# Design, Placement, and Laboratory Evaluation of Rejuvenated Cold Recycled Pavement Mixtures

by

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# ABSTRACT

Cold recycled (CR) pavements, the combination of reclaimed asphalt pavement (RAP) and a recycling agent (foamed or emulsified asphalt binder) at ambient temperatures, can provide a sustainable method to rehabilitate, maintain, and construct roadways. However, to utilize a CR pavement as an equal alternative to a hot mix asphalt base or surface course, the addition of a rejuvenating agent may be needed. This thesis focuses on the laboratory formulation, plant production, and placement of one foamed asphalt CR mixture, two CR mixtures containing rejuvenator, and one engineered emulsion CR mixture. These mixtures were subjected to laboratory evaluation via Indirect Tensile Asphalt Cracking Test (IDEAL-CT), High Temperature Indirect Tension Test (HT-IDT) and Dynamic Modulus testing. The influence of laboratory production versus plant production on mixture performance was investigated, as well as the influence of rejuvenators on mixture performance and density. During the mixture design process, all selected designs performed above the required minimums established for CR except for the mixture containing a CR rejuvenator, which failed the dry strength requirement by a small margin. However, this design surpassed the conditioned strength requirements during mixture design, showed improved strength when conditioned versus dry, and passed all minimum strength requirements when plant produced. Test results indicated that the addition of a rejuvenator led to increased dry densities during mixture design, plant production, and laboratory production and decreased moisture susceptibility versus non-rejuvenated CR mixtures. Rejuvenators also increased the $CT_{Index}$ by at least 35% when compared to other CR mixtures. HT-IDT testing revealed that the rejuvenated mixtures performed slightly below the engineered emulsion mixture, with the foamed asphalt mixture outperforming all others. Dynamic modulus testing showed higher overall moduli in rejuvenated mixtures versus the CR mixture containing foamed asphalt, with the lower modulus of the foamed asphalt CR mixture being indicative of a less temperature and loading susceptible mixture. The engineered emulsion mixture performed between the two rejuvenated mixtures, with the anionic emulsion with bio-based rejuvenator mixture having the highest dynamic modulus values.

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# ABBREVIATIONS

| | |
|---|---|
| AASHTO | American Association of State and Highway Transportation Officials |
| AMPT | Asphalt Mixture Performance Tester |
| ARRA | Asphalt Recycling and Reclaiming Association |
| ASTM | American Society for Testing and Materials |
| CCPR | Cold Central Plant Recycling |
| CIR | Cold In-Place Recycling |
| CR | Cold Recycled |
| $CT_{Index}$ | Cracking Tolerance Index |
| HMA | Hot Mix Asphalt |
| HT-IDT | High Temperature Indirect Tension Test |
| IDEAL-CT | Indirect Tensile Asphalt Cracking Test |
| ITS | Indirect Tensile Strength |
| LMLC | Laboratory Mixed Laboratory Compacted |
| LVDTs | Linear Variable Differential Transformers |
| MS | Marshall Stability |
| MSR | Marshall Stability Ratio |
| NCAT | National Center for Asphalt Technology |
| NCHRP | National Cooperative Highway Research Program |
| OFC | Optimum Fluid Content |
| OMC | Optimum Moisture Content |
| PG | Performance Grade |
| PMLC | Plant Mixed Laboratory Compacted |

| | |
|---|---|
| RA | Rejuvenating Agent |
| RAP | Reclaimed Asphalt Pavement |
| SSD | Saturated Surface Dry |
| TSR | Tensile Strength Ratio |
| WMA | Warm Mix Asphalt |

# CHAPTER ONE: INTRODUCTION

## 1.1 Background

Cold recycling is a method of rehabilitating, maintaining, or reconstructing pavements at ambient temperatures using nearly 100% recycled materials. This sustainable alternative to hot or warm mix asphalt (HMA or WMA) is typically completed through one of two methods: Cold Central Plant Recycling (CCPR) or Cold In-Place Recycling (CIR). CCPR uses a central plant (either stationary or mobile) to mix reclaimed asphalt pavement (RAP) from a stockpile or transported millings from the construction site with the chosen recycling agents. The CR mixture is then hauled to the construction site, placed, and compacted in one or more lifts (ARRA 2015). CIR, unlike CCPR, can only be placed in a single lift, as all the mixing takes place where the final product will be compacted. This process is done in a train-like fashion with multiple pieces of equipment such as a milling machine, cement distributor truck, cold recycler, paver, water truck, and compaction rollers working in tandem.

In the design of HMA or WMA, temperature is one of the largest influences on the effort required to compact a pavement mixture. In CR pavements, fluid is the largest influence over this compactive effort. Fluid aids the workability of the mixture by allowing the RAP particles to move more easily around each other to achieve the maximum density. While water improves compaction across all types of CR mixtures, it also provides additional benefits for CR mixtures containing emulsion. The increased fluid assists the emulsion in adequately coating all particles (ARRA 2015). Due to the added water in CR mixtures, additional time is needed to allow it to evaporate before being tested, surfaced, and/or trafficked. This additional time is referred to as a curing period.

When developing a CR mixture design, two recycling agents are considered: foamed asphalt and emulsified asphalt. In the case of foamed asphalt, a heated asphalt binder is combined with water and pressurized air to expand the binder significantly past its original volume. This produces binder encapsulated steam bubbles that, when in contact with ambient temperature RAP, burst and bind the mixture together through spot-welds. Unlike foamed asphalt binder, emulsified asphalt binder coats most of the RAP particles and binds it together as the water from the mixture evaporates and leaves behind asphalt residue. The addition of a rejuvenator to a CR mixture can help to restore the RAP binder properties and create a more cohesive mixture.

While research on typical foamed asphalt binder or emulsion CR pavement and their behavior is prevalent (Diefenderfer et. al 2019, Xiao et. al 2018, Gu et. al 2019), relatively little work has been published on the performance of CR pavements with rejuvenators (Bowers et. al 2019). Sections incorporating CR layers have been placed at the National Center for Asphalt Technology (NCAT) Test Track; however, none include a rejuvenator. This thesis aims to:

1. Develop four CR mixture designs for field evaluation and laboratory testing,
2. Construct test sections on the off-ramp at the NCAT Test Track,
3. Evaluate the laboratory performance of two CR mixture designs using rejuvenators,
4. Compare the performance of the two mixtures containing rejuvenators to “typical” CR designs with foamed asphalt and engineered emulsion, and
5. Provide recommendations for future research in this field.

## 1.2 Objectives

This study focuses on the following objectives to create a better understanding of CR mixtures, the application of rejuvenators within them, and their performance:

1. Develop mixture designs including rejuvenators that meet CR Indirect Tensile Strength (ITS) or Marshall Stability (MS) minimum strength requirements,
2. Evaluate plant production and constructability of the mixtures.,
3. Compare CR mixtures with their respective recycling and/or rejuvenating agents via multiple performance tests such as: ITS, MS, IDEAL-CT, HT-IDT, and Dynamic Modulus,
4. Investigate the influence of mixture production method on mixture performance, and
5. Explore the influence of mixture production method and rejuvenators on specimen density.

## 1.3 Scope

To complete the research objectives, four CR mixture designs were developed, two containing rejuvenators. Three of the four mixture designs were developed at NCAT and the fourth was developed by an emulsion supplier. The mixtures were then produced, according to the designs, through portable plants at the NCAT Test Track and placed on the off-ramp with a HMA thinlay for trafficking and performance assessment. Plant mixed, laboratory compacted (PMLC) and laboratory mixed, laboratory compacted (LMLC) specimens were fabricated using materials collected on-site during production. These specimens were used for further performance testing to predict pavement performance and compare to the findings from the paved sections.

## 1.4 Organization of Thesis

This thesis is organized into five chapters:

- Chapter One: Introduction - Provides background on CR pavements, thesis objectives, and the scope of the research project.
- Chapter Two: Literature Review - Summarizes the current literature on CR pavements, the CR mixture design process, pavement placement and field performance, and performance testing via ITS, MS, IDEAL-CT, HT-IDT, and Dynamic Modulus.
- Chapter Three: Methodology - Outlines material property determination, the mixture design and acceptance methods followed, the plant production and placement process, the plant produced mixture collection, compaction, and testing, the laboratory production of specimens, specimen preparation for performance testing, and the performance testing process.
- Chapter Four: Results - Presents the results of the material property determination, the results of the mixture design process followed, the plant production and placement of the mixtures, the ITS, MS, IDEAL-CT, HT-IDT and Dynamic Modulus results, and a comparison of the impact of production method and use of rejuvenators on mixture performance and density.
- Chapter Five: Findings, Conclusions, and Recommendations - Provides a summary of the findings and conclusions drawn during mixture production, plant production, lab production, performance testing, comparison of the influence of laboratory production versus plant production, comparison of the impact of rejuvenators on the CR mixtures, and recommendations for further research on rejuvenated cold recycled mixtures.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Cold Recycling

Traditionally, CR pavements can provide a more sustainable option for roadway rehabilitation, maintenance, and construction compared to typical mill-and-fill or deep rehabilitation with typical HMA or WMA mixtures. CR is the process of mixing a recycling agent (foamed or emulsified asphalt binder) and RAP millings, either directly from the roadway or from a stockpile, to create a new pavement layer. By using nearly 100% recycled materials, the CR process reduces the need for virgin material which in turn reduces the material cost. Emissions are also reduced due to the pavement material being mixed and compacted at ambient temperatures and minimal need for hauling trucks to transport materials (Pakes et al. 2018, Stroup-Gardiner 2011).

There are two primary categories of CR pavements: Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR). CIR uses one or more pieces of equipment in a train-like formation, which mills/pulverizes and processes the existing pavement, blends a recycling agent into the newly milled RAP, then places that mixture back on the roadway in a single lift. This type of CR utilizes the RAP on-site, minimizing the need for new materials to be hauled in. CCPR incorporates the same materials as CIR. However, the RAP used must be transported from the site or from a RAP stockpile to a stationary or mobile CR plant to be mixed. Once mixed, the CR pavement mixture must then be transported to the jobsite for paving and compaction (ARRA 2015). Although CCPR requires more material transport than a typical CIR pavement, it does have advantages. CCPR allows for more options and control over the RAP before creating the pavement mixture, gives the option to strengthen foundation layers beneath the CCPR, and also allows a CR pavement to be placed in more than one lift.

## 2.2 Recycling and Rejuvenating Agents

### 2.2.1 Foamed Asphalt

In typical CR pavements, one of two recycling agents are used as a primary method of binding the RAP particles together: foamed asphalt or emulsified asphalt (ARRA 2015). Foamed asphalt is formed when hot asphalt binder is combined with water and pressurized air, resulting in steam bubbles encapsulated by the asphalt binder. Figure 1 shows the formation of these bubbles.

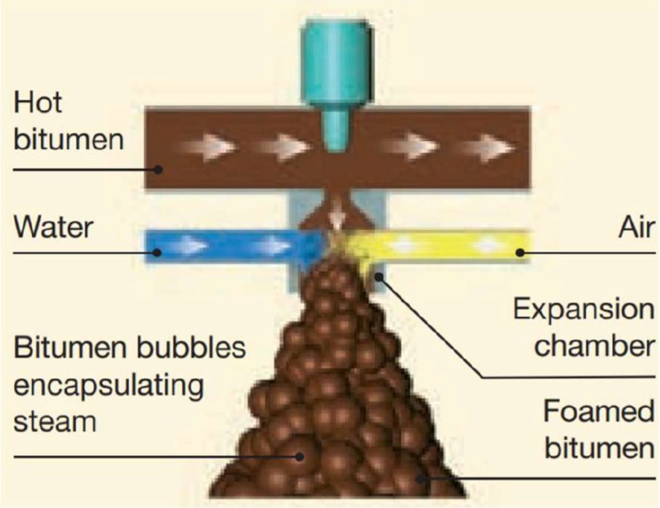

***Figure 1 – Formation of Foamed Asphalt (Wirtgen 2012)***

These newly formed bubbles are immediately foamed onto RAP at their maximum volume for optimal coverage. When the bubbles encounter the RAP, they burst and the asphalt binder creates spot-welds between the RAP aggregate particles; these spot-welds bind the mix matrix together (Wirtgen 2012), as shown in Figure 2.

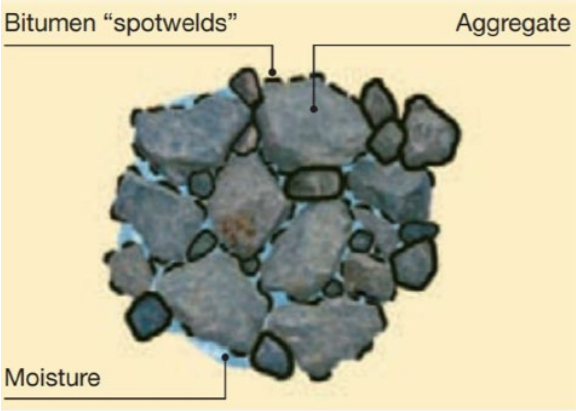

*Figure 2 – Mix Matrix Bound by Spot-Welds (Wirtgen 2012)*

In order for an asphalt binder to be used in a CR design, it must meet the expansion ratio and half-life requirements. The expansion ratio of a foamed asphalt binder is the volumetric ratio of unfoamed binder to foamed binder and the half-life is the time it takes for the foamed binder to collapse to half of its maximum volume (in seconds). To test the binder for these properties, both temperature and the amount of water injected are adjusted until optimal properties are achieved. The foamed binder must have a minimum expansion ratio of 8:1 and a minimum half-life of 6 seconds (Wirtgen 2012). Results from these trials should provide a temperature and water content combination that produces the optimum expansion ratio and half-life for the tested binder.

### 2.2.2 Emulsified Asphalt

Emulsified asphalt is the combination of an asphalt binder, water, and an emulsifying agent. When an emulsion is added to a CR mixture it gains cohesive properties by “breaking” or curing. This breaking process occurs when the excess water in the emulsion begins to evaporate, causing the asphalt residue left to coalesce and adhere to the RAP aggregate. An emulsion can either be categorized as anionic (negatively charged) or cationic (positively charged). The type of emulsion used is selected on a project-by-project basis based on the aggregate used, temperature, and breaking rate. Colder weather and higher moisture contents can cause delayed breaking, which can restrict the ability to use some emulsions (Stroup-Gardiner 2011). Engineered emulsions, however, are a specialized emulsion that can be designed to accommodate potential issues like cooler temperatures.

### 2.2.3 Rejuvenating Agents

A rejuvenating agent (RA) is an additive designed to restore the properties of an oxidized asphalt binder, like on RAP. For asphalt mixtures with high recycled binder ratios, such as CR pavements, RAs can help restore flexibility to the mixture, decrease stiffness, and increase cracking resistance (Sias et al. 2022). For CR mixtures specifically, they help to soften the RAP and increase adhesion between RAP particles. Typically, rejuvenating agents are oil based and can be added to a binder, an emulsion, or to the pavement mixture directly.

It is important to recognize that the term “recycling agent” has been adopted for HMA and WMA applications to cover both rejuvenating agents and softening agents (Epps et al. 2020). In this thesis, the term “rejuvenating agent” is employed to cover either of these materials (rejuvenating or softening) to differentiate them from CR recycling agent terminology (i.e., foamed or emulsified binder) and the HMA/WMA recycling agent terminology (i.e., rejuvenating or softening agent). The terminology should be further discussed amongst agencies, industry, and in academia as rejuvenating and softening agents begin to be used in CR applications as they are in this thesis.

## 2.3 Mixture Design

### 2.3.1 RAP Sampling and Processing

When utilizing RAP in an asphalt mixture design, it is important to collect consistent and accurate samples that are representative of the larger source. Variations within RAP sampling influence mixture performance, as both the gradation and RAP aggregate properties are essential factors. For a CR mixture design, several hundred pounds of material should be collected. In order to obtain proper representative samples from a large stockpile, samples should be collected following the procedures outlined in ASTM D75 Standard Practice for Sampling Aggregates.

### 2.3.2 Determining a RAP Optimum Moisture Content

Establishing an optimum moisture content (OMC) is essential in determining the amount of additional water needed in CR mixtures to reach the maximum achievable density. Having additional water in mixtures containing foamed asphalt binder helps to reduce the compactive effort required to reach optimum density and assists in the coating of RAP particles in mixtures containing asphalt emulsion (ARRA 2015). However, adding too much or too little water to a CR mixture can negatively impact it, leading to potential difficulties reaching the desired density and flushing of binder and rejuvenating agents. The OMC is determined via modified proctor following AASHTO T180 Standard Method of Test for Moisture-Density Relations of Soil Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop and is established when the sample reaches maximum dry density. Typically, CR mixtures containing emulsion and foamed asphalt require 1.5 - 2.5% additional water by weight of RAP (ARRA 2015).

### 2.3.3 Recycling, Stabilizing, and Rejuvenating Agents

The selection of a recycling agent is essential to the performance of a CR pavement, with the two options being foamed asphalt and asphalt emulsion (Wang et al. 2018). In the case of foamed asphalt, a binder is selected based on its expansion ratio and half-life, with these properties correlating with the binder’s ability to become well dispersed and create spot-welds between RAP particles. The spot-welds are also reliant on the percentage of fines (material passing the No. 200 sieve) in the mixture. Typically, a mixture containing foamed asphalt has between 5 and 20% fines (ARRA 2015). Up to 1% cement (by weight of dry RAP) is often added to these mixtures as it provides additional fines and increased strength (Wirtgen 2012). Unlike foamed asphalt, asphalt emulsion is selected based on its ability to fully coat the aggregate and can typically be used for RAP having a lower fines content. In the case of both recycling agents, three or four contents are tested during mixture design to determine the optimum dosage for achieving the desired strength requirements. For mixtures containing foamed asphalt, the typical range is 1.5 to 3.0% and for emulsion it is 0.5 to 4.0%, both by weight of dry RAP (ARRA 2015). Rejuvenators are typically selected based on their compatibility with the recycling agent used. However, little research has been done on the selection of rejuvenating agents for cold recycled mixtures.

### 2.3.4 Specimen Mixing, Compacting, and Curing

When using a laboratory sized pugmill for mixing, such as the Wirtgen WLM-30, it is recommended that 25-30 kg (55-66 lb) batches be used for optimum results (Wirtgen 2012). Mixing at this batch size helps to promote thorough mixing of all additives with a homogenous result. Typically, CR mixture test specimens are compacted to 30 gyrations using a Superpave gyratory compactor or to 75 blows using a Marshall hammer (ARRA 2015). Those specimens are then subjected to a curing period. This curing period allows the moisture within the specimen to evaporate and gives adequate time for the recycling agent to set, increasing the strength. The process is considered complete when there is no moisture left in the sample to evaporate, as indicated by no mass change in the specimen when checked periodically. During laboratory mixture design, mixtures containing foamed asphalt are cured for 72 hours at 40°C and emulsion CR mixtures are cured for 48 hours at 60°C, per their respective specifications: AASHTO MP 38 Standard Specification for Materials Used in Cold Recycled Mixtures with Foamed Asphalt and

AASHTO PP 86 Standard Practice for Emulsified Asphalt Content of Cold Recycled Mixture Designs.

Cured CR specimens are then subjected to strength and moisture susceptibility testing to determine design suitability. For CR mixtures, there are two commonly used test methods: ITS and MS testing. In both cases, a set of dry specimens and a set of conditioned specimens at each recycling agent and/or rejuvenating agent content are tested. For ITS testing, the dry specimens are tested at the ambient temperature of a temperature-controlled laboratory. For MS testing, the dry specimens are tested at 40ºC. Both ITS and MS testing subject specimens to a constant loading rate, however the loading distribution varies. ITS testing subjects the specimen to compressive loading on the top and bottom with two steel loading strips coming in contact with the sample, whereas MS applies the load uniformly around the specimen through two half-circle shaped steel loading frames. It is recommended that dry strengths meet a minimum of 45 psi for ITS testing. MS testing does not have an accepted standard for minimum dry strength; however, it is recommended to be 1,250 lb (567 kg) (ARRA 2015). Both test methods also evaluate moisture susceptibility, which is done through either a tensile strength ratio (TSR) or Marshall stability ratio (MSR). The ratio is the average conditioned specimen strength/stability divided by the average dry specimen strength/stability. Per AASHTO MP 38, foamed asphalt mixtures containing cement should have a minimum TSR of 0.7. There is currently no accepted standard for minimum required MSR, but it is recommended by ARRA (2015) to also be 0.7.

## 2.4 Performance Testing

### 2.4.1 IDEAL-CT

The IDEAL-CT is a recently developed test that aims to capture the cracking resistance of an asphalt mixture. This test was developed at the Texas A&M Transportation Institute by

Zhou et al. (2019) as a simple and economical way to test mixtures using four inputs: specimen air voids, specimen height, testing temperature, and loading rate. The data are collected and analyzed, and a cracking tolerance index ($CT_{Index}$) is produced. When evaluating IDEAL-CT testing run on CR mixtures containing emulsion and cement, an increase in cement lead to a more brittle mixture and a lower $CT_{Index}$ (Dong and Charmot 2019, Diefenderfer et al. 2019). The cracking analysis conducted on CR mixtures using IDEAL-CT by Diefenderfer et al. (2019) found that for a CR pavement mixture containing a slow setting emulsion, an increase in cement from 0 to 1% lead to a decreased $CT_{Index}$ by 32%. Dong and Charmot (2019) also concluded that an increase in emulsion led to a higher $CT_{Index}$. Due to the presence of aged binder in RAP, incorporating it into asphalt mixtures decreases the long-term fatigue and cracking resistance (Alae et al. 2022). Considering that CR mixtures contain nearly 100% RAP, it is important to evaluate the mixtures via tests like IDEAL-CT to gauge cracking resistance. It is also of interest considering the adoption of this test for HMA mixture design in the Balanced Mix Design (BMD) framework and the potential interaction between HMA and rejuvenated CR mixture design processes in the future.

### 2.4.2 HT-IDT

High temperature indirect tension testing helps identify the rutting potential of an asphalt mixture. This test is conducted on dry specimens that have been conditioned for 2 hours prior to testing in a 50°C oven. The testing procedure is nearly identical to that of IDEAL-CT testing, where specimens of a standard air void and height are tested at a standard loading rate and temperature. The specimen is placed on the jig and compressive loading is applied on the top and bottom with two steel loading strips coming in contact with the sample. A study by Yin et al. (2020) showed HT-IDT strengths ranging from 21.3 to 43.6 psi for HMA. There is currently no accepted standard for this testing and little to no research has been conducted on CR mixtures tested using HT-IDT. It has been shown that increasing RAP quantities in pavement mixtures leads to an increase in rutting resistance (Ali et al. 2017). However, the addition of rejuvenators can reduce this resistance (Kim et al. 2019). Therefore, it is important to monitor CR mixture performance, both with and without RAs, via tests such as HT-IDT. The HT-IDT is also under consideration for HMA BMD implementation, and thus was investigated.

### 2.4.3 Dynamic Modulus

Dynamic modulus testing is used to evaluate pavement mixture stiffness during repetitive traffic loading. The dynamic modulus of a mixture is represented by the stress-strain ratio of the tested specimen and can be analyzed at multiple temperatures and loading frequencies (Witczak et al. 2002). The data is typically collected via an Asphalt Mixture Performance Tester (AMPT) and tested per AASHTO T378 Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT). While dynamic modulus testing has been conducted on CR mixtures previously (Schwartz et al. 2017, Diefenderfer et al. 2015), little research has been conducted testing rejuvenated CR mixtures (Bowers et al. 2019).

## 2.5 Summary of the Literature Review

CR pavements combine RAP and recycling agents to create a sustainable option for roadway rehabilitation, maintenance, and construction. The two recycling agents used in CR mixtures are foamed asphalt and emulsified asphalt. For an asphalt binder to be used in a foamed asphalt design, it must meet expansion ratio and half-life requirements. Asphalt emulsion is selected on a project-by-project basis depending on various inputs, including materials and weather. Rejuvenators are typically selected based on compatibility with the recycling agent used. The strength, stability, and moisture susceptibility testing for CR mixtures generally follows the procedures outlined in AASHTO MP 38 and AASHTO PP 86. IDEAL-CT and HT-IDT tests are used to determine cracking tolerance and rutting resistance, respectively. Dynamic modulus testing is used to help determine pavement mixture stiffness under repeated traffic loading.

# CHAPTER THREE: METHODOLOGY

## 3.1 Mixture Design

The design phase for three of the four CR mixtures was conducted at the National Center for Asphalt Technology (NCAT) at Auburn University, with the fourth being developed by a recycling agent supplier. All mixtures were prepared using the Wirtgen WLM-30 laboratory-scale pugmill. For the mixture containing foamed asphalt, the Wirtgen WLB-10S was used to determine the binder foaming properties. Each mixture's specimens were compacted, cured, and tested per their respective specifications, either AASHTO MP 38 or AASHTO PP 86. All specimens were tested to determine dry and conditioned strengths and a TSR or MSR; these values were compared to the typical minimums. The final mixture design was selected based on the mixtures ability to meet these requirements while also achieving the most economically viable mix design (the least amount of recycling agent needed to meet the requirements).

### 3.1.1 Obtaining Materials

To develop the four CR mixture designs, a large quantity of RAP was needed. Samples were collected in 50-gallon plastic drums from the RAP stockpile selected for use in the test track construction phase and transported to NCAT. The stockpiles were sampled per ASTM D75 to ensure that the RAP collected was representative of the overall stockpile.

The virgin asphalt binder selected for the project was a PG 67-22 binder, typical of the design location (Auburn, AL). This binder was shipped to NCAT in multiple five-gallon buckets from an Alabama supplier.

The anionic emulsion, bio-based rejuvenator, and CR rejuvenator used in this project were shipped to NCAT in one-gallon plastic containers by their respective manufacturers.

### 3.1.2 RAP Sampling

The RAP stockpile used for this research was stored outside, uncovered. Therefore, it was exposed to all weather conditions and contained a high moisture content. Since RAP contains asphalt binder, it cannot be dried in an oven at temperatures used for aggregate drying as it risks altering the existing binder properties and gradation. Therefore, once transported to NCAT, each barrel was emptied individually onto a smooth, dry concrete floor in an ambient temperature warehouse to begin the drying process. Box fans were used to promote airflow and drying, and the RAP was stirred frequently to accelerate the process and ensure all portions dried evenly. The RAP was dry approximately one week after being placed on the floor, as determined by a hydroscopic moisture content test resulting in less than 0.5% moisture content. Once dry, the RAP was homogenized by hand to reduce potential segregation and transferred to five-gallon buckets for storage until the mixture design process began.

To create a mixture design, the gradation of the RAP must be obtained. A “black rock” gradation was conducted following AASHTO T27 Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates. A washed gradation was also run to better determine the aggregate content passing the No. 200 sieve per AASHTO T11 Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing. Multiple appropriately sized RAP samples were reduced from the previously dried five-gallon buckets of material for sieve analysis using a mechanical splitter following AASHTO R76 Standard Practice for Reducing Samples of Aggregate to Testing Size. The RAP binder content was also determined following AASHTO T308 Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method.

### 3.1.3 Determination of Optimum Moisture Content

When using RAP in mixture designs, it is necessary to establish the OMC. The OMC was determined by Modified Proctor test following AASHTO T180, Method D, at varying moisture contents. Dried RAP material was split into approximately six-kilogram (13.2 lb) samples using a mechanical splitter. Each sample was weighed before adding incremental amounts of ambient-temperature water. Once the water was added, the RAP was stirred by hand in a smooth metal pan to ensure an even distribution. The moisture contents tested ranged from 2.0% to 6.0% by weight of RAP aggregate. After each addition of water, a sample of the material was collected and dried in an oven at low temperatures to verify the moisture content. During testing, wet and dry density values were collected to calculate the OMC using a graphical approach. The wet and dry densities were calculated using Equations 1 and 2, respectively.

$$\rho_t = \frac{A - B}{V} \tag{1}$$

Where:

$\rho_t$ = wet density of compacted material, lb/ft$^3$

A = mass of the mold, base plate, and wet compacted material, lb

B = mass of the mold, base plate, lb

V = mold volume, ft$^3$

$$\rho_d = \frac{\rho_t}{w+100} * 100 \tag{2}$$

Where:

$\rho_d$ = dry density of compacted material, lb/ft$^3$

$\rho_t$ = wet density of compacted material, lb/ft$^3$

w = moisture content of the specimen, %

### 3.1.4 Determination of Asphalt Binder Foaming Characteristics

To use the selected asphalt binder in a foamed asphalt CR mixture design, the expansion ratio and half-life must be determined. These properties were evaluated per the procedures outlined in Wirtgen's Cold Recycling Technology Manual (2012). Temperature and water content have a large influence over the properties and were both altered during testing. The binder was foamed at three different temperatures, each at three different water contents using the Wirtgen WLB-10S Laboratory foamed bitumen plant, shown in Figure 3.

***Figure 3 – Wirtgen WLB-10S Laboratory Foamed Bitumen Plant***

### 3.1.5 Specimen Fabrication and Strength and Moisture Susceptibility Evaluation

Three of the four mixture designs evaluated in this research were developed at the NCAT laboratory. The fourth CR mixture design used an engineered emulsion as the recycling agent and was developed by the emulsion manufacturer following AASHTO PP 86. Five-gallon buckets of the dried and homogenized RAP were shipped to the emulsion manufacturer for mixture design development.

All three mixture designs developed at NCAT used the Wirtgen WLM-30 pugmill. Per Wirtgen's recommendations for optimum mixing conditions, the material was mixed in batches of 25-30 kg (55-66 lb), and 60-second mixing increments were used between each material added (i.e., RAP, water, etc.). For the design phase, either AASHTO MP 38 or AASHTO PP 86 was followed, dependent on the mixture.

#### *3.1.5.1 – Foamed Asphalt with Active Filler*

AASHTO MP 38 was followed for the fabrication and testing of the foamed asphalt with active filler mixture. For this design, one-gallon metal cans of asphalt binder were heated to 160-170°C in an oven to reduce the viscosity. Once heated, the asphalt was poured into the heated kettle of the WLB-10S laboratory foamed bitumen plant. Before beginning the asphalt foaming process, all parts of the laboratory foamed bitumen plant were set to the optimum foaming temperature for the binder and given adequate time to reach that temperature. The water content was manually adjusted to achieve the optimum foaming conditions.

A 25-30 kg (55-66 lb) RAP sample was poured into the pugmill, followed by 1% of Type I/II cement (by weight of dry RAP), and the water required to reach the RAP OMC, with a 60-second mixing period between each addition. Cement was added to the mixture as an active filler, which was included to add additional fines to the mixture for improved foamed asphalt dispersion. However, it is recognized that there are also early and long-term stiffness benefits along with decreased moisture susceptibility.

Finally, the foamed asphalt binder was introduced to the mixture. The foaming nozzle was attached to the foamed bitumen plant and aligned with a small opening in the pugmill lid to allow the binder to be sprayed into the pugmill (Figure 4).

***Figure 4 – Foaming Nozzle Aligned with Pugmill***

To promote an even distribution, another mixing cycle was started, and after 10 seconds had elapsed, the laboratory foamed bitumen plant was activated, and the binder was distributed across the actively moving mixture in the pugmill as the 60-second cycle was completed.

After the final mixing period, the CR mixture was inspected by hand to verify cohesion and adequate dispersion of the foamed asphalt. This process includes squeezing a palm-sized sample of the loose mixture and evaluating it based on whether it falls apart. If the mixture stays bound together, the mixture has high cohesion and indicates good binder dispersion. Figure 5 shows the squeezed loose material and the dispersion check.

***Figure 5 – Cohesion and Dispersion Check of the Foamed Asphalt CR Mixture***

The foamed asphalt mixture was then placed in a plastic tub and sealed with a lid to maintain the moisture content prior to compaction. All specimens were compacted to 95 +/- 1.5 mm (3.75 +/- 0.06 in) in height in a 150 mm (5.9 in) mold with 30 gyrations in a Superpave Gyratory Compactor. The weight of loose material was varied until the desired height at 30 gyrations was achieved. A minimum of eight specimens were compacted for strength and moisture susceptibility testing. These specimens were then cured in a 40ºC oven for 72 hours.

Once fully cured, the specimens were removed from the oven, their weights were recorded, and heights were measured using calipers to later calculate the specimen's dry densities. Dry densities can be found in *4.5.2 Density*. Specimens were then allowed to rest for 24 hours at room temperature before being subjected to ITS testing. Half of the fully cured specimens were placed in a 25ºC water bath for 24 hours, while the other half rested at ambient temperatures of a temperature-controlled laboratory. After the 24-hour period, the conditioned specimens were removed from the water bath, dried to saturated surface dry (SSD) conditions, and tested per AASHTO MP 38 using the 850D Pine Test Press. The dry specimens were tested following the same procedure. Figure 6 shows a dry specimen post-ITS testing.

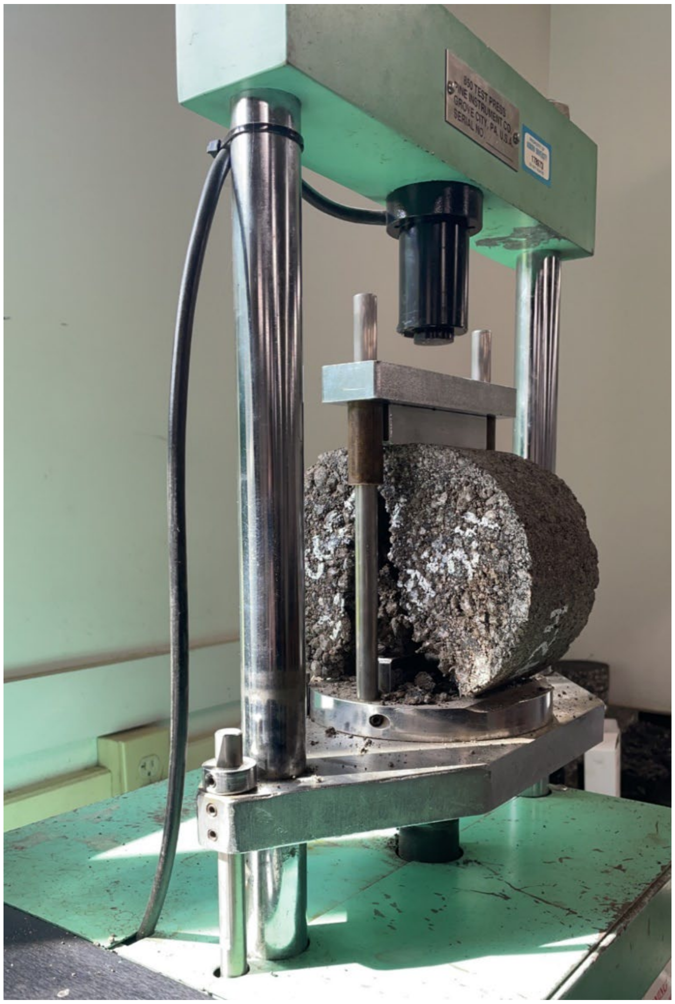

***Figure 6 – Foamed Asphalt with Active Filler Specimen Post-ITS Testing***

From the data collected during testing, the tensile strengths ($S_t$) and the TSR were calculated using Equations 3 and 4, respectively.

$$S_t = \frac{2*P}{\pi*t*D} \tag{3}$$

Where:

$S_t$ = tensile strength, psi

P = maximum load, lbf

t = specimen thickness, in

D = specimen diameter, in

$$TSR = \frac{S_{t,c}}{S_{t,d}} \tag{4}$$

Where:

TSR = tensile strength ratio

$S_{t,c}$ = average conditioned tensile strength, psi

$S_{t,d}$ = average dry tensile strength, psi

For a CR mixture containing foamed asphalt to be considered passing, the dry tensile strength must be equal to or greater than 45 psi, and the TSR of the mixture must be equal to or greater than 0.7. Three different mixture designs containing three different foamed asphalt contents were tested following this procedure. The selected asphalt contents for testing are detailed in *4.1.3 Specimen Strength and Moisture Susceptibility Evaluation*. One of the tested asphalt contents passed these requirements; therefore, no other foamed asphalt contents were tested.

### *3.1.5.2 – Anionic Emulsion with Bio-Based Rejuvenator*

AASHTO PP 86 was followed for the fabrication and testing of the anionic emulsion with bio-based rejuvenator mixture. Before the mixing process began, the appropriate amount of emulsion was weighed and then dosed with 7% bio-based rejuvenator by weight of RAP binder, per manufacturer recommendation. There were no manufacturer recommendations for the blending of the bio-based rejuvenator and emulsion; therefore, the two were blended by hand using a glass stirring rod in 10 seconds increments for a minimum for 30 seconds until visually homogenous. Unlike the foamed asphalt mixture, which operated under an optimum moisture content, this mixture used an optimum fluid content (OFC). This fluid content considers the amount of fluid added to the mixture by the emulsion (i.e., 5% OFC = 3% emulsion + 2% water). To begin the mixing process, a 25-30 kg (55-66 lb) RAP sample was added into the pugmill, followed by the water required to reach the mixture optimum fluid content and the emulsion and rejuvenator blend, with a 60-second mixing period between each addition.

The CR mixture was inspected by hand to verify cohesion, following a similar process to that of the foamed asphalt mixture. A palm-sized sample of the loose mixture was squeezed and evaluated based on whether it falls apart. If the mixture stays bound together, the mixture has high cohesion and is indicative of good binder coating. Figure 7 shows the squeezed loose material.

***Figure 7 – Cohesion Check of the Anionic Emulsion with Bio-Based Rejuvenator CR Mixture***

The rejuvenated emulsion CR mixture was then placed in a plastic tub and sealed with a lid to maintain the moisture content prior to compaction. All specimens were compacted to 63.5 +/- 3 mm (2.5 +/- 0.12 in) in a 100mm (3.9 in) mold in a Superpave Gyratory Compactor to 30 gyrations. The loose weight of the material was varied so that the specified height could be achieved at 30 gyrations. Once the appropriate amount of loose material had been identified, a minimum of eight specimens were compacted for strength and moisture susceptibility testing. The specimens were cured in a 60ºC oven for 48 hours. Two samples of the loose RAP material were also collected and cured for use in determining the theoretical maximum specific gravity ($G_{mm}$) of the mixture.

After the 48-hour curing period, the specimens were removed from the oven, their weights were recorded, and heights were measured using calipers to evaluate the dry densities. They were then allowed to rest for 24 hours at room temperature before further testing. The two samples of cured loose material were loosely broken apart and tested to determine the $G_{mm}$, which is calculated following Equation 5.

$$G_{mm} = \frac{W_S}{(W_S + W_{B,W} + W_{B,S})} \tag{5}$$

Where:

$G_{mm}$ = maximum specific gravity of the mixture

$W_S$ = sample weight, grams

$W_{B,W}$ = bowl weight in water, grams

$W_{B,S}$ = bowl and sample weight in water, grams

Once the $G_{mm}$ was calculated, it was used to determine the air void content of half of the prepared specimens following Equation 6. The specimens were then subjected to moisture conditioning by applying a vacuum of 26 mm of Hg partial pressure until the specimens were saturated within 55-75%. Once saturated, the specimens were transferred to a 25°C water bath for 23 hours, followed by 1 hour in a 40°C bath.

$$V_a = 100 * 1 - \left( \frac{\frac{W_{S,A}}{(W_{SSD} - W_{S,W})}}{G_{mm}} \right) \tag{6}$$

Where:

$V_a$ = air voids of the specimen, %

$W_{S,A}$ = specimen weight in air, grams

$W_{SSD}$ = specimen weight saturated surface dry, grams

$W_{S,W}$ = specimen weight in water, grams

$G_{mm}$ = maximum specific gravity of the mixture

After the 24-hour period, the conditioned specimens were removed from the water bath, dried to saturated surface dry (SSD) conditions, then tested via MS Testing per AASHTO PP 86 using the 850D Pine Test Press. Figure 8 shows a prepared specimen in the Marshall Stability jig on the Pine Test Press.

***Figure 8 – Anionic Emulsion CR Mixture Specimen in the Marshall Stability Jig***

The dry specimens were placed in a 40ºC oven two hours prior to MS testing. The data collected from testing produced a maximum stability per specimen in pounds. The MSR was calculated following Equation 7.

$$\text{MSR} = \frac{S_{t,c}}{S_{t,d}} \tag{7}$$

Where:

MSR = MS ratio

$S_{t,c}$ = average conditioned MS, psi

$S_{t,d}$ = average dry MS, psi

For a CR mixture containing emulsified asphalts strengths to be considered passing, the dry MS must be equal to or greater than 1250 lb (567 kg), and the MSR of the mixture must be equal to or greater than 0.7. Four different mixture designs containing four different emulsified asphalt contents were tested following this procedure. One of the four emulsion content designs passed these requirements; therefore, no additional contents were tested.

#### *3.1.5.3 – Cold Recycle Rejuvenator*

For the mixture design of this CR rejuvenator mixture, no virgin asphalt binder was used. Due to the unfamiliarity of the nature of this mixture and how it would behave, multiple different approaches were taken in the design process. Initially, this mixture was designed following AASHTO MP 38, like the foamed asphalt mixture. RAP samples were split into 8 kg (17 lb) samples, per AASHTO R76, to be mixed in a 5-quart Hobart commercial stand mixer. The weighed RAP was added to the stand mixer, followed by the amount of water required for the material to reach its OMC. The RAP and water were mixed for 60-seconds before the CR rejuvenator was added to the mixture at the dosage rate recommended by the manufacturer. The specimens were then compacted to 95 +/- 1.5 mm (3.75 +/- 0.06 in) in a 150 mm (5.9 in) mold in a Superpave Gyratory Compactor to 30 gyrations. Upon removing the first specimen from the gyratory compactor, a pool of brown fluid remained, as shown in Figure 9. It was determined that the rapid activation of the binder and the low viscosity of the rejuvenator caused the excess fluid. The fluid also contained activated binder, hence its' brown color; therefore, the specimens were discarded.

***Figure 9 – Fluid Containing Binder Remaining in the Compactor***

A second trial was then run, assuming an OFC rather than OMC. This produced similar results, with a slight reduction in fluid loss. For the third trial, the design continued to operate under an OFC assumption but with a reduced rejuvenator content and an addition of a 30-minute "mellowing period" to allow the aged binder adequate time to rejuvenate before compaction, both per manufacturer recommendations. Trial 3 was also replicated with an addition of 1% active filler in the form of cement and labeled as Trial 4. Specimens for both Trials 3 and 4 were successfully compacted without fluid remaining in the gyratory and were then cured per AASHTO MP 38. Once tested, the cement showed some strength benefits and supported a passing TSR value. However, both designs resulted in strengths well below the minimum required dry strength of 45 psi. Results from Trials 3 and 4 can be found in *4.1.3 Specimen Strength and Moisture Susceptibility Evaluation*.

During strength testing, it was observed that when the specimens cracked, they remained bonded in multiple places, as seen in Figure 10.

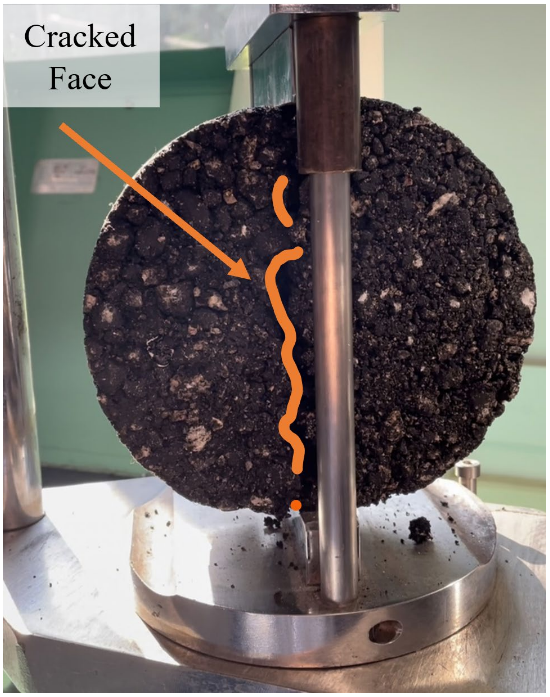

***Figure 10 – CR Rejuvenator Specimen After ITS Testing***

The data was then evaluated, and a longer strength curve with a lower peak was observed. The visual cracking and the data behavior of these specimens presented like that of a typical emulsion CR mixture, unlike a typical foamed asphalt mixture. This suggested a level of ductility in the mixture that may not be captured via ITS testing. It is hypothesized that the ITS specimen's unconfined nature and increased ductility may have made it nearly impossible to produce a passing ITS strength. Upon reaching this conclusion, a fifth trial was conducted following MS testing procedures to see if a minimum stability value typically set for emulsion mixes could be met, as the MS loading jig provides semi-circular confinement along the top and bottom of the indirectly loaded specimen.

The fifth trial followed the mixture design from Trial 3 and was compacted to 63.5 +/- 3 mm (2.5 +/- 0.12 in) in height in a 100 mm (3.9 in) diameter mold in a Superpave Gyratory Compactor to 30 gyrations, per AASHTO PP 86. The specimens were then cured at 60ºC for 48 hours and subjected to MS testing. The results from this trial showed improved strengths; therefore, a full mixture design using the pugmill was run.

This mixture process began like the two prior, with a 25-30 kg (55-66 lb) RAP sample being poured into the pugmill and allowed to mix for 60 seconds. The water required to bring the mixture to the optimum fluid content was added, followed by the CR rejuvenator, with 60-second mixing increments between each addition. The mixture was then transferred to a plastic tub, sealed with a lid, and given a 30-minute mellowing period before compaction. Figure 11 shows the CR rejuvenator mixture post-30-minute mellowing period.

*Figure 11 – CR Rejuvenator Mixture After Mellowing Period*

All specimens were compacted, cured, and tested following AASHTO PP 86. The procedure followed was identical to that of the emulsified asphalt and rejuvenator mixture and can be reviewed in *3.1.5.2 – Anionic Emulsion with Bio-Based Rejuvenator.* For this CR mixture's strengths to be considered passing, the dry MS must be equal to or greater than 1250 lb (567 kg), and the MSR of the mixture must be equal to or greater than 0.7. The Trial 5 mixture design failed the dry strength slightly but surpassed the minimum TSR. Due to the mixture design failing the dry strength requirements by only a small margin and construction related time constraints, this mixture was considered passing and used for construction in agreement with the material suppliers.

## 3.2 Plant Production and Placement

### 3.2.1 Mixture Production

During this research phase, the passing mixture designs were produced in portable plants at the NCAT Test Track for placement on the truck off-ramp. Two portable plants were used during construction. The foamed asphalt and engineered emulsion mixtures were produced in a Wirtgen KMA 240i (Figure 12), and the anionic emulsion with bio-based rejuvenator and CR rejuvenator mixtures were produced in a Pugmill Systems Portable Pugmill (Figure 13). While the plants were different, they operated effectively in the same manner. The equipment selection was made by the research sponsors.

*Figure 12 – Wirtgen KMA 240i*

*Figure 13 – Pugmill Systems Portable Pugmill*

### 3.2.2 Mixture Placement and Paving

After production, all mixtures were loaded into standard dump trucks and immediately transported to the off-ramp for placement. At the off-ramp, the mixtures were loaded from the back of the standard dump truck directly into the hopper of a typical asphalt paver and placed in a similar manner to a HMA mixture. All CR mixtures were placed in a single 4 in (102 mm) thick lift and compacted until refusal. Wet densities were tested with a nuclear density gauge. Due to construction scheduling, the CR sections were placed on different days. However, all sections were allowed to cure for at least two days prior to being overlaid. Once cured, the sections were surfaced with a 1-inch thick, 4.75 mm nominal maximum aggregate size thinlay of HMA in a single, continuous pass.

## 3.3 Plant Mixed Lab Compacted Specimen Production and Testing

### 3.3.1 Mixture Sampling

To create PMLC specimen, loose material samples of each CR mixture were collected on-site approximately halfway through production. Four mixtures were collected; this included the Engineered Emulsion mixture developed by the supplier and the three CR mixtures developed at the NCAT laboratory. To collect a homogenous sample that effectively represents the entire mixture, the conveyor placed a mini stockpile of the mixture onto the ground, where it was sampled per ASTM D75. The collected material was placed in a plastic tub and sealed with a lid to maintain the moisture content until compaction. Each tub of material was immediately transported to the laboratory for specimen fabrication.

### 3.3.2 Specimen Compaction, Curing, and Testing

Once transported to the lab, the mixtures were compacted as they were in the mixture design phase. The engineered emulsion, anionic emulsion with bio-based rejuvenator, and CR rejuvenator mixture specimens were compacted to 63.5 +/- 3 mm (2.5 +/- 0.12 in) in height in a 100 mm (3.9 in) diameter mold to 30 gyrations and cured for 48 hours at 60°C per AASHTO PP 86. The samples were then subjected to MS testing. The foamed asphalt with active filler mixture was compacted into specimen 95 +/- 1.5mm (3.7 +/- 0.06 in) in height in a 150mm (5.9 in) mold to 30 gyrations. The specimens were then cured in a 40°C oven for 72 hours and subjected to ITS testing. All specimens had their heights and weights recorded promptly after being removed from the oven to calculate dry densities. A total of eight specimens were compacted per mixture design.

## 3.4 Lab Mixed Lab Compacted Specimen Production and Testing

### 3.4.1 Material Collection

To create the Lab Mixed Lab Compacted (LMLC) specimens, both RAP and any recycling and/or rejuvenating agents used were collected on-site during production. RAP was sampled from the single stockpile used in production per ASTM D75 and transported in 50-gallon plastic drums to NCAT. The RAP was then dried and split following the process outlined in section 3.1.2 *RAP Sampling*. All recycling and rejuvenating agents were collected in one-gallon metal cans and stored indoors at ambient temperatures for no more than two weeks before use in lab mixture production. The virgin PG 67-22 asphalt binder used for the foamed asphalt mixture design was collected in a five-gallon metal bucket. Once transported to NCAT, it was heated and split into one-gallon metal cans.

### 3.4.2 Specimen Mixing, Compaction, and Curing

All quantities of recycling agents, rejuvenating agents, active fillers, and water used in the laboratory mixing process were based upon those used in mixture production. The mixing of the materials for the three designs developed at NCAT were performed in the same manner as mixture design, which can be found in section 3.1.5 *Specimen Fabrication and Strength and Moisture Susceptibility Evaluation*.

The engineered emulsion mixture design developed by the manufacturer was mixed at the NCAT lab following a similar procedure. The emulsion was placed in a 40$^{o}$C oven in a metal can and stirred by hand with a glass stirring rod every 5-10 minutes until homogenous. Once homogenous, it was removed from the oven and allowed to sit for no longer than a 4-hours before being used. A 25-30 kg (55-66 lb) RAP sample was poured into the pugmill, followed by the quantity of water needed to bring the mixture to the OFC, then the weighed amount of emulsion, with 60-second mixing periods between each addition. The mixture was then visually inspected for homogeneity and placed into a plastic tub with a sealable lid to maintain moisture before compaction.

For the LMLC specimens, three different sizes were compacted, and two different gyratory compactors were utilized. Table 1 shows the specimen dimensions and gyratory compactor used. Once compacted, all specimens were cured based upon their respective specifications. Promptly after curing, all specimens had their weights recorded and heights measured using calipers to record the dry densities. The ITS and MS specimens were tested following the same procedures as in the mixture design to evaluate any differences in strength and density that may have occurred between mixing methods. All LMLC specimens used for dynamic modulus testing were compacted to the wet density measured in the field to better replicate as-built properties for testing.

***Table 1 – LMLC Specimen Dimensions and Compactor Used***

| | *ITS* | *MS* | *IDEAL-CT/ HT-IDT* | *Dynamic Modulus* |
|---|---|---|---|---|
| *Height, mm* | 95.0 +/- 1.5 | 63.5 +/- 1.5 | 62.0 +/- 1.5 | 180.0 +/- 10 |
| *Diameter, mm* | 150 | 100 | 150 | 150 |
| *Gyratory Compactor* | Pine 125X | Pine 125X | Pine 125X | Pine G2 |

### 3.4.3 Specimen Performance Testing

#### *3.4.3.1 - IDEAL-CT*

Specimens from each of the four CR mixture designs were subjected to IDEAL-CT testing to determine a $CT_{Index}$. A minimum of five replicates were tested per design. Fully cured specimens were allowed to rest at ambient temperature in a temperature-controlled laboratory for two days before being tested using the 850D Pine Test Press and were loaded at a displacement rate of 50 mm/min (2.0 in/min). The data collected from the Test Press was input into a spreadsheet developed by Pine that calculated the $CT_{Index}$.

#### *3.4.3.2 - HT-IDT*

Like the IDEAL-CT specimen, the fully cured HT-IDT specimens were allowed to rest at ambient temperature in a temperature-controlled laboratory for two days before testing. HT-IDT testing was conducted following ALDOT-458. A minimum of five specimens were placed in a 50ºC oven for 2 hours to condition prior to testing and were removed one at a time for testing using the 850D Pine Test Press. Each specimen was loaded at a 50 mm/min rate (2.0 in/min), and the maximum load withstood was recorded. To calculate the HT-IDT Strength, Equation 8 was used.

$$\mathrm{HT-IDT\ Strength} = \frac{2 * max\ load}{\pi * D * H} \tag{8}$$

Where:

HT-IDT Strength = strength, psi

Max Load = maximum load withstood, lb

D = specimen diameter, in

H = specimen height, in

### *3.4.3.3 - Dynamic Modulus*

Dynamic modulus testing was performed on 150 mm (5.9 in) tall, 100 mm (3.9 in) diameter specimens for each of the four CR mixtures, with three replicates per mixture. To obtain a specimen for testing, the previously compacted 180 mm (7.0 in) tall, 150 mm (5.9 in) diameter specimens were cored and cut to the appropriate size. Before coring, all specimens were allowed to rest at ambient temperature in a temperature-controlled laboratory for a minimum of two weeks. A wet coring drill (Figure 14) was used to core the specimen and a wet masonry saw was used to cut the specimen to their 150 mm (5.9 in) required height. All cored and cut specimens were allowed to sit in front of fans at ambient temperature in a temperature-controlled laboratory for two weeks minimum to ensure all excess moisture was removed.

***Figure 14 – Coring Drill with 100mm Bit***

All LMLC 180 mm (7.0 in) tall specimens were successfully cored except the foamed asphalt with active filler mixture. Halfway through the coring of the first specimen, the loose aggregate stripped the specimen from the inside, and the specimen crumbled, as seen in Figure 15.

***Figure 15 – Foamed Asphalt Specimen After Coring***

A second trial of coring was run using a dry coring method on a specimen that had been placed in a freezer and allowed to remain there for 2 days prior. This trial produced the same results as the first. A third trial was then run using a frozen specimen and wet drill, which also produced a stripped and broken specimen (Figure 16).

*Figure 16 – Broken Foamed Asphalt Specimen After Wet Coring Frozen*

With none of the LMLC foamed asphalt with active filler specimen being able to be cored intact, surplus material from the off-ramp construction was used to compact new specimens for testing. Since this mixture could not be cored, the new specimens were compacted to 150 mm in height in a 100 mm diameter mold to field density.

Once all specimens were fully cured, dried, and ready for testing, their dry weights were recorded, and heights and diameters were measured. Studs were then placed on the specimen using the IPC Global Gauge Point Fixing Jig in Figure 17.

***Figure 17 – Dynamic Modulus Specimen on Gauge Point Fixing Jig***

The dynamic modulus testing was performed using an IPC Global AMPT PRO. Based on the research completed in National Cooperative Highway Research Program (NCHRP) project 09-51 (Schwartz et al. 2017), three testing temperatures of 4.4ºC, 21.1ºC, and 37.8ºC and six testing frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz were used. The specimens were tested from the lowest to the highest temperature with decreasing frequency to reduce the potential for damage to the specimen. Each testing temperature required different conditioning times, overnight for 4.4ºC, two hours for 21.1ºC, and three hours for 37.8ºC. Before loading the specimen into the AMPT chamber, a linear variable differential transformer (LVDT) target clamp was placed on each stud. For the highest testing temperature, pairs of springs were also placed between pairs of target clamps. Once the specimen was loaded, the LVDTs were placed between each pair of target clamps, Teflon sheets were placed between the specimen and top and bottom loading platens to reduce friction, and the chamber was closed. Figure 18 shows a loaded specimen with LVDTs placed.

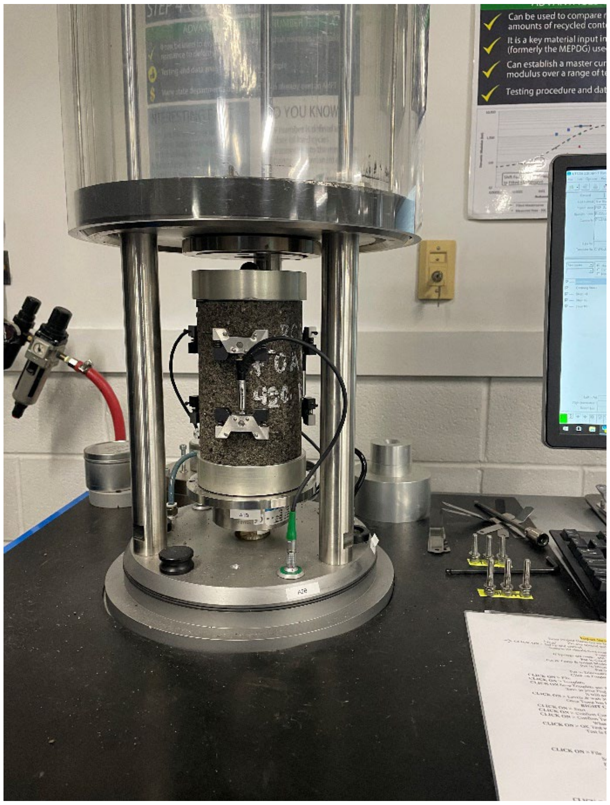

***Figure 18 – Specimen Loaded into AMPT Pro Chamber with LVDTs Placed***

The specimen was left in the chamber for 30 minutes at the conditioning temperature before starting the dynamic modulus testing. Once the data was collected, it was required to meet a set of data quality characteristics shown in Table 2.

***Table 2 – Data Quality Characteristics Used for Dynamic Modulus Data***

| *Data Quality Characteristic* | *Tolerance Value* |
|---|---|
| Load Standard Error | <10% |
| Deformation Standard Error | <10% |
| Deformation Uniformity | <30% |
| Phase Uniformity | <3° |

### 3.5 Summary

Three of the four CR mixture designs were developed at NCAT, with the fourth being developed by a recycling agent manufacturer. The OMC of the RAP and the foamed asphalt binder properties were determined prior to mixture design trials. All final mixture designs were conducted following either AASHTO MP 38 or AASHTO PP 86.

All mixtures were produced in portable plants on-site and were compacted until refusal for density. Mixtures were sampled during production and transported back to the NCAT lab for compaction. Raw materials were also collected on-site to compact laboratory mixed laboratory compacted specimens for performance testing.

Specimens were compacted to various sizes using the collected materials for performance testing. The cracking resistance of each mixture was determined via IDEAL-CT. The rutting potential of the mixture was determined via HT-IDT. Dynamic modulus data was also collected on all mixtures so assess mixture stiffness.

# CHAPTER FOUR: RESULTS

Chapter Four is presented in five sections. The first section highlights the findings pertaining to the mixture design process; these include the RAP gradation, OMC establishment, foamed asphalt binder properties, and the strength and moisture susceptibility evaluation of each mixture. This section is presented separately from the Methodology section as there are distinct, unpublished differences in the developed methodology than in other CR mixture design methodologies outlined in specifications. The second section describes the production and placement of the established mixture designs. This section is broken into two main categories: Production, and Placement, Compaction, and In-Place Properties. Section Three discusses the results of the strength and moisture susceptibility testing completed on the PMLC specimens. The fourth section covers the performance testing conducted on LMLC specimens, which includes IDEAL-CT, HT-IDT, and Dynamic Modulus Testing. Finally, Section Five focuses on the influence of laboratory production versus plant production on mixture performance, as well as the influence of rejuvenators on mixture performance and density.

## 4.1 Mixture Design

### 4.1.1 RAP Gradation and Optimum Moisture Content

A minimum of four black rock and washed gradations were run on the collected RAP and were plotted in a 0.45 power chart (Figure 19). Obtaining a washed gradation allowed for a more accurate estimate of material passing the No. 200 sieve. The washed gradation showed an increase of approximately 1.2% in material passing the No. 200 sieve. Table 3 shows the RAP percentage passing each sieve prior to and after washing.

***Table 3 – RAP Gradations***

| | *Black Rock RAP Gradation* | *Washed RAP Gradation* |
|---|---|---|
| *Sieve Size* | *% Passing* | *% Passing* |
| 2" | 100.0% | 100.0% |
| 1 1/2" | 100.0% | 100.0% |
| 1" | 100.0% | 100.0% |
| 3/4" | 100.0% | 100.0% |
| 1/2" | 97.6% | 96.9% |
| 3/8" | 89.4% | 82.5% |
| #4 | 65.3% | 46.4% |
| #8 | 45.8% | 28.5% |
| #18 | 30.8% | 18.5% |
| #30 | 19.3% | 12.0% |
| #50 | 9.8% | 7.1% |
| #100 | 3.6% | 3.9% |
| #200 | 1.1% | 2.3% |

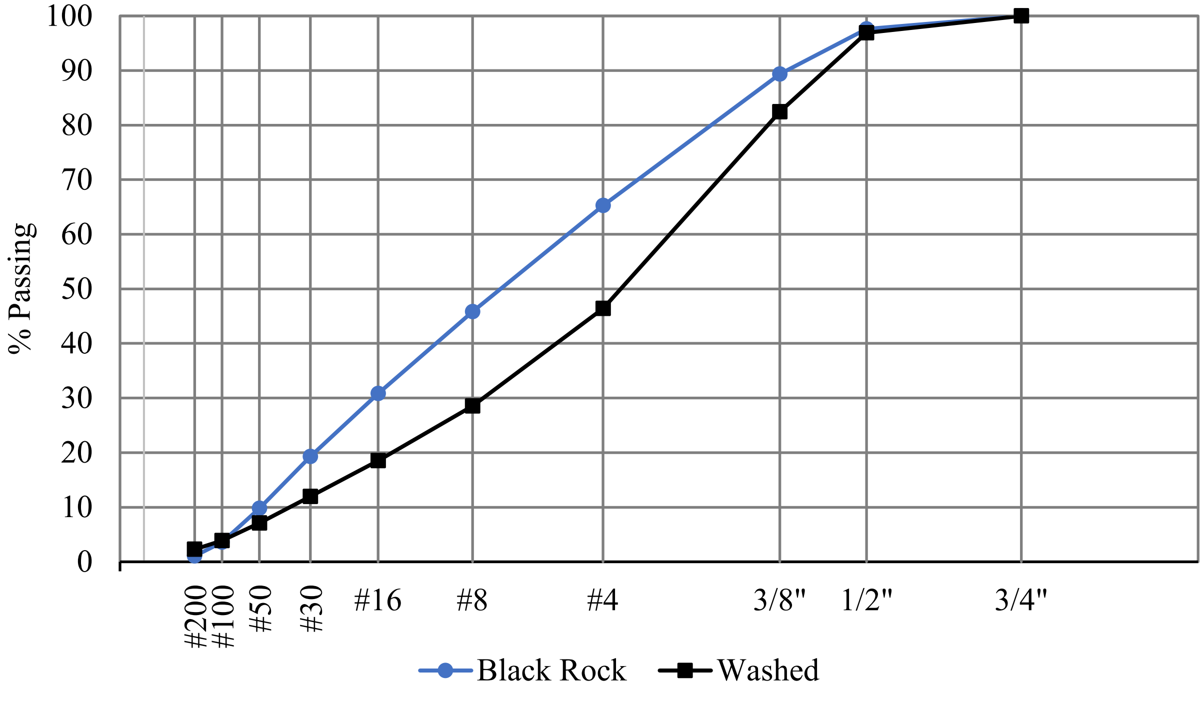

***Figure 19 – Black Rock and Washed Gradations***

The results from the modified Proctor conducted to help determine the OMC are shown in Figure 20.

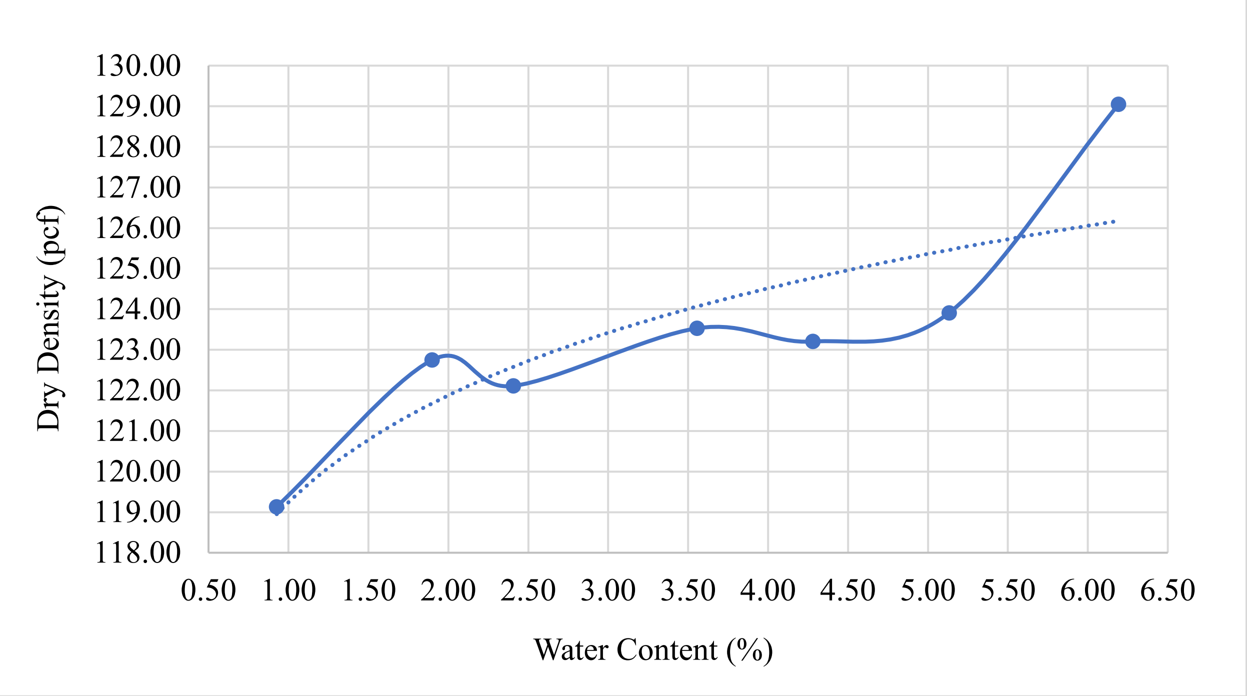

***Figure 20 – Modified Proctor Test Results***

Based on the visual observations made during the Proctor test, the data analysis, and prior knowledge of RAP in CR mixtures, the OMC was identified as 5% for the RAP used. The moisture-density curve is irregular in shape with no distinct peak. A modified Proctor is typically run on soils with more consistency among sources versus RAP, in which gradation, aggregate properties, and binder proportions vary more between sources. Soils with liquid limits below 30 or above 70 have been shown to produce irregularly shaped Proctor curves with no or multiple peaks (Lee and Suedkamp 1972), like the curve in Figure 20. Tests typically run on soils, such as Atterberg limits (liquid limit, plastic limit, etc.), were not run on the RAP used in this research. However, in a study by Locander (2009), multiple sources of RAP were evaluated, and all had liquid limits below 30. It is hypothesized that the RAP used potentially has a low liquid limit which could be a contributing factor toward the irregularly shaped Proctor curve.

### 4.1.2 Foamed Asphalt Binder Properties

For this project, an Alabama sourced PG 67-22 asphalt binder was used. To determine the optimum foaming conditions, the expansion ratio and half-life of the foamed binder were evaluated at 160°C, 170°C, and 180°C at 2%, 3%, and 4% water contents. The results from these trials are shown in Figures 21, 22, and 23. The black, horizontal line in each figure at an expansion ratio of 8.0 and a half-life of 6.0 seconds represents the minimum requirements for both criteria.

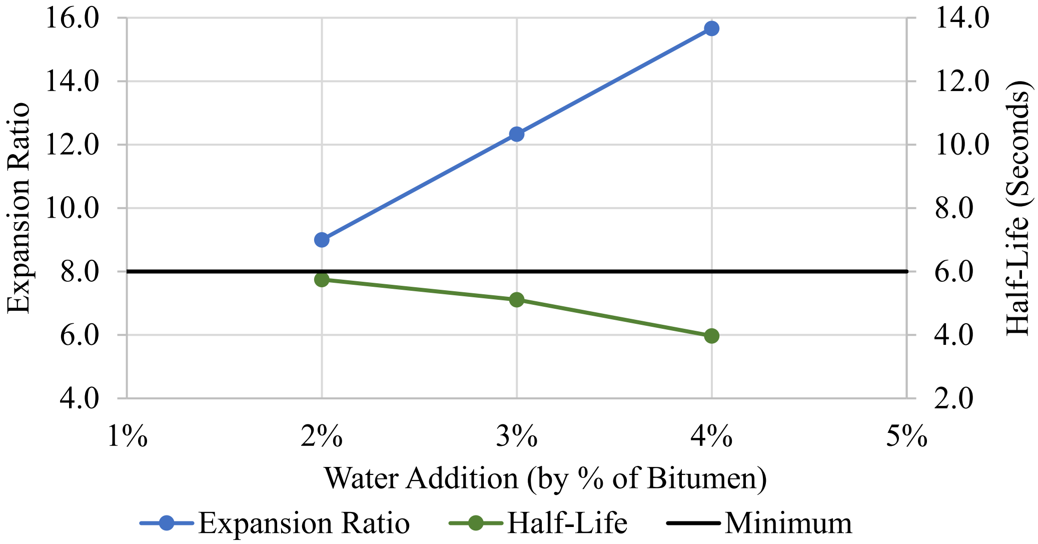

*Figure 21 – Foamed Asphalt Properties at 160°C*

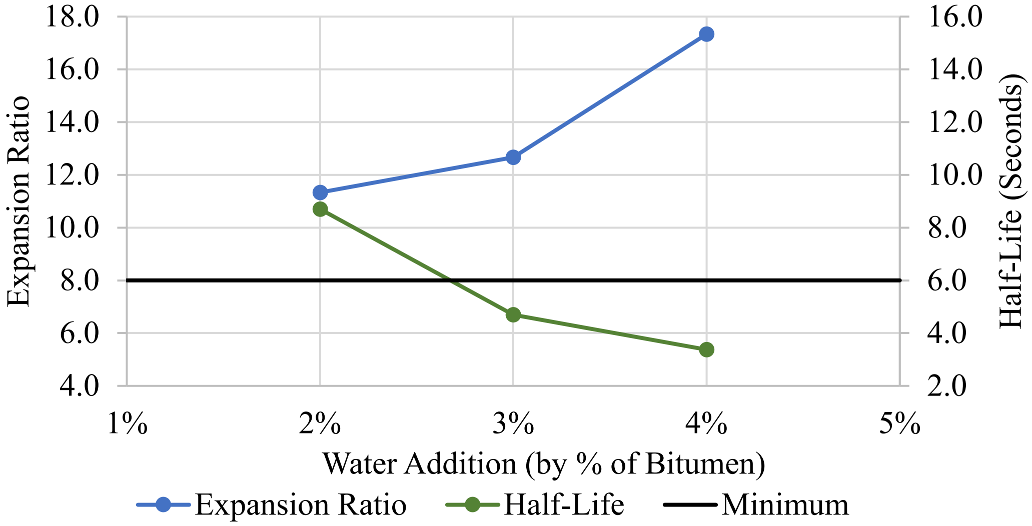

***Figure 22 – Foamed Asphalt Properties at 170°C***

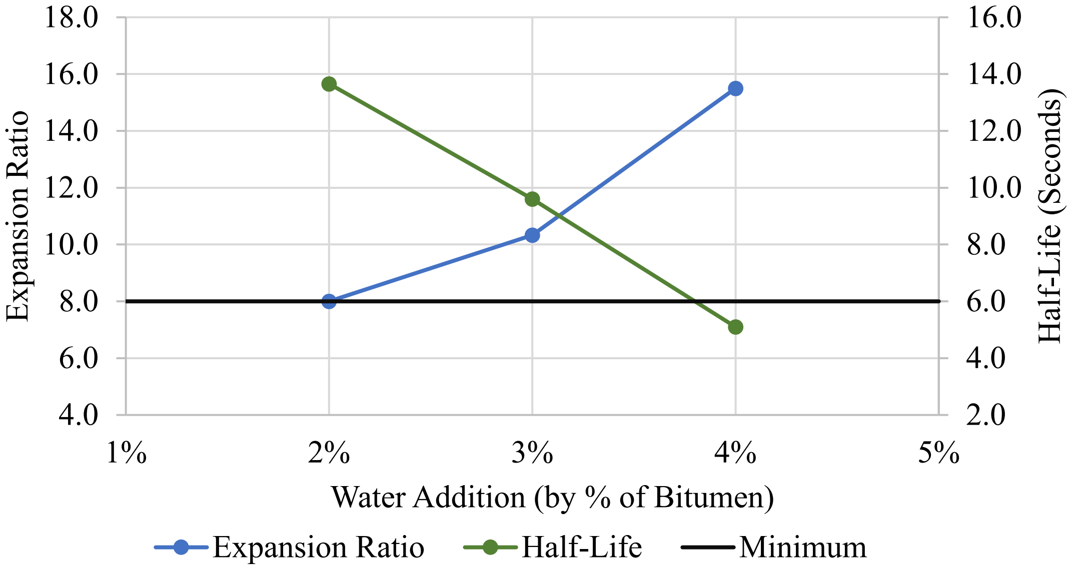

***Figure 23 – Foamed Asphalt Properties at 180°C***

At 160°C, none of the water contents passed the minimum requirements for expansion ratio and half-life. Both 2% and 3% water contents passed the minimum requirements at 180°C. However, 170°C at 2% water content was ultimately chosen for use in mixture design as it provided passing values for both the expansion ratio and the half-life at the lowest temperature and lowest added water content.

### 4.1.3 Specimen Strength and Moisture Susceptibility Evaluation

#### *4.1.3.1 – Foamed Asphalt with Active Filler*

The ITS test results for the mixture design trials for the foamed asphalt with active filler mixture can be found in Figure 24, with a summary of each design trial in Table 4. The recommended minimum dry strength is 45 psi, which is marked with a horizontal red line. The error bars indicate the standard deviation of each specimen set.

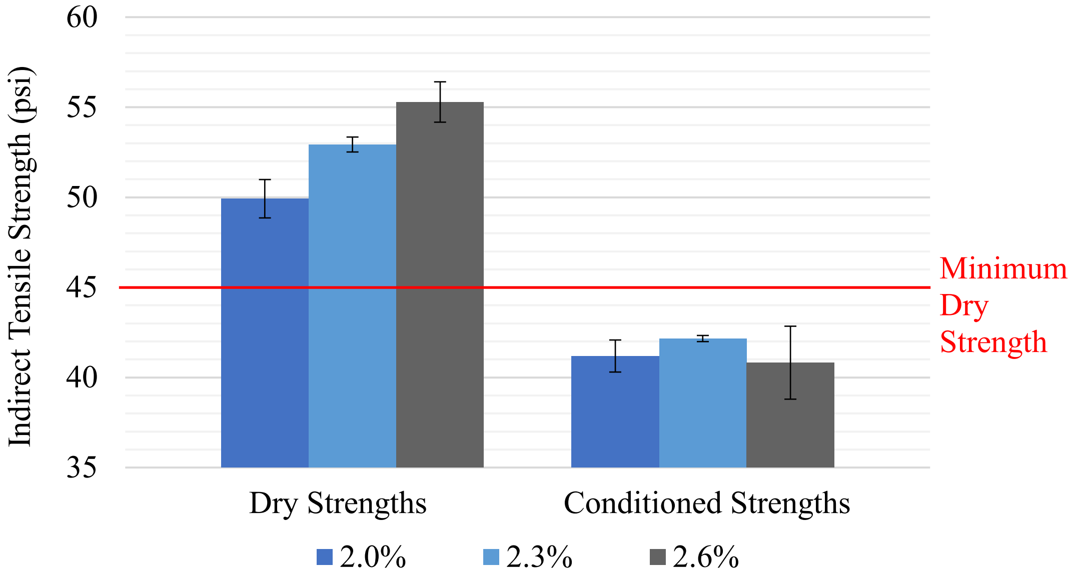

***Figure 24 – ITS Results for Foamed Asphalt with Active Filler Mixture Designs***

***Table 4 – Summary of ITS Results for Foamed Asphalt with Active Filler Mixture Designs***

| *Foamed Asphalt Content (%)* | *2.0%* | *2.3%* | *2.6%* | *Minimum Requirement* |
|---|---|---|---|---|
| *Dry ITS (psi)* | 50 | 53 | 55 | 45 |
| *Conditioned ITS (psi)* | 41 | 42 | 41 | - |
| *TSR* | 0.83 | 0.80 | 0.74 | 0.7 |

The ITS results indicate a reduction in specimen strength when conditioned versus dry, as expected. The dry strength increased as foamed asphalt content increased, while the conditioned strengths only varied slightly and did not show a pattern of consistent increasing or decreasing strength with respect to foamed asphalt content. All mixture design trials passed the minimum requirements for both dry strength and TSR. The 2.0% foamed asphalt content was selected as it met the requirements at the lowest added binder content, which provides both resource and cost benefits.

#### *4.1.3.2 – Anionic Emulsion with Bio-Based Rejuvenator*

The MS testing results for the anionic emulsion with bio-based rejuvenator mixture design can be found in Figure 25, with a summary in Table 5. The minimum recommended dry strength for the 100 mm specimens is 1250 lb and is indicated with a red horizontal line. The error bars indicate the standard deviation of each specimen set.

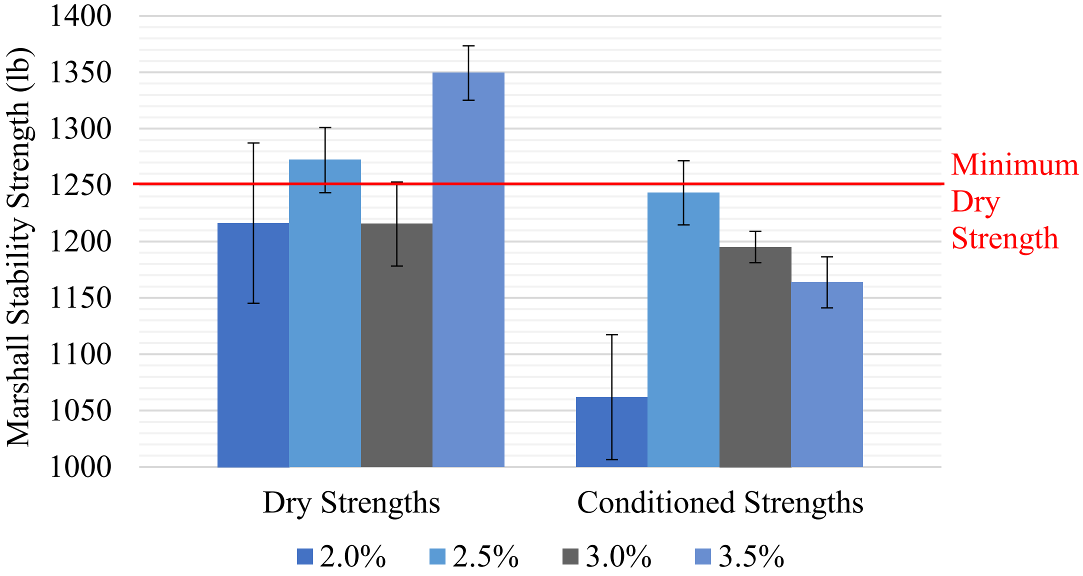

***Figure 25 – MS Results for Anionic Emulsion with Bio-Based Rejuvenator Mixture Designs***

***Table 5 – Summary of MS Results for Anionic Emulsion Mixture Designs***

| *Emulsion Content (%)* | *2.0%* | *2.5%* | *3.0%* | *3.5%* | *Minimum Requirement* |
|---|---|---|---|---|---|
| *Dry MS (lb)* | 1216 | 1272 | 1215 | 1349 | 1250 |
| *Conditioned MS (lb)* | 1062 | 1243 | 1195 | 1163 | - |
| *MSR* | 0.87 | 0.98 | 0.98 | 0.86 | 0.7 |

*Red cells indicate failure to meet criteria

Although both the 2.0% and 3.0% emulsion content designs met the minimum MSR requirement, they failed to meet the minimum strength requirements. Therefore, neither design was considered for final design selection. 2.5% and 3.5% emulsion content mixtures passed all minimum requirements. However, the 2.5% design only passed the dry strength requirement by a small margin. Therefore, 3.5% emulsion content was selected as the final mixture design.

### *4.1.3.3 – Cold Recycle Rejuvenator*

As detailed in Section *3.1.5.3 – Cold Recycle Rejuvenator*, multiple mixture designs were trialed to determine the optimum mixture design and method. The only trials subjected to ITS testing were Trials 3 and 4. These mixtures were identical except for the addition of 1% cement to Trial 4. Table 6 shows the summary of the ITS results. The addition of cement provided some strength benefits and a passing TSR; however, the strengths were well below both the strength of the mixture containing foamed asphalt and the minimum ITS requirement. Therefore, cement was not considered for use in construction.

***Table 6 – Summary of ITS Results for CR Rejuvenator Mixture Designs***

| | *CR Rejuvenator (no cement)* | *CR Rejuvenator (cement)* | *Minimum Requirement* |
|---|---|---|---|
| *Dry ITS (psi)* | 13 | 17 | 45 |
| *Conditioned ITS (psi)* | 7 | 16 | - |
| *TSR* | 0.55 | 0.91 | 0.7 |

Due to time and material constraints, only a single rejuvenator content was used for Trial 5. Trial 5 followed the same mixture design as Trial 3, with the only difference between the two being the testing method. The MS testing results for this mixture design can be found in Table 7.

***Table 7 – Summary of MS Results for CR Rejuvenator Mixture Design***

| *Rejuvenator Content (%)* | *0.9%* | *Minimum Requirement* |
|---|---|---|
| *Dry MS (lb)* | 🟥 1159 | 1250 |
| *Conditioned MS (lb)* | 1351 | - |
| *MSR* | 1.17 | 0.7 |

*Red cells indicate failure to meet criteria

The final mixture failed the dry strength criteria by approximately 90 lb (41 kg). However, the mixture showed increased strength when conditioned, surpassing the minimum strength requirement and indicating low moisture susceptibility. This mixture design was selected in agreement with the product suppliers due to time constraints related to construction.

#### *4.1.3.4 – Engineered Emulsion*

The mixture design process and stability testing were performed by the engineered emulsion supplier with the RAP material provided by NCAT. Results for the final mixture design only were provided and are shown in Table 8 below, with the associated acceptance criteria. The provided engineered emulsion mixture design passed both minimum requirements and was used for construction and further lab testing. Table 9 shows the final mixture designs for all four CR mixtures.

***Table 8 – Summary of MS Results for Engineered Emulsion Mixture Design***

| *Emulsion Content (%)* | *3.0%* | *Minimum Requirement* |
|---|---|---|
| *Dry MS (lbf)* | 3366 | 1250 |
| *Conditioned MS (lbf)* | 3182 | - |
| *MSR* | 0.94 | 0.7 |

*Table 9 – Summary of MS Results for Engineered Emulsion Mixture Design*

| | *Foamed Asphalt + Active Filler* | *Anionic Emulsion + Bio-Based Rejuvenator* | *CR Rejuvenator* | *Engineered Emulsion* | *Minimum Requirement* |
|---|---|---|---|---|---|
| *Foamed Asphalt or Emulsion (%)* | 2.0 | 3.5 | - | 3.0 | - |
| *Cement Active Filler (%)* | 1.0 | - | - | - | - |
| *Rejuvenator (%)* | - | 7.0* | 0.9 | - | - |
| *Water (%)* | 4.7 | 0.5 | 2.1 | 2.25 | - |

*All percentages are by weight of dry RAP, with the exception of the bio-based rejuvenator dosage, which is by weight of RAP binder

## 4.2 Production and Placement of Mixture Designs

### 4.2.1 Production

The RAP used in production was stored outdoors and uncovered. Due to recent rainfall, it contained high moisture contents and mixtures were produced with this in mind. In many cases, the RAP moisture content exceeded the optimum moisture or fluid content of the mixture design. Samples of the RAP stockpile were collected immediately before production and mixture samples were collected mid-production in order to record moisture contents. A summary of the as-built mixture designs, RAP moisture contents, and mixture moisture contents are provided in Table 10 below.

***Table 10 – Summary of Test Results for all Plant Produced CR Mixture Designs***

| | *Foamed Asphalt + Active Filler* | *Anionic Emulsion + Bio-Based Rejuvenator* | *CR Rejuvenator* | *Engineered Emulsion* |
|---|---|---|---|---|
| *Foamed Asphalt, or Emulsion Content (%)* | 2.00 | 3.50 | - | 2.25 |
| *Cement Content (%)* | 1.00 | - | - | - |
| *Rejuvenator Content (%by weight of RAP binder)* | - | 7.00 | 0.90 | - |
| *Added Water (%)* | 2.00 | 2.00 | 0.00 | 0.00 |
| *RAP Moisture Content (%)* | 3.87 | 4.37 | 4.88 | 5.63 |
| *Produced Mixture Moisture Content (%)* | 6.00 | 6.42 | 4.98 | 6.71 |

All percentages are by weight of dry RAP unless otherwise noted.

### 4.2.2 Placement, Compaction, and In-Place Properties

The CR sections were placed in the following order: foamed asphalt with active filler (Figure 26), engineered emulsion (Figure 27), CR rejuvenator (Figure 28), and anionic emulsion with bio-based rejuvenator (Figure 29). Not all sections were placed on the same day; however, they were all allowed for a minimum of two days to cure before the asphalt overlay was placed. All sections were compacted to refusal immediately after paving except for the anionic emulsion with bio-based rejuvenator mixture. During initial compaction, the emulsion began flushing out of the surface. This is likely due to the moisture content of the RAP in combination with the rejuvenator and emulsion increasing total fluid content beyond the OFC. All rollers were immediately removed from the mat and the section was allowed to dry for a few hours. After the drying period, the mat was compacted with no issues.

*Figure 26 – Foamed Asphalt with Active Filler Section*

*Figure 27 – Engineered Emulsion Section*

*Figure 28 – CR Rejuvenator Section*

*Figure 29 – Anionic Emulsion with Bio-Based Rejuvenator Section*

Intelligent Compaction (IC) data was collected during the placement of each CR mixture. From this, the following data was collected: number of passes, amplitude, frequency, and impacts per foot. Figure 30 shows the location of each section and Table 11 shows the section number corresponding to each mixture.

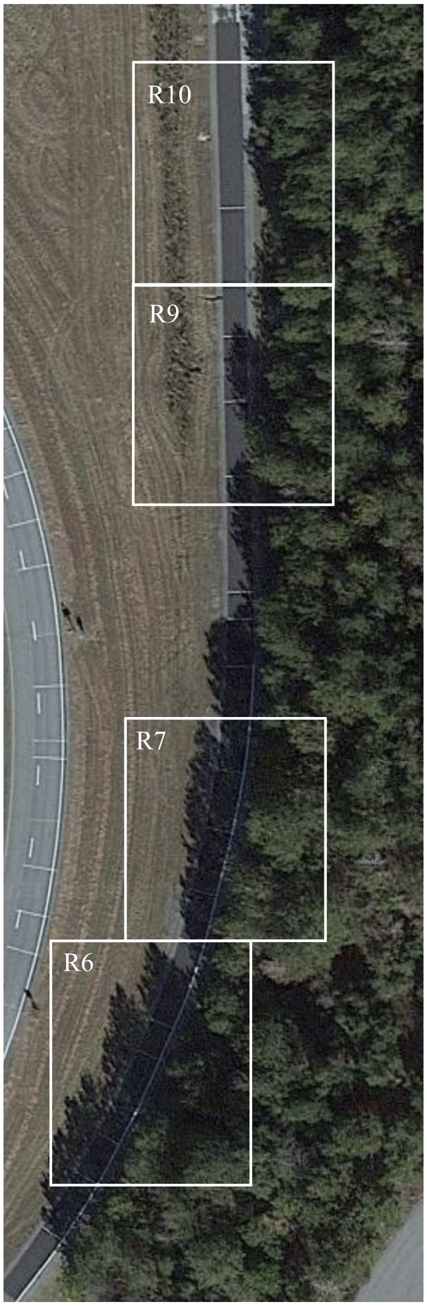

*Figure 30 – Labelled Sections on the Off-Ramp*

***Table 11 – Sections and their Corresponding Mixtures***

| *Section* | *Mixture* |
|---|---|
| *R6* | Foamed Asphalt with Active Filler |
| *R7* | Engineered Emulsion |
| *R9* | CR Rejuvenator |
| *R10* | Anionic Emulsion with Bio-Based Rejuvenator |

***Table 12 – Intelligent Compaction Data by Section***

| | | *R6* | *R7* | *R9* | *R10* |
|---|---|---|---|---|---|
| *Number of Passes* | Mean | 3.00 | 3.00 | 4.00 | 4.00 |
| | Max | 8.00 | 8.00 | 8.00 | 10.00 |
| | Min | 1.00 | 1.00 | 1.00 | 1.00 |
| *Speed (mph)* | Mean | 1.90 | 1.80 | 1.90 | 1.90 |
| | Max | 2.00 | 2.00 | 2.00 | 2.00 |
| | Min | 0.00 | 0.00 | 0.00 | 0.00 |
| *Frequency (vpm)* | Mean | 2831 | 2651 | 2677 | 2679 |
| | Max | 2940 | 2700 | 2700 | 2700 |
| | Min | 1920 | 1920 | 1980 | 2100 |
| *Impacts per Foot* | Mean | 19.17 | 15.21 | 15.83 | 15.39 |
| | Max | 59.74 | 18.29 | 24.69 | 17.03 |
| | Min | 12.11 | 10.97 | 11.32 | 12.34 |

The roller speed across all sections remained nearly consistent, as did the average frequency. Sections R9 and R10 (the sections containing a rejuvenator) required an average of one more pass versus the non-rejuvenated CR sections. Section R6 required on average 20% more impacts per foot versus all other CR sections.

Maximum field wet densities were recorded for each mixture using a nuclear density gauge and are reported in Table 13, along with the percent density achieved versus mixture design.

***Table 13 – Wet Field Densities and Percentage of Lab Density***

| *Mixture* | *Field Wet Density (pcf)* | *% Density* |
|---|---|---|
| *Foamed Asphalt with Active Filler* | 127.7 | 95.3 |
| *Anionic Emulsion with Bio-Based Rejuvenator* | 135.1 | 96.6 |
| *CR Rejuvenator* | 132.5 | 93.9 |
| *Engineered Emulsion* | 131.7 | lab density unknown |

There were no challenges achieving the target densities, indicating that all CR mixtures were providing adequate support. CR sections require an extended period to cure in place before being able to core a representative specimen that would remain intact. Due to this and all off-ramp test sections being shorter than the standard, cores to determine dry densities were not taken as to not compromise the test sections.

## 4.3 Plant Mixed Lab Compacted Specimen Performance Testing

The PMLC specimen strength and moisture susceptibility testing results are summarized in Table 14.

***Table 14 – Summary of Strength and Stability Test Results for PMLC Specimen***

|  | *Foamed Asphalt + Active Filler* | *Anionic Emulsion + Bio-Based Rejuvenator* | *CR Rejuvenator* | *Engineered Emulsion* | *Minimum Requirement* |
|---|---|---|---|---|---|
| *Dry ITS (psi)* | 51 | - | - | - | 45 |
| *Conditioned ITS (psi)* | 37 | - | - | - | - |
| *Dry MS (lb)* | - | 1349 | 1453 | 3366 | 1250 |
| *Conditioned MS (lb)* | - | 2318 | 1636 | 3182 | - |
| *TSR/MSR* | 0.71 | 1.72 | 1.13 | 0.95 | 0.7 |

All plant produced mixtures met their respective minimum criteria. The two rejuvenated mixtures saw greater conditioned strengths than dry strengths, resulting in MSR values above one. Although no research has confirmed a reason as to why the strength of the rejuvenated mixtures increases when conditioned, it is hypothesized that the vacuum saturation of the samples, the increased fluid content of the mixture versus in mixture design, and/or a possible chemical reaction during the conditioning process may lead to these increased conditioned strengths.

## 4.4 Lab Mixed Lab Compacted Specimen Performance Testing

### 4.4.1 IDEAL-CT

IDEAL-CT testing produced a $CT_{Index}$ for each CR mixture, shown in Table 15, with a higher $CT_{Index}$ corresponding to a higher cracking resistance.

***Table 15 – $CT_{Index}$ for all CR Mixtures***

| *Mixture* | *$CT_{Index}$* | *Standard Deviation* |
|---|---|---|
| *Foamed Asphalt with Active Filler* | 19.1 | 5.6 |
| *Anionic Emulsion with Bio-Based Rejuvenator* | 117.9 | 14.1 |
| *CR Rejuvenator* | 113.9 | 27.7 |
| *Engineered Emulsion* | 81.8 | 24.9 |

As seen in the table above, the rejuvenated mixtures provide a higher $CT_{Index}$ than those without rejuvenator. This indicates that the rejuvenating of the RAP binder is resulting in a more ductile and cohesive mixture, thus producing a more cracking resistant mixture versus a typical, non-rejuvenated CR mixture. The lower $CT_{Index}$ seen in the foamed asphalt with active filler mixture is likely due to the addition of the cement, similar to the findings of Diefenderfer et. al (2019).

During data evaluation, the mixtures containing emulsion and/or rejuvenators presented a longer strength curve with a lower peak versus the mixture containing foamed asphalt (Figure 31). With this in mind, the inflection point determined through the calculations currently used in the $CT_{Index}$ equation may vary more significantly between CR mixtures than that of a typical HMA. It is hypothesized that, as is, the fundamental inputs into the equation to determine the $CT_{Index}$ may not be applicable for all CR mixtures. Future research investigating the inflection point of the curve and its influence over the $CT_{Index}$ should be conducted.

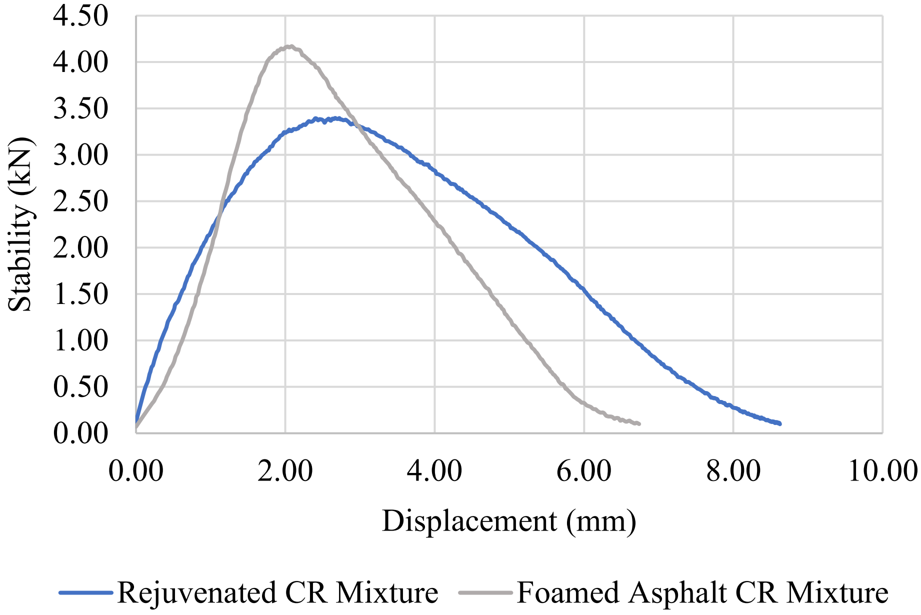

***Figure 31 – CR Mixture Strength Curve Comparison***

In order to determine whether any statistical differences were present, a Tukey Pairwise Comparison and Analysis of Variance (ANOVA) were conducted. Both assumed equal variances and used a significance level of α = 0.05. Table 16 shows the results from this test with the abbreviations being associated with the mixtures as follows: Foamed Asphalt with Active Filler (F), Anionic Emulsion with Bio-Based Rejuvenator (E+R), CR Rejuvenator (CRR), and Engineered Emulsion (EE). The results found that the Engineered Emulsion and CR Rejuvenator mixtures were statistically similar, as were the Anionic Emulsion with Bio-Based Rejuvenator and CR Rejuvenator mixtures. The Engineered Emulsion, Anionic Emulsion with Bio-Based Rejuvenator, and Foamed Asphalt with Active Filler mixtures were statistically different.

***Table 16 – IDEAL-CT p-values***

| *Mixture* | *p-value* |
|---|---|
| *F vs E+R* | 1.44E-07 |
| *F vs CRR* | 3.84E-05 |
| *F vs EE* | 0.0003975 |
| *E+R vs EE* | 0.011 |
| *E+R vs CRR* | 0.762 |
| *CRR vs EE* | 0.061 |

*red cells indicate statistically similar mixtures

### 4.4.2 HT-IDT

HT-IDT testing produced a strength value in psi for each CR mixture, shown in Table 17, with a higher strength corresponding to higher rutting resistance.

***Table 17 – HT-IDT Strength for all CR Mixtures***

| *Mixture* | *HT-IDT Strength (psi)* | *Standard Deviation* |
|---|---|---|
| *Foamed Asphalt with Active Filler* | 9.39 | 0.67 |
| *Anionic Emulsion with Bio-Based Rejuvenator* | 5.89 | 0.33 |
| *CR Rejuvenator* | 4.68 | 0.19 |
| *Engineered Emulsion* | 6.67 | 1.13 |

The rutting resistance of these CR mixtures generally followed the reverse of the results found in the IDEAL-CT testing, with the rejuvenated designs being most prone to rutting. This also follows the general Balanced Mix Design logic that a mixture must balance cracking susceptibility and rutting susceptibility.

Like the IDEAL-CT results, a Tukey Pairwise Comparison and Analysis of Variance (ANOVA) were conducted on the HT-IDT results in order to determine whether any statistical differences were present. Both assumed equal variances and used a significance level of α = 0.05. Table 18 shows the results from this test with the abbreviations being associated with the mixtures as follows: Foamed Asphalt with Active Filler (F), Anionic Emulsion with Bio-Based Rejuvenator (E+R), CR Rejuvenator (CRR), and Engineered Emulsion (EE). The results found that the Engineered Emulsion and Anionic Emulsion with Bio-Based Rejuvenator mixtures were statistically similar, as were the Anionic Emulsion with Bio-Based Rejuvenator and CR Rejuvenator mixtures. However, the Engineered Emulsion, CR Rejuvenator, and Foamed Asphalt with Active Filler mixtures were statistically different.

***Table 18 – HT-IDT p-values***

| *Mixture* | *p-value* |
|---|---|
| *F vs E+R* | 8.50E-05 |
| *F vs CRR* | 1.02E-05 |
| *F vs EE* | 0.010 |
| *E+R vs EE* | 0.234 |
| *E+R vs CRR* | 0.00074 |
| *CRR vs. EE* | 0.016 |

*red cells indicate statistically similar mixtures

### 4.4.3 Dynamic Modulus

The results collected from dynamic modulus testing of each of the four CR mixtures were analyzed in Excel. The master curves were developed by plotting the dynamic modulus values against the values calculated for reduced frequency. A larger reduced frequency value indicates lower assumed pavement temperatures and higher assumed traffic loading, with smaller reduced frequencies assuming the opposite. The traffic loading applied to the specimen is in terms of vehicle speed, with faster speeds corresponding to higher frequencies and lower speeds corresponding to lower frequencies. Figure 32 shows the master curves for all four mixtures.

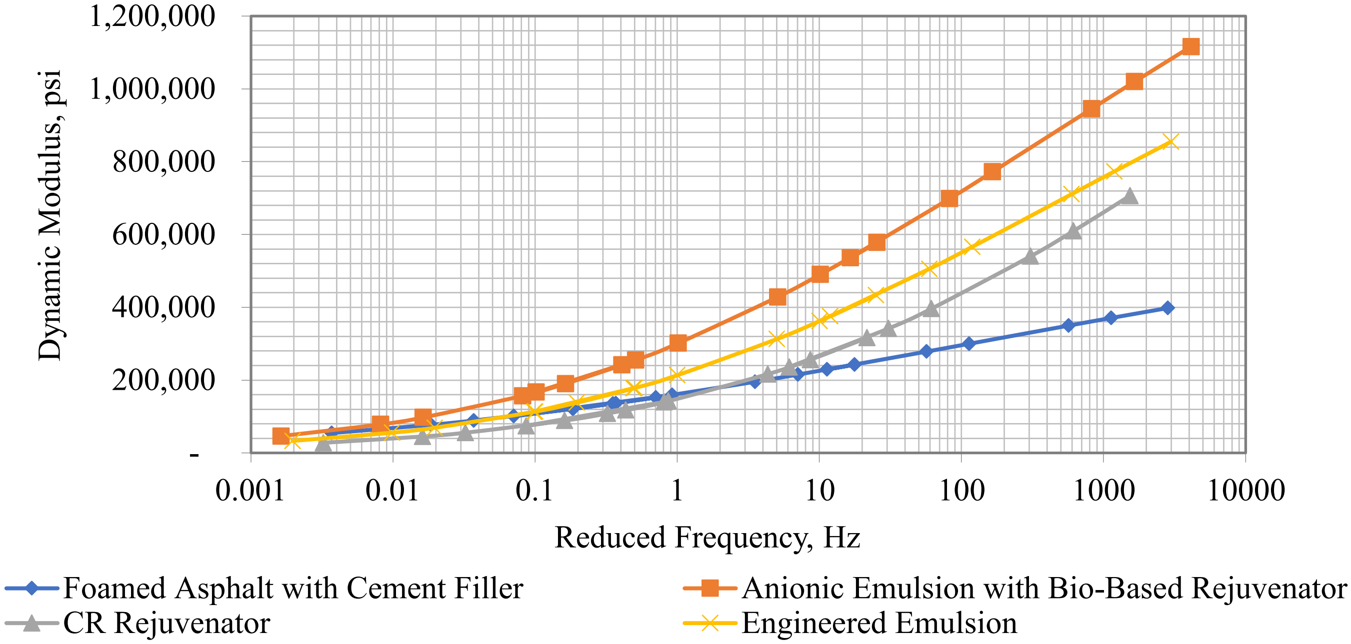

*Figure 32 – Plot of CR Specimen Master Curves*

All of the CR mixtures have similar moduli at lower frequencies but tend to vary more significantly as frequency increases. The mixtures containing emulsion and/or rejuvenators had higher moduli than that of the mixture containing foamed asphalt at values greater than approximately 3 Hz. The stiffness of the foamed asphalt with active filler mixture does not vary as much with respect to loading frequency as the other CR mixtures; this is likely due to the mixture containing cement. It is also indicative of the mixture being less temperature and loading dependent. With the anionic emulsion with bio-based rejuvenator mixture containing both virgin binder and a rejuvenator, as loading frequency increases, the matrix becomes more temperature and frequency dependent. It is hypothesized that the CR rejuvenator mixtures lower dynamic modulus values (versus the two mixtures containing emulsion) is due to the lack of virgin binder in the mixture. When evaluating the CR mixture against a typical HMA, found in NCHRP 09-51, the rejuvenated mixtures perform more closely to HMA than the mixture containing foamed asphalt, with the anionic emulsion with bio-based rejuvenator performing most similarly to HMA (Schwartz et al. 2017).

## 4.5 Impact of Mixture Production Method on Specimen Performance

### 4.5.1 Strength and Moisture Susceptibility

The strengths and moisture susceptibility of the four CR mixtures were evaluated across two different mixture production methods: laboratory production during mixture design and plant production. Figure 33 shows the dry and conditioned strengths for the foamed asphalt with active filler.

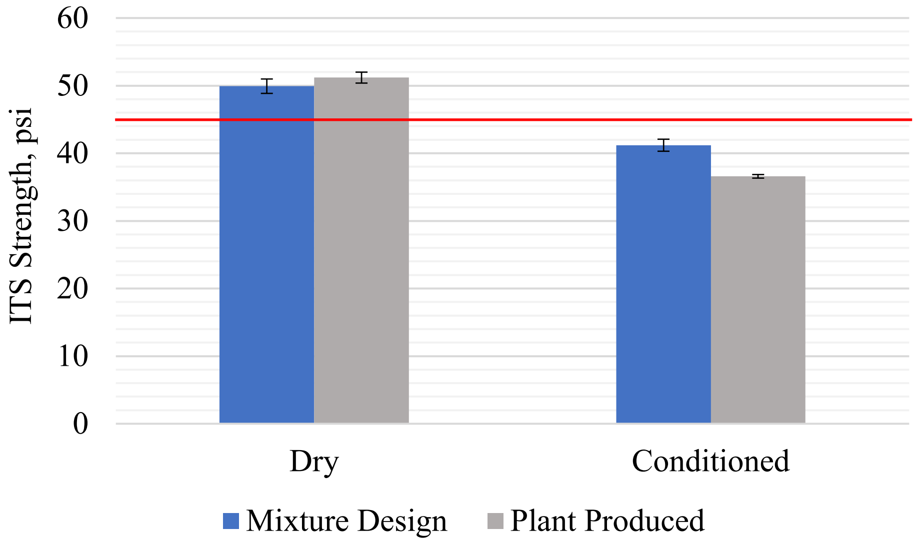

*Figure 33 – Foamed Asphalt with Active Filler Mixture Strength Comparison*

Both production methods produced mixtures that passed the minimum dry strength requirement of 45 psi, as indicated by the red line. The strengths only varied slightly between mixture methods, with a small increase in dry strength and small decrease in conditioned strength.

Figures 34-36 compare the strengths of the specimens produced for the anionic emulsion with bio-based rejuvenator, CR rejuvenator, and engineered emulsion mixtures, respectively. Table 18 provides a summary of the dry and conditioned strengths and TSR/MSR values for both mixture design and plant production of all CR mixtures.

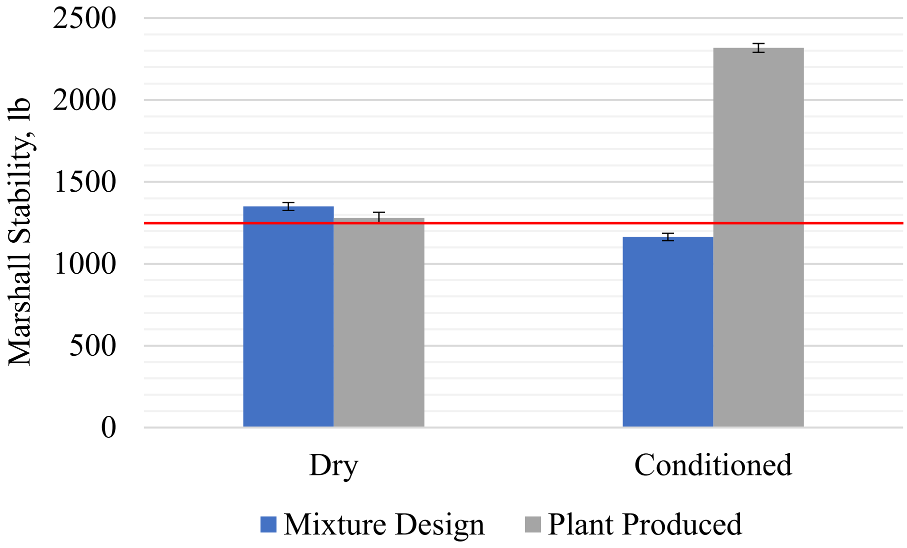

*Figure 34 – Anionic Emulsion with Bio-Based Rejuvenator Mixture Strength Comparison*

Like the mixture containing foamed asphalt, both mixture production methods passed the minimum strength requirements. The dry strength saw a slight decrease between the mixture design and plant produced mixtures. The conditioned strength, however, increased by 99%.

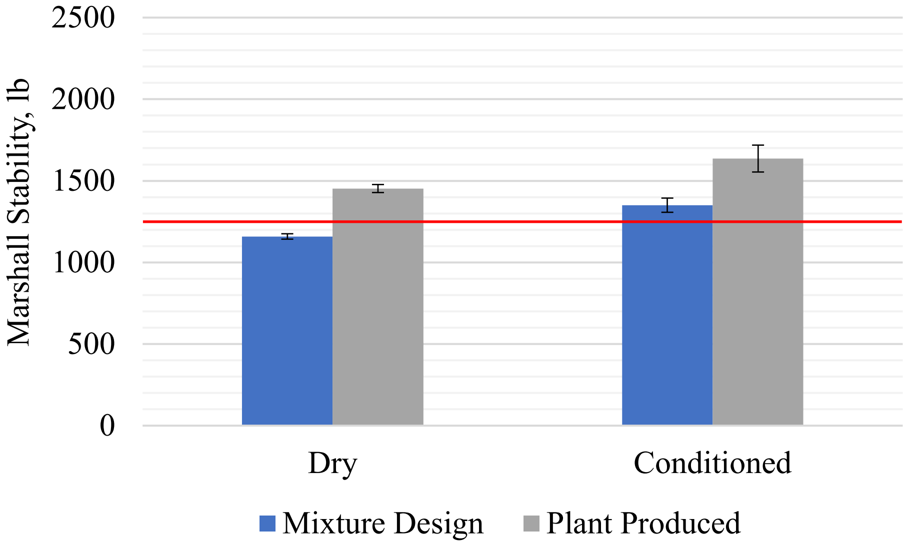

*Figure 35 – CR Rejuvenator Mixture Strength Comparison*

As mentioned previously, the mixture containing the CR rejuvenator failed the dry strength requirement by a small margin during the design phase. However, the plant produced mixture surpassed this requirement. Like the anionic emulsion with bio-based rejuvenator mixture, an increase in conditioned strength was observed. It is hypothesized that the mixture was able to surpass the minimum requirements due to the additional water in the mixture acting as a lubricant, allowing for more dispersion of the CR rejuvenator and leading to an increased density of the sample.

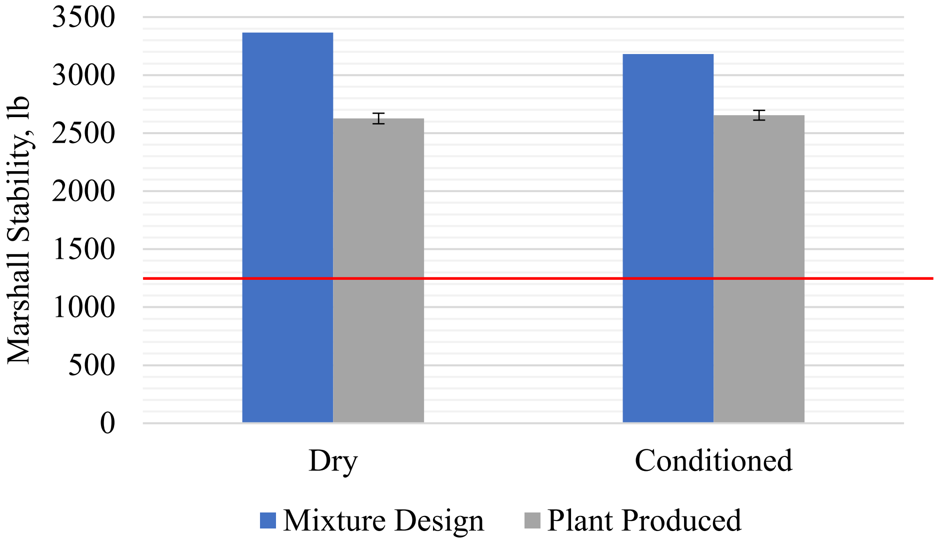

*Figure 36 – Engineered Emulsion Mixture Strength Comparison*

Both the dry and conditioned strengths for the engineered emulsion mixture had nearly identical reductions in strength between mixture design and plant production, with both surpassing the minimum requirements.

***Table 19 – Summary of Strength Comparisons between Mixture Design and Plant Production***

| | | *Foamed Asphalt + Active Filler* | *Anionic Emulsion + Bio-Based Rejuvenator* | *CR Rejuvenator* | *Engineered Emulsion* |
|---|---|---|---|---|---|
| *Dry ITS (psi)* | Mixture Design | 49 | - | - | - |
| | Plant Production | 51 | - | - | - |
| *Cond. ITS (psi)* | Mixture Design | 41 | - | - | - |
| | Plant Production | 37 | - | - | - |
| *Dry MS (lb)* | Mixture Design | - | 1349 | 1159 | 3366 |
| | Plant Production | - | 1280 | 1453 | 2626 |
| *Cond. MS (lb)* | Mixture Design | - | 1164 | 1351 | 3182 |
| | Plant Production | - | 2318 | 1636 | 2654 |
| *TSR/MSR* | Mixture Design | 0.83 | 0.86 | 1.17 | 0.95 |
| | Plant Production | 0.71 | 1.81 | 1.13 | 1.01 |

### 4.5.2 Density

A comparison between the dry densities of each CR mixture by mixture production method was conducted. Figure 37 shows the comparison, grouped by mixture type.

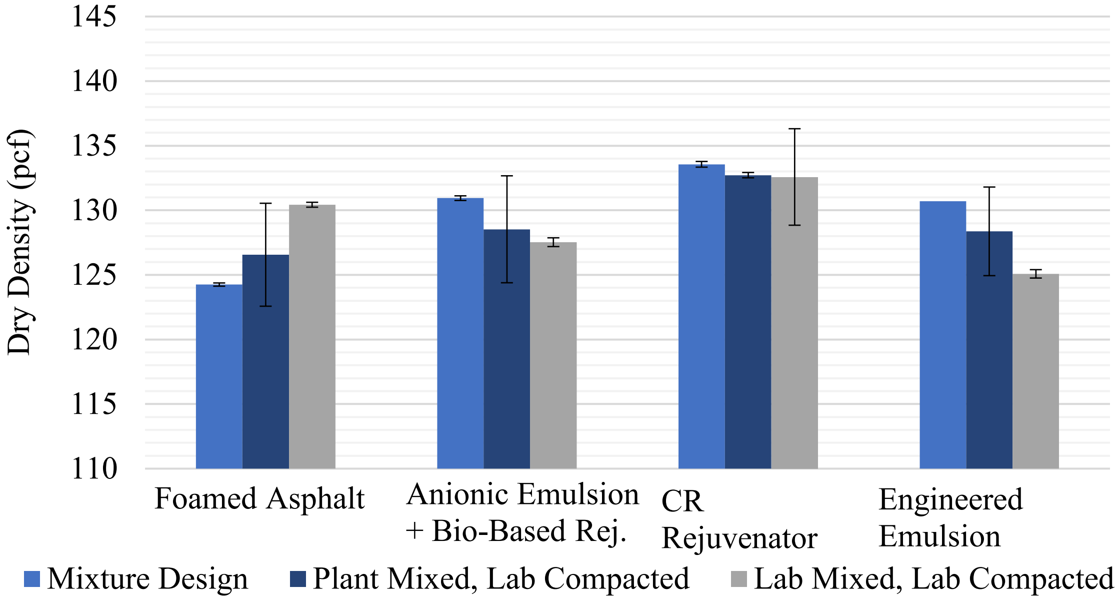

***Figure 37 – CR Mixture Density by Mixture Production Method***

The addition of a rejuvenating agent to a CR mixture activates and softens the RAP binder and should theoretically increase the density. This theory is confirmed in the density comparison, with the average dry densities for both mixtures with a rejuvenator being higher than those without. With all materials used remaining consistent between production methods, the differing densities between mixtures can be directly attributed to the rejuvenating and recycling agents themselves.

***Table 20 – Summary of Dry Densities by Mixture Production Method***

| | *Foamed Asphalt + Active Filler* | *Anionic Emulsion + Bio-Based Rejuvenator* | *CR Rejuvenator* | *Engineered Emulsion* |
|---|---|---|---|---|
| *Mixture Design (pcf)* | 124.25 | 130.94 | 133.56 | 130.70 |
| *PMLC (pcf)* | 126.56 | 128.53 | 132.72 | 128.37 |
| *LMLC (pcf)* | 130.43 | 127.53 | 132.58 | 125.08 |

### 4.6 Summary

All mixture designs produced passed the minimum strength and TSR/MSR requirements with the exception of CR rejuvenator mixture. This mixture failed the dry strength requirement by a small margin, but was selected for production due to construction-related time constraints. However, the PMLC specimen of the CR rejuvenator mixture did pass the minimum strength requirements.

During construction, RAP moisture contents were high and affected compaction on the anionic emulsion with bio-based rejuvenator section. Any potential impacts this may have had on the mixture were not reflected in the PMLC specimen performance testing. All PMLC specimens for all CR mixtures passed the minimum strength requirements.

IDEAL-CT results showed that the rejuvenated mixtures produced $CT_{Index}$ values much higher than the non-rejuvenated mixtures. These mixtures are expected to resist cracking for longer. The mixture containing foamed asphalt is predicted to be more susceptible to cracking given its low $CT_{Index}$. The HT-IDT results reflected the IDEAL-CT results in reverse, with the foamed asphalt with cement active filler mixture having the highest strength, thus being least susceptible to rutting. The two rejuvenated mixtures had the lowest strengths and are therefore predicted to be more susceptible to rutting. Dynamic modulus results showed similar initial responses to the repetitive non-destructive loading for all mixtures. The two rejuvenated mixtures and the engineered emulsion mixture showed a faster rate of increasing modulus versus the foamed asphalt mixture, indicating that the mixture matrix may be more temperature and loading dependent.

# CHAPTER FIVE: FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

## 5.1 Findings

Based on the data collected in this study, the following findings were identified:

- Using an OFC in lieu of an OMC is beneficial in the design of rejuvenated CR mixtures.
- The construction of the rejuvenated CR mixtures was like that of a typical CR mixture.
- CR mixtures with rejuvenators resulted in higher densities during mixture design, plant production, and laboratory production versus non-rejuvenated mixtures.
- The CR mixtures containing a rejuvenator had at least 35% higher $CT_{Index}$ compared to the engineered emulsion mixture.
- HT-IDT testing revealed that the rejuvenated mixtures performed slightly below the engineered emulsion mixture, with the foamed asphalt mixture outperforming all others.
- Dynamic modulus testing indicated that the addition of a rejuvenator produced higher moduli values than a typical foamed asphalt CR mixture.

## 5.2 Conclusions

Based on the observations made during this study, the following conclusions can be made:

- The excess moisture produced during the CR rejuvenator mixture trials was determined to be caused by introducing too much fluid to the mixture by using an OMC versus an OFC.
- IDEAL-CT testing likely does not provide a thorough assessment of CR mixtures containing emulsion and/or rejuvenators, as mixtures exhibited a low peak and long tail in the load-displacement curve that was not fully captured. The higher $CT_{Index}$ values observed in the rejuvenated mixtures are suspected to be due to the activation of the RAP

binder. $CT_{Index}$ values were much higher than other CR mixtures and HMA requirements. During data analysis, different strength curves were observed for emulsion and rejuvenated mixtures versus the foamed asphalt mixture, which may be a contributing factor.

### 5.3 Recommendations

Based on the previous findings and conclusions, the following recommendations should be considered for future research:

- An OFC should be used versus OMC for CR mixtures containing rejuvenators due to the activation of RAP binder, leading to an increased density and forcing excess moisture out of the mixture. Using an OFC takes into account the fluid being added in the form of a rejuvenator.
- Further performance testing, such as Repeated Load Permanent Deformation and Cyclic Fatigue, should be conducted to fully evaluate the influence of rejuvenators on CR mixtures.
- The performance of the CR mixtures placed on the NCAT Test Track off-ramp should be evaluated and compared to the performance indicated by laboratory testing.
- Future research should assess the applicability of current HMA-based IDEAL-CT and HT-IDT specifications for CR mixtures.

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