EVALUATION OF COLD RECYCLED ASPHALT MIXTURES
MODIFIED WITH CONVENTIONAL AND POLYMERIC MODIFIED EMULSION

A Thesis in
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by
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ABSTRACT

Cold recycling (CR) is a partial recycling process through which a portion of the existing recycled asphalt pavement (RAP) material is rejuvenated and placed back on the road as a new base course without introducing heat during the recycling process. Although CR technology is not a new concept, it has not been understood as well as Hot Mixture Asphalt (HMA) and Warm Mixture Asphalt (WMA). Currently, a nationwide standard for CR mixture design does not exist. Furthermore, sufficient data is not available to indicate if there is a difference between the performance of cold mixtures stabilized with conventional emulsions versus those stabilized with polymer modified emulsions.

In this thesis, the performance of lab produced CR specimens with conventional asphalt emulsion and polymer modified asphalt emulsion is investigated through conducting a series of tests. CR specimens were prepared in precise procedures to ensure reliable and consistent specimen production for testing. Through basic volumetric measurements and performance related tests including strength, durability, moisture damage resistance, and rutting resistance, a general CR mixture design procedure was established. Statistical analysis was conducted to determine the difference between performance of CR mixtures modified with conventional and polymer modified emulsion. Although no significant difference in performance was observed for most of the performance measures, polymer modified emulsion was shown to improve the rutting resistance of CR mixtures compared with conventional emulsion.
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CHAPTER 1

INTRODUCTION

1.1 Background
Traffic levels and vehicle loads are increasing each year. Excluding commercial vehicles, the general public requires safer and more efficient roadways with high service levels, which leads to a dramatic increase in demand to rehabilitate existing pavements. Although billions of dollars of government funding are spent on maintaining and rehabilitating existing pavements every year, due to the complexity and scale of the road system in the United States, the budget is still constrained. Due to this reason, low cost, efficient maintenance and rehabilitation methods are gaining popularity. Paving with cold mixtures using recycled asphalt materials is one of the popular techniques, and the focus of this thesis research.

Asphalt recycling is not a new concept. Cold recycling/rehabilitation of roadways with asphalt binder dates back to the early 1900’s (ARRA 2001). Moderate advancements in asphalt recycling technology and equipment occurred until the mid 1970’s due to two reasons: the worldwide petroleum crisis of the early 1970’s and the development and introduction of large scale cold planing equipment in 1975 (ARRA 2001). When properly implemented, the cold recycling techniques is a highly beneficial road rehabilitation approach from technical, economical, and environmental perspectives (Kennedy, Tam and Solaimanian 1998).

The cold recycling (CR) makes use of 100 percent of recycled asphalt pavement (RAP) materials in the recycling process, produces a new and improved pavement layer. It provides economical and environmental benefits when properly implemented.

1.2 Asphalt Pavement Distresses
An asphalt pavement is a multilayered structure. The pavement structure is designed and constructed in a way to carry loads transferred from passing vehicles and resist adverse climatic effects. Each layer is made up of a combination of materials, generally
aggregate, binder, and sometime special additives. The optimum combination of these materials at each layer is achieved through an engineered mixture design. A properly designed mixture of materials along with optimum thickness provides the required structural capacity for each layer. This process is called the structural design (Mallick and El-Korchi 2013). The pressure or stress caused by vehicles is the highest at the top layer, and the lowest at the bottom layer of a pavement structure (Figure 1). In a typical pavement structure, higher quality materials are used at layers closer to the surface.

Figure 1 Typical asphalt pavement cross section and traffic load transfer pattern
(Washington State DOT 2005)

Even the best designed and constructed pavements develop distresses of varying severity during their service life. However, a highly sound pavement structure lasts for decades before manifesting such distresses. There are three primary distresses observed in asphalt pavements: rutting (permanent deformation), fatigue cracking, and thermal cracking (low temperature cracking or transverse cracking).
1.2.1 Rutting (Permanent Deformation)

A rut is defined as a longitudinal depression in the wheelpath, with or without transverse displacement (Figure 2). It is a physical distortion of the surface material and a rut depth of 0.5 in. (0.013 m) is considered as a rutting failure. Rutting is the result of the accumulation of repeated loading from the passing vehicles, which leads to the increase of the permanent deformation. Rutting can be classified into three severities (Mallick and El-Korchi 2013). Low to moderate severity rutting is a one-dimensional densification or vertical compression near the center of the wheelpath, caused by densification of mixtures with excessive air voids. Moderate to high severity rutting is a depression in the wheelpath along with humps on either side of the depression, caused by lateral flow due to plastic deformation, resulting from shear failure of the mixture under traffic and generally associated with very low air voids in the mixture. Rutting accompanied by cracks on the surface of the pavement, is caused by rutting in underlying layers, such as subgrade or subbase.

Figure 2 Rutting in asphalt pavement (Mallick and El-Korchi 2013)

1.2.2 Fatigue Cracking

Fatigue cracking is generally found in the wheelpath (Figure 3). Repeating tensile stress at the bottom of the asphalt mixture layer caused by traffic loads leads to fatigue cracking. It starts from the bottom and moves upward, beginning as a series of interconnected cracks at the surface and develops into a chicken wire/alligator pattern (Mallick and El-Korchi 2013). A low-severity fatigue cracking area is one in which
there are no or few connecting cracks, the cracks are not spalled or sealed, and there is no evidence of pumping. A moderate-severity fatigue cracking area includes cracks that are interconnected, forming a complete pattern, and cracks may be slightly spalled or sealed with no evidence of pumping. In a high-severity fatigue cracking area, the cracks are interconnected with moderate or severe spalls, forming a complete pattern; pieces may move under traffic; cracks may be sealed; and pumping may be evident.

Figure 3 Fatigue cracking in asphalt pavement (Mallick and El-Korchi 2013)

1.2.3 Thermal Cracking (Low Temperature Cracking/Transverse Cracking)
Thermal cracking occurs in the form of transverse cracking, which is perpendicular to the pavement centerline (Figure 4). The thermal cracking can be caused by the fracture of asphalt mixture due to a severe drop in temperature or by thermal fatigue caused by repeated low and high temperature cycle (Mallick and El-Korchi 2013). A low severity thermal crack is one with a mean width of \( \leq 6 \) mm, or a sealed crack with sealant material in good condition and a width that cannot be determined. A medium severity thermal crack is one with a mean width \( > 6 \) and \( \leq 19 \) mm, or any crack with a mean width \( \leq 19 \) mm and adjacent low severity random cracking. A high severity thermal
crack has a mean width > 19 mm, or ≤ 19 mm, but with adjacent moderate to high severity random cracking.

Figure 4 Thermal cracking in asphalt pavement (Mallick and El-Korchi 2013)

When accurately designed and constructed, properly used, and appropriately maintained, an asphalt pavement should give a service life of fifteen to twenty years. Since design and construction of a new roadway is rather expensive, extending the service life of an existing road is a more economical choice. A major rehabilitation for the pavement is necessary to remove the distresses and keep it in service for an extended period beyond its original design life.

1.3 Asphalt Recycling Methods

When pavement condition deteriorates, there is a point when rehabilitation is required. Lots of benefits can be accomplished through the application of asphalt recycling processes. Those processes provide economical and sustainable solutions that largely reduce demands on raw materials, energy consumption, and production of greenhouse gases, while still guaranteeing the functionality and performance of the pavement.

The Asphalt Recycling and Reclaiming Association (ARRA) defined five categories of asphalt recycling methods (ARRA 2001). These categories are:

- Cold Planing (CP)
- Hot Recycling (HR)
- Hot In-Place Recycling (HIR)
Cold Recycling (CR)
Full Depth Reclamation (FDR)

Within these five broad categories of asphalt recycling methods, there are a number of sub-categories that further define asphalt recycling methods (ARRA 2001, Stroup-Gardiner 2011), which are:

- Hot In-Place Recycling (HIR)
  - Resurfacing (Surface Recycling)
  - Repaving
  - Remixing
- Cold Recycling (CR)
  - Cold In-Place Recycling (CIR)
  - Cold Central Plant Recycling (CCPR)
- Full-Depth Reclamation (FDR)
  - Pulverization
  - Mechanical stabilization
  - Bituminous stabilization
  - Chemical stabilization

Cold planing (CP) is the controlled removal of an existing pavement to a desired depth, longitudinal profile, and cross-slope, using specially designed equipment. The resulting textured surface can be immediately used as a driving surface, or further treated with one of the other asphalt recycling methods, or overlaid with HMA.

Hot recycling (HR) is the process of combining Recycled Asphalt Pavement (RAP) with virgin aggregate, new asphalt binder, and/or recycling agents (as required) in a central plant to produce a recycled mixture. This method uses the heat-transfer method to soften RAP materials to permit mixing with virgin aggregates and asphalt binder and/or recycling agent. It is currently the most widely used asphalt recycling method in the world.
Hot in-place recycling (HIR) uses 100 percent recycling asphalt pavement on site. The process consists of heating and softening existing asphalt pavement, permitting it to be scarified or hot rotary milled to the specified depth. The scarified or loosened asphalt pavement is then thoroughly mixed and subsequently placed and compacted with conventional HMA paving equipment. When necessary, virgin aggregate, new asphalt binder, recycling agents and/or new HMA can be added. Typical treatment depths range from ¼ to 2 inches (20 to 50 mm); some equipment can treat up to 3 inches (75 mm).

Full depth reclamation (FDR) is the rehabilitation technique in which the full thickness of the asphalt pavement and a predetermined portion of underlying materials (base, subbase and/or subgrade) are uniformly pulverized and blended to provide an upgraded, homogenous base material. It consists of pulverization/reclamation of the existing materials, adding more materials when necessary, mixing, initial shaping of the resulting mix, compaction, final shaping or “tight blading,” and application of an asphalt surface or wearing course. The whole process is performed on the roadway without the addition of heat. Treatment depth varies depending on the thickness of existing pavement, but generally ranges between 4 to 12 inches (100 to 300 mm).

Cold recycling (CR) consists of recycling asphalt pavement without the application of heat during the recycling process to produce a rehabilitated pavement. The cold in-place recycling (CIR) process is undertaken on site and generally uses 100 percent of RAP materials generated during the process. With typical treatment depth within 2 to 4 inches (50 to 100 mm), the recycling agent used in the CIR process is limited to asphalt emulsion or an emulsified asphalt agent. If chemical additives like Portland cement, lime, and fly ash are added, treatment depth can increase up to 5 to 6 inches (125 to 150 mm). Cold Central Plant Recycling (CCPR) is the process in which the asphalt recycling takes place in a central location using a stationary cold mix plant. The CCPR mixtures can be used immediately or can be stockpiled for late use in such applications as maintenance blade patching or pothole repair. Similar to the CIR process, asphalt emulsion and emulsified asphalt agents are typically used as the recycling additive.

The focus of this thesis will be on cold recycling (CR) technology. Although the CIR and the CCPR technology are taken place in difference locations, the material investigation process is similar.
1.4 Objectives
This thesis is based on the work of a project initiated by the Pennsylvania Department of Transportation (PennDOT), in order to develop a methodology for use of cold recycled mixture using polymer modified emulsion and conventional emulsion. Tasks of this project include:

- Develop a general mixture design process for cold recycled asphalt mixture.
- Evaluate performance of polymer modified cold recycled asphalt mixtures for strength, durability, rutting resistance, and moisture damage resistance through laboratory testing.
- Compare performance of polymer modified cold recycled asphalt mixtures with cold recycled asphalt mixtures with conventional emulsion through laboratory testing.
- Investigate the effect of cement on cold recycled asphalt mixtures through laboratory testing and data analysis.

1.5 Scope of Work
The work discussed in this thesis covers laboratory testing with one single source of RAP materials produced from PennDOT District 1-0 to establish a mixture design procedure and engineering property investigation for lab produced mixture using recycled asphalt pavement and emulsion. Test protocols include characterization of RAP material; measurement of density and air voids of lab-produced CR specimens; and evaluation of strength, durability, moisture damage resistance, and rutting resistance of lab-produced CR mixtures. Two types of asphalt emulsions from two different manufacturers were used in the whole testing process. Type II portland cement was also employed as a recycling agent additive for comparison.

Characterization of RAP materials included gradation analysis of raw RAP materials and determination of asphalt content of raw RAP materials. Design gradation, optimum water and emulsion contents, curing and conditioning procedure, and gyration level were determined in the mixture design process. The density of every lab-produced specimen was measured before testing and the air void content of each specimen was obtained through measured density data. The compressive strength of each specimen
was evaluated using the Indirect Tensile Strength Test (IDT). The Raveling test was used to determine the durability of CR mixtures. The rutting resistance of CR mixtures was evaluated by measuring permanent deformation of lab-produced mixtures using the Superpave Shear Tester (SST). The moisture damage resistance properties were investigated using Indirect Tensile Strength Test (IDT) based on modified AASHTO T283 procedure. Type II portland cement was introduced in each stage of these tests, except the mixture design phase, for performance comparison.

1.6 Organization of the Thesis
This thesis consists of five chapters. The first chapter describes the introduction of this research, objectives, and scope of work, including basic knowledge about pavement distress and asphalt recycling methods; the second chapter gives the literature review summary on CR technology, recycled asphalt pavement used in CR process, asphalt emulsion, existing mixture design protocols of CR process, and engineering properties of CR mixture; chapter three introduces the research methodology, materials, test procedures and details of this research; test results and data analysis will be presented in chapter four; the last chapter will give conclusions and provide recommendations.
CHAPTER 2

LITERATURE REVIEW

This chapter contains the literature review summary on existing information regarding the cold recycling (CR) technology. The summary was focused on knowledge of CR construction process and recycled asphalt pavement (RAP), asphalt emulsion, CR mixture design procedure, and important engineering properties of CR mixtures obtained from lab tests. Special efforts were focused on engineering properties and mixture design protocols on CR mixtures produced with polymer modified asphalt emulsions and conventional asphalt emulsions. Although CIR and CCPR process are taken place in different locations, the research on materials used in these two sub-categories of CR technology is similar.

2.1 Cold Recycling (CR)

CR consists of recycling asphalt pavement without the application of heat during the recycling process to produce a rehabilitated pavement (ARRA 2001). Two sub-categories within CR, Cold In-Place Recycling (CIR) and Cold Central Plant Recycling (CCPR), are two sub-categories of CR technologies classified by their recycling locations.

CR technology brings a number of benefits. It provides an economical and sustainable approach that decreases demands on raw materials, energy consumption, and production of greenhouse gases, while still maintaining the functionality and performance of the pavement (Saloman and Newcomb 2000, Stroup-Gardiner 2011). The other advantages of the CR process include:

- Shortens construction time and minimize traffic disruption and delay,
- Maintenances clearance height while addressing existing pavement distresses and surface irregularities, and
- Decreases the total maintenance and rehabilitation cost.
The disadvantages of the CR process (Saloman and Newcomb 2000, Gardinor 2011, Piratheeapan 2011) include:

- Larger and more unpredictable materials and construction variations than conventional rehabilitation methods,
- Relatively longer curing time than conventional methods to gain initial strength
- Lack of mixture design procedures and specifications, and
- The construction process is sensitive to environmental conditions.

Despite these listed weak points, advantages of CR process generally outweigh its disadvantages.

### 2.1.1 Cold In-Place Recycling (CIR)

Cold in-place recycling is a partial recycling process through which a portion of the bound layer usually involves 2 to 4 inches (50 to 100 mm) of the existing recycled asphalt pavement (RAP) material, is rejuvenated and placed back on the road as a new base course, without introducing heat during the recycling process (Kandhal and Mallick 1997, Saloman and Newcomb 2000, Suleiman 2002). 100 percent of the previous existing pavement materials can be reused during the CIR process; no valuable recourses will be buried in landfills (Cross 2002).

In many situations, the CIR process was used limitedly in road sections with low traffic volume or frequently used as a base layer (Saloman and Newcomb 2000). However, when hot mix asphalt overlay was implemented, the CIR technology can be successfully used in roadways with high traffic levels. Addition of polymer and cementitious materials into the emulsified asphalt used in the CIR process may further increase the engineering properties of the mixture.

The implementing steps of the CIR process in the field consist of preparing the construction area, milling the existing pavement, adding recycling agents and virgin aggregate materials (if needed), laying down the mixed materials, compacting, and placing the necessary surface course (Kandhal and Mallick 1997). Figure 5 shows a flow chart of the CIR field process.
There are two kinds of construction technologies used in the CIR process in the field, the single machine and the equipment train (Kandhal and Malllick 1997).

The single machine is capable of breaking, pulverizing, and adding virgin binder agent in a single pass (Kandhal and Malllick 1997), as shown in Figure 6. It is highly productive, very simple to operate and very well suited for urban roadways in municipal areas with very short construction length (Suleiman 2002). However, it cannot be used to crush thick pavement or pavement with oversized RAP aggregate.

Figure 5 Steps of cold in-place recycling (Kandhal and Malllick 1997)

Figure 6 An example of the single machine (Kandhal and Malllick 1997)
The equipment train (Figure 7), also called single-pass equipment train, consists of a series of equipment, like cold milling machine, portable crusher, travel-plant mixer, and lay down machine; each of them is capable of operating a particular process (Kandhal and Malllick 1997). Compared to single machine, equipment train can be used for much thicker pavement and oversize RAP aggregate is no longer an issue as well. Unfortunately, it requires more operators and in the meantime, corner and turns of roads cannot be easily rehabilitated with this method.

2.1.2 Cold Central Plant Recycling (CCPR)

The CCPR is the process in which the asphalt recycling takes place in a central location (Figure 8) using a stationary cold mix plant (ARRA 2001). The mixture produced through the CCPR process can be used immediately or be stockpiled for later use like repairing potholes.

For the compaction process after the placement of blended materials, both the CIR and the CCPR process use conventional large sized rubber-tired and vibrating steel drum rollers. Then after appropriate amount of curing time, an overlay or proper surface treatment is placed on the surface of the rehabilitated base layer.
2.2 Recycled Asphalt Pavement (RAP) Aggregate in CR Process

The milling, planing or crushing of the existing pavement in the recycling process produces recycled asphalt pavement (RAP) (Saloman and Newcomb 2000, Suleiman 2002). RAP has been widely used in Hot Mix Asphalt (HMA) mixtures and Warm Mix Asphalt (WMA) mixtures to partially replace virgin aggregates. It reduces demand on raw materials and increases the stiffness of the mixture. In cold in-place recycling, RAP is 100 percent reused.

Based on the survey results from 2001 (Brayton, et al. 2001), the most common maximum RAP size allowed to be used in the CR process was 31.75 mm among 46 states, and the range was between 19 to 75 mm. There were also 4 states that stated that they had no limits for maximum RAP size used in the CR process. Since oversized aggregate particles may cause segregation and high air voids during CR construction, it is recommended that the maximum RAP size used in the CR process should not exceed one-third of the thickness of the designed CR layer (ARRA 2001).

In most cases, no additional virgin aggregate is needed for design and construction of CR project. However, corrective virgin aggregate can be added to strengthen the
mineral skeleton (Suleiman 2002) or to increase pavement thickness (Thompson, Garcia and Carpenter 2009), or for the following reasons:

- To increase structural capacity of the designed pavement,
- To enhance mixture properties like stability and durability,
- To decrease binder content,
- To satisfy the gradation requirement when RAP aggregate gradation is not within the specification, or
- To make overall gradation courser since RAP aggregate tend to provide finer aggregate particles during the recycling process.

Although 15 to 50 percent of virgin aggregate was allowed to be added in CR mixture (Brayton, et al. 2001), it is recommended that no more than 25 percent by weight of RAP materials of new aggregates should be added since it will largely increase the needed asphalt emulsion content, thus resulting in higher associated cost (Suleiman 2002).

**2.3 Asphalt Emulsion**

Emulsion is defined as suspension of two immiscible substances that are stabilized with the help of surface active agents like soap (Banerjee 2012). For standard asphalt emulsions, water is in the continuous phase while asphalt is dispersed in water in the dispersed (droplet) phase (Needham 1996, James 2006). Asphalt binder, water, and emulsifying agent occupy 40-75 percent, 25-60 percent, and 0.1-2.5 percent of mass in asphalt emulsions, respectively.

Among asphalt cement, cutback asphalt, and foamed asphalt cement, emulsified asphalt or asphalt emulsion is the most commonly used recycling agent employed in CR process (Saloman and Newcomb 2000). According to the survey results in 2002 (Lee, Brayton and Harrington 2002), among 46 states in the United States that used CIR technology, 24 of them used asphalt emulsion as the recycling agent.

The advantage of asphalt emulsion over conventional asphalt cement is that at 60°C, asphalt emulsion has a viscosity ranging from 0.5-60 Poise. Compared to traditional
asphalt (usually 100-4000 Poise), it is considerably lower, allowing it to be used at relatively low temperatures (James 2006). The ability to construct and maintain at relatively low temperatures makes asphalt emulsion an ideal choice of recycling agent that is able to reduce emulsion and energy consumption, avoid asphalt cement oxidation, and reduce hazards compared to conventional asphalt cement. Compared to cutback asphalt, it is more environmentally and economically friendly.

After the placement of asphalt emulsion in the field, moisture in asphalt emulsion needs to be isolated and evaporated, so asphalt cement can coalesce and hold aggregate particles together. There are two very important processes of removing moisture in the mixture during the application of asphalt emulsion: breaking and curing. Breaking is defined as the combined sedimentation and coalescence of emulsified drops of the dispersed phase, so that they will settle out of the carrier liquid-water (Banerjee 2012). Curing, on the other hand, is the removal of the water from the bituminous material, after the breaking phase is completed or at least sufficiently initiated (Banerjee 2012). Breaking is a chemical process, while curing is a physical process. However, they are all governed by energy differences among forces, such as Van Del Waals interaction, electrostatic forces and stearic repulsion, acting between dispersed particles (Banerjee 2012). The breaking and curing processes help to improve mechanical properties of CR mixtures, and achieve desired binder strength.

2.3.1 Asphalt Emulsion Classification

According to the sign of the charges on the droplet and their reactivity, asphalt emulsion can be classified into three categories (James 2006). Cationic emulsion (Figure 9) contains droplets that carry positive charges. The tail portion of an emulsifying agent aligns itself in the asphalt while the negative portion of the head floats around in the water leaving the rest of the head positively charged and at the surface of the droplet. Positive charged droplets repel each other and push each other away, so all the droplets remain as distinct asphalt drop in liquid suspension.
Anionic emulsion (Figure 10) contains droplets that carry negative charges. The tail portion of an emulsifying agent aligns itself in the asphalt while the positive portion of the head floats around in the water leaving the rest of the head negatively charged and at the surface of the droplet. All the droplets repel each other and remain as distinct asphalt drops in liquid suspension in anionic in the same manner as cationic emulsion.

Another category of asphalt emulsion is nonionic, whose agent is neither negatively nor positively charged. It is a neutral asphalt emulsion agent, and rarely used.

Based on the breaking rate, asphalt emulsions can also be further classified into three categories: quick setting (QS), medium setting (MS), and slow setting (SS) asphalt emulsions (James 2006), with the breaking rate dropping from the highest to the lowest.

2.3.2 Breaking Mechanism of Asphalt Emulsion

The rate of the coalescence process in which asphalt emulsions revert from discreet emulsion droplets to continuous asphalt is called breaking, during which the asphalt droplets will join or coalesce (Needham 1996, Banerjee 2012). The breaking rate largely determines the property of CR mixtures, so its mechanism should be well understood.
For the anionic emulsion, there are two breaking mechanisms (Gaestel 1968). In mixtures with calcareous aggregates like limestone, since it is positively charged, the emulsifier forms a salt with the calcium ions contained in the aggregate, thus removing it from the bitumen-water interface and causing the emulsion to break. In mixtures with negative siliceous aggregates, however, it is the inorganic cation that is adsorbed onto the aggregate surface. As the emulsifier is deactivated through the loss of the counter-ion, the emulsion is destabilized and will break; the breaking rate is proportional to the concentration of the inorganic cation.

For the cationic emulsion, there are three breaking mechanisms (Wates and James 1993). The first breaking mechanism is named the emulsifier abstraction. In this case, the emulsifier is withdrawn from the bitumen-water interface by the aggregate surface. The loss of emulsifier causes the emulsion to become unstable, leading to coalescence of the droplets (Figure 11).

![Diagram of emulsifier abstraction](needham_1996)

Figure 11 The process of emulsifier abstraction (Needham 1996)

The second breaking mechanism is called the emulsifier deprotonation. This process involves deprotonation of acidified emulsifiers, as protons are adsorbed onto basic sites
on the aggregate surface, deactivating emulsifiers and thus causing the emulsion to break (Figure 12).

![Diagram showing emulsifier deprotonation process](image)

Figure 12 The process of emulsifier deprotonation (Needham 1996)

The third breaking mechanism is termed the droplet migration. The bitumen droplets are attracted towards aggregates due to the positively charged emulsifiers on their surfaces. The droplets then spread over the aggregate surface, aided by the surfactant. The final situation is very beneficial as the bitumen is bound to the surface by surfactant molecules, which subsequently act as an adhesion or anti-stripping agents (Figure 13).
In real situations, all of these processes may occur simultaneously during the breaking to some extent (Banerjee 2012). Aggregate reactivity (i.e. surface area, surface charge, and surface chemistry), environment temperature, humidity, wind speed, emulsion activity, and mechanical treatment such as compaction, all determine the breaking rate during the implementation of asphalt emulsion.

2.4 CR Mixture Design
Currently, a nationally accepted standard mixture design method, structural design method, laboratory testing procedures, or quality control specifications for the CR process do not exist (Suleiman 2002), but general design methods and specifications for the CR process based on modification of HMA mixture design methods have been developed and implemented by several agencies (ARRA 2001, Suleiman 2002).

Three basic theories have been proposed for designing CR mixtures with recycling additives (ARRA 2001, Suleiman 2002). The first theory assumes that the RAP will act as a black aggregate, which means residual asphalt on RAP will not be counted, and the
mixture design consists of determining a recycling additive content to coat the aggregate. The second theory evaluates physical and chemical characteristics of the recovered asphalt binder and adds a recycling agent to restore the asphalt binder to its original consistency. The assumption is that complete softening of the old asphalt binder occurs. The third and the most prevalent theory is a combination of the first two, where some softening of the old asphalt binder occurs, which is referred to as the effective asphalt theory, where the recycling additive and the softened aged asphalt binder form an effective asphalt layer. The degree of softening is related to the properties of the old asphalt binder recycling additive and environmental conditions. Due to the difficulties in quantifying the degree of softening, it is recommended that mechanical tests on the residual asphalt be a part of the CR mixture design.

For the early stages of CR application, most state highway agencies use their own CR mixture design procedures (ARRA 2001). The Marshall asphalt mixture design method is the most practical mixture design method among state agencies that used or planned to use the CR process (Lee et al. 1999). Other CR mixture design procedures include Hveem method, California method, Chevron method, Asphalt Institute method, US Army Corps of Engineers method, Pennsylvania method, New Mexico method, and Oregon mixture design method (Saloman and Newcomb 2000, Lee, Brayton and Huston 2002). Later on, there are also some researchers that have adopted Superpave technology into the CR mixture design (Lauter and Corbett 1998, Lee, et al. 1999, Cross 2002). According to the latest survey summary (Stroup-Gardiner 2011) most states choose to do nothing about the CR mixture design; for states using mixture design methods, the Superpave and Marshall methods are most popular.

Generally, the CR mixture design procedure includes two major steps: assessing the in-situ material properties and developing the field job mix formula. The first step includes determining RAP gradation, RAP asphalt content, and RAP moisture content. The second step includes improving design gradation through introducing virgin aggregate when necessary and optimizing water and emulsion content after selecting proper asphalt emulsion type. The general CR mixture design procedure can be summarized as follows (Saloman and Newcomb 2000, ARRA 2001, Suleiman 2002):

- Obtain representative RAP samples from the field
• Evaluate RAP properties, including RAP gradation, asphalt and moisture content. Recovered binder properties may also be tested if necessary
• Choose appropriate amount and gradation of virgin aggregate, when necessary
• Select proper type and grade of recycling agent
• Determine the amount of recycling agent, and additives
• Select optimum pre-mix moisture content for adequate coating on RAP and possible virgin aggregate
• Test trial specimens on initial and final curing properties, and water sensitivity
• Establish job mix formula (JMF)
• Make adjustments on JMF if necessary

2.4.1 RAP Material Evaluation
To characterize RAP materials, representative and proper amount of RAP materials should be obtained from the field through systematic methods including random sampling techniques (Kandhal and Malllick 1997). A sampling plan must be developed that adequately determines the physical properties of RAP materials along the length of the project (ARRA 2001). A minimum of one coring/milling sample should be taken per mile per lane (McDaniel, et al. 2000), and at least five to six sampling locations (Suleiman 2002) should be included. In real situations, the location and frequency of sampling is determined by traffic level and length and location of the candidate project, but is usually based on expert judgments (ARRA 2001).

Gradation plays a major role in the quality of CR mixture, as it affects stiffness, stability, durability, workability, fatigue resistance, fractional resistance, and moisture damage resistance. Therefore gradation is the primary concern in the CR mixture design process. The sieve analysis (AASHTO T 27 or ASTM C136) should be conducted on RAP for both coarse and fine aggregate (ARRA 2001). Asphalt content in RAP should be determined based on AASHTO T 164 (Kandhal and Malllick 1997). For aggregate extracted through AASHTO T 164, sieve analysis should be conducted to determine its gradation. If the previous pavement does not contain cutback asphalt, AASHTO TP 53 ignition test can be used to determine the residual binder content and gradation of the aggregate.
Aged asphalt binder from RAP should be recovered from RAP using AASHTO T 170, or recently preferred test AASHTO TP 2 Rotovap procedure (Kandhal and Malllick 1997, ARRA 2001). Penetration and absolute viscosity should be tested as the minimum requirements. This can help in selecting proper type and amount of recycling agent (ARRA 2001, Suleiman 2002). For smaller projects, where it is not feasible to determine properties of the recovered asphalt cement, the asphalt content may be determined in accordance with ASTM D6307 (ARRA 2001).

When gradation of RAP is not able to satisfy the design specification requirement, excess asphalt binder is presented, or structural improvement is needed, new aggregate will be introduced to benefit overall gradation of CR mixtures (Kandhal and Malllick 1997, ARRA 2001, Suleiman 2002). A large quantity of fine aggregate is often generated due to the milling and pulverizing process, degradation caused by traffic, and contamination from underlying layer (Suleiman 2002), thus introducing virgin aggregates will make the overall gradation coarser. When design traffic level is increasing, structural capacity of pavement is increasing as well; an addition of virgin aggregates will increase mixture properties (ARRA 2001) as well as enhance structural capacity. The gradation of corrective aggregate must be established based on RAP gradation and sieve analysis (AASHTO T 27). The proportion of virgin aggregate should meet specifications (Suleiman 2002).

2.4.2 Selection of Recycling Agent
For existing pavements materials to be recycled, the asphalt content comprises approximately 3 to 7 percent by weight or 10 to 20 percent by volume of the mixture. Although it has been proved that residual asphalt in RAP is partially blending with virgin binder (Al-Qadi, et al. 2009), in existing CR design procedures, RAP is treated as black rock, which means residual asphalt on RAP will not be considered in mixture design.

The type of recycling agent used in CR includes: softer grade of asphalt cement, rejuvenator, cutback asphalt, foamed asphalt, emulsified recycling agent, and combination of emulsion with cement, fly ash, or lime (Kandhal and Malllick 1997, Saloman and Newcomb 2000). As discussed before, emulsified recycling agent or
asphalt emulsion is most commonly used (ARRA 2001, Lee, Brayton and Huston 2002) since it stays liquid at ambient temperature, is easy to disperse on site, and causes the minimum pollution. The other recycling agents are not recommended because of environmental and safety concerns even though they were successfully used in past projects (ARRA 2001).

The basic recycling agent selection standard is based on the recycling agents’ ability to adequately soften the old residual asphalt in RAP materials, to properly coat the RAP material and possible virgin aggregate, and to provide sufficient adhesion and cohesion at early age to prevent mixtures from raveling under traffic and to resist rainfall (Suleiman 2002). The time it takes for emulsion to break and gain initial strength should be considered as well (Kandhal and Malllick 1997). Type of RAP, availability, cost, and performance ratio are also important criteria when selecting recycling agents and additives (Kandhal and Malllick 1997). Moreover, the selected material should be insensitive to small variation of emulsion contents (Suleiman 2002).

The optimum amount of asphalt emulsion added to the mixture is usually determined by strength or stability tests and density curve obtained through trial studies using mixtures with different levels of asphalt emulsions, together with previous experience on RAP sources (ARRA 2001). An empirical equation to determine the emulsion content was developed by the Oregon Department of Transportation (Kandhal and Malllick 1997) based on field experience from 1994 to 1998, as follows:

\[
EC_{EST} = 1.2 + A_G + A_C + A_{P/V}
\]

Where:
EC\_EST = Estimated added asphalt emulsion, percent
1.2 = Base asphalt emulsion content, percent
A_G = Adjustment for milling gradations, percent
A_C = Adjustment for milling residual asphalt content, percent, and
A_{P/V} = Adjustment for millings penetration or viscosity, percent
Generally, the amount of recycling agent required for CR process ranges from 0.5 to 3 percent for emulsified asphalt, which is approximately 0.3 to 2 percent residual asphalt (Epps 1990). Most highway agencies reported optimum recycling additive content to be 0.5 to 3 percent (ARRA 2001, Brayton, et al. 2001). If new aggregates are brought in, higher binder content is needed (Kandhal and Malllick 1997).

Overall, the first consideration for selecting type and amount of asphalt emulsion should be to satisfy the aggregate gradation, traffic conditions of projects that are under construction, and also properties of the new asphalt emulsion including consistency, breaking and curing rate (Kandhal and Malllick 1997). Following this, proper judgment based on experience should be used considering the pavement, environment conditions, location of projects, and the availability of construction equipment.

Before adding asphalt emulsion, adequate amount of water should be introduced as a pre-mixing moisture coating for RAP material to allow the emulsion to uniformly coat the aggregates in the CR process (Lauter 1998). The amount of water to be added is established based on coating test AASHTO T 59 (ARRA 2001), which consists of mixing RAP materials with different levels of water contents. Resultant mixtures are visually evaluated and the one that provides no increase of coating at the lowest water content level is selected. The moisture content must be very carefully selected; the implementation in the field should be monitored as well, because excessive moisture content will cause stability issues while insufficient moisture content will decrease the workability of the mix. Aeration by evaporation of mixture before compaction is necessary to reduce excess fluid and volatile content (Kandhal and Malllick 1997).

Both optimum asphalt emulsion and pre-mix moisture content can be determined using density curve or strength tests (ARRA 2001, Lee, Brayton and Harrington 2002). Experience has shown that the optimum applied emulsion content for CR mixture increases with decreases in residual asphalt content of RAP materials (Suleiman 2002).

The optimum pre-mix moisture and asphalt emulsion content determined in the lab mixture design is just a starting point (Kandhal and Malllick 1997). Necessary adjustment by experience is needed in the field. If the coating of recycled mixture after the surface dries is not satisfied (less than 75 percent), the moisture content is adjusted
before the emulsion content. If coating of recycled mixtures satisfied while the cohesion within the mixture is lacking, emulsion content should be increased. The amount of water added to the mixture should be carefully controlled since high water content will cause instability of the mixture (Saloman and Newcomb 2000).

Other than asphalt emulsion, class C fly ash, lime slurry, and portland cement are also used as chemical recycling additives in the CR process to enhance early stage strength and capability to resist rutting and moisture damage (Kandhal and Mallick 1997, Suleiman 2002, Cross and Jakatimath 2007, Niazi and Jalili 2009). The most common amounts added to RAP for portland cement are 1-2 percent, and 8-12 percent for fly ash, by weight of RAP materials (ARRA 2001).

### 2.4.3 Curing in the Lab

After the chemical breaking process, excess water in the CR mixtures must be removed to help CR mixture gain adequate initial strength. Lab curing process should be simulated in accordance with the curing process that is happening in the field.

The curing time and temperature of laboratory CR mixture design will vary among design procedures. While most of the agencies choose a certain level of short term curing before compaction, some owner/agencies compact specimens immediately after mixing (Cross 2002). The curing process can be divided into two categories, short-term curing and long-term curing. In ARRA manual (ARRA 2001), short-term curing is conducted to condition compacted specimens at 60℃ for 2 to 4 hours. Long-term curing is performed by extending the conditioning time between 24 to 72 hours while still keeping the temperature at 60℃. Some agencies cured their specimens to a constant mass at 110℃. Lee et al. (Lee, Brayton and Harrington 2002) recommended 6 and 24 hours of curing to simulate short-term and long-term curing effects, respectively.

Curing temperatures were recommended as 25℃ and 60℃ for representation of pavement temperatures at night and during daylight time periods (Brayton, et al. 2001). Cross (Cross 2002) cured CIR specimens at 0, 0.5, 1, and 2 hours as initial curing before compaction using the Superpave Gyratory Compactor (SGC), and specimens were then cured at 60℃ for 48 hours right after compaction. Sebaaly (Sebaaly, et al. 2004) suggested that specimens be initially cured at 25℃ for 15 hours before being
extracted from the mold, then curing specimens at 60°C for 72 hours as final curing; curing at 60°C for 30 days is recommended as the long term curing procedure, if necessary. Cross and Jakatimath (Cross and Jakatimath 2007) placed the compacted specimens in a 60°C oven for a minimum of 16 hours. After that, specimens were weighed every 2 hours until mass loss was less than 0.5 percent, up to a maximum of 48 hours of oven curing at 60°C. Kim et al. (Kim, Im and Lee 2011) studied the impact of curing time and moisture content on CIR mixtures containing foamed asphalt or emulsified asphalt through the indirect tensile strength test (IDT), dynamic modulus, and flow number tests. They first cured specimens in the air for 0, 1, 3, and 5 hours after compaction. Then the same specimens were cured at 25°C and 40°C for 0, 7, and 14 days. They concluded that moisture content and curing time had a significant impact on CIR mixture performance. Humidity was not considered during the curing process by most of the agencies (Lee, Brayton and Huston 2002).

2.4.4 Compaction in the Lab
The mixture design compaction efforts must be able to produce specimens with air void level comparable to pavement materials compacted in the field. Historically, 50 blows of Marshall hammer at 140°F (60°C) were used as a standard compaction procedure in the lab for CIR mixture design by some agencies (ARRA 2001, Cross 2002). Some studies have shown that 75 blows by Marshall hammer compaction on field mixtures at a temperature of 100°F (40°C) resulted in densities more comparable with field densities (ARRA 2001). Unfortunately, studies have found that the Marshall mixture design and compaction method is not able to produce satisfactory CIR specimens in the lab (Lauter and Corbett 1998, Committee 1998). There have been many efforts carried out to use the Superpave Gyratory Compactor (SGC) in the CIR mixture design procedure in accordance with AASHTO TP 4 (Lee et al. 1999, Cross 2002, Lee, Brayton and Huston 2002).

Lee (Lee et al. 1999) first used the SGC to determine the optimum moisture and asphalt emulsion content for the CR mixture design. Cross (Cross 2002) determined the SGC compaction efforts needed to match the densities of field produced CIR mixtures. He recommended the use of 30 and 35 SGC gyrations for compaction on specimens produced in the lab before and after the breaking of asphalt emulsion, respectively.
Thomas and Kadrmas (Thomas and Kadrmas 2003) used 30 SGC gyrations on CIR mixtures to reach a target air void range of 9 to 14% percent, Lee et al. (Lee, Brayton and Harrington 2002) showed in their research that 37 SGC gyrations are necessary for CIR mixtures produced in the lab to reach the unit weight of 130 pcf, which is the value mostly common in the field. Kim and Lee (Kim, Lee and Heitzman 2007) suggested that 30 SGC gyrations are enough to produce a CIR specimen with a density similar to the specimens compacted through 75 blows of Marshall Hammer. They recommended the use of SGC due to its consistency in the production of laboratory specimens. Oklahoma Department of Transportation (Cross and Jakatimath 2007) conducted a study on the CIR for rehabilitation and used a SGC compaction level of 30 to 40 gyrations. Piratheepan (Piratheepan 2011) concluded that the best method of determining the mixture design gyration level with the SGC is to carry out trial specimens at a range of moisture and emulsion contents. Following this, the number of gyrations according to the target height of specimen and target air voids should be determined. If the target height is not achieved at the target air voids, the batch mass of a specimen should be adjusted accordingly.

2.5 Important Engineering Properties of CR Mixture
Best performance of the CR mixture is achieved and guaranteed by determination and application of the best engineering properties. Density, strength, durability, rutting resistance, and moisture damage resistance are engineering properties that have been emphasized in CR mixture design for years. Although there is no comprehensive nationwide information system on performance of the CR technology, some states and agencies have kept performance records of various CR projects. Following is a discussion and summary of the research conducted in the past regarding some of the most important factors affecting CR mixture performance.

2.5.1 Air Void
The air void content of asphalt mixtures is a very important factor that largely affects the performance. It is determined by mixture design parameters. For HMA and WMA mixtures in general, the air voids decreases with the increase of binder content and duration of traffic load with time before reaching a certain threshold. The same trend was observed for CR mixtures by some researchers (Saloman and Newcomb 2000,
In general, the air void content of CR mixtures is in the range of approximately 8 to 15 percent. From NCHRP synthesis 160 compiled by Epps (Epps 1990), the air void contents of CR mixtures were reported to be between 10 and 15 percent. In AASHTO Task Force No. 38 (Committee 1998), air void content was specified as a design parameter in mixture design process, and the suggested air void content range was between 9 to 14 percent. Salomon and Newcomb (Saloman and Newcomb 2000) compacted CIR specimens using three different kinds of asphalt emulsions (CSS-1, HFMS-2s with relatively low asphalt residual viscosity, and HFMS-2p) at varying contents through the Superpave Gyroratory Compactor and the Marshall hammer. For specimens compacted using a Marshall hammer, the air void contents were between 12.3 to 13.9 percent by 50 blows, while the air void contents of specimens compacted by SGC were reached between 4.6 to 9.7 percent by 150 gyrations. Given the difference in air void results, the plotted density curve showed that approximately 30 to 40 gyrations on a CIR specimen would be able to give similar air void contents to specimens compacted using the Marshall hammer. Test results indicated that the specimens with HFMS-2p asphalt emulsion gave the lowest overall air void contents compared to the other two asphalt emulsion sources. It was also observed from their research that air void contents affect the Indirect Tensile Strength (IDT) of CIR mixtures; as air void content increases, IDT results drops. Brayton (Brayton, et al. 2001) reported an air void content of 13.4 percent at optimum emulsion content of 1.2 percent and an air void content of 12.6 percent at the optimum water content of 2.3 percent. According to a literature report (Chen and Jahren 2007), given a similar air void content level, CIR mixtures exhibited longer service life compared to conventional HMA mixtures. Yan (Yan, et al. 2009) reported different air void content levels of CIR mixtures from 8.8 to 14.3 percent, obtained from various combinations of asphalt emulsions and cement contents. Based on statistical analysis of CIR mixtures by Chen (Chen, et al. 2010), smaller values of CIR mixture modulus and higher air void contents in CIR mixtures were expected to give better overall CIR specimen performance; they claimed that the CIR layer acts as a stress–relieving layer. The reported air void contents were between 4.5 and 14.3 percent.
2.5.2 Tensile and Compressive Strength

The most common technique used to measure the tensile strength of asphalt mixture is the Indirect Tensile Strength test (IDT). The loading configuration of this test develops a relatively uniform tensile stress that is perpendicular to the direction of the applied load and along the vertical diametrical plane, which ultimately fails the specimen by splitting along the vertical diameter of the test specimen.

In general, the IDT strength of the mixtures produced with CR materials is relatively lower than that of HMA or WMA. However, it is possible to enhance the IDT strength of CR mixtures through the introduction of better asphalt emulsion, better design gradation, higher compaction level, and a better engineered mixture design.

Brayton (Brayton, et al. 2001) reported IDT strengths of 85.1 to 179.3 psi from five different RAP sources at their optimum water and emulsion contents. Specimens were compacted using the SGC and the IDT tests were conducted at -10°C. Cross (Cross et al. 2002) conducted IDT tests on specimens obtained from six field sites in six different states. The specimens were cured for 0, 30, 60, and 120 minutes before testing. Strengths were reported to be between 26 to 73 psi. A study (Lauter 1998) indicated that IDT strength increases with the decreasing test temperature. Based on this, some researchers (Thomas and Kadrmas 2003) used the IDT test to determine thermal cracking temperature of CIR mixtures.

The compressive strength of CR specimens can be measured through various stabilometers such as Marshall or Hveem, or other conventional compressive strength testers. Such tests can be used to determine the optimum water and asphalt emulsion content for CR mixture design.

2.5.3 Durability

One of the problems of recycled pavement shortly after placement is raveling (Thomas and Kadrmas 2003). Thomas et al (Thomas and Kadrmas 2003) ran the Raveling test (ASTM D7196) using SGC compacted CIR specimens. The specimens were compacted with 20 gyrations and cured in ambient temperature for four hours. Different RAP sources from the field and asphalt emulsions were used. Test results showed that most
of the field specimens met the specification of maximum mass loss of 2 percent and better asphalt emulsions gave better performance. Kim et al. (Kim, Lee and Heitzman 2007) conducted the Raveling tests using SGC compacted specimens with 20 gyrations and 1.5 and 2.5 percent foamed emulsion. Two curing periods, 4 and 8 hours were employed. From their test results, they indicated higher emulsion contents and longer curing time resulted in better performance.

Another lab test to verify the asphalt mixture durability is the Cantabro test (TEX-245-F). It uses the Los Angeles abrasion device, but without introducing steel balls in the cabin. It has been widely used for permeable/gap graded asphalt mixtures and pervious concrete.

2.5.4 Moisture Damage Resistance
The ability of CR mixtures to resist against moisture damage should be evaluated. The test to assess this phenomenon, which applies to HMA and WMA, can also be used on CR mixtures. The most commonly used test procedures and devices include AASHTO T 283, the Hamburg Wheel Tracking Device (HWTD), and the Asphalt Pavement Analyzer (APA). APA is suitable to investigate both moisture damage resistance capability and rutting resistance capacity.

Thomas and Kadrmas (Thomas and Kadrmas 2003) investigated the performance-related specification for CIR mixture based on AASHTO T 283 test procedures, which require the retained stability based on long-term stability to be no less than 70 percent. Abiodun (Abiodun, et al. 2013) used a modified AASHTO T 283 test procedure. The specimen conditioning processes included 24 hours under water, 24 hours in a freezer at -15°C, 72 hours in an oven at 50°C, and the reference standard conditioning method which involved air drying at room temperature (20 to 25°C) for 24 hours. The IDT test temperature was 10°C. They reported that the application of portland cement significantly improves the strength and moisture resistance of the CIR mixtures. Their test results also indicated that too high of an emulsion content should be avoided, since it decreases the moisture resistance capability of the mixture.

Portland cement, slurry, and fly ash have been introduced as additives in CR mixture in
order to improve their early strength and capability to resist moisture damage. Cross (Cross 1999) claimed increased tensile strength and conditioned tensile strength of CIR specimens with hot slurry, regardless of water emulsion source used. Niazi and Jalili (Niazi and Jalili 2009) introduced portland cement and lime in CIR mixtures. Specifically, they employed Marshall conditioning (24 hours at 60°C) and the AASHTO T 283 test procedure. The indirect tensile strength ratio (TSR) is calculated as the ratio of preconditioned indirect tensile strength to dry indirect tensile strength. TSR is reported to be the highest (0.83) when 2 percent portland cement was added in the CIR mixtures and almost doubled the TSR of CIR specimens without portland cement.

Cross (Cross 2000) used APA to evaluate the moisture resistance of CIR mixtures. The test procedure was the same used to evaluate the permanent deformation, except that specimens were submerged in 40°C water. He concluded that CIR mixture was not prone to permanent rutting or moisture induced damage. The introduction of fly ash improves the resistance to moisture damage.

2.5.5 Rutting Resistance

Researchers (McDaniel, et al. 2000) have shown that asphalt mixtures containing high percentage of RAP would exhibit more resistance to rutting. The test procedures employed to determine the rutting (permanent deformation) resistance property of CR mixtures included repeated load test, Hamburg Wheel Tracking, Asphalt Pavement Analyzer, and Dynamic Creep Test.

Cross (Cross 1999) reported a decrease in rut depth when introducing hot slurry into CIR mixtures. Through the Asphalt Pavement Analyzer (APA) test results, the effectiveness of hot slurry in reducing wet rut depth was much better with median setting and slow setting emulsions than with high float emulsions. Cross (Cross 2000) tested CIR cores using the Asphalt Pavement Analyzer to determine the resistance to permanent deformation of CIR mixture. When test temperature was 40°C, a 1.4 mm and 0.6 mm rutting depths were observed for cores with hydrate lime slurry and cores with fly ash, respectively. When test temperature was enhanced to 50 °C, rut depth increased for cores with hydrated lime slurry, but decreased slightly for cores with fly ash. Kim et al. (Kim, Lee and Heitzman 2007) conducted the repeated load test on SGC compacted CIR mixtures with foamed asphalt. A load level of 138 kPa at 40°C was applied on the
test specimens. They concluded from their test results that an increase in foamed asphalt content decreased the flow number, which indicates a higher rutting susceptibility. Niazi and Jalili (Niazi and Jalili 2009) used the Dynamic Creep Test to investigate the rutting resistance of CIR mixtures with asphalt emulsion and cement. They reported a reduction of rut depth of 40 and 30 percent when portland cement and hydrate lime slurry were added to the mixtures, compared to CIR mixtures without additives. Overall, the use of hydrated lime slurry results in decreased wet and dry rut depths.

2.6 Summary of Literature Review
The CR is a recycling process through which 100% of the previous existing pavement materials are reused, rejuvenated, and placed back on the road as a new base course without introducing heat during the recycling process. It is an economical and sustainable approach that decreases demand on raw materials, energy consumption, and production of greenhouse gases. It can be accomplished on-site using a single machine or equipment train, or conducted in a central location using a cold mix plant. The Material investigation procedure can be applied to either method.

RAP materials are used as “virgin” aggregates in the CR process; real virgin aggregate may be added when special requirements need to be fulfilled. Emulsified asphalt, or asphalt emulsion, is the most popular recycling agent used in the CR process due to its considerable lower viscosity at low temperatures. According to its chemical configuration, asphalt emulsion can be classified into cationic, anionic, and nonionic asphalt emulsion. Based on the breaking rate, asphalt emulsion can be categorized into quick setting, medium setting, and slow setting asphalt emulsion. The selection of asphalt emulsion type for application is based on its ability to soften the old pavement, to coat the aggregate material, and the breaking time to obtain the minimal strength requirement.

Although there is no national standard mixture design procedure for the CR process at present, there are many developed mixture design protocols from state agencies and contractors, and they all have similar major steps. RAP materials will be evaluated for various aspects. Based on test results, decisions are made on the type and amount of
recycling agent and whether virgin aggregates are needed or not. There are also several methods to determine the optimum recycling agent content; most of them are based on strength tests and density curves through a trial study. Similar methods can be used to determine the optimum content of pre-mix moisture, which is used to coat RAP material before introducing recycling agent. Chemical recycling agents like portland cement, lime, and fly ash have been widely used in the CR process, and they have been shown to be very efficient in improving mixture properties. Study on curing efforts of CR mixture has been conducted to simulate the curing process in the field. Researchers have targeted making lab-produced CR mixtures contain similar air void levels as observed in the field.

Engineering properties of CR mixtures have been deeply investigated as well. Compared to traditional HMA and WMA mixtures, CR mixtures have relatively higher air voids for similar compaction efforts. However, CR mixtures give relatively lower compressive and tensile strengths. Although the moisture damage resistance is lower than for HMA and WMA mixtures, when a chemical recycling agent is employed, the capability of CR mixtures to resist the water damage is largely improved. Similar trends have been observed in various rutting resistance studies on CR mixtures.

Overall, engineering properties of CR mixtures can be investigated through conventional test methods used for HMA and WMA, which result in comparable test results. A national standard mixture design procedure is needed, however, this is not a simple task due to the variations among RAP materials, project requirements, equipment availability, and construction quality.
CHAPTER 3

MATERIALS AND LABORATORY TESTS

This chapter gives information about all the materials used in the research. Study and test procedures with details are then provided in a timely order.

3.1 Materials
The RAP materials used in the laboratory for characteristic study and tests were sampled from PennDOT District 1-0. They are the actual field produced RAP materials and were brought to the laboratory in sealed buckets. Recycling agent, including conventional asphalt emulsion and polymer modified asphalt emulsion, were provided by two emulsion manufacture sources: Manufacturer A supplied conventional cationic slow setting asphalt emulsion (CSS-1h) with 61 percent asphalt residual and polymer modified cationic slow setting asphalt emulsion (CSS-1hp) with 62 percent asphalt residual. Manufacturer B provided cationic slow setting asphalt emulsion (CSS-1h) with 68.14 percent asphalt residual and the latex, which was used in the asphalt emulsion as polymer modification additive. Asphalt emulsions from manufacturer B were used in the mixture design phase only. Specimens prepared for the studies of durability study, moisture damage resistance, and rutting resistance were mixed with emulsified asphalt produced by manufacturer A. In the moisture damage resistance and rutting resistance study phase, Type II portland cement was introduced to replace one percent fines that passing #100 sieve (0.149mm). It was used to compare with specimens without portland cement in engineering properties.

3.2 Mixture Design
The main purpose of the mixture design process in this study is to determine the optimum pre-mix water and asphalt emulsion content to be blended with RAP materials. The mixture design process includes determining the asphalt content in RAP materials, determining RAP gradation, setting the adjusted target design gradation based on original RAP gradation and its deficiency, determining compaction level based on measured air voids, determining the optimum pre-mix water and asphalt emulsion contents using IDT strength study, and setting curing and conditioning procedures.
### 3.2.1 Determination of Asphalt Content in RAP Materials

The asphalt content in RAP material was determined using ignition method based on PA Test Method No. 757, which is a modified version of AASHTO T 308. The residual asphalt binder content in the RAP materials was ignited to reach its flashpoint using furnace equipment. The asphalt content (AC%) was calculated by mass difference of RAP materials before and after ignition as below:

\[ AC\% = \left( \frac{W_s - W_A}{W_s} \right) \times 100 - C_F \]

Where

- \( AC\% \) = Asphalt content in RAP materials;
- \( W_s \) = Weight of test specimen before ignition;
- \( W_A \) = Weight of leftover aggregate after ignition; and
- \( C_F \) = Calibration factor, no specific value for RAP materials, assume -0.5.

Tested RAP materials were randomly chosen and air dried for 24 hours in a ventilated room at room temperature before conducting the ignition test. A single test was conducted. Test results are shown in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of specimen basket, pan and guards</td>
<td>3378.0 g</td>
</tr>
<tr>
<td>Weight of specimen, specimen basket, pan and guards</td>
<td>5136.8 g</td>
</tr>
<tr>
<td>Weight of specimen before ignition (( W_s ))</td>
<td>1758.8 g</td>
</tr>
<tr>
<td>Weight of specimen, specimen basket, pan, guards after ignition</td>
<td>4999.6 g</td>
</tr>
<tr>
<td>Weight of aggregate after ignition (( W_A ))</td>
<td>1621.6 g</td>
</tr>
<tr>
<td>Measure asphalt content (AC%) after correction</td>
<td>7.3 %</td>
</tr>
</tbody>
</table>

### 3.2.2 Determination of RAP Material Gradation and Set Design Gradation

The aggregate gradation affects properties and characteristics of asphalt mixtures, such as durability, permeability, strength, and stability. It plays a major role in mixture design. For CR mixtures, 100 percent RAP materials are used in most cases; virgin aggregate can be introduced when there is a significant deficiency in original mixture gradation or improvement of performance is required. In this research, the gradation of
RAP materials was determined according to AASHTO T27.

Three buckets of RAP materials were randomly chosen to determine the gradation of RAP materials. Before conducting sieve analysis, RAP materials were evenly distributed on a workbench in a room with ventilation and air dried for 48 hours at room temperature. During this period, large aggregate chunks (significantly larger than 25mm) in the distributed RAP materials were manually removed. Upon completion of air drying, RAP materials from each bucket were split using AASHTO T 2 standard splitter (Figure 14) into 4 equal batches. Each batch was further split into 4 smaller but equal batches with a weight around 2000 grams of RAP materials in each batch.

![Figure 14 AASHTO T2 standard splitter](image)

Sieve analysis was processed according to AASHTO T27 under room temperature. To ensure proper sieving, only 1000 grams of RAP materials were sieved each time. The sieve process was finished using a mechanical shaker (Figure 15 Left), with a sieving period set at 12 minutes. This was followed by one minute hand shaking for each sieve smaller than #4 sieve (4.75mm) to ensure less than 0.5 percent of materials were still passing. All sieves (Figure 15 Right) used were the U.S.A standard testing sieves that had passed the ASTM E-11 specification.
The sieve analysis results from the first round of three randomly chosen buckets of RAP materials are show in the Table 2. For larger sieve sizes (above #4 sieve), the gradation of RAP materials varied significantly, which made the average gradation of RAP materials unable to be used without adjustment.

The second round sieve analysis was conducted on RAP materials from all three buckets used in the first round of sieve analysis combined, following the exact same procedures discussed above. The gradations presented in Table 3 are the results of this combined sieving procedure. The gradation after scalping refers to the gradation once all material larger than 7/8 inch (19 mm) was removed. The gradation plots before and after scalping is presented in Figures 15 and 16, respectively.

The after scalping gradation of the RAP materials was considered as the final design gradation for mixture design and engineering property investigation purpose in this research. No virgin aggregate was added to the RAP materials to adjust the gradation.
### Table 2 The Gradation of RAP Materials from Three Randomly Chosen Buckets

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bucket 1</td>
</tr>
<tr>
<td>1 1/2&quot; (37.5mm)</td>
<td>100.00</td>
</tr>
<tr>
<td>1&quot; (25 mm)</td>
<td>98.84</td>
</tr>
<tr>
<td>3/4&quot; (19mm)</td>
<td>91.93</td>
</tr>
<tr>
<td>1/2&quot; (12.5mm)</td>
<td>84.25</td>
</tr>
<tr>
<td>3/8&quot; (9.5mm)</td>
<td>76.36</td>
</tr>
<tr>
<td>#4</td>
<td>48.49</td>
</tr>
<tr>
<td>#8</td>
<td>29.67</td>
</tr>
<tr>
<td>#16</td>
<td>16.94</td>
</tr>
<tr>
<td>#30</td>
<td>8.31</td>
</tr>
<tr>
<td>#50</td>
<td>2.88</td>
</tr>
<tr>
<td>#100</td>
<td>1.88</td>
</tr>
<tr>
<td>#200</td>
<td>0.43</td>
</tr>
<tr>
<td>Pan</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 3 The Gradation of RAP Materials from Three Randomly Chosen Buckets (Combined)

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Percent Passing (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Scalping</td>
</tr>
<tr>
<td>1 1/2&quot; (37.5mm)</td>
<td>100.00</td>
</tr>
<tr>
<td>1&quot; (25 mm)</td>
<td>96.24</td>
</tr>
<tr>
<td>3/4&quot; (19mm)</td>
<td>90.43</td>
</tr>
<tr>
<td>1/2&quot; (12.5mm)</td>
<td>81.96</td>
</tr>
<tr>
<td>3/8&quot; (9.5mm)</td>
<td>74.44</td>
</tr>
<tr>
<td>#4</td>
<td>47.92</td>
</tr>
<tr>
<td>#8</td>
<td>29.31</td>
</tr>
<tr>
<td>#16</td>
<td>16.71</td>
</tr>
<tr>
<td>#30</td>
<td>8.01</td>
</tr>
<tr>
<td>#50</td>
<td>2.68</td>
</tr>
<tr>
<td>#100</td>
<td>1.16</td>
</tr>
<tr>
<td>#200</td>
<td>0.37</td>
</tr>
<tr>
<td>Pan</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 16 Gradation plot of three randomly chosen buckets of RAP materials (before scalping)

Figure 17 Gradation plot of three randomly chosen buckets of RAP materials (after scalping)
3.2.3 Laboratory Production of CR Mixture

After completion of the air drying and sieving procedures discussed above, RAP materials were then batched based on the final design gradation after scalping (Table 3), as shown in Figure 18. Approximate mass for each batch was determined based on the relation \((1010 \times G_{mm})\) to obtain the desired specimen height at 35 or 50 gyrations of compaction using the Superpave Gyratory Compactor (SGC). The theoretical maximum specific gravity \(G_{mm}\) of RAP materials was determined according to AASHTO T209 and found to be 2.408, leading to a trial batch weight of 2450 grams.

![Figure 18 Batched RAP materials in the pan](image)

For every batch of RAP materials, the following procedures (Figure 19) were followed to prepare a compacted specimen for testing:

1. Manually mix the batched RAP materials and tap water according to the selected water content for 90 seconds.
2. Let the wet blended RAP material sit for 2 minutes.
3. Mix the wetted RAP materials with asphalt emulsion according to the selected emulsion content. Ensure uniform blending of the RAP materials and asphalt emulsion through manual mixing of the material for 60 seconds.
4. Immediately after blending, cure the RAP-emulsion blend in a 104°F(40°C) chamber for 30 minutes.
5. Upon completion of the curing process, compact the RAP-emulsion blend using SGC at 87 psi (600 kPa) pressure for 35 or 50 gyrations.
6. Label the specimen and find its weight.
7. Cure the specimen in a 104°F(40°C) chamber for 72 hours.

Figure 19 (a) Batched RAP materials, (b) Batched RAP materials mixed with water after mixing, (c) Blended RAP materials with emulsion after mixing, (d) Materials after 30 minutes of curing at 40°C before compaction, (e) Specimen after compaction (2% water and 2% emulsion), (f) Specimen after 72 hours curing at 40°C
For specimens prepared for durability testing, step 7 was not followed. And for specimens with portland cement, an additional preliminary step (which will be introduced subsequently) was added before the first step. Specimens produced for other purposes followed these procedures precisely. Before mixing, the selected emulsion was heated in a 140°F (60°C) oven for 1.5 hours, and was stirred to ensure homogeneity before mixing with the wetted RAP materials. All mixing and compaction procedures were conducted at room temperature.

All test specimens were produced using the Superpave Gyratory Compactor (SGC) as shown in Figure 20. The target height of a compacted specimen after 50 gyrations was to be between 62 to 66 mm, which is designed to fit for the Indirect Tensile Strength (IDT) test. The calculated trial batch weight of 2450 grams gave a 71 mm specimen height after 50 gyrations. The second trial batch weight 2370 grams reached 67 mm specimen height after 50 gyrations. So the final batch weight was decided to be 2330 grams.

During trial mixing, 35 gyrations were also employed. For the same mixtures (1.5 percent water, and 2.0 percent emulsion), 35 gyrations gave much higher air void than 50 gyrations (17.0% vs. 14.6%), as shown in Figures 21 and 22, respectively. So the 50
gyrations were established as the standard compaction level for a specimen with 2330 grams of batch weight for better stability.

**Compaction Curve of Specimen with 1.5% Water, 2.0% Emulsion, 35 Gyration Sample #1**

![Compaction Curve of Specimen with 35 Gyration Sample #1](image)

\[
y = -0.0004x^3 + 0.0331x^2 - 0.9304x + 83.783
\]

\[R^2 = 0.99611\]

**Figure 21 Compaction curve of a specimen with 35 gyrations**

**Compaction Curve of Specimen with 1.5% Water, 2.0% Emulsion, 50 Gyration Sample #1**

![Compaction Curve of Specimen with 50 Gyration Sample #1](image)

\[
y = -0.0002x^3 + 0.0208x^2 - 0.7662x + 82.526
\]

\[R^2 = 0.98886\]

**Figure 22 Compaction curve of a specimen with 50 gyrations**

Due to the incompressibility of water, when compacting specimens with high moisture content, the SGC mold was retrofitted through inducing holes around the mold. The
perforated mold (Figure 23) allows the water to flow out of the mold, under the compaction induced pressure, to allow compaction of the specimen.

![Perforated SGC mold](image)

Figure 23 Perforated SGC mold to allow pore pressure dissipation

### 3.2.4 Use of Polymer Modified Asphalt Emulsion

Polymer modified asphalt emulsion (PMAE) was used to compare with specimens containing conventional asphalt emulsion through mixture property testing.

There are two ways of manufacturing PMAE. One method starts with processing the polymer modified binder through the production of PMAE in the emulsion plant. The polymer content of binder in this application is limited to 3 percent or less. The other approach is to introduce the latex (Figure 24 Left) into emulsion during milling process in the colloid mill. This approach is referred as co-emulsification pre-addition of the latex. The latex can also be added to the asphalt emulsion after the emulsion has been produced, which is known as post addition of the latex. Compared to the first two approaches, post addition of the latex provides the least efficiency regarding dispersion of the latex within the asphalt emulsion. No matter which method is employed, the latex should be uniformly dispersed in the asphalt emulsion.

In the mixture design stage, emulsions used in the test were from manufacturer B. Only conventional asphalt was provided; the latex was introduced using post addition method.
through shear blender (Figure 24 Right). For the rest of the research stages, asphalt emulsions provided by manufacturer A were used, and PMAE were produced using the first method, so no lab device was employed.

Figure 24 (Left) Latex used in asphalt emulsion, (Right) Shear blender setup

In the mixture design phase, the latex was blended with asphalt emulsion manually at first. Before mixing, both the latex and the asphalt emulsions were heated at 140°F(60°C) for two hours. Then the asphalt emulsions and the latex were stirred for one minute manually after the latex was added into the asphalt emulsions. This method turned out to be ineffective since it couldn’t provide enough blending between two materials; the latex was observed to be floating on the surface of the asphalt emulsions.

The shear blender (Figure 24 Right) was introduced to obtain a uniform dispersion of the two materials. After the same heating procedure used in manual blending, blender sheared in the blended materials at 500 rpm for 5 minutes. The lab produced PMAE were mixed with RAP materials using the same procedures used for the conventional asphalt emulsions.

3.2.5 Density Measurement
Upon completion of 72 hours of curing at 104°F(40°C) and 2 hours of cooling down at 77°F (25°C), the bulk specific gravity ($G_{mb}$) of each specimen was determined using a CoreLok device (Figure 25 Left) according to AASHTO T331-13. The theoretical maximum specific gravity ($G_{mm}$) of the selected specimen was determined using both CoreLok device and Pycnometer (Figure 25 Right). Same preparation procedures used for test specimen were followed to prepare the specimen with a batch weight of 1500 grams for $G_{mm}$ measurement.
For each water content, one specimen without any emulsion was made to determine the $G_{mm}$ through CoreLok device and Pycnometer. The $G_{mm}$ for specimens with various emulsion contents was calculated using the equation as shown below:

$$G_{mm-e} = \frac{G_{mm}(1+p)}{1 + \frac{p \times G_{mm}}{G_b}}$$

Where

$G_{mm-e} =$ Maximum theoretical specific gravity with emulsion

$G_{mm} =$ Maximum theoretical specific gravity without emulsion

$p =$ Percent of emulsion residual (by mass of mix), and

$G_b =$ Specific gravity of emulsion binder

The following equation was used to calculate the air void of every specimen after $G_{mm}$ and $G_{mb}$ were obtained:

$$V_a = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}}$$

Where

$V_a =$ Air voids in compacted mixture, percent of total volume

$G_{mm} =$ Maximum specific gravity of paving mixture, and

$G_{mb} =$ Bulk specific gravity of compacted mixture
3.2.6 Determination of the Optimum Water and Emulsion Content

After the determination of design RAP gradation, the optimum water and emulsion content should be determined to provide a stable and durable cold mixture. Adding water provides the needed lubrication for mixtures and facilitates compaction. Adding emulsions also provides workability, lubrication, and ease of compaction. It also provides the needed asphalt binder to coat and bond RAP materials together.

In a typical mixture design process, a range of water and emulsion contents must be tested to determine the best combination to achieve stability and durability of the mixture after placement. In this research, water content was selected in the range of 1 to 4 percent. The emulsion content was tried at five levels (0, 1.5, 2, 3, and 3.5 percent). Table 4 gives the specimen preparation matrix used to establish optimum water and emulsion content combination in the mixture design phase. Three replicates were used for each water and emulsion combination.

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>0</th>
<th>1.5</th>
<th>2</th>
<th>3</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>----</td>
<td>X</td>
<td>X</td>
<td>----</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>----</td>
<td>----</td>
</tr>
</tbody>
</table>

Table 4 Specimen Preparation Matrix in Mixture Design Phase

(X: three replicates, ----: no specimens)

The Indirect Tensile Strength (IDT) test (Figure 26) was introduced in this study phase to determine the tensile strength of conditioned specimens in order to obtain the optimum water and emulsion content combination.
The IDT test protocol according to ASTM D6931 is a useful experimental method developed to evaluate the strength and creep properties of lab produced or cored specimens. The IDT strength of asphalt mixtures is conducted by loading a cylindrical specimen across its vertical diametral plane (Figure 27 Left) with a compressive load at a specified rate of deformation and test temperature. The peak load at failure is recorded and used to calculate the IDT strength of the specimen.

This loading configuration developed a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane. Thus, the specimen failed by splitting along the vertical diameter as shown in Figure 27 Right.
From the plot of load versus deformation, maximum load carried by the specimen was found, and the following equation was used to calculate the indirect tensile strength at failure.

\[ S_t = \frac{2000 \times P}{\pi \times t \times D} \]

Where
\( S_t \) = IDT strength, kPa
\( P \) = Maximum load, N
\( t \) = Specimen height immediately before test, mm, and
\( D \) = Specimen diameter, mm

After measuring the \( G_{mb} \), an IDT test was conducted on each specimen (Figure 28) to obtain its tensile strength. The test temperature was 77°F (25°C) and the test chamber was turned on 2 hours before testing to ensure a stable temperature environment before and during the test. The rate of deformation and the rate of sampling were 50mm/min and 50/s, respectively.

![Figure 28 Specimen after IDT test (the specimen contained 2% water and 2% emulsion)](image)

The average failure strength of three replicates was used as the tensile strength of a certain water and asphalt emulsion combination. Test results will be presented in Chapter 4.
3.3 Durability of Lab Produced CR Specimens

The Raveling test was used to study the durability of lab produced CR specimens. The Raveling test is processed through inducing a rotate abrasive load to the surface of specimens on the Raveling test machine (Figure 29) based on ASTM D7196-12. The load is applied to simulate what the mixture experiences once exposed to the early traffic after compaction in the field. The emulsion used during the Raveling test stage was CSS-1h from manufacturer A.

![Figure 29 The Raveling test machine](image)

The raveling machine used in this study was a Hobart mixer, model A120, which has been modified to conduct the Raveling test. The raveling head and adapter base were purchased from Precision Machine & Welding, from Salina, Kansas. The raveling head has a rubber hose attached to it, which makes surface contact with the mixture during the Raveling test, to simulate the raveling in the field. The raveling head and rubber hose attachment together weigh roughly 585 grams and is free floating, so it can lower itself during a test if the specimen becomes severely raveled. The rubber hose is rotated after each Raveling test to make sure contact surface of the rubber hose has never been used before.

The height of the test specimen is required to be 70 mm by test specification. For each test specimen, 2450 grams of RAP materials were batched according to design gradation. The following steps were followed to prepare a specimen for the Raveling test:
1. Mix the prepared RAP materials and tap water manually for 60 seconds,
2. Mix the wetted RAP materials and asphalt emulsions manually for 60 seconds immediately after step 1,
3. Compact the RAP-emulsion blend using the Superpave Gyratory Compactor for 20 gyrations under 600kPa immediately after step 2 completed, and
4. Label and weigh the specimen, and cure the specimen in a 104°F(40°C) chamber for 20 hours after compaction.

Before conducting the Raveling test, each specimen was cooled in a 77°F(25°C) chamber for 2 hours and weighed before it was carefully placed on the adapter base. The test is carried out at a speed of 100 rpm for 15 minutes. Upon the completion of the test, the loose material is gently swept off the specimen surface using a brush. Care is taken to avoid removal of any part of the material, which is not loosened to be moved through gentle sweeping, especially at the edges. Once the loose material is cleaned off the surface, the specimen is removed from the adaptor base and weighed. Figure 30 shown a specimen before and after the Raveling test.

![Figure 30](image)

Figure 30 (Left) Specimen before the Raveling test, (Right) specimen after the Raveling test (the specimen contained 2% water and 0% emulsion)

The percent mass loss is calculated as follows:

\[
\% \text{Mass Loss} = 100 \times \frac{(A - B)}{A}
\]

Where
A = Specimen mass (prior to test), and
B = Specimen mass (after test)
3.4 Moisture Damage Resistant of Lab Produced Specimens

Laboratory produced CR specimens with conventional and polymer modified asphalt emulsions were used to conduct IDT tests after several conditioning processes to assess their moisture damage resistance properties based on AASHTO T283-07. Conventional and polymer modified asphalt emulsions used in this part of the study were from manufacturer A.

Material preparation, mix, compaction, and curing procedures before density measurement were the exact procedures used for mixture design. The desired water content was established at 2% based on the IDT strength results obtained from mixture design phase; only specimens with cement to replace fines had 2.25% water content. Two asphalt emulsion contents, 2% and 3%, which were also obtained from IDT strength results during mixture design, were used in specimen preparation. Table 5 indicates the water content, asphalt emulsion content, and number of specimens prepared for the moisture damage resistance study.

Table 5 Specimen Preparation Matrix for Moisture Damage Resistance Study

<table>
<thead>
<tr>
<th>Water Content, %</th>
<th>Cement Content, %</th>
<th>Emulsion Content, %</th>
<th>2.0</th>
<th>3.0</th>
<th>3.0</th>
<th>Total Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>0.00</td>
<td>No Polymer</td>
<td>12</td>
<td>6</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>2.25</td>
<td>1.00</td>
<td>No Polymer</td>
<td>-----</td>
<td>6</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With Polymer</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Number of Specimens</td>
<td>24</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

During the compaction process of the trial study, specimens with cement showed higher air voids. In order to bring down the air voids of specimens with cement and keep the air voids of all test specimens to be within 1 percent variance, 53 gyrations were used to compact specimens with cement and specimens without cement were still kept at 50 gyrations during compaction. From the study process, the specimens with 2 percent emulsion content also delivered higher air voids. In order to bring down the air void values of specimens with 2 percent emulsion content to better compare the test results with specimens with 3 percent emulsion content, 6 more specimens with 2 percent emulsion content with lower air voids obtained by conducting a higher compaction
level were made afterward.

Bulk specific gravity ($G_{mb}$) of every test specimen was measured after 72 hours of curing at 104°F(40°C) and 2 hours of cooling at 77°F(25°C) based on AASHTO-T331-13 using the CoreLok device. The theoretical maximum specific gravity ($G_{mm}$) of each water and emulsion content combination (total of 5) was determined using the CoreLok device. The air void of each specimen was then calculated based on measured $G_{mb}$ and $G_{mm}$.

For every emulsion content and type, 6 specimens were divided into dry or wet subsets after their air voids were obtained. Grouping of specimens into wet and dry subsets was conducted in a way to deliver an average air void of dry subset to be close to that of wet subset. The specimens of dry group were maintained in a 77°F(25°C) chamber until the time for IDT testing, while the wet group specimens were further processed through moisture conditioning according to a modified version of AASHTP T 283-07 procedure as follows:

1. Vacuum saturation was applied to induce partial saturation in the specimens. This was achieved through the use of a pycnometer and a vacuum pump (Figure 31). The pycnometer was first filled with tap water at room temperature so that each specimen was covered with at least 1 inch (25 mm) of water above the surface. A vacuum of 2 to 10 inches (13 to 67KPa) absolute pressure was applied for 20 minutes. Afterwards, volume of absorbed water was determined using simple calculations,

$$J' = B' - A$$

Where

$J'$ = Volume of absorbed water, cm³

$B'$ = Mass of saturated surface-dry specimen after partial vacuum saturation, g;

and

$A$ = Mass of the dry specimen in air, g
2. The degree of saturation was determined by comparing the volume of absorbed water with the volume of air void obtained from bulk and maximum theoretical specific gravity,

\[ S' = \frac{100J'}{V_a} \]

Where

\( S' \) = Degree of saturation, %; and
\( V_a \) = Air void of the specimen, %

The process of inducing water into the specimen through vacuum saturation was repeated with the goal of attaining between 70 and 80 percent for the degree of saturation. Beyond the first time of vacuum application, which lasted 20 minutes, the vacuum time was kept at 5 minutes followed by checking the degree of saturation. However, the total vacuum time for each specimen was not allowed to exceed 30 minutes regardless of saturation level in the specimen.

3. After 30 minutes of vacuum saturation, each of the vacuum-saturated specimens was tightly covered with a plastic film. Each wrapped specimen was placed in a plastic bag containing 10±0.5 mL of water and the bag was sealed. The plastic bags containing the specimens were placed in a freezer at a temperature of 0±5°F (−18 ± 3°C), for a minimum of 16 hours.

4. Specimens were removed from the freezer and placed in a bath containing tap water at 140 ± 2°F (60±1°C) for 24±1 hours. Afterwards, specimens were removed and placed in a water bath at 77 ± 1°F (25±0.5°C) for 2 hours ±10 min.

5. Specimens were then removed from water bath and were subjected to indirect tensile strength testing (IDT).
During the trial study phase, it was found that for procedure 1, the target degree of saturation (70-80 percent) required by AASHTO T 283 cannot be achieved from 45 minutes of vacuum process. Therefore, during the actual study process, 30 minutes of vacuum was applied in one attempt regardless of the degree of saturation requirement.

None of the specimens with 2 percent emulsion content prepared in the first round could stand the moisture conditioning process (hot water bath conditioning process), and collapsed before completion of the conditioning process (Figure 32). The same situation happened to one of the 3 percent emulsion specimens. It is believed that the damage to 2 percent emulsion specimens was due to high air voids (average 10.7 percent). The second set of specimens with 2 percent emulsion content, which had a lower air void (8.5 percent) remained adequately strong after conditioning and could be tested for IDT strength.
It has been shown that introducing portland cement to replace fines in CR mixtures can improve early strength of the mixture and increase moisture damage resistance of the mixture (Niazi and Jalili 2009). While sufficient strength was achieved using emulsions only during the mixture design stage, moisture damage results indicated poor performance when only emulsions were used. Therefore, the laboratory experimental work was extended to include CR mixtures prepared containing one percent type II portland cement in addition to the emulsions (Figure 33). This cement replaced the materials retained in the pan and part of the #200 fines, without any changes in the rest of the gradation. Once the batch was prepared, the cement was manually mixed with the RAP materials delivering a uniform blend. Beyond this point, the specimen preparation and the curing process was followed the same as discussed previously.

![Batched RAP materials with 1% portland cement before mixing](image)

Figure 33 Batched RAP materials with 1% portland cement before mixing

After conditioning, both dry and moisture conditioned specimens were tested using the Indirect Tensile Strength (IDT) test. Deformation and sampling rates were 50mm/min and 50 data points per second, respectively. The IDT machine and the temperature control module were started two hours before conducting the test to ensure a stable test temperature. The temperature in the test chamber was maintained at 77°F (25°C) during the test.
The tensile strength ratio was calculated as follows:

\[ TSR = \left( \frac{S_{tm}}{S_{td}} \right) \times 100\% \]

Where

TSR = Tensile strength ratio

\( S_{tm} \) = Average tensile strength of the wet subset specimen, psi, and

\( S_{td} \) = Average tensile strength of the dry subset specimen, psi

### 3.5 Rutting Resistant of Lab Produced Specimens

The test in this part of the study included evaluating permanent deformation of laboratory produced mixtures using the Superpave Shear Tester (SST). The SST was developed during Strategic Highway Research Program in 1987, as a means to characterize asphalt mixture properties (Shenoy 2001). The SST is a servo-hydraulic machine (Figure 34) that is able to apply both axial and shear loads at constant temperature using a close-loop system.

![Figure 34 The SST test configuration](image)

The SST can perform the following four tests to determine HMA properties.

1. Repeated Shear at Constant Height (RSCH)
2. Frequency Sweep at Constant Height (FSCH)
3. Simple Shear at Constant Height (SSCH)
4. Repeated Shear at Constant Stress Ratio (RSCS)

The Repeated Shear at Constant Height (RSCH) is employed in this study phase. Test preparation and procedures are followed according to AASHTO T 320.

Both conventional and polymer modified asphalt emulsions used in this part of the study were from manufacturer A. As for the moisture damage resistance study, material preparation, mix, compaction, and curing procedures before density measurement were following with exactly the procedures used in the mixture design phase. To obtain a similar air void level for all test specimens, compaction level was kept the same as used during the moisture damage resistance study phase, 50 gyrations for specimens without cement and 53 gyrations for specimens with cement. The desired water content was established at 2 percent and only specimens with cement to replace fines had 2.25 percent water content. Only one emulsion content, 3 percent, was used in specimen preparation. Table 6 indicates the water content, emulsion content, and number of specimen prepared for rutting resistance study. For each group, three replicates were prepared. Type II portland cement was also introduced in this stage of study for property comparison.

Table 6 Specimen Preparation Matrix for Rutting Resistance Study

<table>
<thead>
<tr>
<th>Water Content, %</th>
<th>Emulsion Content, 3%</th>
<th>Number of Specimens with Regular Emulsion</th>
<th>Number of Specimens with Polymer Emulsion</th>
<th>Number of Specimens with 1% Cement</th>
<th>Number of Specimens with Polymer Emulsion and 1% Cement</th>
<th>Total Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>2.25</td>
<td></td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

Both bulk specific gravity and theoretical maximum gravity of each specimen were determined using a CoreLok device; these two values were used to obtain the air void of each test specimen.
Because of the SST test configuration, a specimen has to be glued to the metal platen (Figure 35) before testing. Devcon® Plastic Steel® Putty (A) epoxy (Figure 36 Left) was used to glue test specimens to metal SST platens. The ratio of resin to hardener (Figure 36 Right, resin is dark grey, and hardener is white) was 9:1, and mass of epoxy was 90 grams in total. The resin and hardener were manually blended to ensure a uniform mixture at room temperature before using. The epoxy fully curing time is 20 hours.

Figure 35 The SST test specimen (middle) and metal platen

Figure 36 (Left) Devcon® Plastic Steel® Putty epoxy, (Right) Resin and hardener

The Interlaken Alignment Fixture (Figure 37 Left) was used to bond specimens to metal platens. This fixture was used to ensure that the platens glued to the top and bottom sides of the specimen remain parallel during the epoxy curing process. First, the platens were mounted into the fixture. The epoxy coated specimen was then placed between the two platens. The specimen and platens were fixed onto the fixture (Figure 37 Right) with the top regulator gauge set at a pressure of 55 psi, and lower regulator gauge set at
35 psi. Through this process, the epoxy was cured for 20 hours to reach its minimum required full curing time.

![Figure 37 The Interlaken alignment fixture (Left) with specimen-platen assembly (Right)](image)

After removal of the specimen-platen assembly from the gluing jig, the assembly together with clamps and support used to hook up LVDT (Linear Variable Differential Transformer) and assembly were conditioned at the target temperature 125.6°F (52°C) for 2.5 hours (Figure 38) before testing. The conditioning time was established based on temperature measurements for a dummy specimen (Figure 39), with a thermocouple inserted through a drilled hole to the center of the specimen. It was found that the specimen typically reached the target test temperature after 2 hours of conditioning. However, 2.5 hours of conditioning time was applied to be conservative.
After conditioning the test specimen at the test temperature, specimens were tested according to AASHTO T 320, the Repeated Shear Test at Constant Height (Figure 40). The test temperature was selected at 125.6°F (52°C) to represent the high pavement temperature. A repeated haversine shear stress of 10 psi (69±5 kPa, approximately 275 pounds or 1220N shear load for a 6 inch or 150 mm diameter test specimen) was applied to the specimen for 0.1 s followed by a 0.6 s rest period (Figure 41). During the loading cycle, the specimen height was maintained to be constant within ± 0.013 mm by controlling the axial stress during the loading cycle. This was accomplished by controlling the vertical actuator using closed-loop feedback from the axial LVDT. Shear deformation was measured using an LVDT mounted horizontally (Figure 42).
Figure 40 The Repeated Shear at Constant Height (RSCH) test configuration

Figure 41 Stress pulse during RSCH testing process

Figure 42 Schematics showing transduce configuration measuring shear deformation
The LabView® software package was used to control and monitor the test (Figure 43). Data were recorded at a rate of 100 points per second. The test was conducted either to 5000 cycles or to the point of failure if it happened before 5000 cycles. Failure was defined as the specimen deformation exceeding 5 mm, which was beyond the LVDT measuring capability. LabView® was then used to translate the raw signals results into the shear deformation data at each data point.

Figure 43 LabView® software interface for RSCH testing
CHAPTER 4

TEST RESULTS AND ANALYSIS

This chapter includes test results from all four parts of the researches. Test results in the mixture design phase include density, air void, and strength of specimens with different combinations of emulsion and water contents. The Raveling test results will be shown in the second part of this chapter. Moisture damage results of CR specimens including air void contents of each specimen, grouping, IDT strength, and TSR will be presented in the third section of this chapter. The final section will show permanent deformation test results of all tested specimens with air void of each tested specimen. Appropriate statistical analysis will be conducted on all obtained data using the Minitab software package.

4.1 Mixture Design

4.1.1 Density of All Specimens

Densities of compacted specimens were measured at two stages using a CoreLok device: once immediately after compaction, which is used to calculated the wet bulk specific gravity (wet $G_{mb}$) that simulate what can be obtained right after compaction in the field, and once after 72 hours of curing at 104°F (40°C), which is used to calculated the dry bulk specific gravity (dry $G_{mb}$) that simulate what can be obtained right before implementing the surface treatment or overlay. The results shown in Figures 44 to 45 and Tables 7 to 8 indicate that at all water contents, both dry $G_{mb}$ and wet $G_{mb}$ increase as the emulsion content increased. This trend is expected because higher emulsion content provides more moisture to lubricate and facilitate compaction, hence increasing the density. For each water and emulsion content combination, dry $G_{mb}$ is relatively lower than wet $G_{mb}$ because water evaporated from the specimen during the curing process. Between different water contents, however, there is no clear trend of both bulk specific gravities in terms of emulsion content.
Figure 44 Wet $G_{mb}$ of all specimens in mixture design phase (Error bars are shown as the average value plus and minus one standard deviation)

Figure 45 Dry $G_{mb}$ of all specimens in mixture design phase (Error bars are shown as the average value plus and minus one standard deviation)
Table 7 Wet $G_{mb}$ of All Specimens in Mixture Design Phase

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Emulsion Content (%)</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.0</td>
<td>2.130</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.156</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>2.170</td>
<td>0.003</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>2.084</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.120</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.155</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.154</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>2.174</td>
<td>0.008</td>
</tr>
<tr>
<td>3.0</td>
<td>1.5</td>
<td>2.137</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.148</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.170</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>2.180</td>
<td>0.005</td>
</tr>
<tr>
<td>4.0</td>
<td>0.0</td>
<td>2.117</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.158</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.191</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Table 8 Dry $G_{mb}$ of All Specimens in Mixture Design Phase

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Emulsion Content (%)</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.0</td>
<td>2.112</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.137</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>2.152</td>
<td>0.003</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>2.056</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.090</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.112</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.122</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>2.145</td>
<td>0.009</td>
</tr>
<tr>
<td>3.0</td>
<td>1.5</td>
<td>2.091</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.102</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.125</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>2.139</td>
<td>0.005</td>
</tr>
<tr>
<td>4.0</td>
<td>0.0</td>
<td>2.055</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.094</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.130</td>
<td>0.026</td>
</tr>
</tbody>
</table>
For specimens with certain water content and no asphalt emulsions, theoretical maximum specific gravity \(G_{\text{mm}}\) was determined using a CoreLok device. Then the rest of the \(G_{\text{mm}}\) values of specimens with the same water content and different emulsion contents were obtained through the backcalculation. The equation is shown as below:

\[
G_{\text{mm-e}} = \frac{G_{\text{mm}}(1 + p)}{1 + \frac{p \times G_{\text{mm}}}{G_b}}
\]

Where

\(G_{\text{mm-e}}\) = Maximum theoretical specific gravity with emulsion at certain water content

\(G_{\text{mm}}\) = Maximum theoretical specific gravity of RAP without emulsion

\(p\) = Percent of emulsion residual (by mass of mix), and

\(G_b\) = Specific gravity of emulsion binder

Maximum theoretical specific gravity of RAP materials was obtained using a CoreLok device. Two results were obtained and an average value of 2.408 was used in the backcalculation. The CSS-1h asphalt emulsions used in this stage were provided by manufacturer B that has a 68.14% asphalt residual with the penetration of 64. The specific gravity of asphalt emulsion binder is 1.02044. According to these known values, the theoretical maximum specific gravity of specimens with every water and emulsion content combination was obtained and shown in Figure 46 and Table 9.

Figure 46 Backcalculated \(G_{\text{mm}}\) of specimens with all water and emulsion content combinations in mixture design phase
Table 9 Backcalculated $G_{mm}$ of Specimens with All Water and Emulsion Content Combinations in Mixture Design Phase

<table>
<thead>
<tr>
<th>Water Content %</th>
<th>Emulsion Content %</th>
<th>Backcalculated $G_{mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.0</td>
<td>2.457</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>2.437</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>2.428</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>2.519</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.465</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>3.0</td>
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<tr>
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<td>2.354</td>
</tr>
<tr>
<td>4.0</td>
<td>0.0</td>
<td>2.502</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.468</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.460</td>
</tr>
</tbody>
</table>

Contrary to wet and dry $G_{mb}$ values, backcalculated $G_{mm}$ values of all water contents decrease with an increase in asphalt emulsion contents. Similar to $G_{mb}$, $G_{mm}$ values between different water contents do not show significant difference.

4.1.2 Air Void Distribution

Using dry $G_{mb}$ and $G_{mm}$ results listed in Table 8 and Table 9, the volume of air voids of all specimens were calculated using the following equation.

$$V_a = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}}$$

Where

$V_a =$ Air voids in compacted mixture, percent of total volume

$G_{mm} =$ Maximum specific gravity of paving mixture, and

$G_{mb} =$ Bulk specific gravity of compacted mixture
Based on dry $G_{mb}$ and backcalculated $G_{nm}$ results and the volume of air voids calculation equation, a decrease of air voids with the increase of emulsion contents for specimens with certain water contents is expected, as shown in Figure 47 and Table 10. It is understandable to see this result since more moisture provides more lubrication for compaction, which leads to the lower air void. Specimens with 4% water have relatively high air voids levels, this may be due to the reason that too much fluid content in the mixture will form an extra layer, which increases the difficulties of compaction. Thus increase the air void level.

![Air void of all specimens in mixture design phase (Error bars are shown as the average value plus and minus one standard deviation)](image)

Figure 47 Air void of all specimens in mixture design phase (Error bars are shown as the average value plus and minus one standard deviation)
Table 10 The Air Void Distribution of All Specimens in Mixture Design Phase

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Emulsion Content (%)</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.0</td>
<td>14.059</td>
<td>0.349</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>12.303</td>
<td>0.120</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>11.381</td>
<td>0.111</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>18.357</td>
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<td>1.5</td>
<td>15.203</td>
<td>0.120</td>
</tr>
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<td></td>
<td>2.0</td>
<td>14.016</td>
<td>0.266</td>
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<td></td>
<td>3.0</td>
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<td>3.5</td>
<td>11.613</td>
<td>0.311</td>
</tr>
<tr>
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<td>1.5</td>
<td>12.651</td>
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<td>11.798</td>
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<td></td>
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<td>10.232</td>
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<tr>
<td></td>
<td>3.5</td>
<td>9.161</td>
<td>0.212</td>
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<td>4.0</td>
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<td>1.5</td>
<td>15.186</td>
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</tr>
<tr>
<td></td>
<td>2.0</td>
<td>13.422</td>
<td>0.975</td>
</tr>
</tbody>
</table>

Regression analysis was conducted to find out the relationship between air voids to water contents, emulsion contents, and water/emulsion content interaction.

The regression analysis results (Figure 48) obtained from Minitab software package gives a regression equation with a very high R-squared value (85.89%). From the residual plots of the analysis in Figure 49 it is easy to draw the conclusion that the regression analysis results are reliable: the normal probability plot is linear and close to central line; versus fits plot shows a random distribution; histogram plot shows a normal distribution.

The factor emulsion content and water/emulsion content interaction give a low P-value (less than 0.05), which means they are relevant in regression equation at 95% confidence level. Although the water content factor had a relatively high P-value (0.725), it is due to the influence of water/emulsion content interaction. To verify this explanation, another regression analysis was conducted. This time no water/emulsion interaction was considered. From the results shown in Figures 50 and 51, both water content and asphalt emulsion content are relevant to the regression equation, and the analysis results are reliable.
Regression Analysis: Air Void % versus Water Content %, Emulsion Content %

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>3</td>
<td>242.858</td>
<td>80.9525</td>
<td>83.17</td>
<td>0.000</td>
</tr>
<tr>
<td>Water Content %</td>
<td>1</td>
<td>0.122</td>
<td>0.1223</td>
<td>0.13</td>
<td>0.725</td>
</tr>
<tr>
<td>Emulsion Content %</td>
<td>1</td>
<td>13.106</td>
<td>13.1062</td>
<td>13.47</td>
<td>0.001</td>
</tr>
<tr>
<td>Water Content %*Emulsion Content %</td>
<td>1</td>
<td>5.391</td>
<td>5.3910</td>
<td>5.54</td>
<td>0.023</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>39.906</td>
<td>0.9733</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack-of-Fit</td>
<td>11</td>
<td>31.675</td>
<td>2.8796</td>
<td>10.50</td>
<td>0.000</td>
</tr>
<tr>
<td>Pure Error</td>
<td>30</td>
<td>8.231</td>
<td>0.2744</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>44</td>
<td>282.764</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model Summary

\[
S = R-sq R-sq(adj) R-sq(pred)
0.986570 85.89% 84.85% 83.48%
\]

Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T-Value</th>
<th>P-Value</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>17.615</td>
<td>0.976</td>
<td>18.04</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Water Content %</td>
<td>0.114</td>
<td>0.322</td>
<td>0.35</td>
<td>0.725</td>
<td>5.03</td>
</tr>
<tr>
<td>Emulsion Content %</td>
<td>-1.395</td>
<td>0.390</td>
<td>-3.67</td>
<td>0.001</td>
<td>8.13</td>
</tr>
<tr>
<td>Water Content %*Emulsion Content %</td>
<td>-0.327</td>
<td>0.139</td>
<td>-2.35</td>
<td>0.023</td>
<td>7.88</td>
</tr>
</tbody>
</table>

Regression Equation

\[
\text{Air Void %} = 17.615 + 0.114 \text{ Water Content %} - 1.395 \text{ Emulsion Content %} - 0.327 \text{ Water Content %*Emulsion Content %}
\]

Figure 48 Regression analysis results of relationship between air voids and water content, emulsion content, and water/emulsion interaction

Figure 49 Residual plots of regression analysis on relationship between air voids and water content, emulsion content, and water/emulsion content interaction
Regression Analysis: Air Void % versus Water Content %, Emulsion Content %

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>2</td>
<td>237.467</td>
<td>118.733</td>
<td>110.09</td>
<td>0.000</td>
</tr>
<tr>
<td>Water Content %</td>
<td>1</td>
<td>12.226</td>
<td>12.226</td>
<td>11.34</td>
<td>0.002</td>
</tr>
<tr>
<td>Emulsion Content %</td>
<td>1</td>
<td>231.386</td>
<td>231.386</td>
<td>214.54</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>42</td>
<td>45.297</td>
<td>1.079</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack-of-Fit</td>
<td>12</td>
<td>37.066</td>
<td>3.089</td>
<td>11.26</td>
<td>0.000</td>
</tr>
<tr>
<td>Pure Error</td>
<td>30</td>
<td>8.231</td>
<td>0.274</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>44</td>
<td>282.764</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model Summary

<table>
<thead>
<tr>
<th>S</th>
<th>R-sq</th>
<th>R-sq(adj)</th>
<th>R-sq(pred)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.03851</td>
<td>83.98%</td>
<td>83.22%</td>
<td>81.80%</td>
</tr>
</tbody>
</table>

Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T-Value</th>
<th>P-Value</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>19.439</td>
<td>0.625</td>
<td>31.11</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Water Content %</td>
<td>-0.550</td>
<td>0.163</td>
<td>-3.37</td>
<td>0.002</td>
<td>1.17</td>
</tr>
<tr>
<td>Emulsion Content %</td>
<td>-2.223</td>
<td>0.152</td>
<td>-14.65</td>
<td>0.000</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Regression Equation

Air Void % = 19.439 - 0.550 Water Content % - 2.223 Emulsion Content %

Figure 50 Regression analysis of relationship between air voids and water and emulsion content

![Residual Plots for Air Void %](image1)

Figure 51 Residual plots of regression analysis of relationship between air voids and water and emulsion content
4.1.3 IDT Strength Results

For each specimen tested with IDT, a graph of stress versus strain (Figure 51) was developed, showing the change in stress and strain during the test. The stress shown in these graphs presents the maximum tensile stress of the tested specimen, which occurs at the center of the specimen in the horizontal direction. The strain shown in these graphs presents the ratio of the vertical deformation of the specimen during the test over the diameter.

![IDT Strength Results of A Specimen with 2.0% water, 2.0% emulsion, and 50 gyrations](image)

Figure 52 Sample graph of stress vs. strain (specimen with 2% water and 2% emulsion)

It must be noted that the vertical deformation also includes any deformation of the loading head so it is not completely deformation of the specimen alone. However, it is expected that any deformation from the machine compliance is minimal.

The peak stress (i.e. stress at failure) is referred to as the tensile strength. It can be observed that the strength of the specimen with 2 percent water and 2 percent emulsion (as shown in Figure 52) was approximately 58 psi, corresponding to a strain level of 1.8 percent (i.e. strain at failure). Figures 53 and 54, and Table 11 provide the summary of average strength results of all specimens with various water and emulsion contents.
Figure 53 Average IDT strength of all specimens with various water contents

Figure 54 Average IDT strength of all specimens with various emulsion contents and air void distribution of all specimens in mixture design phase (Error bars are shown as the average value plus and minus one standard deviation)
Table 11 The Average Strength of All Specimens in Mixture Design Phase

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Emulsion Content (%)</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.0</td>
<td>51.270</td>
<td>5.270</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>49.650</td>
<td>3.080</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>44.890</td>
<td>3.800</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>54.130</td>
<td>3.340</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>55.680</td>
<td>5.190</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>55.320</td>
<td>3.270</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>45.275</td>
<td>1.148</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>39.059</td>
<td>0.381</td>
</tr>
<tr>
<td>3.0</td>
<td>1.5</td>
<td>52.020</td>
<td>3.470</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>51.170</td>
<td>3.510</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>38.360</td>
<td>1.800</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>36.770</td>
<td>2.700</td>
</tr>
<tr>
<td>4.0</td>
<td>0.0</td>
<td>50.288</td>
<td>0.826</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>49.210</td>
<td>3.270</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>40.770</td>
<td>1.800</td>
</tr>
</tbody>
</table>

From Figure 54, it is clear that in general, 2 percent water content and 1.5 percent emulsion content provide the highest strength. Overall, the 2 percent water content group provides the highest strength. For the same water content, the highest strength comes from specimens with 1.5 percent and 2 percent emulsion content. Water content of 1 percent yields the second highest tensile strength, while 4 percent water content delivers the lowest strength. Once emulsion content reaches 3 percent, a noticeable drop in strength is observed. This drop in strength continues as the emulsion content increased beyond 3 percent, as more than adequate emulsions cause the instability of specimens, thus drops the IDT strength. The development trend of the IDT strength is similar to that of air voids.

A regression analysis was also conducted to verify the relationship between water content, emulsion content, water/emulsion content interaction and IDT strength. As shown in Figure 55, despite the high P-value obtained in water/emulsion content interaction (same explanation as presented in air void distribution analysis), regression equation still gives a high R-squared value (60.17%) at 95% confidence level. Residual plots shown in Figure 56 suggested that the analysis results are reliable.
Regression Analysis: IDT Strength (psi) versus Water Content %, Emulsion Content %

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>3</td>
<td>1197.26</td>
<td>399.086</td>
<td>20.64</td>
<td>0.000</td>
</tr>
<tr>
<td>Water Content %</td>
<td>1</td>
<td>91.18</td>
<td>91.178</td>
<td>4.72</td>
<td>0.036</td>
</tr>
<tr>
<td>Emulsion Content %</td>
<td>1</td>
<td>148.35</td>
<td>148.365</td>
<td>7.67</td>
<td>0.008</td>
</tr>
<tr>
<td>Water Content %*Emulsion Content %</td>
<td>1</td>
<td>0.31</td>
<td>0.306</td>
<td>0.02</td>
<td>0.900</td>
</tr>
<tr>
<td>Error</td>
<td>41</td>
<td>792.67</td>
<td>19.333</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack-of-Fit</td>
<td>11</td>
<td>489.76</td>
<td>44.523</td>
<td>4.41</td>
<td>0.001</td>
</tr>
<tr>
<td>Pure Error</td>
<td>30</td>
<td>302.91</td>
<td>10.097</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>44</td>
<td>1989.93</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model Summary

\[
S \quad R\text{-sq} \quad R\text{-sq(adj)} \quad R\text{-sq(pred)} \quad 4.39699 \quad 60.17\% \quad 57.25\% \quad 51.85\%
\]

Coefficients

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T-Value</th>
<th>P-Value</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>65.67</td>
<td>4.35</td>
<td>15.09</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Water Content %</td>
<td>-3.12</td>
<td>1.64</td>
<td>-2.17</td>
<td>0.036</td>
<td>5.03</td>
</tr>
<tr>
<td>Emulsion Content %</td>
<td>-4.69</td>
<td>1.69</td>
<td>-2.77</td>
<td>0.008</td>
<td>8.13</td>
</tr>
<tr>
<td>Water Content %*Emulsion Content %</td>
<td>-0.078</td>
<td>0.620</td>
<td>-0.13</td>
<td>0.900</td>
<td>7.88</td>
</tr>
</tbody>
</table>

Regression Equation

\[
\text{IDT Strength (psi)} = 65.67 - 3.12 \text{ Water Content %} - 4.69 \text{ Emulsion Content %} - 0.078 \text{ Water Content %*Emulsion Content %}
\]

Figure 55 Regression analysis of relationship between IDT strength to water content, emulsion content, and water/emulsion interaction

![Residual Plots for IDT Strength (psi)](image)

Figure 56 Residual plots of regression analysis results of relationship between IDT strength to water content, emulsion content, and water/emulsion interaction
Although it is desirable to have a minimum tensile strength of 45 psi for CR mixtures, the mixtures with the highest tensile strength do not necessarily provide the best performing mixture. This is because the mixture may be strong in the beginning, but durability is sacrificed if there is not sufficient binder to maintain integrity of the mixture once it is exposed to extended traffic and environmental loading. It is preferred to design the mixture at a higher emulsion content but lower tensile strength, as long as the minimum strength is satisfied. For example, for the CR specimens tested in this research, using the mixture at 2.5 to 3 percent emulsion is preferred to the mixture at 2 percent emulsion, even though the 2.5 to 3 percent emulsion delivers lower strength but satisfies the minimum required strength of 45 psi. Further testing to assess the CR mixture performance in terms of durability, moisture damage, and rutting resistance will complement this CR mixture design process for optimization of the emulsion content.

4.1.4 IDT Strength with Various Polymer Modified Asphalt Emulsions

Polymer modified asphalt emulsions were prepared and used with RAP materials in three ways: hand blending of latex in the lab, high shear blending of latex in the lab, and polymer modified emulsion received directly from the manufacture. The strength results for all specimens (with and without polymer) are presented in Table 12. There are several important observations based on these results. First, it can be noticed that the mixtures with 1.5 percent hand blended latex did not yield strength different from the no polymer mixtures (average of 55.3 psi for mixtures with no polymer emulsion versus average of 53.4 psi for mixtures with latex emulsion). Second, it appears that increasing the latex contents to 2.25 percent and 3 percent decreased the strength to some extent. Third, it can be observed that shear blending of latex into the emulsion provided a higher strength compared to hand blending (57 psi versus 48 psi at 2.25 percent latex). This is probably due to higher efficiency in dispersing the latex within the emulsion. Finally, it can be seen that mixtures with the manufactured polymer modified emulsion delivered the same strength as the mixtures with no polymer (average of 45.2 for no polymer mixtures versus 45.4 psi for the mixtures with polymer).
Table 12 IDT Strength of Specimens with Various Combinations of Asphalt Emulsions and Polymer

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Emulsion Manufacturer</th>
<th>Polymer and Source</th>
<th>IDT Strength (psi)</th>
<th>Strain at Failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B</td>
<td>No Polymer</td>
<td>55.7</td>
<td>1.788</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>Hand Mix with 1.5% Latex</td>
<td>54.4</td>
<td>1.555</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>Hand Mix with 2.25% Latex</td>
<td>49.4</td>
<td>1.366</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>Hand Mix with 3% Latex</td>
<td>56.5</td>
<td>1.411</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>Shear Blending with 2.25% Latex</td>
<td>48.0</td>
<td>1.200</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>Shear Blending with 2.25% Latex</td>
<td>49.1</td>
<td>1.777</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>No Polymer</td>
<td>57.2</td>
<td>1.355</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>No Polymer</td>
<td>41.7</td>
<td>1.090</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>Manufactured with Polymer</td>
<td>45.8</td>
<td>1.532</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>Manufactured with Polymer</td>
<td>48.2</td>
<td>1.232</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>Manufactured with Polymer</td>
<td>46.3</td>
<td>1.376</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>Manufactured with Polymer</td>
<td>42.9</td>
<td>1.665</td>
</tr>
</tbody>
</table>

4.2 Durability Study

To investigate the durability of lab-produced CR mixtures, the Raveling test was conducted. Results from the Raveling test are presented in Table 13. The tests were conducted on CR mixtures with no emulsion and CR mixtures with 2 percent water content and 2 percent emulsion content. No polymer was used in the Raveling test.

It is obvious that the mass loss due to abrasion is significantly reduced once emulsion is added to the mixture. It is recommended that if the percent mass loss is larger than 2 percent, the specimen would be considered as failure. For all specimens tested, the results (Table 13) were all less than 1 percent and no failure occurred. Since the level of mass loss at 2 percent emulsion content without polymer is significantly low, it is expected that the loss will be extremely small at higher emulsion contents and inclusion of polymer, therefore no further testing was conducted.
Table 13 The Raveling Test Results

<table>
<thead>
<tr>
<th>Water Content, %</th>
<th>Emulsion Content, %</th>
<th>Specimen Mass Prior to Test, g</th>
<th>Specimen Mass Abraded, g</th>
<th>% Mass Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>2407.5</td>
<td>2405.2</td>
<td>0.10</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>2368.5</td>
<td>2366.1</td>
<td>0.10</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>2399.9</td>
<td>2396.7</td>
<td>0.13</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>2366.8</td>
<td>2349.1</td>
<td>0.75</td>
</tr>
<tr>
<td>2.0</td>
<td>0.0</td>
<td>2372</td>
<td>2357.8</td>
<td>0.60</td>
</tr>
</tbody>
</table>

4.3 Moisture Damage Resistance Study

4.3.1 Air Void of Specimens in Moisture Damage Resistance Study
An important factor when preparing specimens for moisture damage resistance study is to make sure for every tested specimen, target air void for a specified height of specimen can be reached when compacting in the Superpave Gyratory Compactor (SGC). This requirement on height and air voids is further complicated when attempts are made to keep the average density of specimens for one emulsion content closely matching that of specimens with a different emulsion content. This closeness in air voids is important to ensure a meaningful assessment of test results for the effect of emulsion content and category on the moisture damage resistance of the CR mixtures.

To achieve the target of reaching similar air voids, two factors could be adjusted: one is the mass of materials used to prepare the specimens and the other is the number of gyrations. Therefore, trial study was undertaken to determine which approach provides desired specimens for the moisture damage study of RAP mixtures.

In the first test round, designed gradation was used for all twelve specimens (both 2 percent emulsion and 3 percent emulsion content) to prepare batches weighing 2330 grams per specimen. Due to emulsion content differences, the compacted specimens with 3 percent emulsion weighed approximately 20 g more than the compacted specimens with 2 percent emulsion. Difference compaction level was used to adjust the air voids of the tested specimen. Specimens with 2 percent emulsion content were compacted at 50 gyrations while specimens with 3 percent emulsion content were compacted at 47 gyrations. Even at lower number of gyrations, 3 percent emulsion specimens delivered significantly lower air voids.
Further reduction in batch weight was applied to the mass of specimens with 3 percent emulsions to increase air voids. Two more trial specimens with the batching weight of 2310 grams were produced, and 47 gyrations were applied during compaction. Even this action did not help to bring the air void of specimens with 3 percent emulsion content close to those for specimens with 2 percent emulsion content. Values of $G_{mm}$ and $G_{mb}$ measure with a CoreLok device were used to obtain the air voids.

Comparing the moisture damage resistance of 2 percent emulsion specimens with that of 3 percent emulsion specimens was complicated because of the difference observed in air void levels (average air voids of 10.7 percent for the former versus average air void of 8.5 percent for the later). However, curing and testing specimens continued in spite of this air voids difference. The study was then extended by producing more specimens with 2 percent emulsion, with an attempt to lower the air voids by increasing the compaction level and bringing the air void level closer to that of specimens with 3 percent emulsion. This last attempt was successful as the produced specimens with 2 percent emulsion delivered air voids in the range of 8.5 percent, as presented in Table 14 and Figure 56.

Table 14 Air Voids of All Specimens Produced for Moisture Damage Resistance Study

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% Emulsion, no polymer, no cement</td>
<td>10.67</td>
<td>0.51</td>
</tr>
<tr>
<td>3% Emulsion, no polymer, no cement</td>
<td>9.58</td>
<td>0.19</td>
</tr>
<tr>
<td>3% Emulsion with polymer, no cement</td>
<td>8.00</td>
<td>0.29</td>
</tr>
<tr>
<td>3% Emulsion with cement, no polymer</td>
<td>10.00</td>
<td>0.25</td>
</tr>
<tr>
<td>3% Emulsion with cement and polymer</td>
<td>11.23</td>
<td>0.19</td>
</tr>
<tr>
<td>2% Emulsion, no polymer, no cement, high compaction level</td>
<td>8.67</td>
<td>0.23</td>
</tr>
</tbody>
</table>
As seen in Table 14 and Figure 57, in spite of reducing gyrations levels and the specimen batch mass, the air voids of 3 percent emulsion specimens were lower than that of 2 percent emulsion specimens. This is probably an indication that emulsion content has a larger impact on the specimen’s air voids compared to the slight changes made in the gyration level or the mass adjustment. Based on the results obtained, the mass was established to remain the same as used in the mixture design stage (2330 g) and the number of gyrations was kept at 50 to prepare the next round of specimens for 3 percent polymer emulsion, as presented in the bottom section of Table 14. An average air void of 8 percent was delivered for this last set of specimens.

A similar approach was followed to determine the air voids of specimens containing cement. As indicated by Table 14 and Figure 57, the air voids for cement modified specimens were approximately between 10 and 11 percent. Specimens without cement delivered air voids ranges from 8 percent to around 11 percent.

Based on the air voids data, specimens with the same emulsion type and content were then grouped into dry and wet subsets, with 3 specimens in each subset, as shown in Table 15 and Figure 17. The principle of grouping was to make sure the average air voids of dry subset and the average air voids of wet subset were close, so conclusions
can be drawn that the difference of test results are purely due to conditioning process, not the test specimen itself.

Table 15 Dry and Wet Subsets of All Moisture Damage Specimens

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dry/Wet</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% Emulsion, no polymer, no cement</td>
<td>Dry</td>
<td>10.79</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>10.83</td>
<td>0.33</td>
</tr>
<tr>
<td>3% Emulsion, no polymer, no cement</td>
<td>Dry</td>
<td>9.60</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>9.59</td>
<td>0.14</td>
</tr>
<tr>
<td>3% Emulsion with polymer, no cement</td>
<td>Dry</td>
<td>8.01</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>8.00</td>
<td>0.01</td>
</tr>
<tr>
<td>3% Emulsion with cement, no polymer</td>
<td>Dry</td>
<td>10.01</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>9.94</td>
<td>0.15</td>
</tr>
<tr>
<td>3% Emulsion with cement and polymer</td>
<td>Dry</td>
<td>11.24</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>11.20</td>
<td>0.17</td>
</tr>
<tr>
<td>2% Emulsion, no polymer, no cement</td>
<td>Dry</td>
<td>8.62</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>8.69</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Figure 58 Air voids of dry and wet subset specimens (Error bars are shown as the average value plus and minus one standard deviation)

In order to prove that there is no difference between each dry and wet subset, two-sample t-test was conducted to verify the grouping results. The null hypotheses (H₀) of the two-sample t-test is that the air void results of dry and wet subset are equal, while
the alternative hypotheses ($H_a$) is that the air void results are not equal. Two-sample $t$-test results are summarized and shown in Table 16. Detailed Minitab analysis results outputs are provided in Appendix A.

Table 16 Two-Sample T-Test Results of All Grouping Subsets

<table>
<thead>
<tr>
<th>Materials</th>
<th>P-Value</th>
<th>95% Confidence Interval for Difference [Difference = $\mu$ (Dry) - $\mu$ (Wet)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% Emulsion, no polymer, no cement</td>
<td>0.933</td>
<td>(-1.534, 1.449)</td>
</tr>
<tr>
<td>3% Emulsion, no polymer, no cement</td>
<td>0.979</td>
<td>(-0.553, 0.563)</td>
</tr>
<tr>
<td>3% Emulsion with polymer, no cement</td>
<td>0.992</td>
<td>(-1.087, 1.092)</td>
</tr>
<tr>
<td>3% Emulsion with cement, no polymer</td>
<td>0.794</td>
<td>(-0.660, 0.790)</td>
</tr>
<tr>
<td>3% Emulsion with cement and polymer</td>
<td>0.863</td>
<td>(-0.712, 0.780)</td>
</tr>
<tr>
<td>2% Emulsion, no polymer, no cement, high compaction level</td>
<td>0.766</td>
<td>(-0.921, 0.786)</td>
</tr>
</tbody>
</table>

All P-values are significantly larger than 0.05, all the alternative hypotheses are rejected. It can be stated that dry and wet subsets of each material category are equal at the 95% confidence level.

4.3.2 Degree of Saturation of Specimens in Wet Subset

It was discussed previously that specimens of the wet group were exposed to vacuum saturation for 30 minutes before processing for the freeze-thaw cycle. Table 17 and Figure 59 show the degree of saturation achieved by various specimens through this process.
### Table 17 Degree of Saturation of All Wet Subset Specimens

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% Emulsion, no polymer, no cement</td>
<td>55.63</td>
<td>2.34</td>
</tr>
<tr>
<td>3% Emulsion, no polymer, no cement</td>
<td>56.37</td>
<td>0.58</td>
</tr>
<tr>
<td>3% Emulsion with polymer, no cement</td>
<td>50.97</td>
<td>0.64</td>
</tr>
<tr>
<td>3% Emulsion with cement, no polymer</td>
<td>41.37</td>
<td>6.65</td>
</tr>
<tr>
<td>3% Emulsion with cement and polymer</td>
<td>36.73</td>
<td>1.42</td>
</tr>
<tr>
<td>2% Emulsion, no polymer, no cement, high compaction level</td>
<td>61.03</td>
<td>11.81</td>
</tr>
</tbody>
</table>

The saturation level varies within a wide range from 34 to 68 percent. The lowest value was obtained for specimens modified with cement, while the highest value was achieved by the second set of 2 percent emulsion group. No correlation between air voids and degree of saturation is observed during this test.

#### 4.3.3 IDT Strength of All Specimens in Moisture Damage Resistance Study and Tensile Strength Ratio (TSR)

All specimens prepared for moisture damage study, except those that were damaged during conditioning process, were tested for indirect tensile strength (IDT). The ratio of average strength of conditioned specimens (wet) to that of unconditioned (dry) specimens in each category was used to establish the tensile strength ratio (TSR).
Tensile strength was calculated using the following equation.

\[ S_t = \frac{2000 \times P}{\pi \times t \times D} \]

Where

\( S_t \) = IDT strength, kPa

\( P \) = Maximum load, N

\( t \) = Specimen height immediately before test, mm, and

\( D \) = Specimen diameter, mm

A typical stress-strain graph from indirect tensile strength testing of specimens prepared for moisture damage study is presented in Figure 60 (Left). This figure shows the results for a dry specimen, i.e. one that has not been exposed to moisture damage conditioning. Figure 60 (Right) presents the result for a conditioned specimen, and it can be clearly seen that the strength has drastically decreased due to the effect of water damage. Examples for stress-strain graph for cement treated emulsion mixtures are presented in Figure 61 for dry and conditioned mixtures.
Figure 61 Stress-strain curve of a dry specimen (Left) and a wet specimen (Right), with cement.

The strain level at peak stress for these specimens without cement is within the range of the strain for specimens with cement. In fact, a general review of the strain levels at peak stress, shown in Table 18 and Figure 62, indicates that cement treated specimens do not exhibit a more brittle behavior compared with the mixtures without cement. This is perhaps because the dosage of cement for these mixtures is limited to one percent. It appears that this limited addition of cement expedites curing, increases strength, and increases TSR without sacrificing other mixture properties.

Table 18 Strains at Failure Strength of All Specimens in Moisture Damage Resistance Study

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dry/Wet</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% Emulsion, no polymer, no cement</td>
<td>Dry</td>
<td>1.30</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3% Emulsion, no polymer, no cement</td>
<td>Dry</td>
<td>1.37</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.40</td>
<td>0.00</td>
</tr>
<tr>
<td>3% Emulsion with polymer, no cement</td>
<td>Dry</td>
<td>1.37</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>2.00</td>
<td>0.17</td>
</tr>
<tr>
<td>3% Emulsion with cement, no polymer</td>
<td>Dry</td>
<td>1.83</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>2.27</td>
<td>0.29</td>
</tr>
<tr>
<td>3% Emulsion with cement and polymer</td>
<td>Dry</td>
<td>1.57</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.67</td>
<td>0.31</td>
</tr>
<tr>
<td>2% Emulsion, no polymer, no cement, high compaction level</td>
<td>Dry</td>
<td>1.83</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.87</td>
<td>0.06</td>
</tr>
</tbody>
</table>
The tensile strength ratio (TSR) was calculated as follows:

$$TSR = \left( \frac{S_{tm}}{S_{td}} \right) \times 100\%$$

Where

TSR = Tensile strength ratio

$S_{tm} =$ Average tensile strength of the wet subset specimen, psi, and

$S_{td} =$ Average tensile strength of the dry subset specimen, psi

For Hot Mix Asphalt (HMA) materials, the threshold of TSR to define a qualified material is 80 percent. Although a drop of TSR ratio in CR mixture is expected, failure strength of the two subsets should also be compared, since TSR is a ratio between two subsets, adequate strength is more significant in application.

Table 19 and Figures 63 and 64 present all test results from IDT for both dry and wet subsets, along with group average TSR.
Table 19 The IDT Strength of All Specimens

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dry/Wet</th>
<th>Mean</th>
<th>St. Dev.</th>
<th>Average TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Emulsion, no polymer, no cement</td>
<td>Dry</td>
<td>52.16</td>
<td>2.26</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>19.13</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>3% Emulsion with polymer, no cement</td>
<td>Dry</td>
<td>46.47</td>
<td>3.02</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>17.57</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>3% Emulsion with cement, no polymer</td>
<td>Dry</td>
<td>60.96</td>
<td>2.86</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>51.65</td>
<td>2.27</td>
<td></td>
</tr>
<tr>
<td>3% Emulsion with cement and polymer</td>
<td>Dry</td>
<td>58.99</td>
<td>3.77</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>49.98</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>2% Emulsion, no polymer, no cement</td>
<td>Dry</td>
<td>49.13</td>
<td>4.29</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>29.54</td>
<td>2.76</td>
<td></td>
</tr>
</tbody>
</table>

Figure 63 IDT strength and TSR of all specimens (by material) (Error bars are shown as the average value plus and minus one standard deviation)
In general, it was found that specimens with 2 and 3 percent emulsion content, regardless of presence of polymer, did not retain adequate tensile strength levels after moisture conditioning, as shown in Table 19 and Figures 63 to 64. The highest TSR for specimens without addition of cement belonged to 2 percent emulsion specimens with an average air void of 8.5 percent. It should be noted that reduction in strength after conditioning is significant for all specimens, hence resulting in low tensile strength ratio (TSR). Results also indicate that addition of one percent cement delivers a significant increase in dry strength, wet strength, and TSR, in spite the fact that specimens with cement have higher air void level, which should give lower TSR from previous experience.

From both strength and TSR plots, the effect of polymer was not observed. Statistical analysis has been employed to find out if there is any property improvement when polymer is introduced.

A two-sample t-test is used to see if there is any difference between strength of the first group (3 percent emulsion with or without polymer, both no cement) and the second group (3 percent emulsion with or without polymer, both with cement), therefore to test
the effect of polymer in improving CR mixtures’ capability in resisting moisture damage.

The null Hypotheses ($H_0$) in this two-sample t-test is that strength results are equal, while the alternative hypotheses ($H_a$) is that strength results are different. Analysis results are summarized in Table 20. Detailed Minitab analysis outputs are provided in Appendix A.

Table 20 Two-Sample T-Test Results of IDT Strength of All Specimens with 3% Emulsion

<table>
<thead>
<tr>
<th>Materials</th>
<th>P-Value</th>
<th>95% Confidence Interval for Difference [Difference = $\mu$ (Dry) – $\mu$ (Wet)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% emulsion, no cement, dry subset</td>
<td>0.080</td>
<td>(-12.62, 1.25)</td>
</tr>
<tr>
<td>3% emulsion, no cement, wet subset</td>
<td>0.037</td>
<td>(-2.8813, -0.236)</td>
</tr>
<tr>
<td>3% emulsion with cement, dry subset</td>
<td>0.522</td>
<td>(-6.72, 10.66)</td>
</tr>
<tr>
<td>3% emulsion with cement, wet subset</td>
<td>0.363</td>
<td>(-4.47, 7.81)</td>
</tr>
</tbody>
</table>

For specimens with cement, IDT strength results of both dry and wet subset turned out with a high P-value (larger than 0.05), the alternative hypotheses are rejected. Clearly, from a statistical perspective, when cement is introduced in the mixture, polymer in asphalt emulsion will not improve moisture damage resistance for CR mixtures in this study. As for specimens without cement, IDT strength of wet subset specimens gives a low P-value (lower than 0.05), which rejected the null hypotheses that IDT strength of specimens with or without polymer are equal. While IDT strength of dry subset specimens turned out a P-value higher than 0.05, 0.08 is not convincing. But the conclusion can still be drawn that when cement is not employed in CR mixtures, polymer modified asphalt emulsion can improve the moisture damage resistance for conditioned specimens.
The above conclusions are simply based on statistical analysis results. Effect of air voids must also be considered. For the same materials, higher air voids will most certainly decrease moisture damage resistance of asphalt mixture. There is still a chance that polymer modified asphalt emulsion can play a positive role in improving moisture damage resistance of CR mixtures.

For each material category, 9 TSR ratios can be obtained using 3 dry strength results and 3 wet strength results. These TSR values can be seen as independent, as they are obtained from a set of dry and wet IDT strength value. The TSR results obtained from 3×3 matrix are shown in Table 21 and Figure 65.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Emulsion, no polymer, no cement</td>
<td>0.37</td>
<td>0.01</td>
</tr>
<tr>
<td>3% Emulsion with polymer, no cement</td>
<td>0.38</td>
<td>0.02</td>
</tr>
<tr>
<td>3% Emulsion with cement, no polymer</td>
<td>0.85</td>
<td>0.05</td>
</tr>
<tr>
<td>3% Emulsion with cement and polymer</td>
<td>0.85</td>
<td>0.05</td>
</tr>
<tr>
<td>2% Emulsion, no polymer, no cement, high compaction level</td>
<td>0.60</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Figure 65 TSR of all specimens in moisture damage resistance study (Error bars are shown as the average value plus and minus one standard deviation)
To find out the effect of polymer in improving the moisture damage resistance of CR mixtures, a two-sample t-test was conducted on TSR of two groups of specimens: the first group contains specimens with and without polymer, all without cement; the second group contains specimens with and without polymer, all with cement. Detailed Minitab outputs are shown in Appendix A. Boxplots are shown below.

Figure 66 Boxplots of TSR of specimens with and without polymer (no cement)
The P-value of specimens with and without cement is 0.235 and 0.960, respectively. From a statistical perspective, there is no difference between the two TSR values at 95% confidence level, but specimens with polymer provide similar strength and TSR values given its relatively higher air void level. There is a possibility that polymer can improve the moisture damage resistance capability of CR mixtures. The statistical analysis results based on strength and TSR values are consistent.

4.4 Rutting Resistance Study

4.4.1 Air Void of Specimens in Rutting Resistance Study

Preparation of specimens for this task produces a similar challenge with preparing specimens for moisture damage resistance study. The goal was to produce specimens with air voids within a specified range (10±2%), a specified height (50 mm), and a similar compaction level (50±3 gyrations). Satisfying all three criteria at the same time is not an easy task with different binding material and addition of cement. Table 22 and
Figure 68 present the distribution of air voids for different mixtures. However, inclusion of cement produced specimens with air voids higher than the target range, indicating the higher energy of compaction needed for such mixtures. These specimens were used for evaluating the rutting resistance in spite of air void variation.

Table 22: Air Voids Distribution of All Specimens in Rutting Resistance Study

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion, no polymer, no cement</td>
<td>12.16</td>
<td>0.33</td>
</tr>
<tr>
<td>Emulsion with polymer, no cement</td>
<td>10.77</td>
<td>0.14</td>
</tr>
<tr>
<td>Emulsion with cement, no polymer</td>
<td>13.84</td>
<td>0.11</td>
</tr>
<tr>
<td>Emulsion with cement and polymer</td>
<td>14.91</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Figure 68 Air void distribution of all specimens in rutting resistance study (Error bars are shown as the average value plus and minus one standard deviation)

4.4.2 Permanent Deformation Results

Graphical presentation of permanent deformation results from the repeated shear test is shown in Figures 69 through 72, each figure shows test results of one material category with three replicates, the average values are presented in Figure 73.
Figure 69 Permanent deformation vs. number of cycles of specimens with no polymer, no cement (3 replicates)

Figure 70 Permanent deformation vs. number of cycles of specimens with polymer, no cement (3 replicates)
Figure 71 Permanent deformation vs. number of cycles of specimens with cement, no polymer (3 replicates)

Figure 72 Permanent deformation vs. number of cycles of specimens with cement and polymer (3 replicates)
The results indicate that the poorest performance belongs to the mixtures with regular emulsion, for which deformation exceeded 0.2 inches (5 mm) after 1200 to 1400 pulses of load. Better performance is observed for the polymer emulsion mixtures, for which it took 2600 and 4000 cycles for two of the specimens to exceed 0.2 inches of deformation, and one of the specimens lasted for the 5000 cycles delivering 0.1 inches (2.5 mm) of deformation. Apparently, without the influence of cement, polymer plays a significant role in improving rutting resistance of CR mixture.

Table 23 and Figure 74 show the permanent deformation results of all specimens at certain cycle number. Another level of significant performance improvement is observed for specimens with 1 percent cement, where all specimens stood the applied 5000 cycles before reaching 5 mm permanent deformation. However, there is no clear difference between specimens with or without polymer when cement was introduced. Statistical analysis is employed to find out if there is a difference between these two material categories.
<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>Materials</th>
<th>Mean</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3% Emulsion, no polymer, no cement</td>
<td>-0.264</td>
<td>0.069</td>
</tr>
<tr>
<td>10 Cycles</td>
<td>3% Emulsion with polymer, no cement</td>
<td>-0.186</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with cement, no polymer</td>
<td>-0.116</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with polymer and cement</td>
<td>-0.161</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion, no polymer, no cement</td>
<td>-0.897</td>
<td>0.207</td>
</tr>
<tr>
<td>100 Cycles</td>
<td>3% Emulsion with polymer, no cement</td>
<td>-0.429</td>
<td>0.130</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with cement, no polymer</td>
<td>-0.287</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with polymer and cement</td>
<td>-0.385</td>
<td>0.144</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion, no polymer, no cement</td>
<td>-2.187</td>
<td>0.251</td>
</tr>
<tr>
<td>500 Cycle</td>
<td>3% Emulsion with polymer, no cement</td>
<td>-0.869</td>
<td>0.256</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with cement, no polymer</td>
<td>-0.551</td>
<td>0.121</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with polymer and cement</td>
<td>-0.658</td>
<td>0.208</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion, no polymer, no cement</td>
<td>-3.986</td>
<td>0.448</td>
</tr>
<tr>
<td>1000 Cycles</td>
<td>3% Emulsion with polymer, no cement</td>
<td>-1.331</td>
<td>0.440</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with cement, no polymer</td>
<td>-0.836</td>
<td>0.199</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with polymer and cement</td>
<td>-0.901</td>
<td>0.291</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion, no polymer, no cement</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2000 Cycles</td>
<td>3% Emulsion with polymer, no cement</td>
<td>-2.290</td>
<td>1.093</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with cement, no polymer</td>
<td>-1.383</td>
<td>0.267</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with polymer and cement</td>
<td>-1.341</td>
<td>0.419</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion, no polymer, no cement</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5000 Cycles</td>
<td>3% Emulsion with polymer, no cement</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with cement, no polymer</td>
<td>-2.658</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>3% Emulsion with polymer and cement</td>
<td>-2.363</td>
<td>0.650</td>
</tr>
</tbody>
</table>
Figure 74 The Permanent deformation of all specimens at certain load cycle (Error bars are shown as the average value plus and minus one standard deviation)

A paired t-test can be used here to find out the difference between two materials. First of all, the independence of the two data sets must be verified. The deformation difference vs. cycle number is plotted in Figure 75.

Figure 75 Deformation difference vs. cycle number of specimens with and without polymer (both with cement)
The deformation difference has a pattern of first decreasing then increasing with the cycle number. The deformation difference is not randomly distributed. When the deformation difference vs. cycle number of each material was plotted as shown in Figures 76 and 77, it is indicated that each deformation results at difference cycles are independent.

![Figure 76 Deformation difference vs. cycle number of specimens with cement and no polymer](image)

![Figure 77 Deformation difference vs. cycle number of specimens with cement and polymer](image)
In this circumstance, a Two-sample Kolmogorov-Smirnov test is used to compare the difference between two materials. The Kolmogorov-Smirnov test (K–S test or KS test) is a nonparametric test of the equality of continuous, one-dimensional probability distributions that can be used to compare two samples (two-sample K–S test). The Kolmogorov–Smirnov statistic quantifies a distance between the empirical distribution functions of two samples. The null distribution of this statistic is calculated under the null hypothesis that the samples are drawn from the same distribution (in the two-sample case) or that the sample is drawn from the reference distribution (in the one-sample case) (Eadie and Drijard 1971). In each case, the distributions considered under the null hypothesis are continuous distributions but are otherwise unrestricted.

In this study, the null hypothesis ($H_0$) is that the two materials have same rutting resistance under this test temperature, while the alternative hypothesis ($H_a$) is that there is difference between their ability to resistance permanent deformation. The analysis was conducted using R language.

From the analysis output, a P-value of 0.1744 at 95% confidence level was reported, so the alternative hypothesis was rejected. From a statistical perspective, there is no difference in resistant permanent deformation between specimens with and without polymer when cement was used in CR mixtures.

However, specimens with both cement and polymer had air voids around 15 percent while the air void level of specimens with only cement were kept at 14 percent. Given the higher air void level, specimens with both cement and polymer still showed similar performance in permanent deformation. Considering the influence of air voids of CR mixtures in resisting rutting, it can be deduced that no matter if cement is used or not, polymer can improve the rutting resistance capability of CR mixtures compare to CR specimens without polymer.
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This study was designed to investigate the performance of lab produced CR mixtures modified by conventional asphalt emulsion and polymer modified asphalt emulsion, in order to determine the effect of polymer in improving the performance of CR mixtures. Based on experimental results, analysis and discussion, plus the comparison study with cement modified CR specimens, the following conclusions and recommendations are made:

• In the mixture design study phase, the specimen preparation technique, curing, and conditioning procedures were able to produce CR specimens that were strong and consistent enough to conduct further testing and analysis using 100% RAP. These procedures are proposed to be used as the standard CR mixture design protocols to be implemented in the future, while maintaining flexibility for any necessary adjustments.

• Compaction energy induced through 50 gyrations using the Superpave Gyratory Compactor is capable of producing CR specimens containing 100% RAP with enough tensile strength. For the specific RAP materials and asphalt emulsions used in this research, 2 percent water and 1.5 percent asphalt emulsion provided the highest tensile strength. Considering the durability of CR specimens, relatively higher asphalt emulsion content is preferred, as long as specimens can still achieve the strength threshold. The optimum water content is recommended as 2 percent, while up to 3 percent asphalt emulsion content is recommended.

• In general, whether polymer is included in emulsion or not, higher specimen densities were achieved at higher water and emulsion contents as expected, and emulsion content has a more significant effect on increasing densities of lab produced CR specimens. The air void level of CR specimens in this study is in the range of 8 to 16 percent. Increasing emulsion content or batch weight can bring down the air void level. When batch weight is small, air voids difference between specimens with different recycling agent categories (with/without
polymer, with/without cement) varies tremendously. The gap shrinks with the increase of batch weight.

• The Raveling test is not the best test method to evaluate durability of the lab produced CR specimens. Even specimens with the highest possibility to ravel (0 percent asphalt emulsion content) passed test threshold of 2 percent mass loss, no failure of CR specimen was observed during the whole study phase. For specimens with 2 percent emulsion content, a significantly drop in material loss was observed. Higher emulsion contents are expected to reduce the material loss even further. To investigate the durability of lab produced CR mixtures, severer test like the Cantabro test should be introduced.

• Modified AASHTO T 283 can be used to determine the moisture damage resistance property of lab produced CR mixtures. Recommended adjustments on test procedure include degree of saturation requirement and hot water bath conditioning process. It was observed that it is very hard for CR specimens to reach the requirement of 70-80 percent of degree of saturation. CR specimens with high air voids easily collapsed during hot water bath conditioning process shortly after they were placed in the hot water bath. Further moisture damage resistance study on CR mixtures based on AASHTO T 283 may consider employing lower temperature during hot water bath conditioning process, or alternative conditioning procedures.

• Based on moisture damage resistance test results and data analysis, CR specimens with conventional and polymer modified asphalt emulsion cannot reach the TSR threshold of 0.8, which is easy to obtain for HMA and WMA specimens. However, when addition of one percent portland cement was introduced, the moisture damage resistance performance of lab produced CR specimens improved tremendously, even with its relatively higher air void level, TSR threshold of 0.8 was easily achieved. Polymer modified emulsions did not produce any improvement in moisture damage resistance of mixtures compared with mixtures with no polymer emulsion.
• The RSCH test results indicate that the poorest rutting performance belong to the mixtures with regular emulsion, better performance is observed from the polymer emulsion mixtures. Specimens containing one percent portland cement, with or without polymer, showed the least permanent deformation. Similar to test results of moisture damage resistance, one percent portland cement exhibited great effect in improving performance of CR mixtures. Polymer modified asphalt emulsion also improves the rutting behavior of lab produced CR mixtures, although its contribution was relatively small compared to portland cement.

• Based on statistical analysis results, neither lab manufactured polymer modified asphalt emulsion, nor polymer modified asphalt emulsion provided by asphalt product manufacturers exhibited significantly better overall performance compared with specimens prepared with conventional asphalt emulsion, for tensile strength and moisture damage resistance. However, from the rutting resistance perspective, specimens with polymer modified asphalt emulsion showed better performance in terms of rutting resistance.

• Further tests and other asphalt emulsion sources are needed to assess if comparisons obtained through this study still hold. Fatigue resistance of these mixtures also needs to be evaluated so that performance measures are available in all categories.

• Portland cement plays a significant role in improving overall performance of lab produced CR mixtures for all performance measures (moisture damage resistance and rutting resistance), which has been observed by many researchers.
REFERENCES


K. Wayne Lee, Todd E. Brayton, Jason Harrington. "New Mix-Design Procedure of Cold In-Place Recycling for Pavement Rehabilitation." *Transportation Research Record,* 2002: CD-ROM.


TexasDOT. "Asphalt Emulsion." By Texas Department of Transportation. Texas Department of Transportation, 2006.


Minitab outputs of statistical analysis results are presented in this Appendix. The following results are from moisture damage resistance study, grouping of specimens into dry/wet subsets based on air voids distribution.

**Two-Sample T-Test and CI: Dry, Wet**

Two-sample T for Dry vs Wet

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>3</td>
<td>10.788</td>
<td>0.570</td>
<td>0.33</td>
</tr>
<tr>
<td>Wet</td>
<td>3</td>
<td>10.831</td>
<td>0.578</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Difference = μ (Dry) − μ (Wet)

Estimate for difference: -0.043

95% CI for difference: (-1.534, 1.449)

T-Test of difference = 0 (vs ≠): T-Value = -0.09  P-Value = 0.933  DF = 3

Figure A-1 Two-sample t-test results of specimen with 2% emulsion, no polymer, and no cement

**Two-Sample T-Test and CI: Dry, Wet**

Two-sample T for Dry vs Wet

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>3</td>
<td>9.599</td>
<td>0.186</td>
<td>0.11</td>
</tr>
<tr>
<td>Wet</td>
<td>3</td>
<td>9.594</td>
<td>0.238</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Difference = μ (Dry) − μ (Wet)

Estimate for difference: 0.005

95% CI for difference: (-0.553, 0.563)

T-Test of difference = 0 (vs ≠): T-Value = 0.03  P-Value = 0.979  DF = 3

Figure A-2 Two-sample t-test results of specimen with 3% emulsion, no polymer, and no cement
**Two-Sample T-Test and CI: Dry, Wet**

Two-sample T for Dry vs Wet

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>3</td>
<td>8.008</td>
<td>0.438</td>
<td>0.25</td>
</tr>
<tr>
<td>Wet</td>
<td>3</td>
<td>8.0049</td>
<td>0.0233</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Difference = μ (Dry) - μ (Wet)
Estimate for difference: 0.003
95% CI for difference: (-1.087, 1.092)
T-Test of difference = 0 (vs ≠): T-Value = 0.01 \( P-Value = 0.992 \) | DF = 2

Figure A-3 Two-sample t-test results of specimen with 3% emulsion with polymer, no cement

**Two-Sample T-Test and CI: Dry, Wet**

Two-sample T for Dry vs Wet

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>3</td>
<td>10.006</td>
<td>0.304</td>
<td>0.18</td>
</tr>
<tr>
<td>Wet</td>
<td>3</td>
<td>9.941</td>
<td>0.252</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Difference = μ (Dry) - μ (Wet)
Estimate for difference: 0.065
95% CI for difference: (-0.660, 0.790)
T-Test of difference = 0 (vs ≠): T-Value = 0.29 \( P-Value = 0.794 \) | DF = 3

Figure A-4 Two-sample t-test results of specimen with 3% emulsion with cement, no polymer

**Two-Sample T-Test and CI: Dry, Wet**

Two-sample T for Dry vs Wet

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>3</td>
<td>11.2356</td>
<td>0.0651</td>
<td>0.038</td>
</tr>
<tr>
<td>Wet</td>
<td>3</td>
<td>11.202</td>
<td>0.293</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Difference = μ (Dry) - μ (Wet)
Estimate for difference: 0.034
95% CI for difference: (-0.712, 0.780)
T-Test of difference = 0 (vs ≠): T-Value = 0.20 \( P-Value = 0.863 \) | DF = 2

Figure A-5 Two-sample t-test results of specimen with 3% emulsion with polymer and cement
Two-Sample T-Test and CI: Dry, Wet

Two-sample T for Dry vs Wet

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>3</td>
<td>8.6194</td>
<td>0.0713</td>
<td>0.041</td>
</tr>
<tr>
<td>Wet</td>
<td>3</td>
<td>8.607</td>
<td>0.336</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Difference = μ (Dry) − μ (Wet)
Estimate for difference: -0.067
95% CI for difference: (-0.921, 0.786)
T-Test of difference = 0 (vs ≠): T-Value = -0.34 P-Value = 0.766 DF = 2

Figure A-6 Two-sample t-test results of specimen with 2% emulsion, no polymer, no cement, and high compaction level

The following results are from moisture damage resistance study, the IDT strength comparison between different material categories.

Two-Sample T-Test and CI: C2, C4

Two-sample T for C2 vs C4

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>3</td>
<td>46.47</td>
<td>3.02</td>
<td>1.7</td>
</tr>
<tr>
<td>C4</td>
<td>3</td>
<td>52.16</td>
<td>2.26</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Difference = μ (C2) − μ (C4)
Estimate for difference: -5.68
95% CI for difference: (-12.62, 1.25)
T-Test of difference = 0 (vs ≠): T-Value = -2.61 P-Value = 0.080 DF = 3

Figure A-7 Two-sample t-test results of dry subset of specimens with 3% emulsion and no cement

Two-Sample T-Test and CI: C3, C5

Two-sample T for C3 vs C5

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>3</td>
<td>17.567</td>
<td>0.512</td>
<td>0.30</td>
</tr>
<tr>
<td>C5</td>
<td>2</td>
<td>19.125</td>
<td>0.120</td>
<td>0.085</td>
</tr>
</tbody>
</table>

Difference = μ (C3) − μ (C5)
Estimate for difference: -1.558
95% CI for difference: (-2.881, -0.236)
T-Test of difference = 0 (vs ≠): T-Value = -5.07 P-Value = 0.037 DF = 2

Figure A-8 Two-sample t-test results of wet subset of specimens with 3% emulsion and no cement
**Two-Sample T-Test and CI: C2, C4**

Two-sample T for C2 vs C4

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>3</td>
<td>60.96</td>
<td>2.86</td>
<td>1.6</td>
</tr>
<tr>
<td>C4</td>
<td>3</td>
<td>58.99</td>
<td>3.77</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Difference = μ (C2) - μ (C4)
Estimate for difference: 1.97
95% CI for difference: (-6.72, 10.66)
T-Test of difference = 0 (vs ≠): T-Value = 0.72  P-Value = 0.522  DF = 3

Figure A-9 Two-sample t-test results of dry subset of specimens with 3% emulsion and cement

**Two-Sample T-Test and CI: C3, C5**

Two-sample T for C3 vs C5

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>3</td>
<td>51.65</td>
<td>2.27</td>
<td>1.3</td>
</tr>
<tr>
<td>C5</td>
<td>3</td>
<td>49.80</td>
<td>0.972</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Difference = μ (C3) - μ (C5)
Estimate for difference: 1.67
95% CI for difference: (-4.47, 7.81)
T-Test of difference = 0 (vs ≠): T-Value = 1.17  P-Value = 0.363  DF = 2

Figure A-10 Two-sample t-test results of wet subset of specimens with 3% emulsion and cement

The following results are from moisture damage resistance study, the TSR values comparison between different material categories.

**Two-sample T for TSR 1 vs TSR 2**

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSR 1</td>
<td>6</td>
<td>0.3671</td>
<td>0.0145</td>
<td>0.0059</td>
</tr>
<tr>
<td>TSR 2</td>
<td>9</td>
<td>0.3791</td>
<td>0.0240</td>
<td>0.0080</td>
</tr>
</tbody>
</table>

Difference = μ (TSR 1) - μ (TSR 2)
Estimate for difference: -0.01194
95% CI for difference: (-0.03361, 0.00972)
T-Test of difference = 0 (vs ≠): T-Value = -1.20  P-Value = 0.253  DF = 12

Figure A-11 TSR of specimens with or without polymer, no cement
Two-Sample T-Test and CI: TSR 1, TSR 2

Two-sample T for TSR 1 vs TSR 2

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSR 1</td>
<td>9</td>
<td>0.8485</td>
<td>0.0473</td>
<td>0.016</td>
</tr>
<tr>
<td>TSR 2</td>
<td>9</td>
<td>0.8496</td>
<td>0.0495</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Difference = μ (TSR 1) - μ (TSR 2)
Estimate for difference: -0.0012
95% CI for difference: (-0.0498, 0.0475)
T-Test of difference = 0 (vs ≠): T-Value = -0.05  P-Value = 0.960  DF = 15

Figure A-12 TSR of specimens with or without polymer, with cement