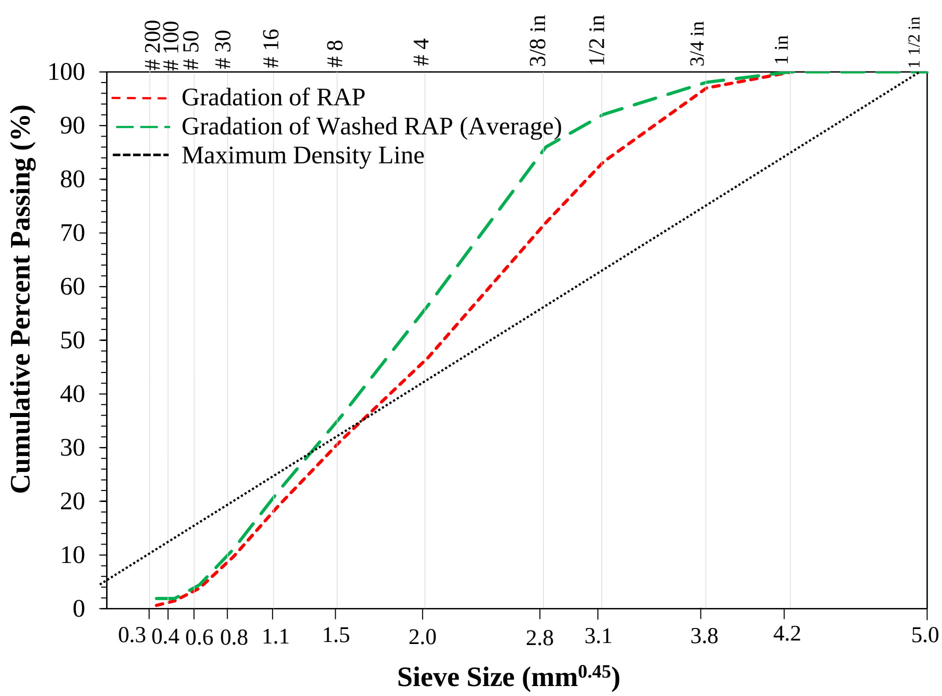


Figure 2. Dry and washed gradations of RAP millings

RAP Millings Maximum Specific Gravity

The maximum theoretical specific gravity (G_{mm}) of the RAP millings was determined using the CoreLok device according to ASTM D6857 standards (ASTM

2018a) . Three replicates of dry RAP samples were obtained in accordance with AASHTO T2 (AASHTO 1991), and then batched to the general gradation of RAP (Figure 2). The results of G_{mm} are presented in Table 7.

Table 7

Maximum Specific Gravity of RAP

Sample ID	G_{mm}	Av. G_{mm}	STD
RAP-1	2.491		
RAP-2	2.488	2.491	0.003
RAP-3	2.496		

Asphalt Binder Content in RAP Millings

Extraction and recovery tests were conducted on dry RAP millings in accordance with AASHTO T319 (AASHTO 2008) and mineral matter tests were conducted in accordance with T111 (AASHTO 2011). These tests were used to determine the asphalt content existing in RAP as well as the mineral matter content (passing sieve No. 200). Three replicates of RAP millings batched to the general gradation (Figure 1) were tested. The results of extraction and recovery and mineral matter tests are presented in Table 8. The average RAP binder content is 5.65% and the average mineral matter is 0.5% by total RAP weight.

Table 8

Extraction and Recovery and Mineral Matter of RAP Millings

RAP millings	Binder Content (%)	Average (%)	Mineral Matter (g)	Average (g)
Sample 1	5.46	5.65	7.1	7.8
Sample 2	5.77		8.2	
Sample 3	5.71		8.1	

Asphalt Emulsion

A slow setting cationic asphalt emulsion (CSS-1h) was selected as the bituminous additive for preparing CRM mixtures. This emulsion was selected because it performed well in the first phase of this project (Saidi et al., 2019a). This emulsion was obtained and stored in one-gallon bottles from Asphalt Paving Systems Inc., a local suppler in New Jersey (APS). A picture of the emulsion is shown in Figure 3 and its properties are presented in Table 9.

Figure 3. CSS-1h emulsified asphalt.

Table 9

Properties of CSS-1h Emulsified Asphalt

Properties	Results
Sieve (%)	0.00
25°C SF Viscosity (sec)	22.0
25°C, 100G, 5 sec Penetration	29
pH	5
Residue (%)	63.15

Portland Cement

Type I/II portland cement was used as the cementitious additive to enhance the strength of the CRM mixtures and to accelerate their curing. A picture of the used cement.

Experimental Program

The laboratory experimental program focused on performance testing at two levels: (1) binder level by assessing the properties and performance of emulsion-cement paste (ECP), and (2) mixture level by evaluating rutting susceptibility and cracking resistance of emulsified CRM mixtures.

Emulsion-Cement Paste (ECP) Production and Materials' Evaluation

A literature review was carried out to determine the contents of emulsion, cement, and water used in previous studies that yielded satisfactory performance for CRM mixtures (Issa et al. 2001, Yan et al. 2017, Du 2015, Ma et al. 2015, Grilli et al. 2016, Kavussi et al. 2016). Cationic slow-setting emulsions (CSS-1H) were often used as a recycling agent in CIR, while portland cement Type I/II was used as chemical additives.

In addition, the optimal dosages of the constituents used in CRM mixtures ranged between: 2.0% and 4.0% for emulsion, 1.0% and 3.0% for cement, and 1.0% and 5.0% for water, by total mixture weight. At these contents, CRM mixtures presented satisfactory performance. Therefore, the ECP specimens were be produced for this study using a combination of these contents of emulsion, cement, and water as shown in Figure 4.

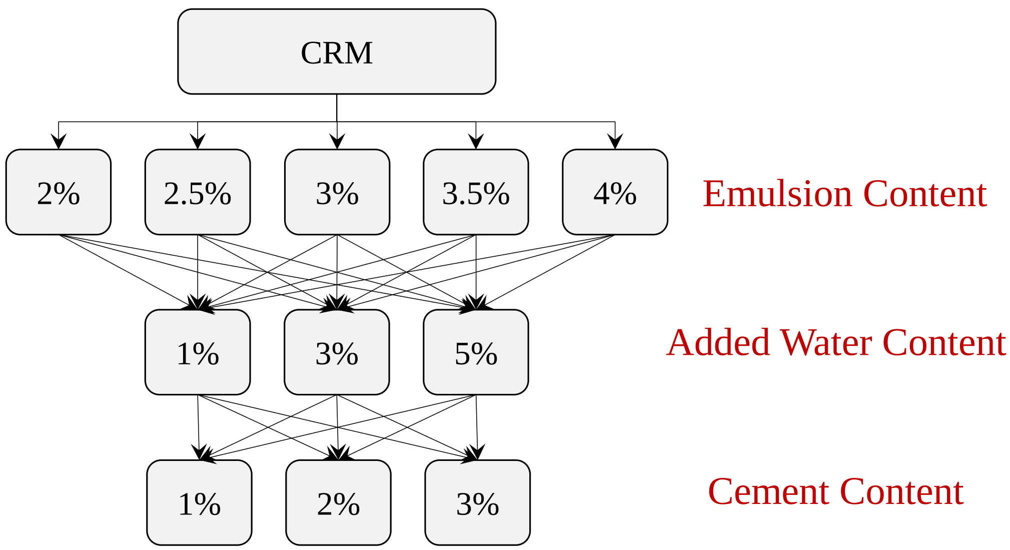


Figure 4. Experimental design for ECP production

The proportions of emulsion, cement, and water were then expressed by total ECP weight, simply excluding RAP from the total CRM weight. This means that, a CRM mixture prepared with 2.0% emulsion, 1.0% cement, and 1.0% water by total CRM weight, is equivalent to an ECP prepared with 50% emulsion, 25% cement, and 25% water by total ECP weight. The produced CRMs are designated as XY-Z%, where X is the cement content, Y is the water content, and Z is the emulsion content. In this study, the designation of ECPs followed the one of CRMs for the sake of simplicity and to better see the trends for changing the proportions of ECP constituents. All ECP combinations produced and tested in this study are presented in Table 10.

Table 10

ECP Combinations of Emulsion, Cement, and Water

CRM	Proportions in ECP		
	Cement (%)	Water (%)	Emulsion (%)
11-2%	25.0	25.0	50.0
11-2.5%	22.2	22.2	55.6
11-3%	20.0	20.0	60.0
11-3.5%	18.2	18.2	63.6
11-4%	16.7	16.7	66.7
13-2%	16.7	50.0	33.3
13-2.5%	15.4	46.2	38.5
13-3%	14.3	42.9	42.9
13-3.5%	13.3	40.0	46.7
13-4%	6.3	18.8	25.0
15-2%	6.3	31.3	12.5
15-2.5%	11.8	58.8	29.4
15-3%	11.1	55.6	33.3
15-3.5	10.5	52.6	36.8
15-4%	10.0	50.0	40.0
21-2%	40.0	20.0	40.0
21-2.5%	36.4	18.2	45.5
21-3%	33.3	16.7	50.0
21-3.5%	30.8	15.4	53.8
21-4%	28.6	14.3	57.1
23-2%	28.6	42.9	28.6
23-2.5%	26.7	40.0	33.3
23-3%	25.0	37.5	37.5
23-3.5%	23.5	35.3	41.2
23-4%	22.2	33.3	44.4
25-2%	22.2	55.6	22.2
25-2.5%	21.1	52.6	26.3
25-3%	20.0	50.0	30.0
25-3.5%	19.0	47.6	33.3
25-4%	18.2	45.5	36.4
31-2%	50.0	16.7	33.3
31-2.5%	46.2	15.4	38.5
31-3%	42.9	14.3	42.9
31-3.5%	40.0	13.3	46.7
31-4%	37.5	12.5	50.0
33-2%	37.5	37.5	25.0
33-2.5%	35.3	35.3	29.4

CRM	Proportions in ECP		
	Cement (%)	Water (%)	Emulsion (%)
33-3%	33.3	33.3	33.3
33-3.5%	31.6	31.6	36.8
33-4%	30.0	30.0	40.0
35-2%	30.0	50.0	20.0
35-2.5%	28.6	47.6	23.8
35-3%	27.3	45.5	27.3
35-3.5%	26.1	43.5	30.4
35-4%	25.0	41.7	33.3

The method for producing and characterizing ECP specimens consisted of four steps described as follows:

Step 1: Select Dosages for Emulsion, Cement, and Water. The ECP dosages were first selected according to the amounts of emulsion, cement, and water used in preparing the CRM mixtures (Table 10).

Step 2: Mix Emulsion, Cement, and Water. ECP specimens were produced by mixing CSS-1h emulsion, portland cement Type I/II and water using a low-shear mixer at the proportions in Table 10. The mixing procedure consisted of two steps: (1) mixing cement and water in a small container for at least one minute and no more than 2 minutes, and (2) adding emulsion to the cement-water container and mixing for at least 1 minute.

Step 3: Cure ECP Mix. The ECP specimens were placed in an oven at 60°C for 72 hours to cure. This process was similar to that typically used for curing CRM mixtures (Saidi et al. 2019a). This step is essential to allow the specimens to gain strength and water to evaporate.

Step 4: Evaluate Rheological and Morphological Properties. Several binder-scale performance tests were performed on the cured ECP samples to assess the resistance of the ECP to rutting and low temperature cracking. For instance, rheological tests such as the high-temperature performance grading (AASHTO T315) using dynamic shear rheometer (DSR), multiple stress creep recovery (MSCR), bending beam rheometer (BBR), linear amplitude sweep (LAS), and penetration were conducted. In addition, isothermal calorimetry test was used to quantify the hydration rate of ECP specimens at different amounts of emulsion, cement and water. Additional details about the binder-scale tests are presented in the following.

High Temperature Performance Grade of ECP Using DSR (AASHTO T 315). The DSR test was used to assess the rheological properties of ECP specimens at high temperatures at different contents of emulsion, cement, and water (Figure 5). Two ECP replicates were tested at each temperature to measure dynamic shear modulus (G*) and phase angle (δ) for each. Using the failure criteria of $\frac{G^*}{\sin(\delta)} \leq 1$ in accordance with AASHTO T320, the performance grade (PG) of ECP was determined at high temperatures ranging between 64oC and 106°C.

Figure 5. DSR machine

Multiple Stress Creep Recovery (MSCR) Test (AASHTO T 350). The MSCR test was used to determine the non-recoverable creep compliance (J_{nr}) and percentage of recovery (MSCR $_{recovery}$) of ECP at two loading conditions: 10 cycles at a low shear stress (0.1 kPa) and 10 cycles at a high shear stress (3.2 kPa). This test was conducted using the DSR (Figure 5) at 64^{o}C. Generally, J_{nr} and percent recovery can be used to assess the rutting potential of asphalt mixtures (good correlation with APA rut depth values). Three replicates of each ECP combination were tested to assess variability.

Linear Amplitude Sweep (LAS) Test (AASHTO TP 101). The LAS test was performed to evaluate the cracking resistance of ECP due to damage by means of systematic, linearly increasing cyclic loading amplitudes. The outcomes of this test are correlated to CRM mixtures' cracking resistance using number of cycles to failure and LAS fracture energy. The test was conducted using the DSR machine at two temperatures: 0^{o}C and 25^{o}C. The LAS results are compared to the SCB (semi-circular bend) fracture energy test results. Three replicates of each ECP combination were prepared for the LAS test.

Bending Beam Rheometer (BBR) Test (AASHTO T 313). The main purpose of running BBR test was to assess resistance of ECP specimens to loading when different dosages of cement and water are mixed with emulsion (Figure 6). The BBR test was conducted at 0°C to assess the cracking resistance of ECP specimens, which can be later validated by LAS and SCB tests that were similarly conducted at 0°C. The cracking resistance of ECP specimens was evaluated by computing the creep stiffness and m-value. For the BBR test, two replicates of each ECP combination were prepared.

Figure 6. BBR machine

Penetration Test (AASHTO T 49). The penetration test was conducted using a penetrometer (Figure 7) to assess the viscoelastic properties of ECP at three temperatures: 10°C, 25°C, and 40°C. A stainless-steel needle (50 mm long and 1 mm wide) was applied vertically (under gravitational forces) on a flat surface of an ECP specimen at five different locations. The penetration values were measured 5 seconds after test start and reported in units of 0.1 mm.

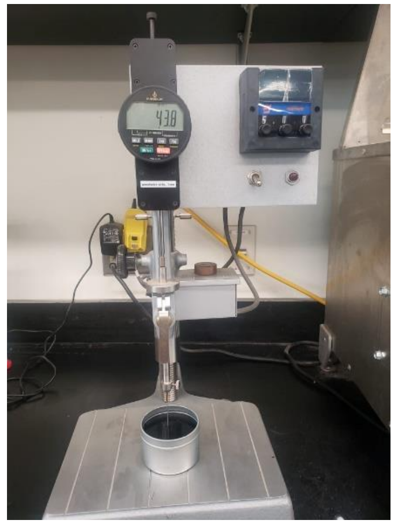


Figure 7. Penetrometer

Calorimetry Test (ASTM C1679). The calorimetry test was performed using an isothermal calorimeter to assess the hydration process of cement in ECP. Prior to mixing, emulsion, cement, and water were allowed to condition overnight at 20°C. Once conditioned, ECP specimens were produced by mixing cement, water, and emulsion at different proportions, then placed immediately in one of the channels of the calorimeter. Two replicates of each ECP specimen were tested for 72 hours at 20°C. The hydration power was then determined and used to evaluate the strength of ECPs at different proportions of emulsion, cement, and water.

CRM Design and Performance Testing Program

A systematic method for preparing CRMs was adopted as part of this study, which was successfully used in a previous research study by Saidi et al. (2019a). The proposed mix design method consisted of the seven steps summarized below:

Step 1. Procuring and Characterizing RAP Millings, Bituminous, and Chemical Additives. RAP was collected by milling a portion of an HMA pavement located at RUAPTF. RAP millings were characterized in terms of gradation, binder content, and theoretical specific gravity, then were mixed with cement, water, and emulsion at varying amount of CRM constituents. To produce CRM mixtures, the following materials were selected: (1) CSS-1h emulsion as bituminous additive, (2) portland cement Type I/II as chemical additive, and (3) water.

Step 2. Selecting Dosages of Bituminous Agents, Chemical Additive, and Water. Each CRM constituent was added according to the dosages shown in Figure 4. Forty-five CRM combinations were produced.

Step 3. Mixing Bituminous Agents, Chemical Additive, and Water. The CRMs were produced by mixing batches of dry RAP millings with portland cement and water using a bucket mixer for at least two minutes. This allows for coating all RAP millings with cement. The emulsion was then added to the mix and mixing commenced for at least two more minutes. Five hundred seventy CRM test specimens were prepared using varying dosages of emulsions, cement, and water.

Step 4. Compacting CRMs. Once mixed, CRM loose mix samples were compacted using 30 gyrations in a SGC to produce test specimens for performance testing (more details on this are provided in Step 6). This compaction effort was used because it achieved good CRM density levels during the first phase of this project (Saidi et al., 2019a). This compaction effort also represents low to medium traffic levels.

Step 5. Curing Process of CRMs. The compacted samples were cured in an oven for three days at 60°C. This curing process was selected based on the outcomes of previous studies suggesting that optimal performance is achieved after this curing (Bessa et al., 2016; Saidi et al., 2019a).

Step 6. Measuring Volumetric Properties of CRM Mixtures. For CRM each combination, three loose CRM samples were produced to determine their Gmm using the CoreLok device as in the study of Cox and Howard (2015) and Saidi et al. (2019a). In addition, the Gmb was measured for the compacted and cured CRM specimens using CoreLok. Using both Gmm and Gmb data, the air void levels were determined for each CRM combination.

Step 7. Evaluating Rutting and Cracking Performance of CRMs. Two laboratory tests were used to evaluate the rutting and cracking performance of CRMs and ultimately select their optimal constituent dosages. Rutting was assessed using the asphalt pavement analyzer (APA; AASHTO T 340) and cracking was evaluated using the Semi-circular bend test (SCB; AASHTO TP124). A brief description of these performance tests is presented below:

Asphalt Pavement Analyzer (APA) Test (AASHTO T 340). The APA test was used to assess the rutting potential of CRMs at 64°C (Figure 8). This test involved applying a 100-lb force, using a steel wheel, on top of a pressurized hose (100 psi). At the end of this test, the rut depth values of the different CRMs were measured. A total of six APA replicates compacted to a height of 75 mm using the SGC were prepared. The rut depth measurements were taken after completion of a total of 8000 loading cycles. The test was stopped if 14 mm of rutting occurred before completing 8000 loading cycles.

Figure 8. APA machine

Semi-Circular Bend (SCB) (AASHTO TP124). The SCB test was used to characterize the cracking resistance of CRM mixtures. In this study, SCB specimens were notched using a 12.5 mm long and 1 mm wide notch to simulate a crack. Testing was conducted using asphalt mixtures performance tester (AMPT) shown in Figure 9. Two testing modes were adopted for this study: (1) at 0^{o}C using three replicates for each CRM mixture with a loading rate of 12.5 mm/min, and (2) at 25^{o}C using three replicates for each CRM mixture with a loading rate of 50 mm/min. These testing temperatures were selected to represent a more conservative temperature at which thermal cracking (0^{o}C) and fatigue cracking (25°C) are more pronounced. For purposes of this study, a total of three SCB replicate for each CRM combination were produced, cut, notched, and tested.

Figure 9. AMPT machine

Chapter 4

Laboratory Assessment of the Rheological and Mechanical Properties of ECP

Overview of ECP Testing Results

One of the main goals of this research study was to understand the interactions occurring when mixing bituminous agents, cementitious additives, and water, and continuing to exist during the curing process and throughout the service life of CRM mixtures. Therefore, several laboratory binder-scale tests were conducted to assess the rheological and mechanical properties of the ECP at varying proportions of emulsion, cement, and water. The following subsections discuss the results of ECP properties at various testing conditions.

Rheological Properties using Dynamic Shear Rheometer

The dynamic shear rheometer was used to assess the rheological properties of ECP specimens at high temperatures ranging from 64°C to 106°C. First, the CSS-1h emulsion was graded at high temperature prior to preparing ECP combinations. Results showed that the residual asphalt used in preparing ECPs presented a high-temperature PG of 73.4. Afterwards, ECP combinations were tested at the following temperatures until meeting the failure criteria of $\frac{G^*}{sin\,\delta} < 1$: 64°C, 70°C, 76°C, 82°C, 88°C, 94°C, 100°C, and 106°C. The results of high-temperature PG of ECP specimens at different proportions of emulsion, cement, and water are presented in Figure 10. At least 85% of ECP did meet the failure criteria and could be graded at high temperature. Given the same emulsion content, increasing the cement content increased $\frac{G^*}{sin\,\delta}$, which indicates that the ductility of

ECPs is reduced at high temperature. This suggests that increasing the cement content to a certain threshold improves rutting resistance of ECPs. When cement content increases at low emulsion contents, the ECPs result in a concrete-like paste (e.g., ECP with 2% emulsion, 1% cement, and 1% water), which tends to be less sensitive to high temperatures (i.e., $\frac{G^*}{sin\,\delta}$> 1 at 100ºC and 106ºC). Although these observations may suggest that ECPs with high cement contents but low emulsion contents are better at resisting rutting, the performance of these specimens may be less efficient at low and intermediate temperatures compared to the rest of combinations. Therefore, further testing was conducted on ECPs to assess their properties at intermediate and low temperatures:

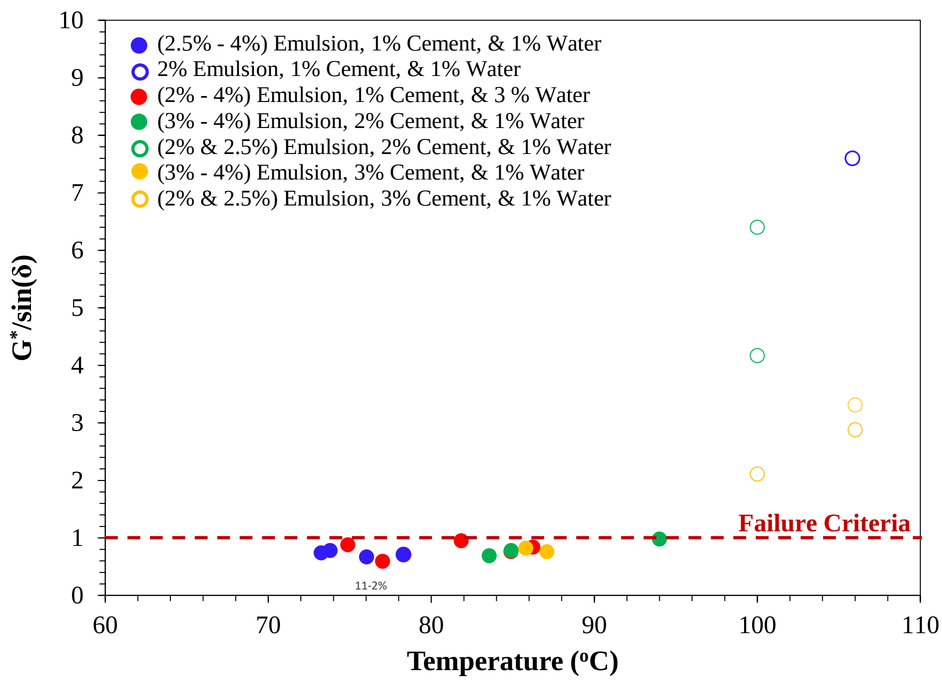
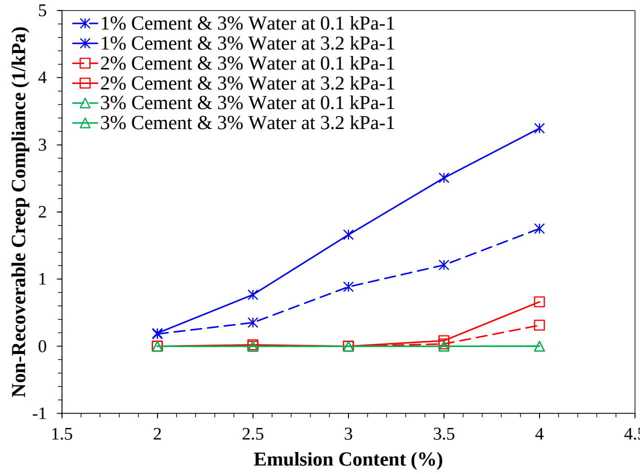


Figure 10. Viscoelastic properties of ECP at high temperature

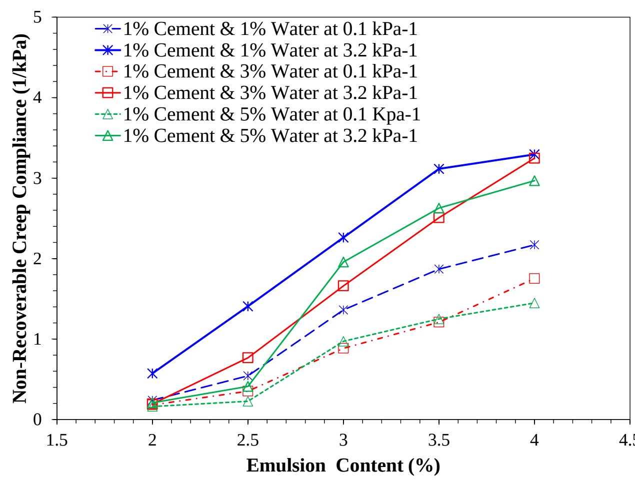
Multiple Stress Creep Recovery (MSCR) Results

The results of the MSCR test conducted at 64^{o}C on ECP specimens with varying amounts of emulsion, cement, and water are presented in Figure 11. The results shown are the non-recoverable creep compliance (J_{nr}) at stress levels: 0.1 and 3.2 KPa. Increasing the emulsion content caused an increase in J_{nr} values at both low and high stress levels (Figure 11a). The effect of varying emulsion on J_{nr} values was more pronounced for ECPs with low cement contents (1%). While at high cement contents (3%), the Jnr values remained constant with the increase of emulsion content. This suggests that increasing the emulsion content at low cement contents may result in increasing the rutting susceptibility of ECPs, while increasing cement content may improve ECP's resistance to rutting. In addition, increasing the stress level from 0.1 to 3.2 KPa caused an increase in J_{nr} values at high emulsion contents (3% through 4%) and low cement contents (1% and 2%), while increasing the stress level did not have any influence on J_{nr} values at high cement contents (3%). This suggests that ECPs with high cement are better at resisting rutting under heavier loading conditions.

Similarly, the impact of varying water content on the J_{nr} values of ECP specimens was assessed and illustrated in Figure 11b. From this figure and given the same stress level and cement content, increasing the water content from 1% to 5% with incremental amounts of 2% caused a reduction in Jnr values of ECP specimens. The reduction in Jnr values was more pronounced at higher emulsion contents. These observations suggest that the increase of water may boost the hydration process of cement minerals, which in turn provide ECPs with more resistance to rutting at high temperature (i.e., 64^{o}C). In addition, increasing the stress level from 0.1 to 3.2 KPa caused a meaningful increase of J_{nr} values (specifically at higher emulsion contents) where ECPs at 3% and 5% presented the lowest J_{nr} values, This suggest that increasing the water content may improve the resistance of ECPs to rutting at higher loading conditions.



(a)



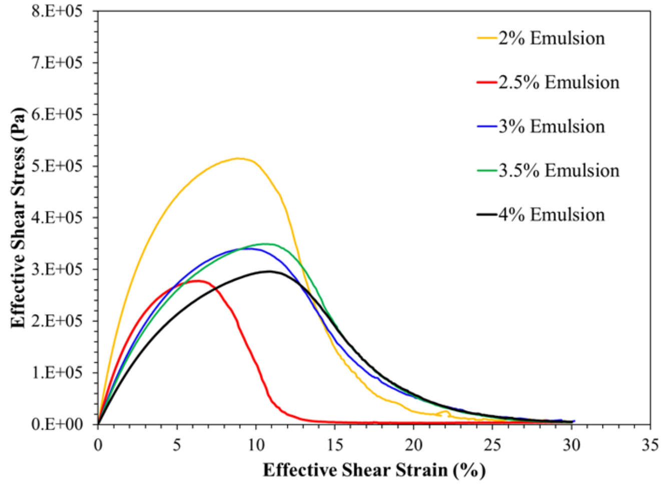
(b)

Figure 11. Non-recoverable creep compliance results of ECP combinations: (a) impact of emulsion & cement, (b) impact of emulsion & water

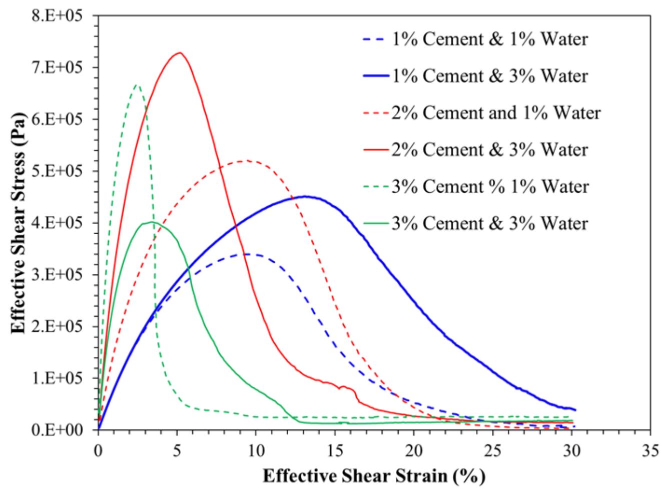
Linear Amplitude Sweep (LAS) Results

The LAS test was conducted to assess the fatigue resistance of ECP combinations at intermediate temperatures (25°C). The strain-stress curves developed for ECPs at different proportions of emulsion, cement, and water are shown in Figure 12. These curves translate the resistance of ECP specimens to cyclic loading and can be interpreted using two different methods: (a) peak stress: the higher the stress value the more brittle the ECP, and (2) peak time: the longer the time it takes the peak to occur the more fatigue resistant the ECP. ECP specimens with 2% emulsion presented the highest peak while the ECPs with 2.5% emulsion presented the earliest peak. This suggests that at low emulsion contents, ECPs are brittle, thus, more susceptible to fatigue cracking. ECPs with 3.5% emulsion (at 1% cement and 1% water) were most resistant to fatigue cracking.

Alternately, the impact of varying the amounts of cement and water was assessed and presented in Figure 12b. Increasing the cement content from 1% to 3%, the peak stress shifts to the left (peak time decreases) and increases in magnitude at 1% water, except for ECPs at 1% cement. This suggests that increasing the cement content at low water contents (1%) increases the brittleness of ECPs, which become more fatigue susceptible. When the water content increases to 3%, the peak stress shifts to the right (peak time increases) at low cement content (1%). This suggests that increasing the water content improves the cement hydration within the ECPs, which results in improved fatigue resistance. However, the increase in water content seems to have a negative effect on the ECPs fatigue resistance at high cement contents (2% and 3%). This could be due to the nature of the ECP that loses its ductility as more cement minerals are hydrated, which increases the susceptibility of ECPs to fatigue cracking.



(a)



(b)

Figure 12. LAS strain-stress curves of ECP combinations: (a) impact of emulsion at 1% cement and 1% water, (b) impact of cement and water at 3% emulsion

The stress-strain curves of ECPs were then used to compute LAS fracture energy (LAS-FE) by integrating the area under the stress-strain curves. The results of LAS-FE for ECPs at different emulsion, cement, and water contents are shown in Figure 13. It is noted that the LAS-FE results for ECPs at high cement contents and low emulsion and water contents were excluded from Figure 13 due to the powdery nature of the paste, which made the ECPs difficult to be tested using the DSR device. Iincreasing the emulsion content resulted in trends with a peak of LAS-FE at all water contents with 1% cement. Each peak represents the optimal proportion of ECP constituents to maximize the resistance to fatigue cracking. For instance, these peaks were observed at 3% emulsion for ECPs prepared with 1% and 3% water and a peak at 3.5% emulsion for ECPs prepared with 5% water. As cement content increased to 2% (Figure 13b), the LAS-FE peaks were observed at 3% emulsion for ECPs prepared with 1% water and at 3.5% emulsion for ECPs prepared with 3% and 5% water. Alternately, varying the water content did not show a specific trend for LAS-FE at the different emulsion and cement contents. Only a few peaks of LAS-FE were observed when varying the water content such as in Figure 13b (at 3% water, 2% cement, and 3.5% emulsion) and Figure 13c (5% water, 3% cement, and 4% emulsion). Conversely, increasing the cement content caused a reduction in LAS-FE given the same emulsion and water content, except for the ECPs specimens prepared with 3% and 3.5% emulsion where LAS-FE peaked at 2% cement (Figure 13b). Overall, the increase in cement content causes the ECP specimens to harden, thus, become more susceptible to fatigue cracking.

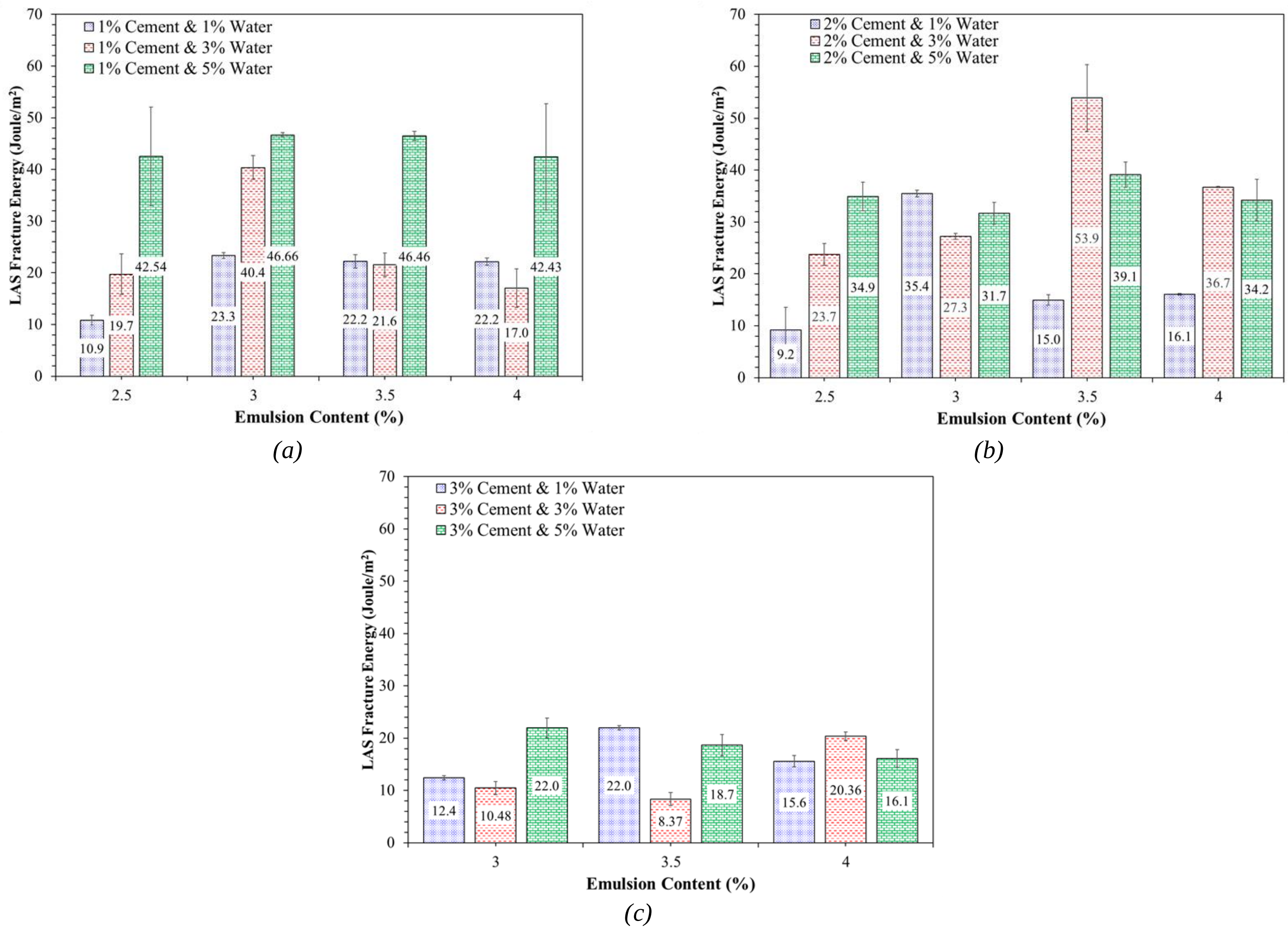


Figure 13. LAS strain-stress curves of ECP combinations: (a) 1% cement, (b) 3% cement, and (c) 5% cement

Bending Beam Rheometer Results at 0°C

Creep stiffness and m-value were used to characterize the cracking performance of ECP specimens at 0°C. At low values of creep stiffness and high values of m-value, ECP specimens are more flexible and, therefore, exhibit a good resistance to low-temperature cracking. In accordance with AASHTO M 320, the creep stiffness of ECP specimens should be less than 300 MPa while m-value should be higher than 0.30.

The creep stiffness of ECP specimens at different proportions of emulsion, cement, and water at 0°C are illustrated in Figure 14. Only the two ECP specimens at 3% cement content, 2% emulsion, and 1% or 3% water contents did not meet the requirement from AASHTO M 320 with respect to creep stiffness. When water content increases to 5%, the creep stiffness of ECP prepared with 2% emulsion and 3% cement dropped to 233. This suggests that the addition of water improved the ductility of ECP specimens by allowing the asphalt phase of emulsion to enclose the cement minerals during the mixing process of ECP. Overall, all the ECPs prepared with low cement contents (1%) presented the lowest creep stiffness regardless of the amounts of emulsion and water. Increasing the emulsion content to at least 3% reduced the creep stiffness values by over 30 MPa for ECPs prepared with 2% cement. As cement increases to 3%, at least 3.5% emulsion along with at least 3% water were needed to drop the creep stiffness by over 200 MPa. All ECP specimens presented relatively similar mechanical behavior at high emulsion contents, which result in better resistance to low-temperature cracking.

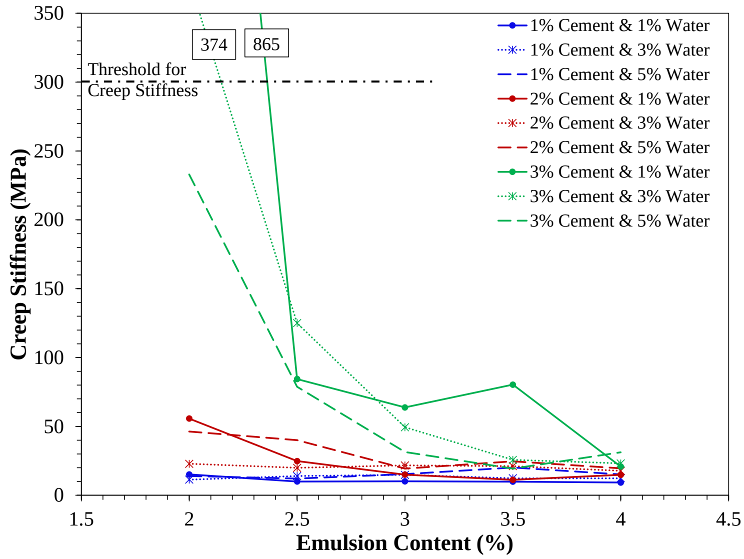


Figure 14. Creep stiffness of ECP combinations at 0°C

The results of the creep rate, also known as m-value, of ECP specimens at different proportions of emulsion, cement, and water at 0°C are presented in Figure 15 . In general, the greater the m-value the better the ability of ECPs to resist loading and the less susceptible to low temperature cracking. The ECPs prepared with high amounts of cement (2% and 3%) at low emulsion and water contents had m-Values less than 0.3, and therefore, failed the BBR test. ECPs with 1% cement presented higher m-values, followed by the ECPs prepared with 2% cement and 5% water. At low emulsion contents, ECPs prepared with 1% cement and 5% water presented the highest m-value. At higher emulsion contents, less added water is needed (3%) to achieve the highest m-value, because of the contribution from the water phase of the emulsion. The results of m-value fall in line with those of creep stiffness and suggest that a combination of low cement content (1%) with 3% water and at least 3% emulsion ensures a better resistance to low-temperature cracking.

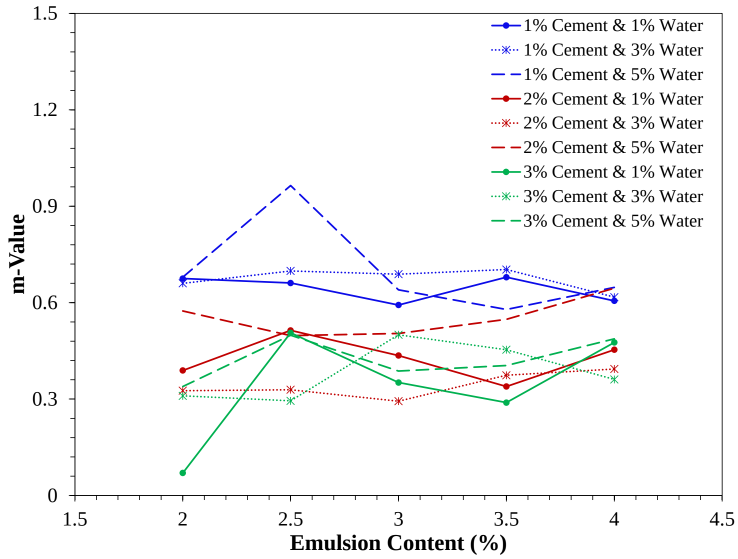


Figure 15. Creep rate (m-value) results of ECP combinations at 0°C

Penetration Results

The results of penetration tests conducted at 10°C, 25°C, and 45°C for ECP specimens at different combinations of emulsion, cement, and water are presented in Figure 16. The ECP specimens had similar penetration values at 10°C even when increasing the amounts of emulsion or decreasing the amounts of cement. This suggests that varying the proportions of emulsion, cement, and water does not have an impact on the ductility of ECP at 10°C. When the testing temperature increases to 25°C, the penetration values of ECP specimens increase by up to 15 dmm (dmm=0.1 mm) at low emulsion contents (2% and 2.5%) and 5 mm at high emulsion contents (3% through 4%), given the same cement and water contents. This suggests that intermediate temperatures (25°C) improves the ductility of ECP specimens, which presents different penetrations values at different amounts of emulsion, cement and water. At 40°C, the penetration values of ECP specimens with cement contents above 2% and with low emulsion contents increased by approximately 0.1 mm, but increased by over 0.7 mm at high emulsion contents (3% through 4%). While at 1% cement, the penetration values increased when varying the emulsion and water contents. This suggests that the penetration resistance of ECP specimens at 40ºC are sensitive to an increase of cement content and a decrease of emulsion and water content.

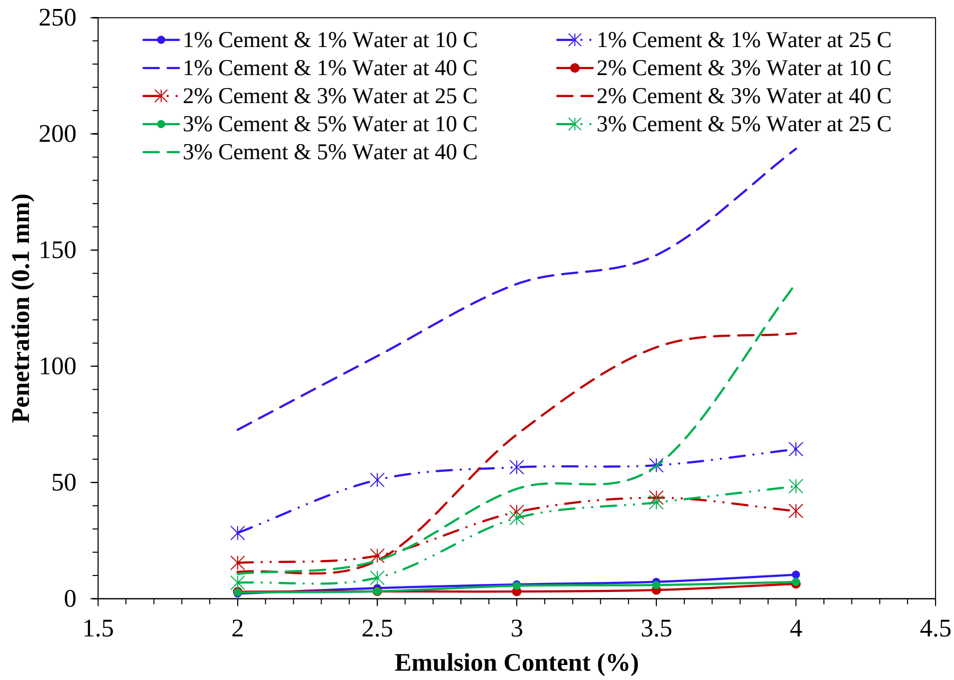


Figure 16. Influence of temperature variation on penetration results of ECP Specimens

Isothermal Calorimetry at 20ºC

Figure 17 presents the heat power results obtained by testing ECP specimens with different combinations of materials at extreme amounts (e.g., highest contents of emulsion, lowest content of water, etc). As can be seen from Figure 17, the peak heat power of all the ECP specimens occurred within the first 24 hours of curing. However, the hydration of cement within the ECP specimens continued until the end of testing. In addition, the ECP specimens prepared with highest cement proportions (3% cement, 1% water, and 2% emulsion) had the highest hydration rate, while the ECPs prepared with the lowest added water content (1% water, 1% cement, and 2% emulsion) presented the lowest hydration of cement. This indicates that, as cement content increases given the same water and emulsion contents, the cement hydration rate increases. Conversely, ECP specimens prepared with highest contents of all constituents (4% emulsion, 3% cement, and 5% water) presented the same hydration rate of cement as the ECP specimens at lowest contents of all constituents (2% emulsion, 1% cement, and 1% water). This suggests that, although cement is at its highest content (3%), the hydration rate is inhibited by the excessive amounts of emulsion, which may enclose the minerals of cement and prevent them from reacting with water. This hypothesis can be also valid for the ECP specimens with lowest contents of constituents. Alternately, ECP specimens at highest emulsion contents (4% with 1% cement and 1% water), at lowest cement content (1% with 4% emulsion and 5% water), or lowest water content (1% with 4% emulsion and 3% cement) presented similar hydration rate of cement. This indicates that the amounts of emulsion and water play an important role in the hydration of cement. In fact, the increase of water stimulates cement hydration while the increase of emulsion inhibits it.

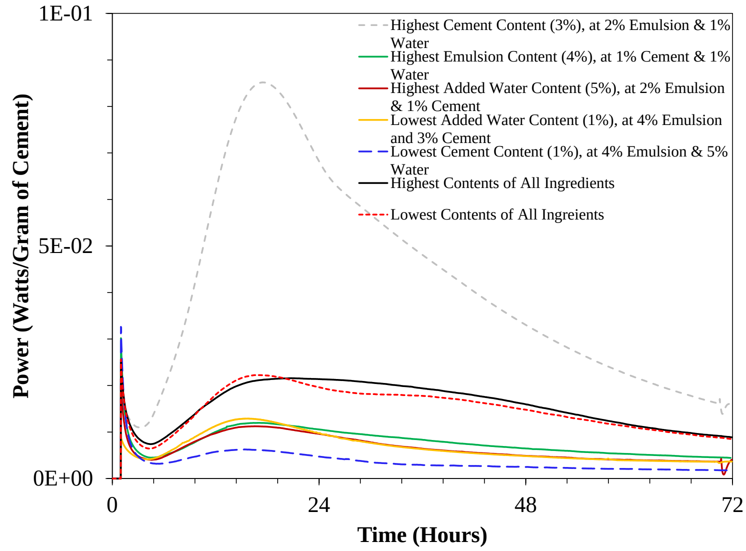


Figure 17. Hydration power results of ECP specimens

To look closely at the impact of the amounts of emulsion and water on the hydration rate of cement within ECP, Figure 18 illustrates the heat power results for three different ECP specimens at constant cement and water contents (3% and 1%, respectively), and different emulsion contents (2%, 3%, and 4%). The increase in emulsion contents from 2% to 3% decreased the hydration rate by about 80%, and an increase from 2% to 4% further decreased it by about 600%. This validates the hypothesis that the asphalt phase of emulsion prevents the cement from achieving maximum hydration. This may also suggest that, at higher emulsion contents, cement plays the role of a filler.

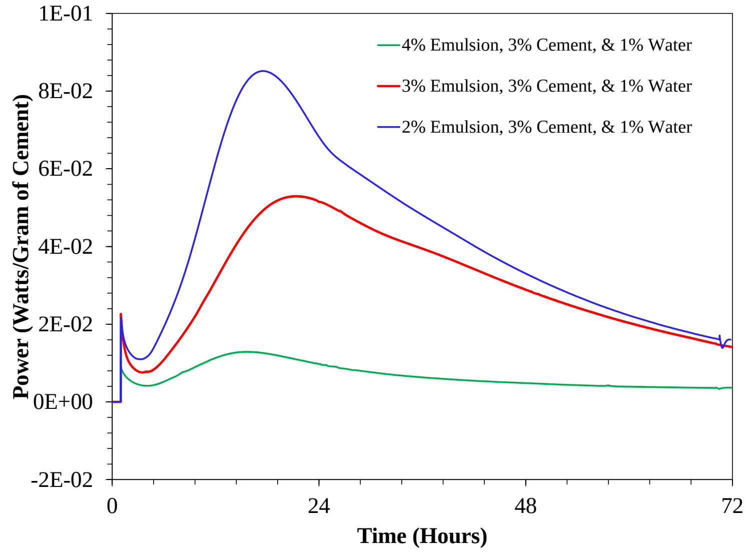


Figure 18. Impact of emulsion content on cement hydration

The impact of water on the hydration rate of cement within ECP specimens is illustrated in Figure 19. From this figure, one can notice that water plays different roles depending on the emulsion contents used to prepare the ECPs. At low emulsion contents (2%), the increase of water content from 1% to 5% caused a reduction in the heat generated during cement hydration, while at high emulsion contents (4%), the increase in water contents from 1% to 5% improved cement hydration. This suggests that, at low emulsion contents, excessive amounts of water ensures more contact between the asphalt phase of emulsion and cement particles, which can impede the hydration process of cement. Alternately, at higher emulsion contents, increasing the water content results in better contact between the water (the added water and the water phase of emulsion) and cement, which may result in better hydration of cement within the ECPs.

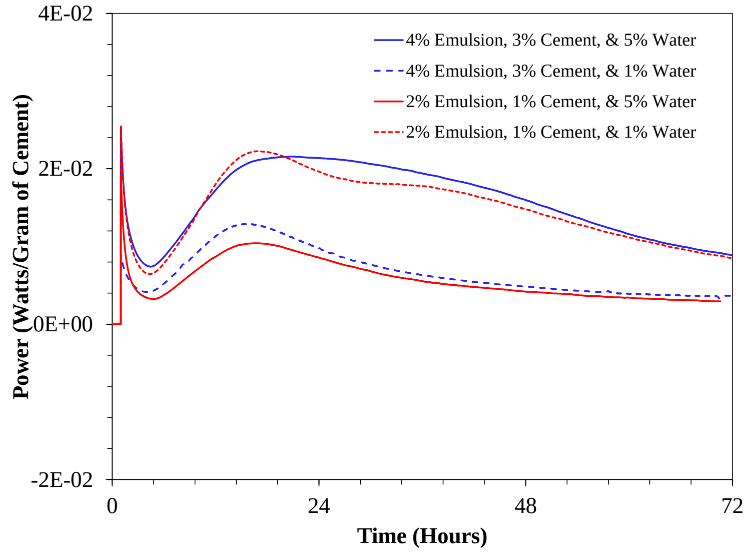


Figure 19. Impact of added water content on cement hydration

Chapter 5

Laboratory Assessment of the Density and Performance of CRMs

Overview of the Laboratory Testing Results of CRMs

This chapter discusses the laboratory testing results of CRMs at varying amounts of emulsion, cement, and water. The air void level was assessed using CoreLok device, rutting susceptibility was evaluated using APA test, and cracking resistance at low and intermediate temperatures were determined using SCB test. Performance testing results were then used to develop performance interaction charts using the BMD approach to select the optimal amounts of emulsion, cement, and water maximizing the cracking resistance and minimizing the rutting susceptibility.

Volumetric Results

The air void levels for the different CRMs at varying amounts of emulsion and cement contents at each water content are presented in Figure 20. At the same water and cement content, increasing the emulsion content resulted in a reduction of air voids by up to 3.0%. Furthermore, given the same dosages of water and emulsion, increasing the cement content from 1% to 3% caused a reduction in air void level by more than 5.0%. In this case, cement may act as a fine aggregate at higher dosage levels as there is not enough water to hydrate it. If so, the cement fills the voids between RAP aggregates, and consequently, reduces air void level.

Alternately, varying the water content did not result in a specific trend of air void level of CRM mixtures. For instance, increasing the water content from 1% to 3% at 2% and 3% cement content increased the air void level, while at 1% cement content, the increase in water content did not have a meaningful impact on CRM air void level. Further, increasing the water content to 5% caused a more pronounced influence on the air void level. At 1% cement and lower emulsion content, increasing the water content from 3% to 5% caused a considerable increase in air void by up to 4%, while at higher emulsion content, a meaningful drop of air void level can be observed by up to 5%. These results suggest that the increase in air void level of CRM mixtures could be due to the evaporation of water (both added water and the water phase of emulsion) during the curing process, which leaves behind air pockets. While the decrease of air void level when increasing cement and emulsion contents could be due to: (a) residual binder of emulsion filling up the spaces between RAP, or (b) excessive amounts of cement play the role of a filler.

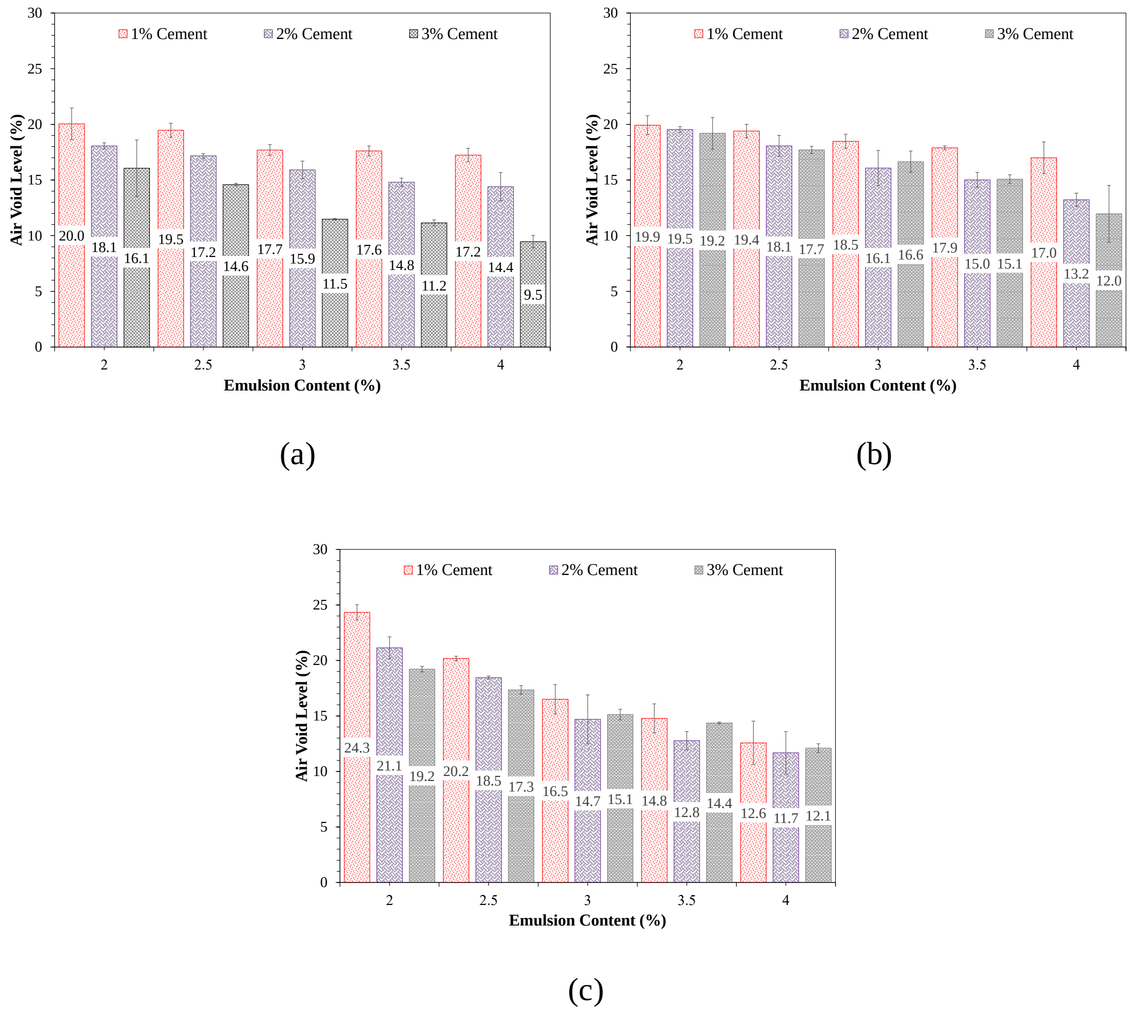


Figure 20. Volumetric analyses of emulsified asphalt CRM mixtures: (a) at 1% water content, (b) at 3% water content, and (c) at 5% water content

Rutting Susceptibility of CRM Mixtures

The results of APA rut depth for CRM mixtures prepared at varying amounts of emulsion (from 2% to 4%, by total weight), cement (from 1% to 3%, by total weight), and water (from 1% to 5%, by total weight) are presented in Table 11. Each CRM constituent had an impact on the rutting performance of these mixtures. Increasing the emulsion content increased the rutting susceptibility of CRM mixtures, given the same cement and water contents. This agrees with previous research on CRM mixtures (Cox and Howard 2015, Saidi et al. 2019a, Cross 1999).

Conversely, an increase in cement content from 1% to 3% improved the rutting resistance of CRM mixtures, at the same water and emulsion contents, most likely due to the reduction in air void level for these mixtures. Finally, a decrease in rut depth of up to 4 mm was observed with an increase in water content from 1-5%, while keeping emulsion and cement contents the same. It is also important to mention that mixtures prepared with 1% cement and 1% water had no structural strength after compaction and prior to testing. The specimens were crumbling after compaction, yet testable still. This explains the high APA rut depth values recorded for this mix design. The impact of water dosage on rutting performance could be due to additional water improving the hydration process of cement, which can provide more strength to CRM mixtures to resist rutting.

Table 11

APA Results of CRM Mixtures at Different Emulsion, Cement, and Water Contents (64°C)

		APA Rut Depth (mm)								
Water %		**1.0**			**3.0**			**5.0**		
Cement %		**1.0**	**2.0**	**3.0**	**1.0**	**2.0**	**3.0**	**1.0**	**2.0**	**3.0**
Emulsion %	**2.0**	9.6	8.0	7.3	6.5	5.9	4.9	9.4	7.9	4.4
	2.5	10.1	8.6	8.1	7.8	7.3	5.2	9.7	7.1	5.4
	3.0	12.1	11.6	8.7	8.2	7.6	6.5	7.2	6.4	7.3
	3.5	13.2	12.33	10.7	9.2	8.7	7.2	7.7	7.3	7.2
	4.0	Failed At 5,167 Cycles	14.1	12.4	11.9	10.2	9.7	9.7	8.1	7.7

Cracking Resistance of CRMs

The results of SCB peak load and fracture energy for CRM mixtures prepared at varying contents of emulsion, cement, and water (by total weight) are shown in Figures 21 through 26. All of the constituents increased the cracking resistance of CRM mixture, at both low and intermediate temperatures, as constituent (emulsion, cement, and water) quantity was increased.

Intermediate-Temperature Cracking

At intermediate temperatures, increasing the emulsion content (while keeping the water and cement contents constant) showed two types of trends of peak loads: (1) increasing trends for some CRM mixtures (e.g., mixtures prepared with 3% cement) and (2) trends with a peak for other mixtures (e.g., mixtures prepared with 1% water and 2% cement). These peak loads were associated with an emulsion content ranging between 2.5% and 3.5%, depending on cement and water contents (Figure 21). In addition, increasing the cement content, given the same amounts of water and emulsion, usually caused a reduction in peak load values of CRM mixtures. This could be due to the fact that, as cement content increases, CRM specimens tend to be more brittle (flexibility decreases), which makes the mixture more cracking susceptible. Moreover, increasing the water content from 1% to 5%, given the same emulsion and cement contents, did not seem to have much impact on the peak load values. In addition, no distinctive trend of peak load can be observed.

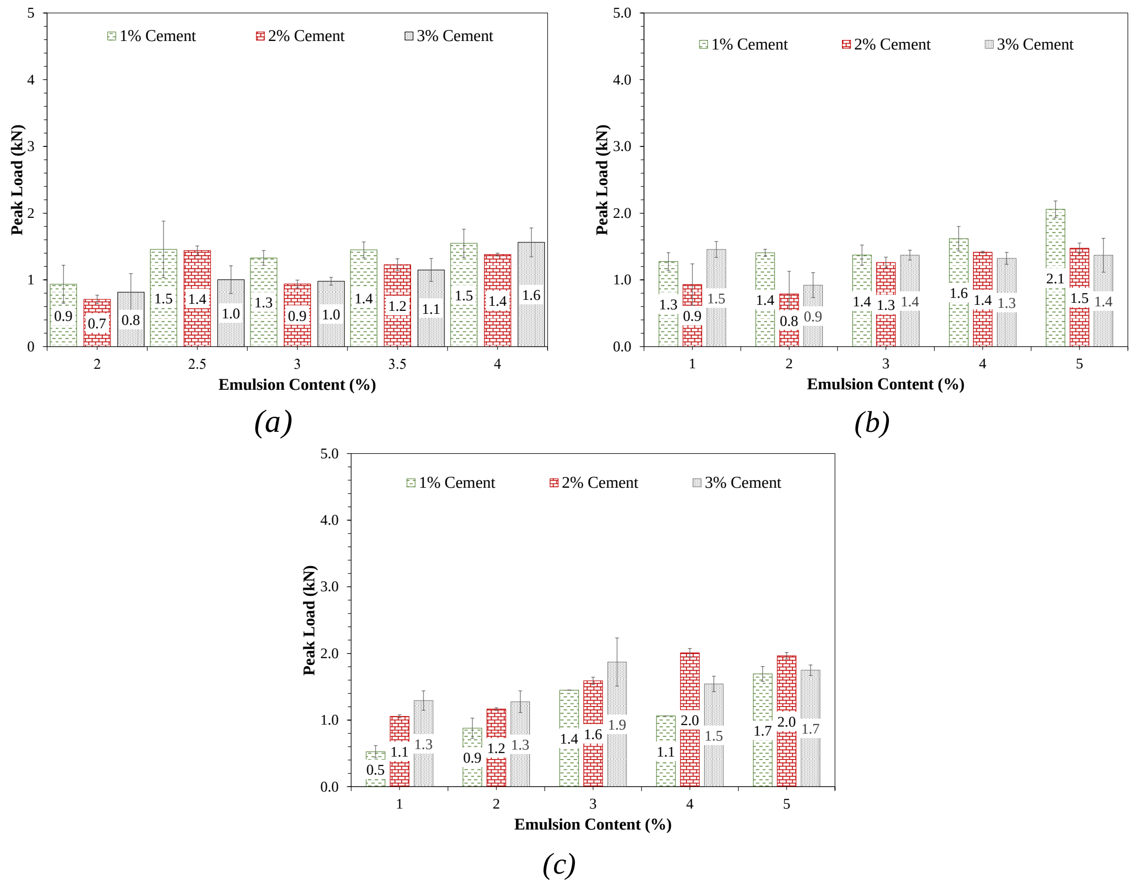


Figure 21. Peak loads of CRMs at different cement and emulsion contents (25°C): (a) at 1% water content, (b) at 3% water content, and (c) at 5% water content

Using the load-displacement curves (Figure 23) obtained from SCB test for each of the CRM mixtures, fracture energy was determined. Figure 22 illustrates the results of SCB fracture energy (SCB-FE) of the CRM mixtures at different emulsion, cement, and water contents, under intermediate temperature conditions. Given the same amounts of water and cement, increasing the emulsion content resulted in increasing trends of SCB-FE values for the CRM mixtures except for the mixes prepared with 2% cement and 1% water. Additionally, when cement content increases from 1% to 3%, given the same contents of emulsion and water, SCB-FE values decrease for the mixtures prepared at a water content of 3%, then increase at 5% water content, while presented increasing trends for the mixtures prepared at 1% water content. This suggests that, at low water contents (e.g., 1% by total mix weight) and at high cement contents (e.g., 2% and 3% by total mix weight), the performance of CRM mixtures is improving because water is hydrating more cement minerals without reaching a threshold of cement hydration at which the cracking resistance is reduced. In addition, when water and cement are used at 1%, CRM mixtures presented low SCB-FE values, which is expected as the specimens were weak in structure after compaction, as mentioned in the previous section.

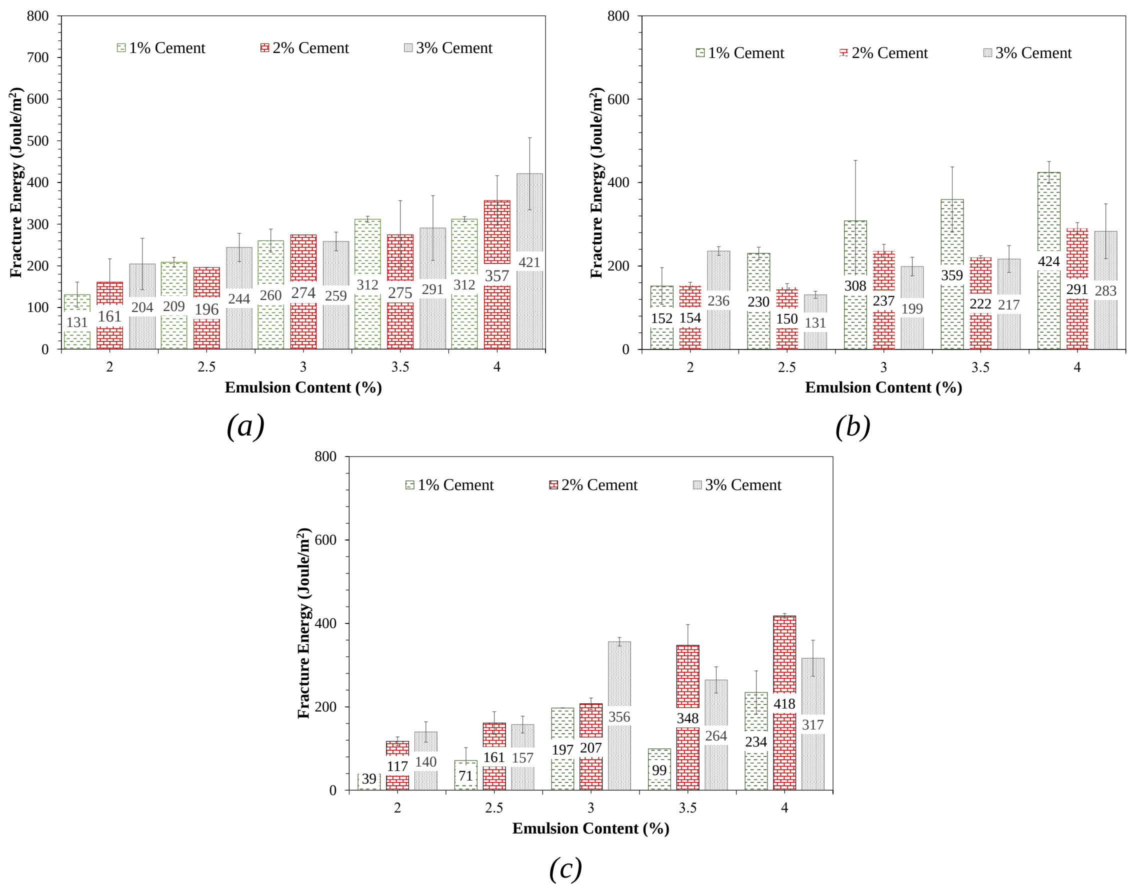
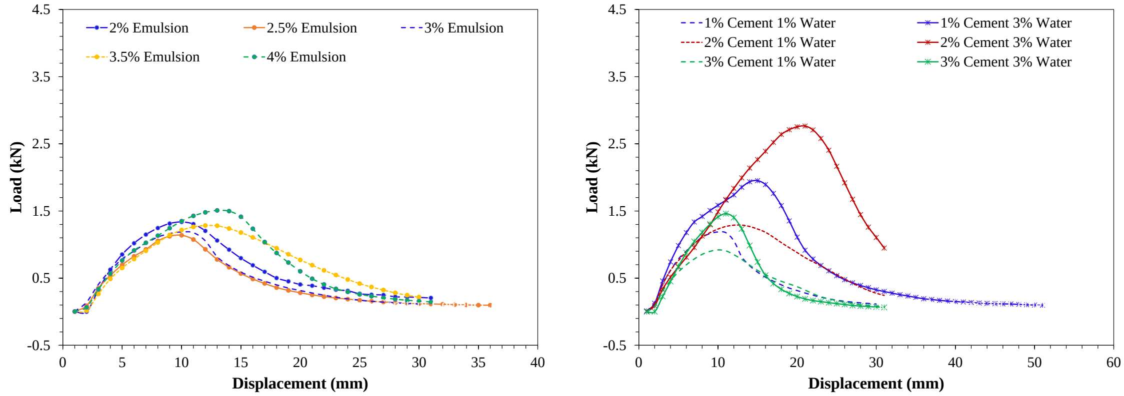


Figure 22. Fracture energy of CRMs at different cement and emulsion contents (25°C): (a) at 1% water content, (b) at 3% water content, and (c) at 5% water content

The variation of SCB loading magnitude in terms of displacement was analyzed and computed for the CRM mixtures at both low and intermediate temperatures. Example load displacement curves for mixtures prepared with varying amounts of emulsion, cement, and water at 25°C are presented in Figure 23. As emulsion content increased, given the same amounts of cement and water, both peak load and fracture time (at loading rate of 50 mm/min and 12.5 mm/min at 25°C and 0°C, respectively) increased as well. The emulsion in CRM mixtures improves the elasticity of these mixtures and improves their resistance to cracking.

The impact of cement and water on the peak load and fracture time of CRM mixtures is illustrated in Figure 23b. Increasing the cement content gradually from 1% to 3% had a negative impact on both peak load and fracture time. As cement content increases, the elasticity of emulsion decreases, and flexibility of CRM mixtures decreases as well. Therefore, the cracking susceptibility of CRM mixtures increases. On the other hand, the increase of water from 1% to 3% seemed to improve the peak load and fracture time of CRM mixtures. This implies that the addition of increased amounts of water can improve the hydration process of cement, which will provide more strength to CRM mixtures. Therefore, the cracking resistance is improved.



a. *b.*

Figure 23. Load-displacement curves of CRMs at 25°C: (a) at varying emulsion contents and (b) at varying cement and water contents

Low-Temperature Cracking

At 0°C (Figure 24), increasing the emulsion contents caused an increase in peak load by up to 50% for the CRM mixtures. This highlights the impact of reducing the testing temperature, which increases the stiffness of CRM and makes it more resistant to loading. Similar increasing and load trends with a peak are also observed to ones tested at intermediate temperature as emulsion, and cement contents varied.

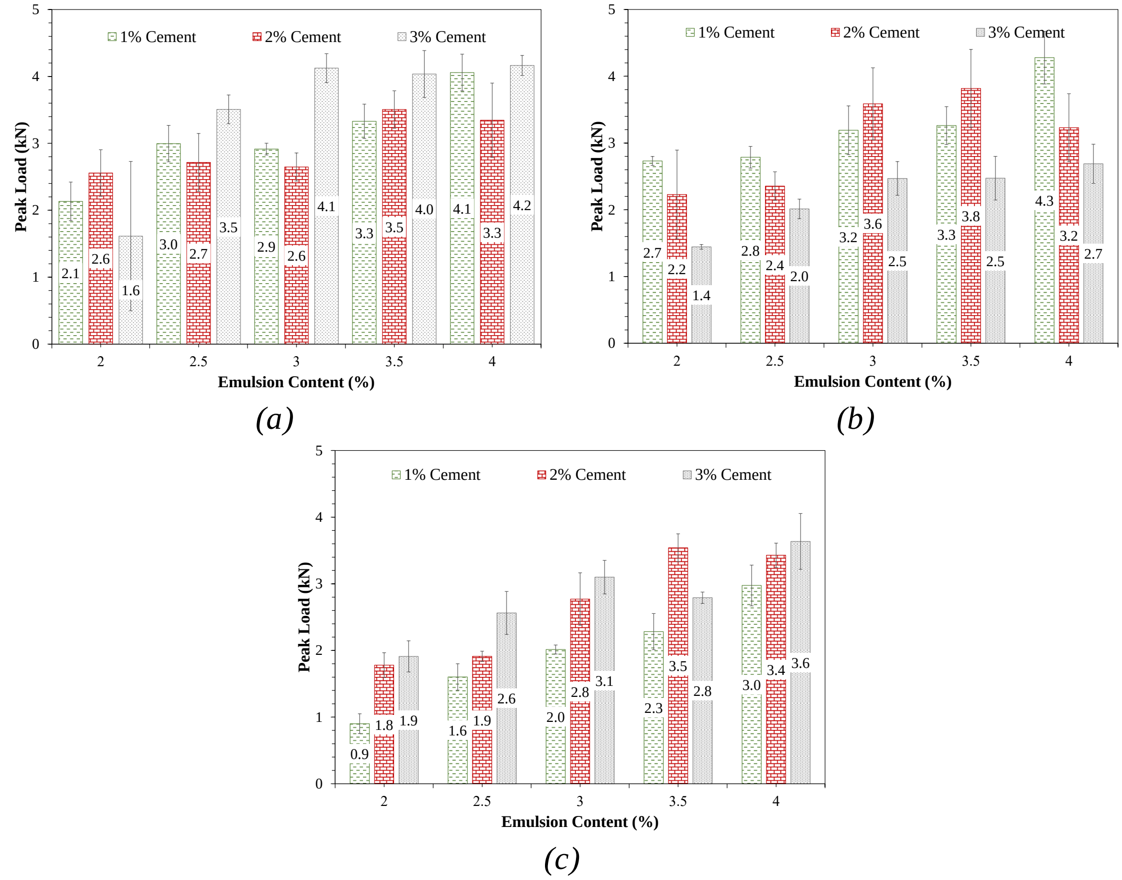


Figure 24. Peak loads of CRMs at different cement and emulsion contents (0°C): (a) at 1% water content, (b) at 3% water content, and (c) at 5% water content

The results of SCB fracture energy (SCB-FE) tests of the CRM mixtures at different emulsion, cement, and water contents, under low temperature conditions (0°C) are illustrated in Figure 25. Increasing the emulsion contents resulted in trends with a peak of SCB-FE values. Similarly to the SCB-FE results obtained at 25°C, increasing the cement content resulted in decreasing SCB-FE values for the mixtures prepared at 1% water content (when cement content passes from 1% to 2%) and increasing SCB-FE values when cement content passes from 2% to 3%. At 3% water and 2%, 2.5%, or 4% emulsion, the SCB-FE values presented decreasing trends, while a trend with a peak of SCB-FE was observed at 3% and 3.5% emulsion. At 5% water content, increasing trends of SCB-FE values were observed when emulsion contents ranged between 2% and 3%, while trends with a peak of SCB-FE were seen at higher emulsion contents (3.5% and 4%). Overall, CRMs prepared with lower cement contents (1% and 2%) at high emulsion contents (3.5% and 4%) presented the highest peak load and SCB-FE values. This was expected as the ductility of CRMs improve at low temperatures with the increase of emulsion and the decrease of cement.

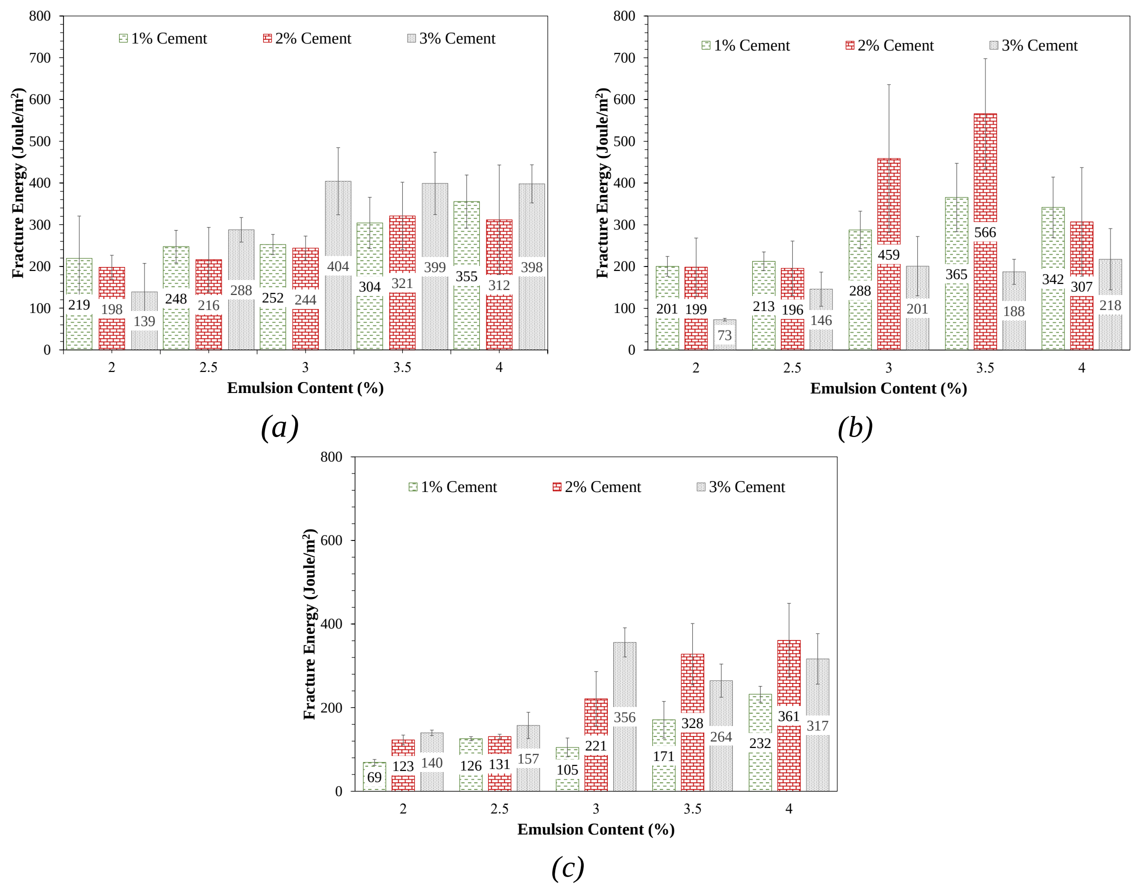
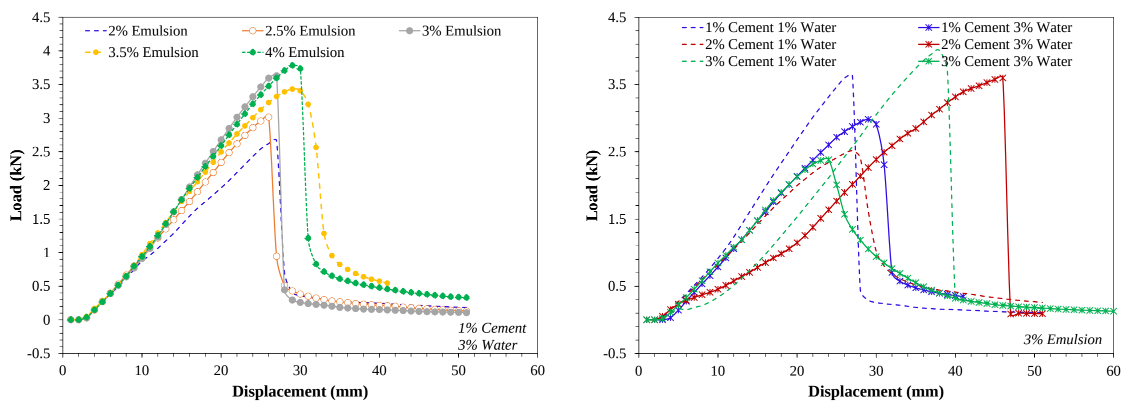


Figure 25. Fracture energy of CRMs at different cement and emulsion contents (0°C): (a) at 1% water content, (b) at 3% water content, and (c) at 5% water content

The variation of SCB loading magnitude in terms of displacement was also evaluated for the CRM mixtures at low temperature. Examples of load displacement curves for mixtures prepared with varying amounts of emulsion, cement and water at 0°C are presented in Figures 26an. As emulsion content increased (Figure 26a), both peak load and fracture time increased as well. At 1% water and 3% cement, the best cracking resistance of CRM mixtures was achieved at an emulsion content of 3.5%, by total mix weight. This may imply that at low temperatures, lower emulsion content is needed to provide CRMs with a satisfactory resistance to thermal cracking. Similarly to the results under intermediate conditions, increasing the cement reduced the peak load and delayed the fracture time at low temperature, while increasing the water content increased the peak load and fracture time values (Figure 26b).



(a) *(b)*

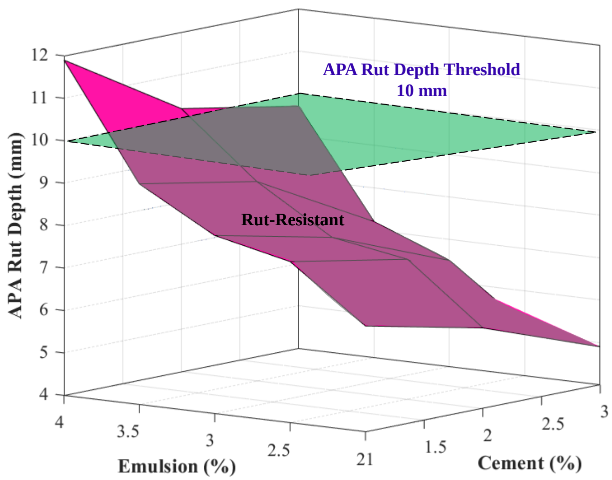
Figure 26. Load-displacement curves of CRMs at 0°C: (a) at varying emulsion contents and (b) at varying cement and water contents

Performance Interaction Charts for CRMs

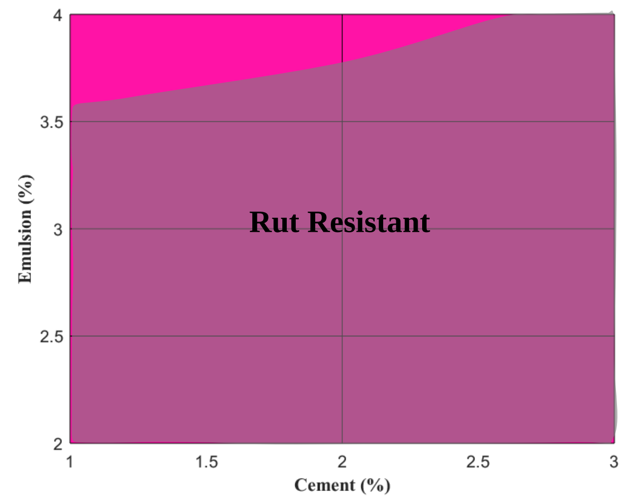
As part of this research study, it was important to identify mixtures that can exhibit an optimal resistance to rutting, fatigue and thermal cracking. Thus, for this effort, performance interaction charts were developed displaying the relationship between CRM rutting measures (APA rut depth) and cracking measures (SCB-FE at $0^{o}C$ and $25^{o}C$) following the BMD approach. The contents of emulsion and cement were used as factors in the performance interaction charts at different water contents. Each performance interaction chart includes four main areas, as presented in Figure 27:

- *Crack resistant*: only cracking measures of CRM mixes are within threshold,
- *Rut resistant*: only rutting measures of CRM mixes are within threshold;
- *Balanced performance*: when both rutting and cracking measures fall within their respective thresholds; and,
- *Weak performance:* neither performance measures are within respective thresholds.

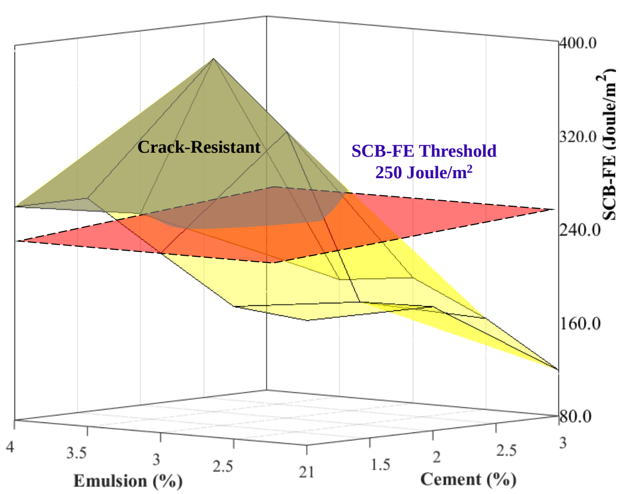
Based on literature, the thresholds used for the CRM performance interaction charts were selected as APA rut depth threshold of 10 mm and SCB-FE threshold 250 Joule/m^2 (equivalent to 1 MPa) (Saidi et al.2019a). Thus, CRMs are rut resistant when their APA rut depth falls within the grey-shaded area of the chart in Figures 27a and 27b, while CRMs are crack resistant when their SCB-FE at $0^{o}C$ and $25^{o}C$ falls within the grey-shaded area in Figures 27c and 27d, respectively. The intersection between the rut-resistant and crack-resistant areas results in the balanced-performance area, where rutting and cracking performances are both within respective thresholds (Figures 27e and 27f). From the performance interaction charts, one can determine the balanced contents for emulsion and cement at different water contents. The final step consists of determining the balanced water content from the balanced CRMs (at optimum emulsion and cement contents) by selecting those with highest SCB-FE (either at $0^{o}C$ or $25^{o}C$) and lowest APA rut depth values. If the performance of CRMs at the balanced water contents is not statistically significant, then the optimum water content should be selected based on the cost-efficiency of the materials (emulsion, cement, and water). If designed properly, performance interaction charts will help practitioners and CRM designers select the contents of materials providing CRMs with a good resistance to rutting, cracking, or both.



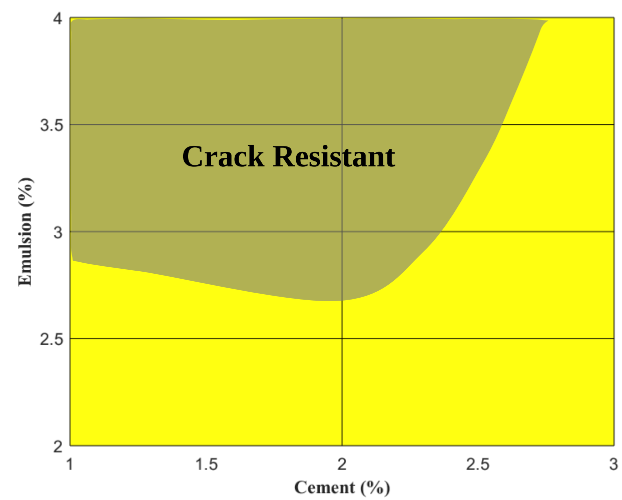
(a) APA rut Depth at 3% Water



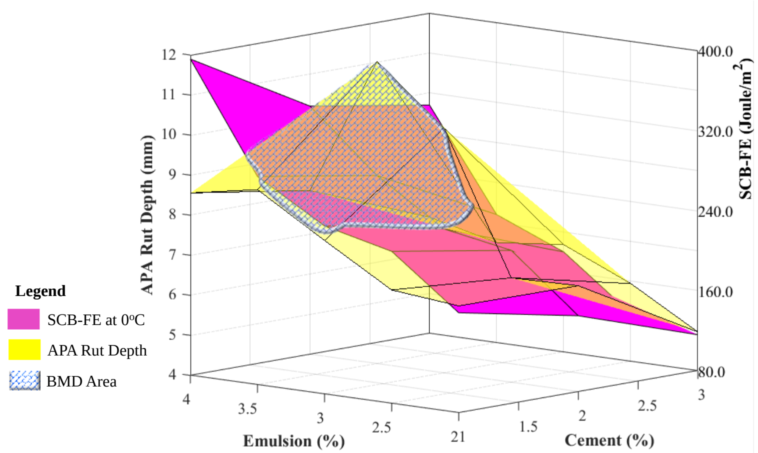
(b) Top view of the Rut-Resistant Area



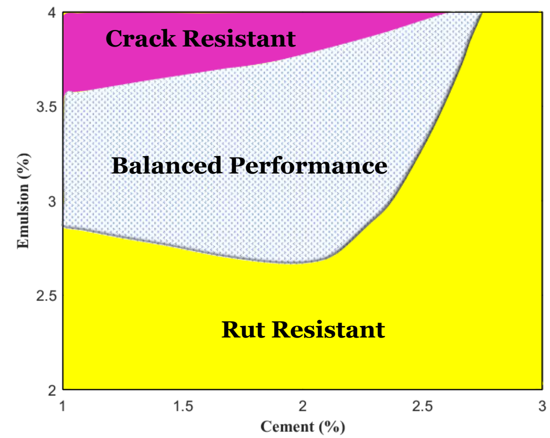
(c) SCB-FE at 0°C



(d) Top view of the Crack-Resistant Area



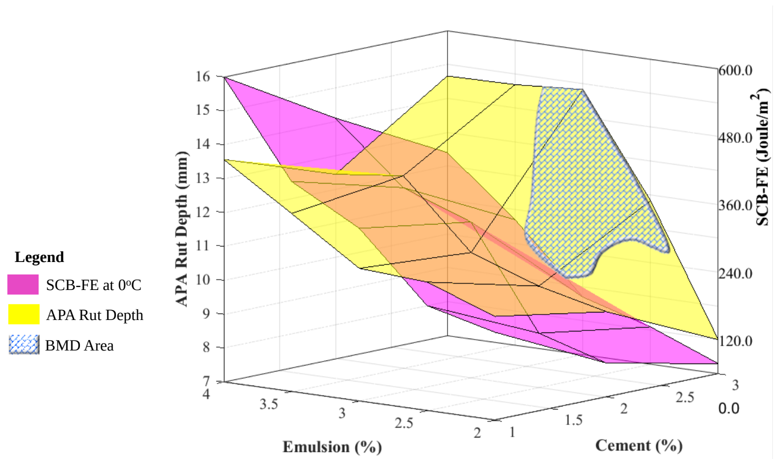
(e) Balanced-Performance Area



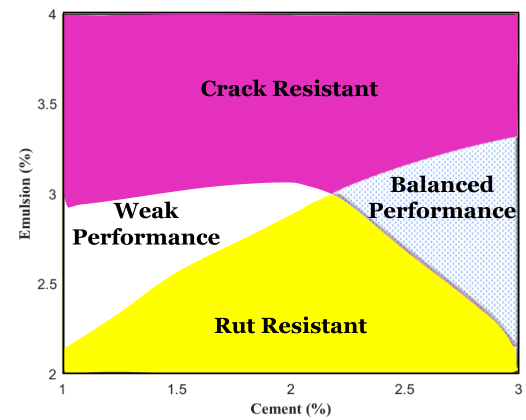
(f) Top view of the Performance-based Area

Figure 27. Process for developing performance interaction charts

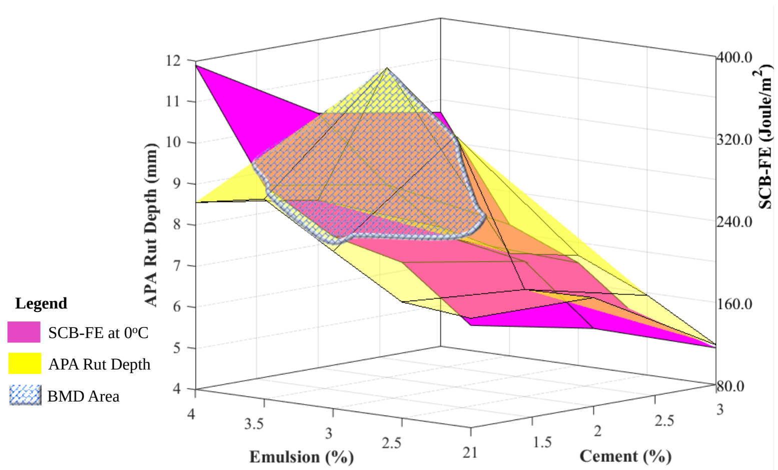
Performance interaction charts were developed in terms of the percentage amounts of emulsion and cement at varying amounts of water contents (1%, 3%, and 5%), as illustrated in Figures 28 and 29. Balanced-performance areas were identified at all the water contents and SCB testing temperatures. Also, there are weak performance areas at lower emulsion and cement contents. At 1% water, the balanced-performance areas are relatively smaller (Figure 28a, 28b, 29a, and 29b) compared to those at higher water contents. In addition, these balanced-performance areas are found at high cement contents (2% - 3%) and at emulsion contents ranging between 1.5% and 3.5%. As the water content increases to 3%, the balanced-performance areas became larger, while the weak-performance areas disappeared from the charts (Figure 28c, 28d, 29c, and 29d). At 3% water, the balanced cement contents ranged between 1% and 2.6%, while the balanced emulsion contents ranged between 2.7% and 4%. As the water increases to 5% (Figure 28e, 28f, 29e, and 29f), the balanced-performance area was slightly shifted to the right (towards higher cement contents). The balanced cement contents ranged from 1.3% to 3%, while the balanced emulsion contents ranged between 2.5% and 4%. Based on the performance interaction charts, several combinations of emulsion, cement, and water can lead to balancing the performance of CRMs. The following step was to select optimum contents of emulsion, cement, and water from the balanced-performance areas at both low (10^{o}C) and intermediate (25^{o}C) temperatures.



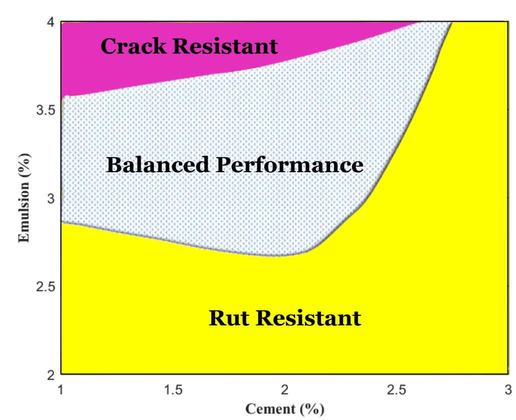
(a) *At 1% Water*



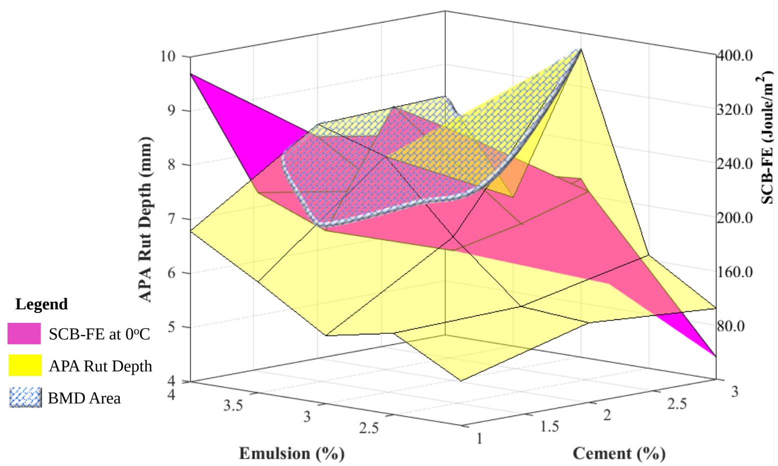
(b) Top View at 1% Water



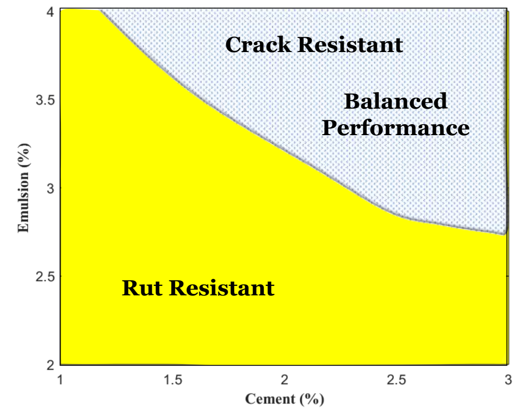
(c) *At 3% Water*



(d) Top View at 3% Water

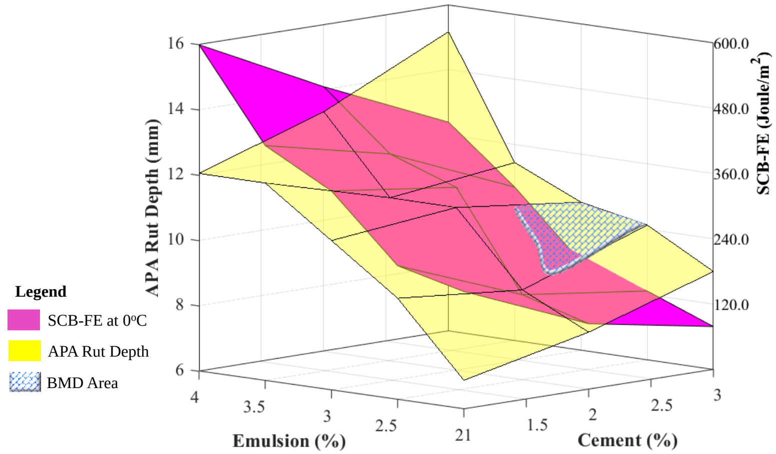


(e) *At 1% Water*

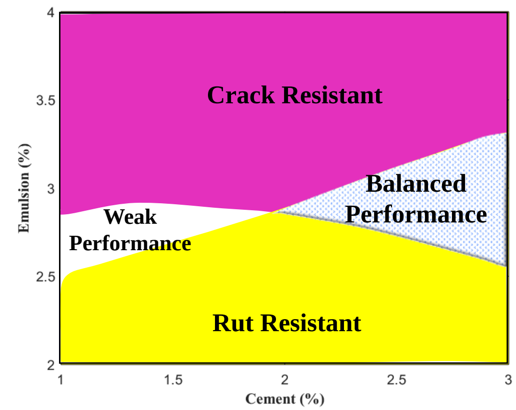


(f) Top View at 5% Water

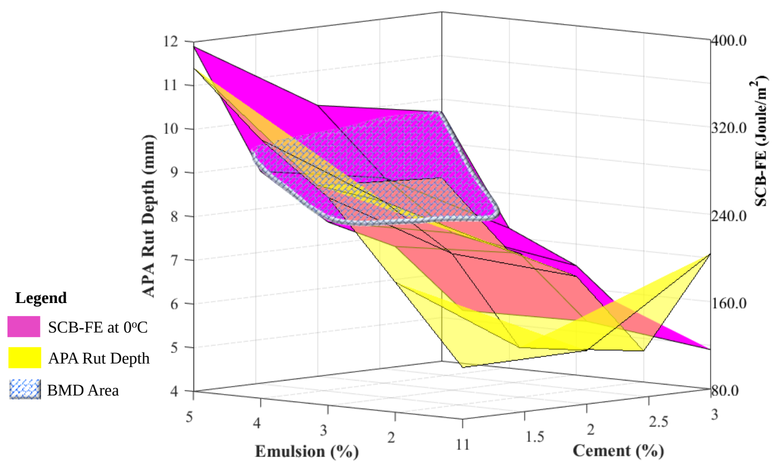
Figure 28. Performance interaction charts of CRMs at 0°C



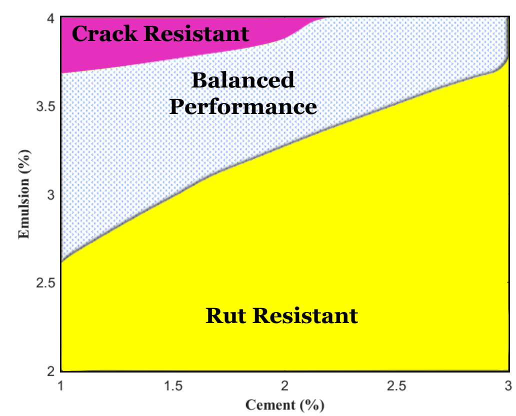
(a) At 1% Water



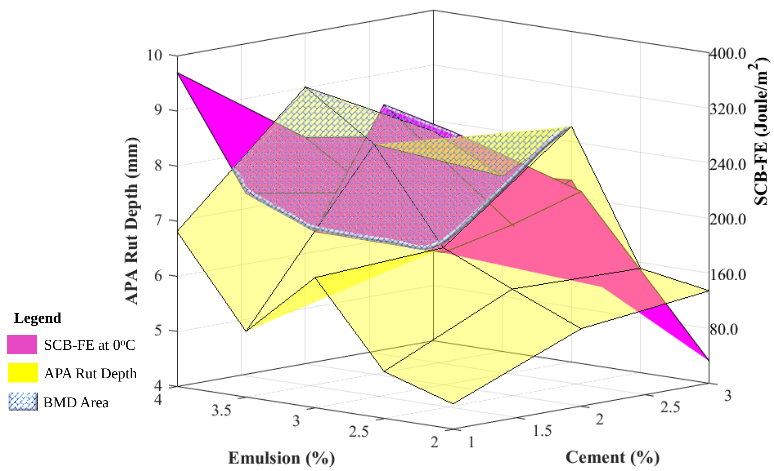
(b) Top View at 1% Water



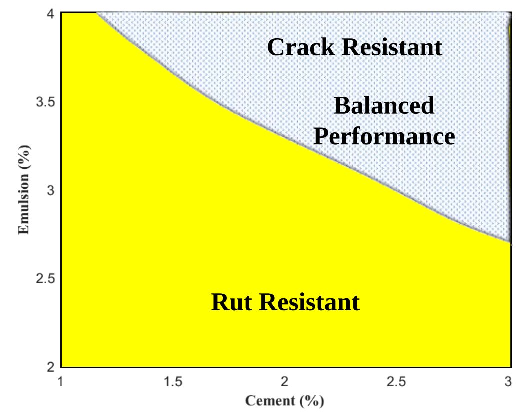
(c) At 3% Water



(d) Top View at 3% Water



(e) At 5% Water



(f) Top View at 5% Water

Figure 29. Performance interaction charts of CRMs at 25°C

From the balanced-performance areas obtained at 1%, 3%, and 5% water contents and using the performance interaction charts at 0°C and 25°C, the optimum emulsion and cements contents were determined as the minimum contents needed to balance the performance of CRMs in terms of rutting and cracking. The results of optimum emulsion and cement contents based on the performance interaction charts are presented in Table 12. The optimum contents of emulsion and cement were relatively similar at 0°C and 25°C. At optimum emulsion and cement contents, the APA rut depths of CRMs were within 1 mm at the various water contents. Similarly, both low-temperature rutting and fatigue cracking performances are relatively similar at all water contents, with SCB-FE value within 30 Joules/m^2. This suggests that the selection of the optimum water content should not be based only on the performance. The amounts of emulsion and cement should also be considered because these are the more costly components. Therefore, the optimum water content of CRMs designed for low and intermediate temperatures is 3%. Thus, the optimum contents of CRM constituents at 0°C are:

1- Emulsion content: 2.9% by mix weight;
2- Cement content: 1% by mix weight; and,
3- Water content: 3% by mix weight.

Alternately, the optimum contents of CRM constituents at 25°C are:

1- Emulsion content: 2.5% by mix weight;
2- Cement content: 1% by mix weight; and,
3- Water content: 3% by mix weight.

Table 12

Optimum Emulsion and Cement Contents at Different Water Contents

Temperature (^oC)	Optimum Emulsion (%)	Optimum Cement (%)	Water (%)	APA Rut Depth (mm)	SCB-FE (J/m^2)
0^oC	3	2.2	1	9.1	262.4
	2.9	1	3	8.2	273.5
	4	1.3	5	8.0	283.5
25^oC	2.7	2	1	9.1	273.5
	2.5	1	3	8.2	290
	4	1.3	5	8.0	300.2

Chapter 6

Statistical Analyses

Overview of the Results of Statistical Analyses

The impact of varying the proportions of emulsion, cement, and water on the properties of ECP and the density and performance of CRMs was statistically assessed using multivariate analysis of variance (MANOVA) and Bonferroni-adjusted post-hoc analysis. The analyses were performed on a 95% confidence level, which means that a significant impact is identified when p-value is less than 0.05. Regression analyses were also conducted to assess the correlation between the testing parameters for ECPs and those for CRMs. The following subsections discusses the results of MANOVA, post-hoc, and regression analyses.

Verification of MANOVA Assumptions

Prior to conducting statistical analyses, two assumptions of MANOVA were tested on the selected dependent (performance measures such as creep stiffness and m-value) and independent variables (emulsion, cement, and water contents). The assumptions considered for MANOVA are as follows: (a) linear relationship between dependent variables, (b) no multicollinearity between dependent variables, (c) no outliers, and (d) multivariate normality. It is important to mention that a few assumptions such as equality of covariance matrices and homogeneity of variances were not performed as the size of samples was not sufficiently large.

The correlation between the dependent variables (performance testing parameters) were assessed in this study. Results are presented in Table 18 and discussed further towards the end of Chapter 6. Based on the results of Pearson correlation (Table 18), there is a linear relationship between the testing parameters for both ECPs and CRMs. Alternately, all Pearson correlations were smaller than 85%, which suggests that there is no strong correlation between the dependent variables. Therefore, linearity relationship and no multicollinearity assumptions were met for MANOVA. The multivariate normality is sensitive to outliers (univariate and multivariate). To verify this assumption, there should be a linear relationship between each pair of dependent variables at each level of independent variables. One way to assess the no outliers assumption is through determining the maximum Mahalanobis distance using linear regression analyses. The results of maximum Mahalanobis distance (for ECPs and CRMs) are then compared to the critical values of degree of freedom. For ECP testing parameters, the degree of freedom (df) is 8 (the number of dependent variables), therefore, the critical value of df is 26.13 for ECPs. While for CRM testing parameters, df is 3, which corresponds to a critical value of df of 16.27. The results of residual statistics from linear regression analyses showed that only 4 outliers from 90 were higher than df critical values for both ECPs and CRMs. Overall, the assumption of no multivariate outliers was considered met. The next step was to test the normality relationship between the dependent variables. Based on normality indices such as skewness and ketosis, the multivariate normality assumption did not hold for all the dependent variables of ECPs (i.e., assumption was met for LAS-FE, hydration power, and penetration at 25^{o}C, while was not met for creep stiffness and m-value). Nevertheless, the multivariate normality assumption was met for all CRMs' dependent variables.

Statistical Evaluation of ECPs' Testing Results

After verifying the abovementioned assumptions, MANOVA analyses were performed on performance measures for ECPs: creep stiffness at 0°C, m-value at 0°C, LAS-FE at 25°C, J_{nr} at 0.01 KPa and 3.2 KPa at 64°C, and penetration depth at 10°C, 25°C, and 40°C are presented (Table 13). Varying the amounts of one ECP constituent (emulsion, cement, or water) had a significant impact on both rheological and mechanical properties of ECP. Similarly, the interactions between (a) emulsion and cement and (b) emulsion and water had a significant impact on all the testing parameters for ECP. However, the interactions between emulsion and water did not present a statistically significant impact on m-value and LAS-FE, while the interaction between the three constituents presented a significant impact on all the testing parameters except for m-value. Overall, MANOVA results suggested that the rutting measures (J_{nr} at 0.1 KPa and 3.2 KPa) were able to capture the variation in the amounts of ECP constituents. As per cracking, LAS-FE (at 25°C) and creep stiffness (at 0°C) presented a high sensitivity to the change in the amounts of emulsion, cement, and water.

Table 13

Results from MANOVA for ECP Performance Measures

Source	Significance (p-value < 0.05)?							
	p-value = 0.01							
	Creep Stiffness	m-Value	LAS-FE	J_{nr} (kPa)		Penetration		
				0.1	3.2	10°C	25°C	40°C
Emulsion	.001	.027	.001	.001	.001	.001	.001	.001
Cement	.001	.001	.001	.001	.001	.001	.001	.001
Water	.001	.001	.001	.001	.001	.016	.001	.001
*Emulsion * Water*	.001	**.109**[**]	**.192**[**]	.001	.001	.003	.001	.001
*Emulsion * Cement*	.001	.016	.001	.001	.001	.001	.001	.001
*Water*Cement*	.001	.028	.001	.001	.001	.001	.001	.001
*Emulsion*Cement*Water*	.001	**.184**[**]	.001	.001	.001	.006	.001	.001

[**] denotes combinations that were smaller than the 95% confidence level

The family-wise error rate (FWER) was then calculated using the equation below to determine the probability of rejecting the null hypothesis that is true.

$$FWER = 1 - (1 - \alpha)^n \tag{2}$$

Where α is the significance level (0.05) and n is the number of tests.

The FWER was determined for each of the independent variables (emulsion content, cement content, and water content). Results showed a higher FEWR (40%) for emulsion content followed by a FWER of 19% for both cement and the water content. This suggest that the impact of varying emulsion, cement, and water content on the rheological and mechanical properties of ECPs might not be statistically significant for certain combinations although it was found significant using MANOVA. Therefore, Bonferroni-adjusted post hoc analyses were conducted on ECP testing results to assess the impact of the selected amounts of ECP constituents, individually, on the rheological and mechanical properties of ECPs. The results of post hoc analyses for emulsion, cement, and water, respectively are presented in Tables 14 through 16. Changing the emulsion contents from 2% through 4%, with 0.5% increments, presented a significant impact on J_{nr} at 0.1 KPa, at 3.2 KPa, penetration at 25^{o}C, and at 40^{o}C. Although MANOVA analyses showed that emulsion presented a significant impact on creep stiffness, m-value, and LAS-FE, this was not the case at all the emulsion contents as presented in Table 14. In fact, increasing the emulsion content from 3% to 3.5%, 3.5% to 4%, or 3% to 4% did not impact the creep stiffness of ECP significantly. Similarly, varying the emulsion content did not present a significant impact on m-value except for when increasing it from 2% to 2.5%. While for LAS-FE, varying the emulsion contents did not show a distinctive pattern for when the impact is significant. For instance, increasing emulsion from 2% to 2.5% or to 4% did not result in a significant change of LAS-FE results, while increasing the emulsion content from 2% to 3% or to 3.5% presented a significant impact on LAS-FE of ECP.

Table 14

Results from Adjusted Post-Hoc Analyses in Terms of Emulsion

Emulsion	Bonferroni-adjusted Post-Hoc Analysis (Sig.)							
	Creep Stiffness	m-Value	LAS-FE	J_{nr} (kPa)		Penetration		
				0.1	3.2	10°C	25°C	40°C
2% & 2.5%	.001	.023	**1.00****	.001	.001	.001	.001	.001
2% & 3%	.001	**1.00****	.004	.001	.001	.001	.001	.001
2% & 3.5%	.001	**1.00****	.028	.001	.001	.001	.001	.001
2% & 4%	.001	**.126****	**1.00****	.001	.001	.001	.001	.001
2.5% & 3%	.011	**1.00****	.001	.001	.001	**.099****	.001	.001
2.5% & 3.5%	.004	**.827****	.004	.001	.001	.001	.001	.001
2.5% & 4%	.001	**1.00****	**.355****	.001	.001	.001	.001	.001
3% & 3.5%	**1.00****	**1.00****	**1.00****	.001	.001	.001	.001	.001
3% & 4%	**.682****	**1.00****	**.213****	.001	.001	.001	.001	.001
3.5% & 4%	**1.00****	**1.00****	**.964****	.001	.001	.001	.001	.001

** denotes combinations that were smaller than the 95% confidence level

The results of Bonferroni-adjusted post hoc analyses conducted on ECP testing results at different cement contents are presented in Table 15. Increasing the cement content had a significant impact on creep stiffness, m-value, J_{nr} at 0.1 KPa and 3.2 KPa, and penetration at 10°C, 25°C, and 45°C. However, increasing the cement content from 1% to 2% did not have a significant impact on the LAS-FE, suggesting that at these contents, ECP may exhibit similar resistance to fatigue cracking.

Table 15

Results from Adjusted Post-Hoc Analyses in Terms of Cement

Cement	Bonferroni-adjusted Post-Hoc Analysis (Sig.)							
	Creep Stiffness	m-Value	LAS-FE	J_{nr} (kPa)		Penetration		
				0.1	3.2	10°C	25°C	40°C
1% & 2%	.005	.001	**.152****	.001	.001	.001	.001	.001
1% & 3%	.001	.001	.001	.001	.001	.001	.001	.001
2% & 3%	.001	.032	.001	.001	.001	.023	.001	.001

** denotes combinations that were smaller than the 95% confidence level

The results of Bonferroni-adjusted post hoc analyses for different water contents are presented in Table 16. Increasing the water content had a significant impact on J_{nr} at 0.1 KPa and 3.2 KPa, and penetration at 25°C and 45°C. However, the impact of varying water content was not significant for the following performance measures when increasing the water content from: (1) 3% to 5% for creep stiffness, (2) 1% to 3% for m-value and LAS-FE, and (3) 1% to 5% for penetration at 10°C.

Table 16

Results from Adjusted Post-Hoc Analyses in Terms of Water

Water	Bonferroni-adjusted Post-Hoc Analysis (Sig.)							
	Creep Stiffness	m-Value	LAS-FE	J_{nr} (kPa)		Penetration		
				0.1	3.2	10°C	25°C	40°C
1% & 3%	.001	**1.00****	**.150****	.001	.001	.035	.001	.001
1% & 5%	.001	.001	.001	.001	.001	**1.00****	.001	.001
3% & 5%	**.170****	.001	.001	**.053****	.001	.038	.001	.001

** denotes combinations that were smaller than the 95% confidence level

In summary, MANOVA and Bonferroni-adjusted post hoc analyses demonstrated that varying the amounts of emulsion, cement, and water influence the rheological and mechanical properties of ECP. The level of influence tends to increase at higher testing temperatures (MSCR at 64°C and penetration at 40°C), while the significance of this impact decreases at intermediate and lower testing temperatures (BBR at 0°C and LAS at 25°C). Overall, the following performance measures showed the highest sensitivity to the change in the amounts of ECP's contents:

- J_{nr} at 0.1 KPa^{-1} or 3.2 KPa^{-1} as rutting measure.
- LAS-FE as a fatigue cracking measure.
- BBR creep stiffness as a low-temperature cracking measure.

Statistical Evaluation of CRMs' Testing Results

Results from MANOVA analyses for CRM air void level, APA rut depth, and SCB fracture energy at 0°C and 25°C are presented in Table 17. Varying the amounts of emulsion, cement, and water had different effects on the density and performance of CRM mixtures. For instance, the emulsion content had significant impact on air void level, rutting, and cracking performance of CRM mixtures (p-value < 0.05). While varying the contents of cement or water showed significant impact only on air void level and APA rut depth. P-values measured for SCB-FE at 0^{o}C and 25^{o}C were 0.336 and 0.212, respectively, which indicates varying the cement content did not have a significant impact on the cracking resistance of CRM mixtures. Similarly, water content showed a significant impact on air void level and rutting performance and not on cracking resistance (p-values of 0.470 and 0.239 for SCB-FE at 0^{o}C and 25^{o}C, respectively).

The factor interactions between the CRM constituents were included in the MANOVA. From Table 17, the interaction between the amounts of emulsion and cement had a significant impact only on the air void level of CRM mixtures. While the interaction of the amount of emulsion and water did not show any significant impact on CRM air void level and performance measures. Alternately, the interaction between the amounts of emulsion, cement, and water had significant impact on air void level, APA rut depth, and cracking resistance of CRM mixtures (p-value less than 0.05).

Table 17

Results from MANOVA Analyses of CRMs

Source	**Significance (p-value < 0.05)?**			
	p-value = 0.017			
	Air Void	**APA Rut Depth**	**SCB-FE at 0°C**	**SCB-FE at 25°C**
Emulsion	.000	.000	.004	.000
Cement	.000	.000	**.336**	**.212**
Water	.007	.000	**.470**	**.239**
*Emulsion * Cement*	.027	**.622***	**.535**	**.205**
*Emulsion * Water*	**.187***	**.089***	**.580**	**.621**
Water to Cement Ratio	.000	.030	.016	.000
*Emulsion*Cement*Water*	.000	.023	.031	.001

*denotes combinations that were smaller than the 95% confidence level

Assessment of Relationships between ECP and CRM Testing Parameters

Correlation between ECP Properties and CRM Performance

The relationships between the parameters from binder testing for ECPs (MSCR, LAS, BBR, penetration test, and isothermal calorimeter) and mixture testing for CRMs (APA, SCB at 0°C, and SCB at 25°C) were developed to identify similarities between rutting and cracking measures for ECPs and CRMs.

A Pearson correlation matrix was generated to compare: (1) between the performance measures of ECPs, and (2) the performance measures of ECPs to those of CRMs. A 95% confidence level was also selected to determine the significance of each correlation coefficient. The coefficients of Pearson correlation for all cracking and rutting measures considered in this study are presented in Table 18.

The hydration power, also designated as hydration rate obtained from the isothermal calorimetry test, correlated well with BBR parameters (creep stiffness and m-value). However, the correlation between the hydration power and penetration at 10°C was weak (0.238). This suggests that the hydration rate of cement correlates strongly with the strength of ECPs at low temperatures. Conversely, weaker correlations were observed between creep stiffness and m-value, penetration at 10°C and m-value, and creep-stiffness and penetration at 10°C. At intermediate temperature (25°C), the hydration power presented stronger correlation with LAS-FE (Pearson coefficient of 0.655) than the other correlations of hydration power with penetration at 25°C (Pearson coefficient of 0.566), followed by the correlation of LAS-FE with penetration at 25°C (Pearson coefficient of 0.367). Alternately, the MSCR parameters J_{nr} at 0.1 kPa presented a strong correlation with J_{nr} at 3.2 kPa with Pearson coefficient of 0.988. Similarly, the penetration at 40°C correlated well with J_{nr} at 0.1 (Pearson coefficient of 0.76) and J_{nr} 3.2 (Pearson coefficient of 0.757), while the hydration power presented weaker correlations with all testing parameters at high temperatures. The underlying relationships that exist between these testing parameters (at low, intermediate, and high temperatures) of ECP are highlighted in Table 18. Further, this table showed that stronger correlations were observed for (1) hydration power with creep stiffness at low temperature (0°C), (2) hydration power with LAS-FE at intermediate temperature (25°C), (3) J_{nr} 0.1 kPa with penetration at 40°C, and (4) J_{nr} 0.1 kPa with J_{nr} 3.2 kPa at 64°C.

Table 18

Pearson Correlation Matrix for Binder-Scale Tests of ECP

Cracking Performance at Low Temperatures				
Testing Parameters	Creep Stiffness	m-value	Pen. at 10°C	Hydration Power
Creep Stiffness	1	0.539	0.277	0.844
m-Value	0.539	1	0.429	0.734
Penetration at 10°C	0.277	0.429	1	0.238
Hydration Power	0.844	0.734	0.238	1
Cracking Performance at Intermediate Temperatures				
Testing Parameters	LAS-FE	Pen. at 25°C	Hydration Power	
LAS-FE	1	0.367	0.655	
Penetration at 25°C	0.367	1	0.566	
Hydration Power	0.655	0.566	1	
Rutting Performance at High Temperatures				
Testing Parameters	J_{nr} at 0.1	J_{nr} at 3.2	Pen. at 40°C	Hydration Power
J_{nr} at 0.1	1	0.988	0.76	0.304
J_{nr} at 3.2	0.988	1	0.757	0.317
Penetration at 40°C	0.76	0.757	1	0.542
Hydration Power	0.304	0.317	0.542	1

Relationships between the testing parameters of ECPs and those of CRMs were also developed to assess the correlations between the rheological and mechanical properties of ECPs with the rutting and cracking performance of CRMs. Pearson correlation coefficients for ECP and CRM testing parameters at low temperatures are presented in Table 19. The Pearson coefficients were low, indicating that correlations between SCB-FE at 0°C of CRMs and BBR and penetration testing parameters are weak.

The Pearson correlation coefficients for ECP and CRM testing parameters at intermediate temperatures are presented in Table 20. A relatively higher Pearson coefficient (0.404) was observed between SCB-FE at 25°C of CRMs and the penetration at 25°C of ECP, while a poor Pearson coefficient (-0.089) was observed for the correlation between SCB-FE at 25°C and LAS-FE. Overall, the CRM testing parameters for intermediate cracking did not correlate well with the ECP testing parameters (LAS-FE and penetration at 25°C).

The Pearson correlation coefficients for ECP and CRM testing parameters at high temperatures are presented in Table 21. Compared to cracking measures (i.e., SCB-FE at 0°C and 25°C), The APA rut depth had better correlation with MSCR parameters at 64°C and penetration at 40°C indicated by higher values of Pearson coefficients.

Table 19

Pearson Correlation Matrix for Low-Temperature Cracking Tests of CRMs and ECPs

Test	Measures	SCB-FE (0°C)	Creep Stiffness	m-Value	Pen. at 10°C
SCB (CRM)	SCB-FE at 0°C	1	-.289	-.069	.244

Table 20

Pearson Correlation Matrix for Intermediate-Temperature Cracking Tests of CRMs and ECPs

Test	Measures	SCB-FE (25°C)	LAS-FE	Pen. at 25°C
SCB (CRM)	SCB-FE (25°C)	1	-.089	.404

Table 21

Pearson Correlation Matrix for Rutting Tests of CRMs and ECPs

Test	Measures	APA rut Depth	J_{nr} 0.1	J_{nr} 3.2	Pen. at 40°C
APA (CRM)	Rut Depth	1	.573	.542	.728

Regression Analyses and Predictive Models of CRM Performance

Regression analyses were performed on each testing parameter of ECP (J_{nr} 0.1 at kPa, LAS-FE, etc.) to see if models can be developed to predict the performance of CRMs based on the properties of ECPs and their constituent contents. To improve these models and maximize their coefficient of determination (R^2), several parameters governing the performance of CRMs should be considered, which are as follows:

- <u>CRM constituents:</u> all the materials used to prepare CRMs should be considered in regression predictive models such as: bituminous agents, cementitious additives, water, and RAP. In this study, bituminous agents and cementitious additives used in preparing ECPs are the same as the ones used in preparing CRMs, which are CSS-1h emulsion and portland cement, respectively. Also the proportions of emulsion, cement, and water selected for ECPs were equivalent to those selected for CRMs (see the experimental program presented in chapter 4). Therefore, at each content of emulsion, cement, and water in ECP, there is only one CRM prepared with equivalent proportions. The only difference between ECPs and CRMs is the presence of RAP in CRMs. The content of RAP is CRMs is given by the following equation:

  $$\text{RAP Content (\%)} = 100 - \text{Emulsion Content} - \text{Cement Content} - \text{Water Content} \qquad (3)$$

  Thus, equation (2) should be considered in regression predictive models.
- <u>RAP properties</u>: RAP millings have several properties that may vary from one RAP source to another such as gradation, aged binder content, theoretical maximum specific gravity, RAP aggregate properties, etc…. If these properties do

not have a significant impact on the performance of CRMs, they can be excluded from regression analyses.

a. Gradation and shape of RAP: RAP millings are obtained using a cold in-place recycling (CIR) milling machine that mills asphalt pavements using at a typical milling rate and to a maximum depth of 100 mm. This suggests that the obtained RAP may have similar gradations and aggregate properties, such as angularity and shape. A study by Ghavibazoo et al. (2017) reported that the performance of CRMs is not influenced by RAP gradations. Therefore, the gradation and shape of RAP were excluded from regression predictive models.

b. RAP binder properties and content: CRMs are generally prepared at ambient temperatures without preheating the materials including RAP, which performs as a black rock. The binder contained in RAP remains inactive during the mixing, compaction, and curing processes of CRMs. Therefore, RAP binder properties and content were excluded from regression analyses.

- ECP testing parameters: Each performance measure of ECPs was used as independent variable, along with other parameters if needed, to generate the predictive models.
- Models: Two types of regression models were attempted in this study: linear and polynomial.

The results of regression analyses for predicting CRM rutting performance are presented in Figure 30. As can be seen from this figure, 93% of predicted CRM rutting data using ECP performance measures presented less than 30% error, while 7% CRM rutting data presented an error less than 50%. Overall, the testing parameters of ECP at high temperatures (J_{nr} at 0.1 kPa, J_{nr} at 3.2 kPa, and penetration at 25°C) correlated well with CRM rutting measure (APA rut depth), presenting a coefficient of determination (R^2) of around 77%. These results suggest that J_{nr} at 0.1 kPa, J_{nr} at 3.2 kPa, and penetration at 25°C, along with ECP constituent contents (or RAP content) can be used to estimate the rutting performance of CRMs, using the following equations:

$$APA_{Rut\ Depth} = 7.033 + 0.22 \times E - 0.96 \times C - 0.82 \times W + 0.38 \times J_{nr}(0.1) \qquad (4)$$

$$APA_{Rut\ Depth} = 7.16 + 2.11 \times E - 1.09 \times C - 0.83 \times W + 0.06 \times J_{nr}(3.2) \qquad (5)$$

$$APA_{Rut\ Depth} = 7.06 + 1.85 \times E - 0.90 \times C - 0.80 \times W + 0.06 \times Pen(40) \qquad (6)$$

where

E = emulsion content,

C = cement content,

W = water content,

J_{nr} (0.1) = J_{nr} at 0.1 kPa,

J_{nr} (3.2) = J_{nr} at 3.2 kPa, and

Pen(40) = Penetration at 40°C.

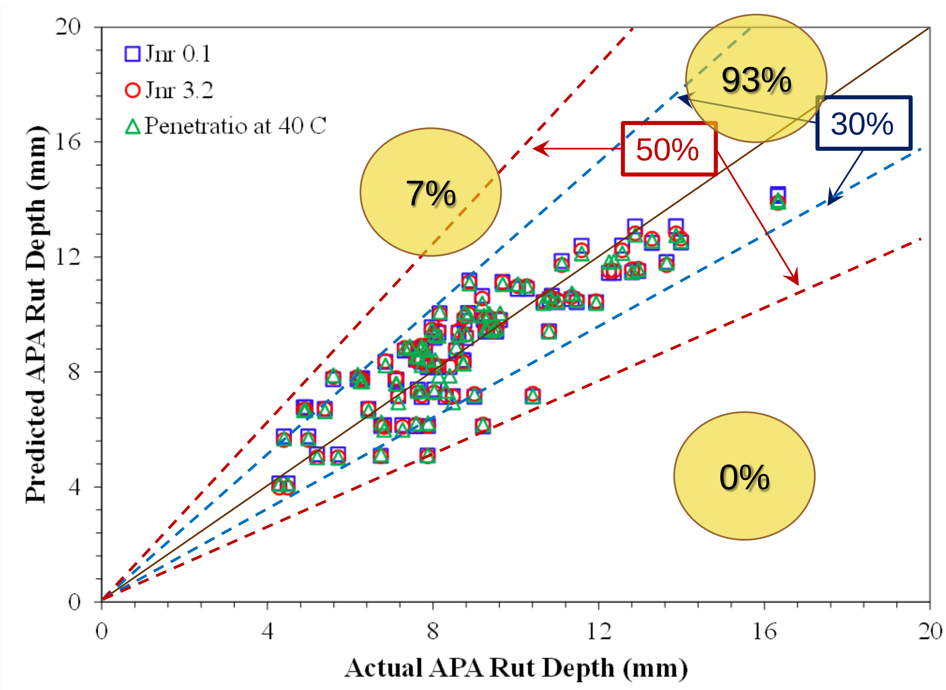


Figure 30. Regression analysis estimating rutting meausres of CRMs based on ECP constituent contents and ECP rutting measures: (a) J_{nr} at 0.1 kPa, (b) J_{nr} at 3.2 kPa, and (c) penetration at 40^{o}C

The results of regression analyses for predicting CRM performance in terms of low-temperature cracking are illustrated in Figure 31. As can be seen from this figure, 39% of predicted cracking performance data of CRMs at 0^{o}C using ECP cracking measures presented less than 30% error, while 25% predicted cracking performance data at 0^{o}C presented an error higher than 50%. Overall, the testing parameters of ECP at low temperature (creep stiffness, m-value, and penetration at 10^{o}C) did not correlate well with CRM cracking measure (SCB-FE at 0^{o}C), with respective R^2 of 37.2%, 34.7%, and 36.5%. Therefore, these testing parameters may not be suitable for estimating the cracking performance of CRMs at low temperatures.

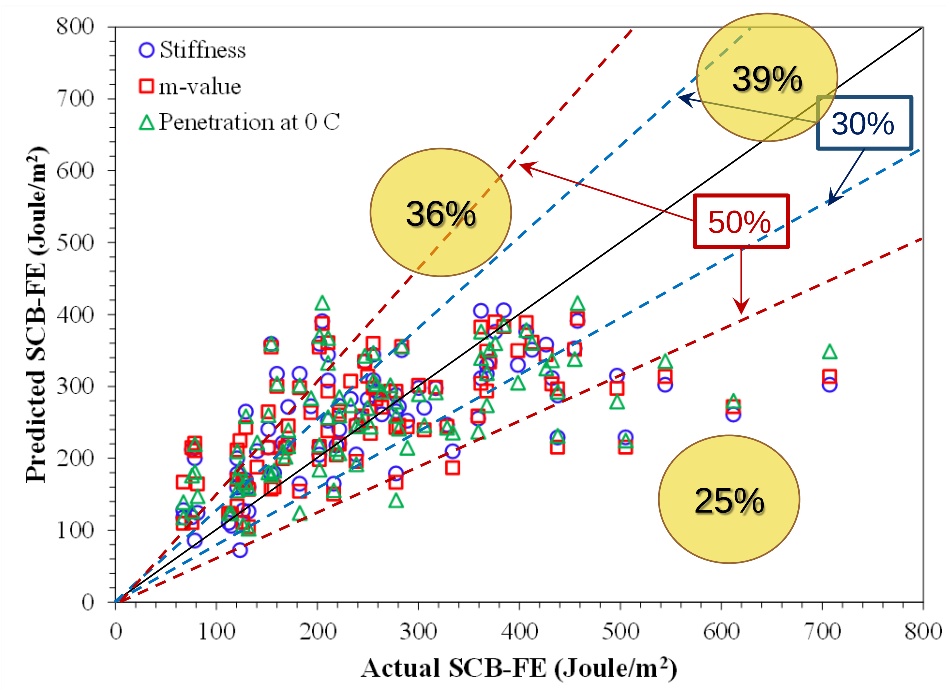


Figure 31. Regression analysis predicting low-temperature cracking meausres of CRMs based on ECP constituent contents and ECP rutting measures: (a) creep stiffness, (b) m-value, and (c) penetration at 10°C

The results of regression analyses for predicting CRM performance in terms of fatigue cracking are shown in Figure 32. As can be seen from this figure, 66% of predicted cracking performance data of CRMs at 25°C using ECP cracking measures presented less than 30% error, while 15% predicted cracking performance data at 25°C presented an error higher than 50%. The testing parameters of ECP at intermediate temperature (LAS-FE and penetration at 25°C) did not correlate well with the fatigue cracking measure for CRMs (SCB-FE at 25°C), showing similar R^2 values of 49.7%. Similar to ECP test parameters at low temperatures, LAS and penetration parameters may not be suitable to estimate the resistance of CRMs to fatigue cracking.

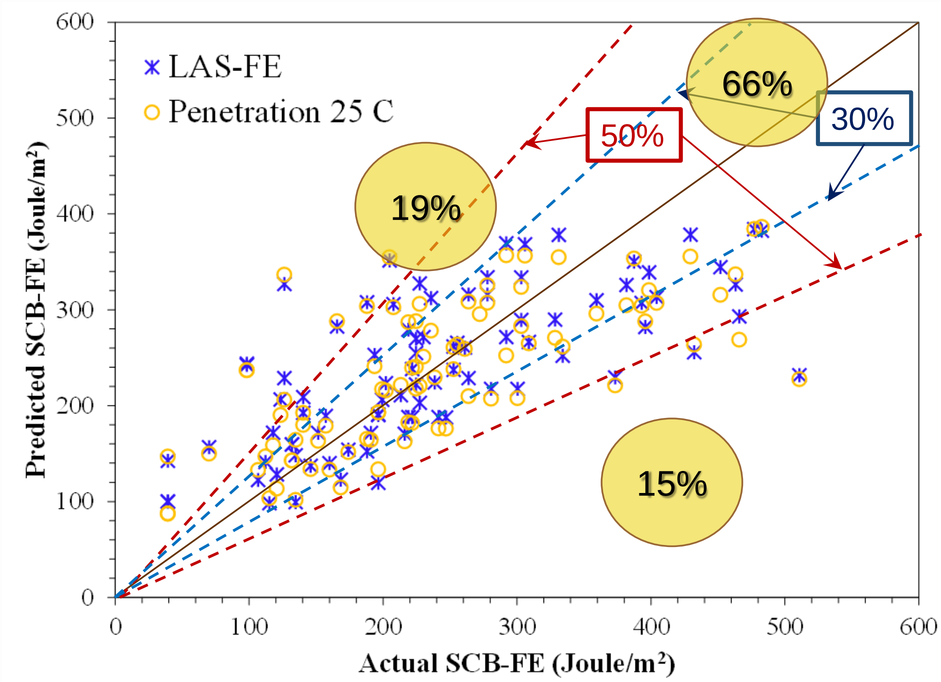


Figure 32. Regression analysis predicting intermediate-temperature cracking meausres of CRMs based on ECP constituent contents and ECP rutting measures: (a) LAS-FE and (b) Penetration at 25°C

In summary, statistical analyses were conducted on ECP and CRM testing results to assess the impact of varying the amounts of emulsion, cement, and water on: (1) the rheological and mechanical properties of ECPs and (2) rutting and cracking performance of CRMs. MANOVA analyses showed that the combinations of emulsion, cement, and water had a significant impact on ECP properties and CRM density and performance. Post hoc analyses showed that not all the selected contents of emulsion, cement, and water resulted in a significant change of ECP properties at low and intermediate temperatures. Pearson correlations and regression analyses showed that ECP testing parameters at high temperatures (e.g., J_{nr} at 64°C and penetration at 40°C) presented stronger correlations with CRM rutting performance than ECP testing parameters at low and intermediate temperatures with CRM cracking performance. These observations suggest the following explanations:

- At high temperatures, the strength of CRMs is mostly governed by the binder (ECP), which is temperature sensitive. If ECP has higher non-recoverable creep compliance, CRM is also rutting susceptible.
- At low and intermediate temperatures, the strength of CRMs is partially dictated by ECP. In fact, the properties of RAP (e.g., strength) as well as the binding properties of RAP with ECP contribute to CRMs strength and influence their resistance to cracking.

Chapter 7

Summary of Findings, Conclusions & Future Work

Summary of Findings

This study focused on evaluating the rheological and mechanical properties of emulsion-cement paste (ECP), and the density and performance of cold recycled mixtures (CRM) at varying amounts of emulsion, cement, and water. ECPs and CRMs were subjected to similar mixing and curing processes (72 hours at 60°C). Forty five combinations of ECPs and CRMs were produced using five emulsion contents (2% - 4%, with 0.5% increments), three cement contents (1% - 3%, with 1% increments), and three water contents (1% - 5%, with 2% increments). The first phase of this study aimed to assess the impact of varying the amounts of emulsion, cement, and water on the rheological and mechanical properties of emulsion-cement paste (ECP). The rheological properties of ECP were assessed using dynamic shear rheometer (DSR) in accordance with AASHTO T315, multiple stress creep recovery (MSCR) test at 64°C, and penetration test at three temperatures (10°C, 25°C, and 40°C). The mechanical properties of ECPs were determined using bending beam rheometer (BBR) at 0°C, linear amplitude sweep (LAS) test at 25°C, and isothermal calorimetry test at 20°C. A design procedure for mixing and curing ECPs developed following the design process for cold recycled mixtures (CRMs). The findings from this study are summarized below:

- ECP specimens at high cement proportions (2% and 3%) and low emulsion contents (2% and 2.5%) had the $\frac{G^*}{\sin(\delta)}$ values superior to 1kPa at temperatures exceeding 100°C.

- At low cement contents, the increase in emulsion contents caused an increase in J_{nr} values of ECPs by over 100% at both low and high stress levels. While the increase in water content caused a reduction in J_{nr} values by up to 300% at high emulsion contents. As cement contents increased, varying emulsion and water contents did not influence the performance of ECPs translated by relatively similar Jnr values (within 1 kPa^{-1}).
- Increasing the temperature from 10°C to 25°C caused an increase in penetration by up to 10 dmm at low emulsion contents (2% and 2.5%) and by up to 50 dmm at high emulsion contents (3% through 4%). At 40°C, the penetration values increased further by about 70 dmm. In addition, varying the amount of emulsion, cement, and water did not have a significant effect on all penetration values of ECPs at 10°C (within 10 dmm). However, increasing the emulsion contents and decreasing the cement contents caused a meaningful increase in penetration values at both 25°C and 40°C (by over 100 dmm).
- The LAS results showed that varying the amounts of emulsion, cement, and water influenced the strain-stress curves and LAS-FE values for ECPs at 25°C. In fact, increasing the emulsion content at 1% and 2% cement resulted in trends with a peak of LAS-FE values (increasing by over 30%). While increasing the cement contents from 1% to 3% showed decreasing trends of LAS-FE (decreasing by over 50%).
- Increasing the emulsion content (from 2% to 4%) and water content (from 1% to 5%), or decreasing the cement content from 3% to 1% caused the creep stiffness and creep rate of ECPs to drop by over 100% at 0°C.

- The isothermal calorimetry results showed that increasing the cement proportions along with water content increased the heat power related to cement hydration in ECPs by up to 100%. Increasing the cement content from 1% to 3% at low emulsion and water contents (2% and 1%, respectively) caused an increase in cement hydration by over 800%. As emulsion increased from 2% to 3%, the hydration rate of cement decreased by 50%, while when emulsion increased to 4%, the hydration rate decrease by over 100%. This could be due to the residual asphalt (asphalt phase of emulsion) inhibiting the cement minerals from hydrating.

The second phase of this research study aimed to evaluate the impact of varying the amounts of emulsion, portland cement, and water on the density and the performance of cold recycled mixtures (CRM). Air void level was determined through measuring theoretical and bulk specific gravities using CoreLok device. Asphalt Pavement Analyzer (APA) was used to measure rutting susceptibility, and cracking resistance was assessed at two temperatures (0^{o}C and 25^{o}C) using Semi-Circular Bend-(SCB) test. For this study, reclaimed asphalt pavement (RAP) was obtained by milling a portion of an HMA pavement located at Rowan University Accelerated Pavement Testing Facility (RUAPTF). RAP was characterized in terms of gradation, binder content, and theoretical specific gravity, then was mixed with cement, water, and emulsion at varying amount of CRM constituents. Prior to testing, all CRM mixtures were compacted using 30 gyrations and allowed to cure for 72 hours at 60^{o}C. The significance of the impact of varying CRM constituent contents was assessed using MANOVA analysis. The findings from this study are summarized as:

- Increasing the emulsion content by 2% of total mix weight resulted in: (a) reduction of CRM air void level by up to 3.0%, (b) increased APA rut depth values by up to 3 mm, (c) increasing trends of SCB-FE values at 25°C, and (d) trends with a peak of SCB-FE values at 0^{o}C.
- Increasing the cement content by up to 2% of total mix weight resulted in: (a) reducing CRM air void level by up to 5.0%, (b) reducing APA rut depth values by up to 3 mm, (c) decreasing trends of SCB-FE values at 3% and 5% water content, and (d) increasing trends at 1% water content.
- The air void level of CRM mixtures did not show a specific trend when varying the water content. While, increasing the water content dropped APA rut depth by up to 4 mm. Increasing the water content from 1% to 5% (with 2% increment) resulted in peak SCB-FE values at 3% water.
- Performance interaction charts showed that CRM mixtures exhibited different resistance to rutting and cracking (at intermediate and low temperatures) at various interactions of emulsion, cement, and water. At least 80% of the combinations showed a resistance to one or more of the distresses (rutting or cracking). Approximately 25% of the combinations presented a balanced performance.

Statistical analyses were conducted to evaluate the constituents' proportions on the performance of ECP and CRM. Regression analyses were performed to assess the correlations between ECP and CRM testing parameters. The findings from this study are presented below:

- Most performance measures of ECPs (J_{nr} at 0.1 KPa and 3.2 KPa, LAS-FE at 25°C, creep stiffness at 0°C, and penetration at 10°C, 25°C, and 40°C) had a strong sensitivity to the variation in the amounts of emulsion, cement, and water.
- Varying the CRM constituent contents had significant impact on air void level, APA rut depth, and SCB-FE (at 0°C and 25°C) of CRM mixtures. Analyses also showed that the interaction between the three CRM constituents had a significant impact on air void level, rutting, and cracking performance of CRMs.
- The correlations between ECP testing parameters varied in strength with Pearson coefficient values ranging between 7% and 98.8%. The hydration rate of cement correlated well with the creep stiffness of ECPs at 0°C and LAS-FE at 25°C, while there was weak correlation with MSCR and Penetration parameters ECP at high temperatures. Similarly, J_{nr} at 0.1 kPa had a strong correlation with penetration at 40°C and with J_{nr} at 3.2 kPa at 64°C.
- The cracking measures of CRMs at low and intermediate temperatures did not correlate well with the ECP testing parameters (creep stiffness at 0°C, m-value, penetration at 10°C, LAS-FE, and penetration at 25°C,). Conversely, APA rut depth had better correlation with MSCR parameters at 64°C and penetration at 40°C.
- Predictive models were developed for the APA rutting performance of CRMs with a good coefficient of determination (R^2= 77%). The inputs of these models included ECP constituent contents along with one of the following parameters: J_{nr} at 0.1 kPa, J_{nr} at 3.2 kPa, and penetration at 40°C. The predictive models had weaker coefficient of determination (R^2 less than 55%) for cracking performance.

Conclusions

Based on the findings from the two phases of this study, the following conclusions can be drawn:

- Impact of Cement on ECP Properties: The proportions of emulsion, cement, and water had a significant effect on the rheological and mechanical properties of ECP. Increasing the cement content improves the rutting resistance of ECPs at high temperatures. However, excessive amounts of cement reduces the ductility of ECP. This reduction in ductility at higher cement contents may result in a poor performance of ECPs at low and intermediate temperatures.
- Impact of Emulsion on ECP Properties: An increase of emulsion content reduces the stiffness of ECPs at high temperatures and increases their susceptibility to rutting. At low and intermediate temperatures, increasing the emulsion content improves the ductility of ECPs and their resistance to rutting.
- Impact of Water on ECP Properties: At low water contents, an increase in emulsion contents reduces the strength of ECPs as the asphalt phase of emulsion enclose the minerals of cement and prevents them from hydrating. However, increasing the water content at high emulsion contents increased the chances for the cement minerals to hydrate, which in return improves the strength of ECP.
- CRM Density: Emulsion, cement, and added water content impacted the density level of CRM mixtures. Analysis showed that all three had a statistically significant impact on CRM air void level.

- Impact of Cement on CRM Performance: Higher cement contents improved the rutting performance, but decreased the cracking resistance of CRMs. Reduction in cracking resistance was due to a more brittle failure with higher cement contents.
- BMD and Performance Chart Interactions: Performance interaction charts were successfully developed to evaluate the relationship between different CRM mixtures and their laboratory performance. The performance interaction charts can be used in future BMD strategies to develop and select CRM mix designs.
- CRM Performance Prediction: The regression models were successful in predicting the rutting performance of CRMs based on the contents of emulsion, cement, water, RAP, and one ECP testing parameter at high temperatures.

Future Work

This study focused on assessing the impact of varying the amounts of emulsion, cement, and water on ECP properties and CRM density and performance. Performance interaction charts were successfully developed based on laboratory testing program that included APA rut depth as rutting measure, SCB-FE at 0°C as a low-temperature cracking measure, and SCB-FE at 25°C as a fatigue cracking measure. In addition, regression models were developed for the performance of CRMs from the ECP properties and contents. As future activities, there is a need to validate the performance interaction charts in the field by constructing full-scale pavement sections and conducting accelerated pavement testing (APT) on each section. Conversely, additional parameters will be considered in the development predictive models for CRM performance, which include:

- Conducting other binder-scale tests such as bending beam rheometer Pro (BBR Pro), which is capable of assessing the binding properties between RAP and ECP at low and intermediate temperatures. Therefore, cracking predictive models can be improved.
- Assessing the impact of RAP gradations and aggregate properties on CRM performance. If found significant, RAP gradations and aggregate properties should be considered in regression models.
- Identify the role of cement in CRMs at different water and emulsion contents. This will allow defining thresholds for cement contents at which cement plays the role of a filler.
- Study the impact of adding different additives (e.g., finely ground limestone or lime slurry) at similar proportions of cement contents on the performance of CRMs.

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Appendix

Acronyms and Abbreviations

AASHTO	American Association of state Highway and Transportation Officials
MANOVA	Multivariate Analysis of Variances
APA	Asphalt Pavement Analyzer
ARRA	Asphalt Recycling and Reclaiming Association
BBR	Bending Beam Rheomter
BMD	Balanced-Mix Design
CRM	Cold Recycled Mixture
CREATEs	Center for Research and Education in Advanced Transportation Engineering Systems
CRREL	Cold Regions Research and Engineering Laboratory
DSR	Dynamic Shear Rheometer
ECP	Emulsion-Cement Paste
HMA	Hot Mix Asphalt
IDT	Indirect Tension Test
ITS	Indirect Tensile Strength
LAS	Linear Amplitude Sweep
LAS-FE	Linear Amplitude Sweep Fracture Energy
RAP	Reclaimed Asphalt Pavement
RUAPTF	Rowan University Accelerated Pavement Testing Facility
SCB	Semicircular Bend
SCB-FE	Semicircular Bend Fracture Energy
SGC	Superpave Gyratory Compactor