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Exploring Compaction Effects on Cold In-Place Recycling Mixtures using Emulsified Asphalt

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Exploring Compaction Effects on Cold In-Place Recycling
Mixtures using Emulsified Asphalt

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering

by

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Abstract

Cold in-place recycling (CIR) is a process that takes three to four inches of existing pavement surface and reuses 100% of it by milling and crushing it, adding asphalt emulsions and/or additives to it, before placing and re-compacting it. There is currently very little research regarding the interaction between the crushed aggregate and asphalt emulsion during the CIR process. In this study, the interactions between the combinations of crushed aggregates and asphalt emulsions were investigated along with select compaction metrics and a raveling performance test. The three types of aggregates included coated limestone, recycled asphalt pavement (RAP), and coated syenite. The two types of emulsifiers included a commodity and a proprietary one. The compaction metrics explored the compaction behavior of CIR and the raveling test is a standard test that evaluates a mixture's resistance to raveling under initial traffic. The results of this project indicated crushing aggregate and waiting between one hour to one day before mixing can be more optimal for easier compactibility than crushing and mixing immediately or waiting one week later. Not only were the results seen in the compaction metrics, but in the raveling test as well.

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First of all, I would like to thank Dr. Andrew Braham for exposing me to so much asphalt—both as an undergraduate and graduate student. Without Dr. Braham's guidance, I wouldn't have had this opportunity and am glad for the experience, which will hopefully pave paths toward new research in the future.

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I. Introduction

The objective of this research was to analyze the effect of surface charge of aggregates over time and asphalt emulsion types on the compactibility of cold in-place recycling (CIR).

Currently, there is little to no research on examining surface charge on material milled during CIR operations. In theory, when the milling head is grinding the pavement, a charge is built on the recycled pavement material as it is milled. This surface charge may influence how asphalt emulsion breaks on the recycled material, and thus impact how the material compacts in the field. In addition, there is little found research on laboratory compaction metrics using asphalt emulsions in a CIR mix, because the metrics have mainly investigated hot mix asphalt (HMA) and warm mix asphalt (WMA).

This research consisted of measuring the surface charge of crushed recycled asphalt pavement (RAP) to observe how charges could potentially deteriorate over time while also manufacturing different asphalt emulsions in the laboratory using various emulsifiers. The surface charge of RAP should have been quantified using electrokinetic technique, but due to time constraints, the surface charge was indirectly obtained using data from compaction. The two emulsifiers included a commodity and a proprietary cationic emulsifier. The asphalt emulsions were produced on a Raschig mill and evaluated through a series of standard quality control tests. In addition, compaction properties and raveling performance testing of CIR were explored in order to relate it to performance in the field.

II. Research Objectives

The first documented use of CIR can be dated back to as early as the 1940s (Alcoke, et al., 1979). However, it is still not as widely accepted as HMA or WMA and this could mainly be due to the lack of understanding and available research on it. To better understand CIR, there is

a need to first understand the components that make up CIR, which are recycled asphalt pavement (RAP) and asphalt emulsion. During the CIR process, the existing asphalt pavement is broken into small chunks during the milling process. In theory, a surface charge develops during this process that is expected to deteriorate over time. For this research, a limestone-based field RAP was used and the surface charge of crushed RAP was investigated to see how it behaves with asphalt emulsion. In addition, RAP material created in the laboratory (lab RAP) to simulate the field RAP using both limestone and syenite aggregates was also investigated, which might find any potential differences in the types of aggregate used.

In addition to investigating different forms of RAP, a common binding agent for CIR, asphalt emulsion, was explored. Asphalt emulsion is essentially the glue that holds the RAP together. Because various emulsifiers have different effects when introduced to aggregates, two types of emulsifiers were examined in a CIR mix to see how performance varied. The first emulsifier was a commodity emulsifier (which will produce a cationic medium set, CMS, emulsion) and the second emulsifier was a proprietary emulsifier. The commodity emulsifier is one of the slower emulsifiers, but is formulated for mixing, coating, and workability. The commodity emulsifier is generally not as expensive as the proprietary type emulsifier and is more prevalent than the proprietary emulsifier. The proprietary emulsifier is engineered and designed to have better field performance than the commodity, but will also produce a CMS emulsion. The proprietary emulsifier is one of the faster emulsifiers and provides mixing, coating, and workability, while achieving curing for the depths of mixtures common in the process. This interaction between the components of CIR could lead to different compaction behavior, so quantifying this compaction behavior could be very beneficial. The compaction behavior can be quantified in the lab using compaction metrics. These metrics reveal how

compaction effort varied, based on the surface charge of aggregates and different asphalt emulsifiers in CIR. Finally, the raveling test was run on the different aggregate and asphalt emulsion combinations to determine the effect of surface charge on lab raveling performance of CIR.

The objectives of this research included:

- Measuring the surface charge of crushed RAP to determine how the charge changes over time

- Exploring the compactibility of CIR with different surface charged RAP and asphalt emulsions based off of selected laboratory compaction metrics

- Investigating the raveling performance of CIR with different surface charged RAP and asphalt emulsions using the raveling test

III.   Background

Preservation of the environment, mainly recycling of resources, can impact what limited resources are left for human use. In the transportation pavement world, the CIR process or incorporating RAP into asphalt mixtures are two alternatives that have been explored. CIR is a process done on-site, milling 3 to 4 inches of existing pavement surface. This milled pavement surface is blended together with an emulsified asphalt and/or additives (see Figure 1). Once the material has been mixed, the recycled layer is placed and recompacted, creating a recycled base layer which is then coated with a surface treatment and/or HMA overlay (Federal Highway Administration, 2015) to provide a smooth and safe traveling surface.
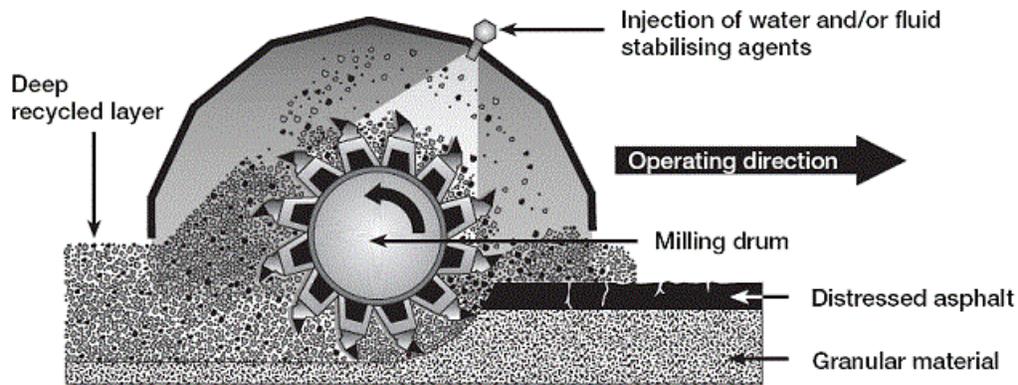
Figure 1. The CIR recycling process (http://intro.fehrl.org/)

CIR consists of two broad categories, surface recycling or base and surface recycling. In surface recycling, the objective is to improve pavement roughness and skid resistance; in contrast, the objective in base and surface recycling is to improve the surface conditions and the load-carrying capacity of the pavement (Alcoke, et al., 1979). CIR is more of a rehabilitation process and is ideal to use when pavements are aged, distressed or failing (cracks, ruts, etc), but are still structurally sound in the aggregate base and subgrade layers.

There have been several current research projects to help expand the understanding of CIR. Kim, et al (2011), from University of Iowa, explored the minimum curing times and moisture contents to determine when the hot mix layer could be placed. Sanjeevan, et al (2014) evaluated various emulsion types and compared CIR with a HMA overlay and surface treatment versus CIR with only a surface treatment. They (Sanjeevan, et al., 2014) found that the first alternative performed significantly better. Charmot and Romero (2010) successfully used fracture energy tested from field cores to differentiate between satisfactory and poor performing CIR mixtures. These are just a few examples of the contributions to CIR mixes to date, but they still, nevertheless, do not indicate field compactibility performance.

Surface chemistry of aggregate particles plays an important role on performance, because asphalt emulsion must wet the aggregate surface and bind to the aggregate (Roberts, et al., 1996).

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This project studies the effect of surface charge over time on RAP. In the 1970s, the use of RAP increased, because of higher costs of crude oil during the Arab oil embargo (Federal Highway Administration, 2011). RAP is obtained through a milling process of existing pavement, but the duration from when the RAP was milled to the time it arrives at the lab will be neglected in this research, since the milling speed at large jobs are controlled at the job site so that the resulting RAP is kept uniform and consistent (Federal Highway Administration, 2011).

For the CIR on-site process, the train of equipment used to mill, mix, place and re-compact is almost immediate. In this project, it is thought that surface charge builds up during the milling process and over time, this charge decreases. It is important to know this length of time, in case it weakens the interaction with asphalt emulsion. It is also believed that having surface charge can help the aggregates and asphalt emulsion interaction and allow for easier compactibility.

The size of RAP particles can also affect charge and reactivity. Usually, the larger the particle size, the less of an impact the charge will have, whereas the smaller the particle size, the more of an impact the surface charge will have.

Unfortunately, little work has been done on the interaction of surface charge over time on crushed RAP mixed with asphalt emulsion. There have been studies on the surface charge of aggregate and its interaction with asphalt emulsion (Sherwood, 1967), which concluded that differently charged asphalt emulsions bond significantly better with different types of aggregates. Cheng (2002), used a gas sorption approach to determine surface energies of aggregates, but concluded that the test procedures still needed improvement. Bhasin and Little (2006) also investigated the surface properties of aggregates used in hot mix asphalt with the Universal Sorption Device, the Wilhelmy Plate, and a Micro Calorimeter, but these results were aimed at

the selection of materials based on resistance to moisture damage. In this proposed research, the surface charge of RAP will be tested using an electrokinetic technique, similar to the one used by Banerjee and Bhasin (2013) to test asphalt emulsions at the University of Texas (Banerjee, et al., 2013).

IV. Materials & Experimental Matrix

Materials for this project consisted of three types of aggregate, two emulsifiers and two binder types, PG76-22 for precoating aggregates and PG64-22 for making asphalt emulsions. Two types of aggregates were used to create lab RAP to be more consistent and controlled. The three types of aggregates investigated were Class 7 limestone from Sharp's Quarry, C-Ballast syenite from Granite Mountain Quarries, and field RAP obtained off I-49, also from Sharp's Quarry. The asphalt emulsifiers were a commodity and a proprietary type.

Table 1 shows the experimental matrix for this research project. The deterioration of charge over time on crushed RAP is not known, but the mixing time spanned from immediately after crushing until a week later, when the charge is assumed to no longer change. A cold in-place recycling mix design with one binder source was selected while the aggregates and emulsifiers were varied.

Table 1. Experimental Matrix

Surface Charge (after crushing)	Aggregate Types	Asphalt Emulsifiers	Compaction Metrics	Raveling Test (ASTM D7196)
Immediately	Limestone	Commodity	N_{92}	4 hours @ 21°C
1 hour	Field RAP	Proprietary	Locking Point	
1 day	Syenite		GCI	
1 week			CEI	
			WEI	
			CDI	

A. Surface Charge

To determine the surface charge of aggregates, an electrokinetic technique was applied. This required a pint-sized container to measure the aggregate, a Volteq HY1503D DC power supply to create an electric field, an instrument to measure amperage (NI USB-4065 ammeter) and a computer to record the data using LabView software. The devices were connected in series, and the container had a rubber plug on top with a nail through the middle of it. The plug was used to avoid interference between the two opposing electrodes. Electrodes are connected to the top of the nail in the middle of the plug and on the side of the container. Deionized water was used to avoid any additional charge to the surface charge of aggregates.

Simulations using asphalt emulsion were conducted to achieve similar results to the University of Texas study (Banerjee, et al., 2013). Figure 2 used CMS-1 emulsion in three separate trials using 15.0 volts.
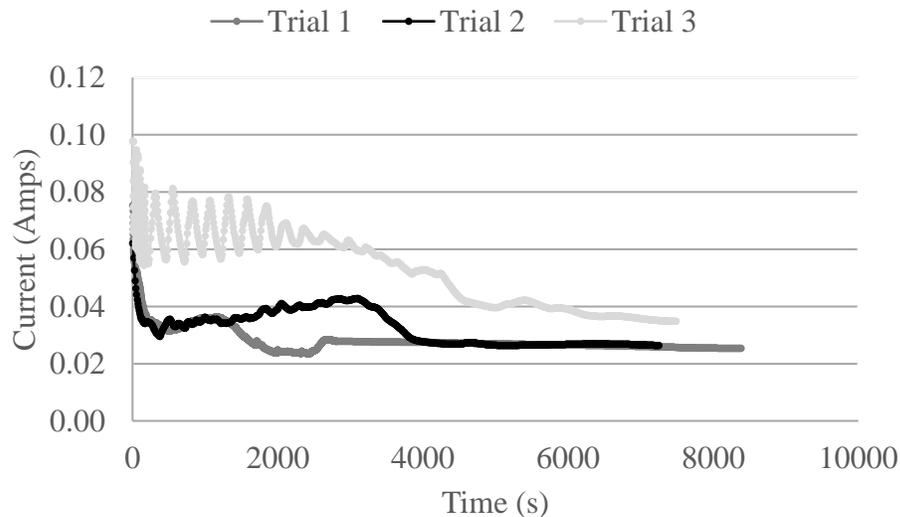
Figure 2. Current flow for CMS-1 emulsion with applied voltage of 15.0 V

After successfully recreating similar results to Dr. Bhasin's study, the next task was to move onto deionized water with crushed aggregate. To test a solid with an instrument used to test liquids, deionized water was used so as not to interfere with any charge the crushing effect had on

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aggregate. Deionized water was first tested on its own, before adding crushed limestone to the next two trials. See Figure 3.
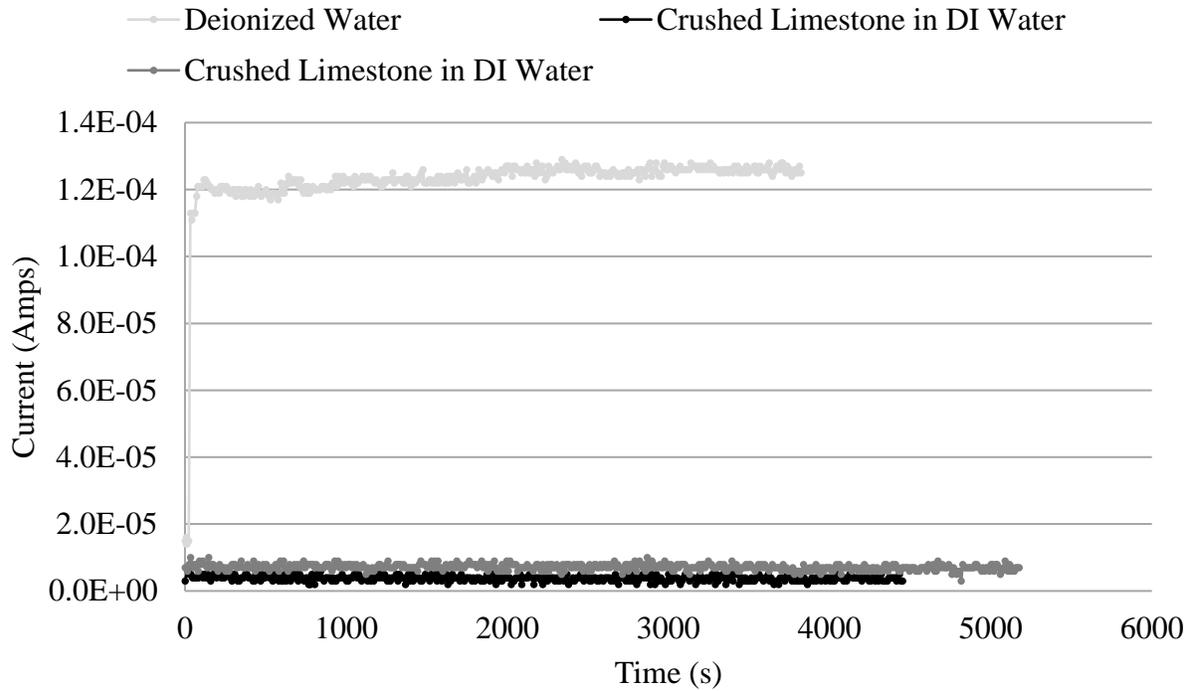
Figure 3. Current flow for deionized water alone and with crushed limestone aggregate with applied voltage of 15.8 V

By introducing the crushed limestone to the deionized water, nothing appeared to pick up. Because of time constraints, the surface charge on the crushed aggregate will be explored indirectly through the compaction metrics.

B. Recycled Asphalt Pavement (RAP)

Traditionally, research labs are dependent on contractors in order to obtain samples of Recycled Asphalt Pavement (RAP). In this research, this type of RAP is called field RAP. However, the source of field RAP is not easily controlled, and often multiple sources of field RAP are processed and combined into a single stockpile. When sampling the stockpile, the base aggregate and asphalt cement is highly variable on a day-to-day basis. Therefore, it is of great interest to be able to explore field RAP in the laboratory with virgin aggregate and asphalt

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cement to execute research with a consistent source of RAP. This exploration is only looking at the coating aspects of it, no aging effects were induced and this project did not anticipate any activation of binder. In this research, this type of RAP is called lab RAP. For this project, two types of virgin aggregate were used with significantly different properties: limestone and syenite. The limestone was used because a local contractor provided samples from a known limestone field RAP. The syenite helped compare any differences that may have occurred throughout the entire process, as syenite as a rock source has significantly different properties versus limestone.

In order to create lab RAP, four different methods were explored using 1-½" – 1" sized aggregate to closely represent the unprocessed field RAP: uncoated limestone, precoated limestone that was crushed (P/C), crushed limestone that was coated (post-coated) (C/P), and a blend of precoated and post-coated limestone.

The first method consisted of using uncoated limestone aggregate. In order to simulate the CIR process without wasting the limited supply of RAP, uncoated limestone was used to take the place of RAP. Samples of 2000g were batched and run through the jaw crusher at ½" width between the jaws. Next, the samples were mixed with 2% water for one minute before adding asphalt emulsion and then mixed for an additional minute before compaction. The amount of asphalt emulsion used was significant and different for each method, because it had to equal the same 6% binder content found in the original RAP, plus any additional amount of asphalt emulsion that was incorporated in the RAP.

The second method was the precoated limestone aggregate, which was then crushed afterward (P/C). Precoating consisted of using 6% of PG76-22 asphalt binder with the limestone in a mechanical mixer and curing the mixture for two days. The curing method was consistent with Kandhal's and Motter's approach (Kandhal & Motter, 1991). The percentage binder of the

field RAP was found using ASTM D6307, the ignition oven method, to be 6%. The job mix formula obtained from APAC stated 5.5%, but because the actual test results showed 6%, therefore 6% of PG76-22 binder was used for all materials. After curing, the samples were placed in a freezer for one day before crushing. The freezing of samples allowed them to be crushed without sticking to the sides of the jaw crusher. After crushing, the samples were mixed with 2% water for one minute before adding asphalt emulsion and then mixed for an additional minute before compaction.

The third method was similar to the second method, but the limestone aggregate was crushed before precoating (C/P). The precoating was consistent with the second method, using 6% of PG76-22 asphalt binder in a mechanical mixer and then allowed to cure for two days before mixing with 2% water for one minute and then adding asphalt emulsion to mix for an additional minute before compaction.

The fourth method was a blend of both the second and third methods, but used 25% of the (P/C) aggregate and 75% of the (C/P) aggregate. The blended mix was frozen for one day before crushing and then mixed with 2% water for one minute before adding asphalt emulsion to mix for an additional minute before compaction.

The recreation of RAP involved a few trials, the first of which was comparing different gradations of each mix type. In order to obtain the gradations, 2000g samples of each type were measured and ran through the laboratory jaw crusher at the biggest closed side setting of one-half inch. Ten samples of RAP, uncoated limestone aggregate, and precoated limestone (P/C) aggregate types were measured and an average was taken. Figure 4 shows the average gradations of uncoated limestone, precoated/crushed (P/C) limestone and crushed RAP obtained according to ASTM C136.

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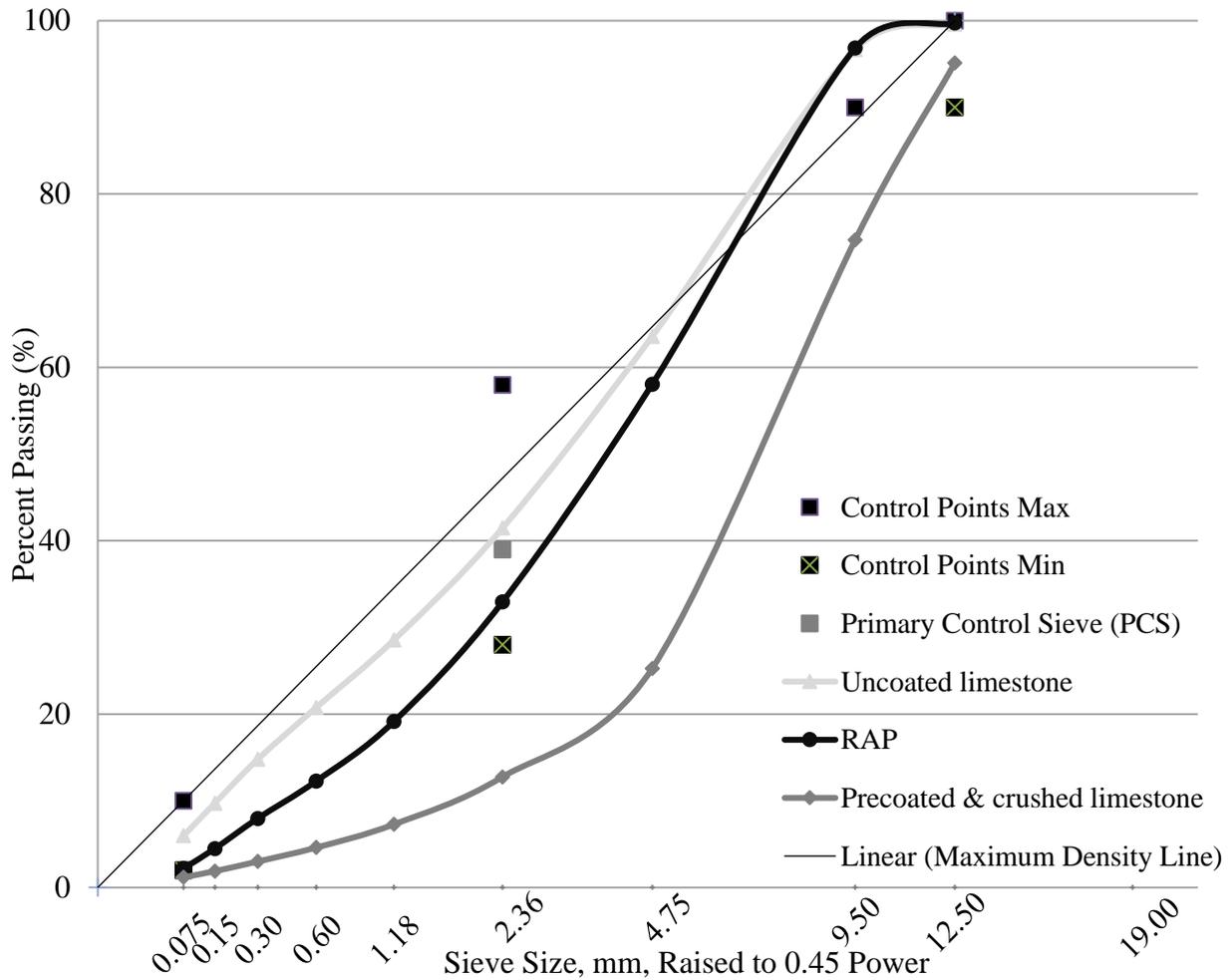
Figure 4. Medium gradations of CIR sample mixtures

After looking at Figure 4, it was apparent that a new type of lab RAP creation method

needed to be developed, which would bring the lab RAP closer to the field RAP. This new type

was then labeled crushed/precoated (C/P) limestone aggregate, which is method three.

Gradations of the crushed/precoated (C/P) limestone could not be determined because precoating

occurs after the crushing, and the asphalt binder would absorb any fines, making it difficult to

represent a true gradation.

Because true gradations of all of the different sample types were slightly difficult to

obtain, as the asphalt binder coated particles can clog sieves, a visual technique of looking at the

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sample types was investigated as exhibited in Figure 5. This method involved obtaining photo images of each mix type, which were then run through an image-processing program named ImageJ, which calculated the intensity of gray for each sample type, producing a gray scale analysis graph.
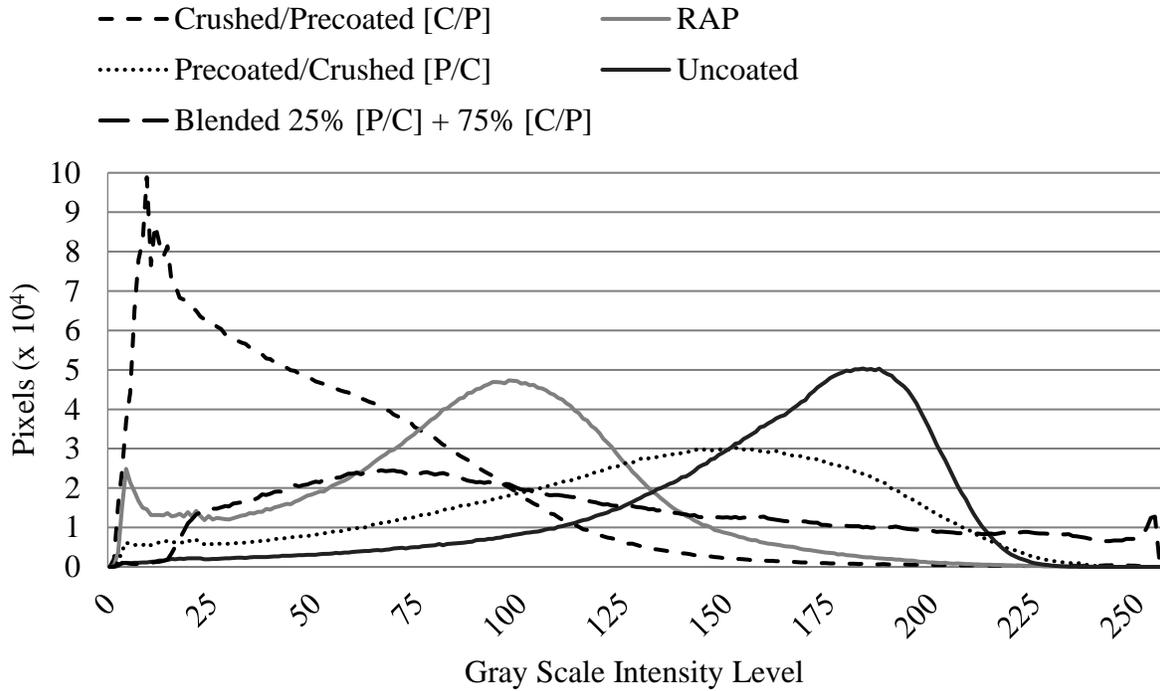
Figure 5. Gray scale analysis of lab RAP

The crushed/precoated (C/P) sample is shown on the far left of the RAP sample, but the uncrushed and precoated/crushed (P/C) samples are on the right of the RAP. To refine this further, a blend of 25% P/C and 75% C/P was developed and analyzed, which is represented as the sample closest to the actual RAP. This became the fourth method and for purposes of this project, the blend of 25% P/C limestone and 75% C/P limestone was used for both types of aggregate, limestone and syenite, to recreate RAP. However, for purposes of this project, the intent is to look at coated black rock, not the activation of binder and did not induce any aging effects.

C. Asphalt Emulsion

Asphalt emulsion is a key input in CIR and two types will be considered for this project. Asphalt emulsion consists of asphalt droplets that have been sheared using mechanical energy and suspended in a surfactant solution. The surfactant solution is made up of water and emulsifying agents, which allow the asphalt droplets to stay suspended and controls the breaking time. In order to keep the asphalt droplets in suspension, the emulsifying agents impart an electric charge to the surface of the droplets which cause them to repel one another, preventing the droplets from coalescing (Roberts, et al., 1996). Emulsions are created to decrease the asphalt viscosity for lower application temperatures which reduce the cost and energy requirements and thus are popular for pavement maintenance in road construction. The early part of the 20th century paved the way toward using the first asphalt emulsions in road construction. The United States represents about 5% to 10% of asphalt consumption and produces approximately 3 million tons (James, et al., 2006).

Generally, when first applied asphalt emulsions appear as a thick brown liquid. The emulsion works through a process called flocculation where the asphalt droplets overcome repulsion. The asphalt cement in the emulsion then starts to adhere to the surrounding material such as aggregate, existing surfaces, subgrade, etc. The emulsion "breaks" when it turns from brown to black because of the interaction between the asphalt droplets and the surface of the aggregates. This interaction is called coalescence which breaks the surfactant film and causes the water to be squeezed out. The emulsion "sets" when the water evaporates, producing a continuous film of asphalt (Roberts, et al., 1996). The time required to break and set depends upon the materials used in the emulsion, the techniques in application and environmental conditions (James, et al., 2006). Under most circumstances, an emulsion will set in about 1 to 2

hours. Two most commonly used types of emulsified asphalts are anionic and cationic—

specified in ASTM D977 and D2397 respectively.

As previously mentioned, the breaking and setting

speeds depend on the type of asphalt emulsion, which are

classified according to the setting rate and the sign of

charge on the droplets. The setting rate of emulsions

include rapid-setting (RS), medium-setting (MS) and

slow-setting (SS) (Roberts, et al., 1996). RS emulsions

Figure 6. University of Arkansas Raschig Mill

set quickly when in contact with aggregates of low surface

area, MS emulsions set less quickly than RS and SS emulsions are used mainly with aggregates

of high surface area. If an anionic asphalt emulsion is used, no letter is added in front of the

setting rate abbreviation, however, if a cationic emulsion is used, a "C" is added in front of the

rate abbreviation. For example, an anionic rapid set emulsion is often called simply an RS

emulsion, whereas a cationic rapid set emulsion is often called a CRS emulsion. The CIR

process usually uses an MS or CMS emulsion. A positive charge on the asphalt droplets

indicates a cationic emulsion, while a negative charge indicates an anionic emulsion (James, et

al., 2006). When in contact with aggregate surfaces, these asphalt emulsion charges may react

differently because of the surface charges on the aggregates. For this research, the asphalt

emulsions were made on the Raschig mill located at the University of Arkansas (see Figure 6).

Asphalt emulsions produced were subjected to five standard quality control tests. They are as

follow:

1) Residue Burn Off (also known as Percent Solids Test or Moisture Analysis (ASTM D7404))—This determines the percent of solids produced from the emulsion mill and is subject to a +/- 2% of the mix design.

2) Particle Size Analysis—This determines the size of asphalt particles to indicate the quality and performance of the materials used.

3) pH Testing—This determines the pH of the emulsion produced.

4) Viscosity Testing using a Rotational Paddle Viscometer [ASTM D7226-13]—This determines the consistency of emulsified asphalt.

5) Sieve Test [ASTM D6933]—This determines the amount of asphalt particles retained on the No. 20 (850-µm) mesh sieve.

Seven trials of proprietary emulsions and five trials of the commodity type were produced and used after quality controls tests were found to be adequate. The quality control tests are as follow:
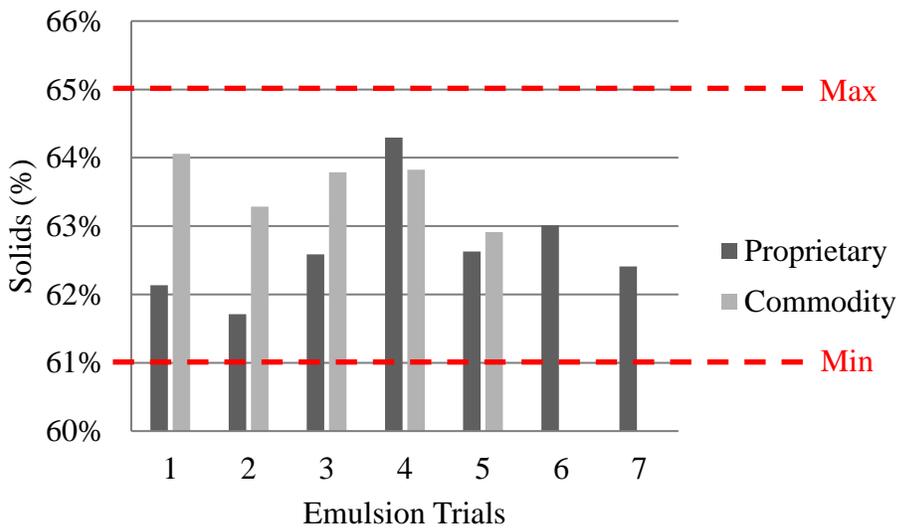
Figure 7. Individual residue burn off on emulsions produced
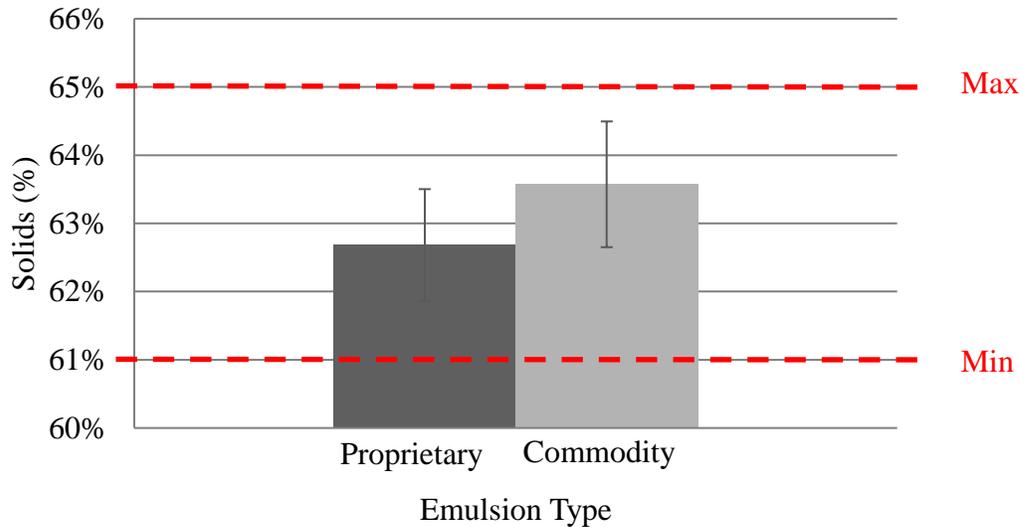
Figure 8. Average residue burn off on emulsions produced

       For residue burn off, the target amount of solids based off of the mix designs is 63%. For quality control purposes, this amount can be +/- 2% off of the target amount. To run this test, an amount of at least 50 grams is taken from the mill during the asphalt emulsion production and the amount is noted before applying heat. The sample is then allowed to "burn off" everything but solids (asphalt binder and some emulsifier) on a hot plate set to about 400°F. The final weight is then divided by the original weight to find the percentage of solids that remain. The emulsions used in this project all fell within this range, as seen in Figures 7 and 8.
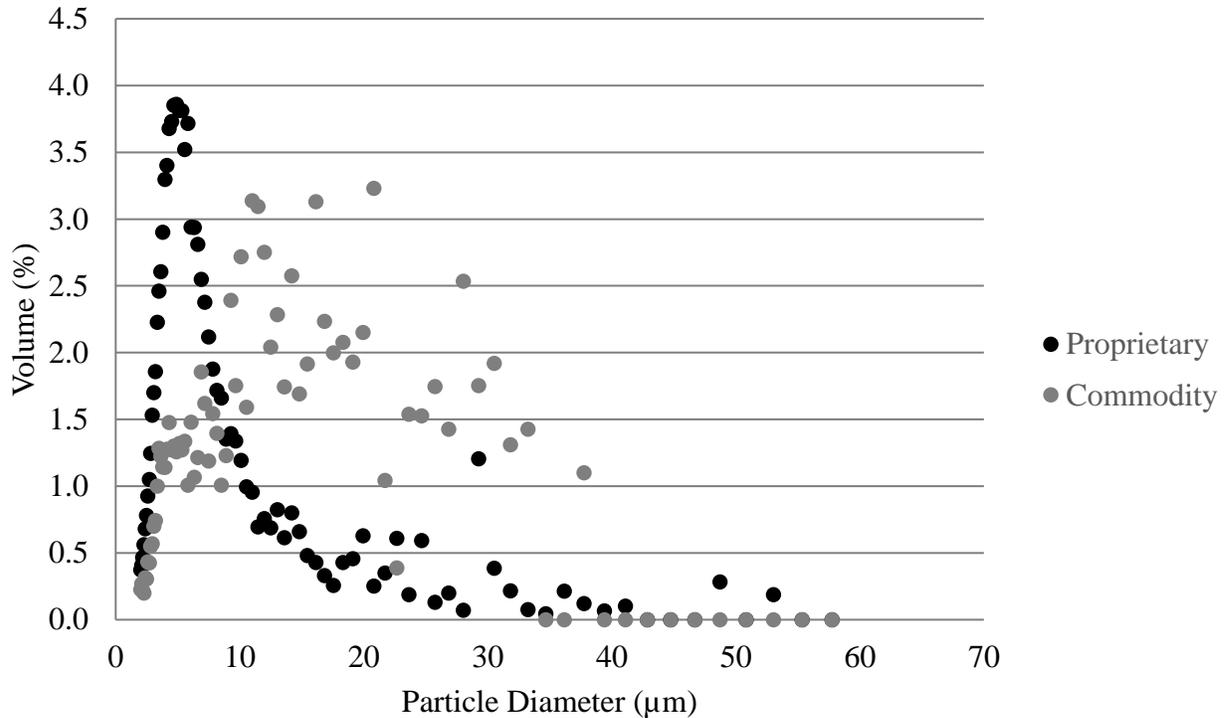
Figure 9. Differential volume of particle size distribution of asphalt emulsions produced

Typically, asphalt droplets range from 0.1-20 micron in diameter (James, et al., 2006).

For this project, a Beckman coulter counter was used to determine particle size distribution for

each batch of emulsion produced and used. Based on Figure 9, for the proprietary emulsion

produced, the particle sizes fell within the desired range (majority of the particles were 0.1-20

µm) with an obvious clear peak, but the commodity emulsion did not fall within the desired

range (more around 0.1-30 µm) and had a wider distribution. This is a function of emulsifier and

warrants further investigation, but is beyond the scope of this study.
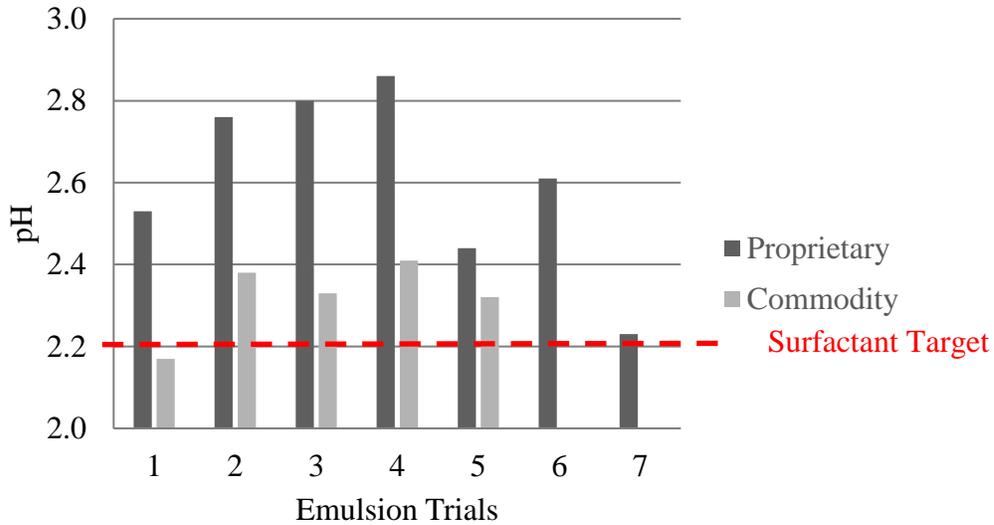
Figure 10. Individual pH results on emulsions produced
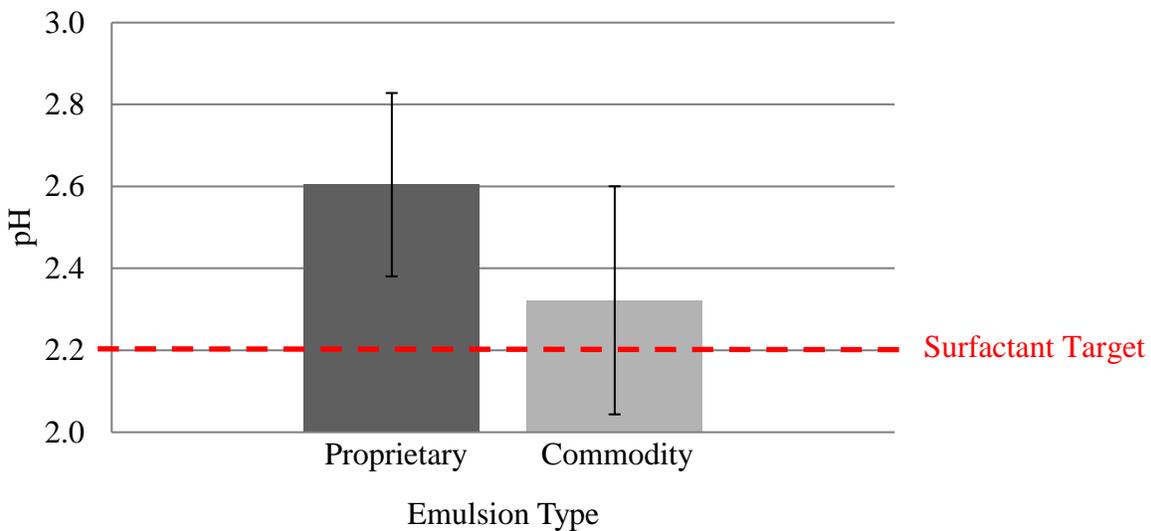
Figure 11. Average pH results on emulsions produced

The pH tests for asphalt emulsions are run at a room temperature of about 25°C. Because the emulsions are stored at 60°C, pH tests are not run until cooled for a few hours when they reach room temperature. The target pH for the surfactant solution is 2.20, but when adding in asphalt binder, the pH should increase. The pH of 2.20 for the surfactant solution is mainly industry standard for international shipping purposes, but is used as a general target overall on this project.
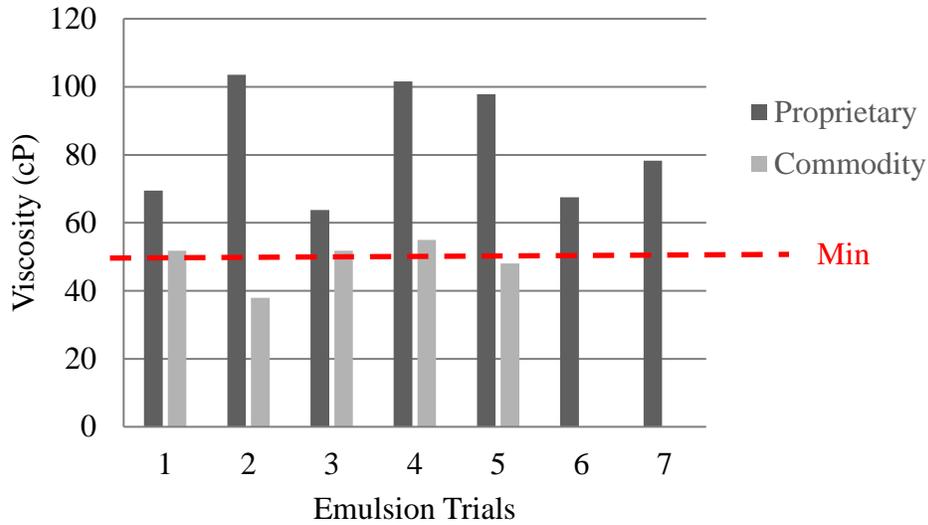
Figure 12. Individual viscosity results on emulsions produced on paddle viscometer
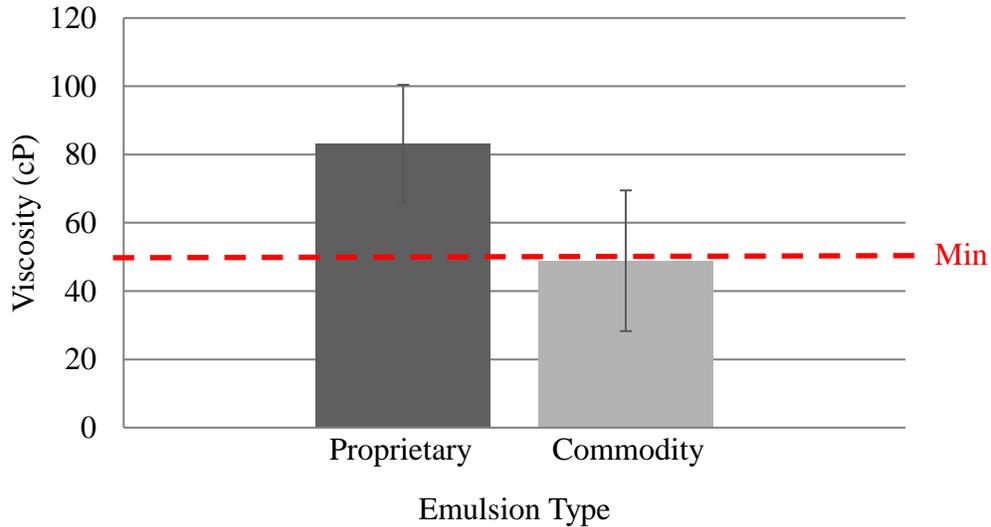
Figure 13. Average viscosity results on emulsions produced on paddle viscometer

Viscosity tests were run at 50°C for all asphalt emulsions in this project. Because asphalt emulsions are stored at 60°C, the viscometer allows the emulsions to cool until 50°C +/- 1°C, before running the actual tests. Viscosity results show emulsions produced with the proprietary emulsifier tended to have higher viscosities. In contrast, emulsions produced with the commodity emulsifier tended to have lower viscosities. Viscosities of asphalt emulsions are

typically in the 50-1000 cP range, which allow use of lower temperatures as opposed to virgin

hot mix asphalt (James, et al., 2006).
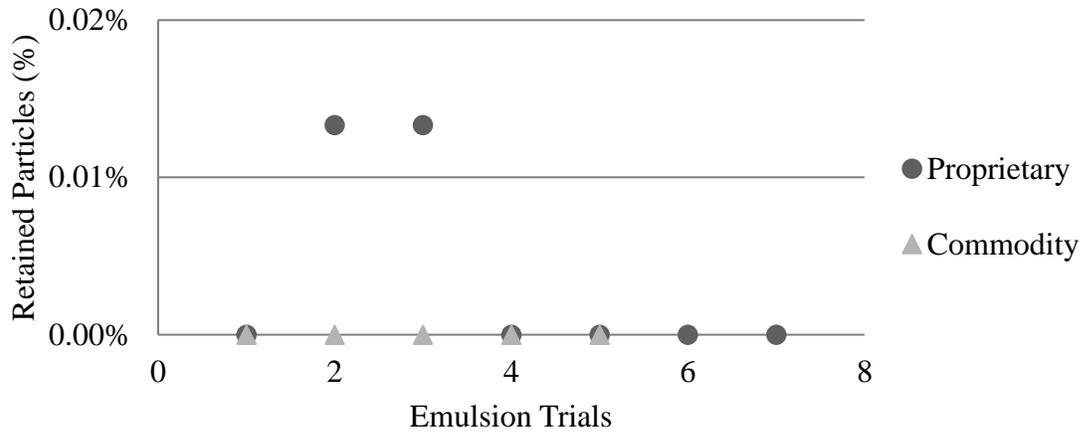
Figure 14. Sieve test showing percentage of retained particles on emulsions produced

The sieve test can predict whether the asphalt emulsion has deteriorated to a degree that it

would interfere with spray nozzles. The standard specification for a CRS-2 emulsion is less than

0.10% of oversized particles within a sample. Oversized particles are

those retained on an 850-µm mesh sieve, which are about 850-µm in

diameter or larger. For this project, 0.10% was also adapted, but the

emulsions produced fell well below this specification. Although the

particle size distribution for the commodity emulsion was flatter, it

still fell within specification for this sieve test.

D. Compaction Metrics

Not only is the interaction between asphalt emulsifiers and

surface charge of RAP important, but the resulting compactibility of

CIR is also crucial. Determining CIR performance in the field could

potentially reduce energy and material cost savings during production

Figure 15. Troxler SGC

and construction (Alcoke, et al., 1979). Currently, compaction metrics have mainly been

examined using HMA and WMA. In a previous study that explored some of these metrics, compaction temperature and pressure were varied to observe which metric provided the most consistent results. In addition to varied temperatures and pressures, the sample preparation methods were also explored and results showed the workability energy index (WEI) to be the most consistent (Yeung, et al., 2015). This work with HMA and WMA shows that understanding the compaction characteristics of CIR in the lab could be very beneficial to field performance.

Field compaction was modeled in the lab using a Troxler Superpave Gyratory Compactor (SGC) (see Figure 15). This compactor was appropriate as it had the capability of handling water in the compacted mixture, and CIR often has water in the mixture during the compaction process before all the asphalt emulsion has broken.

The inputs of the Troxler SGC consist of a known diameter mold (4- or 6-inch), a known weight of mix, a set pressure (600 kPa), and compaction to a certain number of gyrations or to a certain height. The outputs from the compactor give us the height at each gyration, angle of gyration, and density. From these inputs and outputs, various compaction metrics were explored to establish relevancy. The original compaction metrics developed for hot mix asphalt that were researched in this project are as follow:

1) N_{92}—The number of gyrations it takes to reach 92% G_{mm} (theoretical maximum density).

2) Locking Point—The locking point was first defined as the first of the three gyrations at the same height preceded by two gyrations of the same height. This has since been redefined to the first gyration of two consecutive gyrations of the same height (Locking point 2-1), the second gyration of two consecutive gyrations of the same

height (Locking point 2-2), or the third gyration of two consecutive gyrations of the same height (Locking point 2-3) (Leiva & West, 2008). For the purposes of this research, Locking Point 2-2 will be used, which is the second gyration of two consecutive gyrations resulting from the same sample height.

3) Gyratory Compatibility Index (GCI)—The ratio of the height at 60 gyrations to the height at 30 gyrations (ASTM D7726-13).

4) Compactibility Energy Index (CEI)—The energy necessary to compact a sample from 92% G_{mm} to 96% G_{mm}. The CEI measures the compactibility and stability of the pavement as it is loaded over its service life. The more stable a mix, the more traffic loads it can handle while deforming less (Dessouky, et al., 2013).

5) Workability Energy Index (WEI)—The energy necessary to compact a sample from zero gyrations to N92. A lower WEI signifies the mix is difficult to compact from a loose state to N92% G_{mm}, resulting in a higher number of gyrations (Dessouky, et al., 2013).

6) Construction Densification Index (CDI)—The area under the densification curve from eight gyrations to N92 gyrations. The CDI was developed through the University of Wisconsin, and does not include the shear measurement or effort needed to compact material from a loose state to the 8th gyration. According to the Superpave mix design, the density at the 8th gyration is at a maximum of 89% G_{mm}, so the CDI measures roughly 89% - 92% G_{mm} (Bahia, et al., 1998).

Table 2 shows the equations and significant variables used for calculating the compaction metrics.

Table 2. Compaction Metrics for Hot Mix Asphalt

Compaction Metric	Equation	Significant Variable(s)
N_{92}	$92\% \, Gmm = \left(\dfrac{G_{mb}}{G_{mm}} * 100\right) * \left(\dfrac{Final\ Height}{h_{92}}\right)$	h_{92}
Locking Point	2nd gyration of two consecutive gyrations of same height	---
Gyratory Compactibility Index	$GCI = \dfrac{height_{n=60}}{height_{n=30}}$	$height_{n=60}$
Compactibility Energy Index	$CEI = \dfrac{\left(\frac{\pi d^2}{4}\right) * P * (h_{92} - h_{96})}{N_{96} - N_{92}}$	h_{96}, h_{92} N_{96}, N_{92}
Workability Energy Index	$WEI = \dfrac{\left(\frac{\pi d^2}{4}\right) * P * (h_{n=0} - h_{92})}{N_{92}}$	h_{92} N_{92}
Construction Densification Index	$CDI = \displaystyle\sum_{N=8}^{N92} \%G_{mm}$	N_{92}

E. Raveling Test

Finally, in addition to compaction performance, performance of the different charged RAP and the emulsifiers will be examined using the raveling test (ASTM D7196-12).   The raveling test is a measure of the resistance to raveling characteristics of emulsified asphalt and field aggregates or RAP mixtures by simulating an abrasion similar to early return to traffic (ASTM D7196-16, 2006). In compliance with ASTM D7196, an aggregate sample with an approximate mass of 2700g yielding 70 ± 5mm in height after

Figure 16. Hobart mixer for raveling test

compaction is required (see Figure 16). Test samples of various masses were explored to find the required height to perform this test. Once the sample mass was established, the sample was placed into a 150mm gyratory mold and compacted for 20 gyrations. Compaction of 20

gyrations is an industry standard for 150mm diameter samples and 30 gyrations for 100mm diameter samples. After compaction, the samples were cured for 4 hours at 21°C before running a G_{mb} on the samples and then undergoing the raveling test. The mass of the sample was recorded prior to the test, then the sample was abraded for 15 minutes before recording the mass immediately after the test. The percent loss was then determined in order to explore the best performance between asphalt emulsifiers and aggregates.

V.   Mix Design

After establishing the final lab RAP production technique, the next step was to find the optimal asphalt emulsion content for the CIR. It was decided that a single mix design would be developed using the coated limestone (lab RAP), and the optimal asphalt emulsion content found from that mix design would be used for all the mixtures moving forward (in order to not introduce a variable of multiple asphalt emulsion contents). A challenge to CIR mix designs is the incorporation of water into the mix design process. Unlike traditional hot mix asphalt, asphalt emulsions inherently contain water, and additional water can be added during the mixing to help with lubrication and dust control (Cox & Howard, 2015). In order to begin the mix design process, two sources were utilized: a report from the University of Iowa (Lee, et al., 2009) and correspondence with industry on best practices. This discussion is a summary of those sources.

For the mix design process of CIR, 4-inch diameter molds were chosen so that the Marshall Stability test could be run. Material preparation for 4-inch samples utilized the fourth method of lab RAP. This method was a blend of 25% of the (P/C) aggregate and 75% of the (C/P) aggregate. The blended mix was frozen for one day before introducing it into the jaw crusher.

Once the lab RAP was created, the samples were mixed with 2% water for one minute using a mechanical mixer. Next, the asphalt emulsion was added and mixed for an additional minute before being compacted in a Troxler compactor with a water catch-pan beneath the mold. Four asphalt emulsion contents were investigated: 2%, 3%, 4% and 5%. In addition to investigating asphalt emulsion contents, the curing process was also explored. One set of compacted specimens of all four emulsion types were cured in a 60°C oven for two days, while another set of compacted specimens were cured in the oven at 40°C for three days. Based on a study conducted by the University of Iowa, the strength of samples cured in the oven at 60°C for two days should be significantly higher than that of the samples cured in the oven at 40°C for three days (Lee, et al., 2009).

Bulk specific gravity (G_{mb}) tests using the CoreLok method, ASTM D6752, and Marshall Stability tests using ASTM D6927-15 were completed on all samples at each emulsion content. The theoretical maximum specific gravity (G_{mm}) test, ASTM D2041, was run on the highest asphalt emulsion content of 5% and the other maximum specific gravities were estimated by linear interpolation by calculating the effective specific gravity of aggregates (G_{se})and applying it toward each different asphalt content. For the Marshall Stability tests, half of the samples went through vacuum saturation using the Iowa Highway Research Board method, in order to reach 55% - 75% saturation. This method consisted of soaking the sample in a 25°C water bath for 30 minutes, then applying a vacuum saturation of 20 mmHg for 30 minutes and then soaking in a 25°C water bath for an additional 30 minutes (Lee, et al., 2009). The weights of the sample before and after vacuum saturation were obtained to ensure saturation. The Iowa Highway Research Board method was used because following the AASHTO T283 method did not yield 55% saturation on samples. The other half of the samples were cured at 25°C uncovered to

represent the curing process of CIR pavement in the field (Lee, et al., 2008). The results from

the Marshall Stability test are shown in Figure 17.
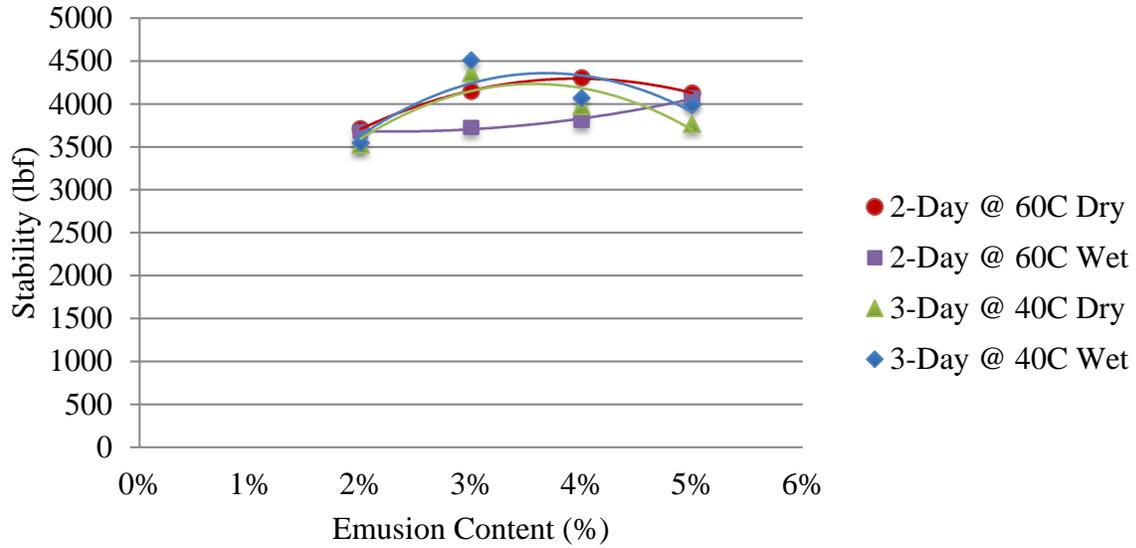
Figure 17. Marshall stability data for the preliminary study

A. Phase I

After applying the preliminary data toward compaction metrics, it was immediately

apparent that CIR did not behave in the same way as hot mix asphalt, which determined the

limits established in Table 1. Looking at Table 3, there were no samples that reached 92% G_{mm},

which was a significant variable for calculating many of the hot mix asphalt metrics.

Table 3. Preliminary Compaction Data

Type	Emulsion (%)	Sample	Gmm	Gmb	%Gmm	Final Height	Air Voids
Precoated	2	S1	2.396	1.726	72	62.6	27.97%
		S2	2.396	1.822	76	66.2	23.96%
		S3	2.396	1.809	75.5	66.5	24.51%
	4	S4	2.353	1.886	80.2	65.8	19.85%
		S5	2.353	1.848	78.5	68.3	21.46%
		S6	2.353	1.771	75.3	72.3	24.73%
Uncoated	11.52	S7	2.364	2.032	85.9	66.5	14.05%
		S8	2.364	2.091	88.4	64.7	11.56%
		S9	2.364	1.966	83.2	68.8	16.85%
	13.52	S10	2.322	2.057	88.6	66.7	11.41%
		S11	2.322	2.099	90.4	65.5	9.60%
		S12	2.322	2.107	90.7	65.2	9.26%

The emulsion content in Table 3 for the uncoated aggregates were significantly higher since these aggregates were uncoated and to be able to compare against the precoated aggregates, the binder contents needed to be equal. Since the precoated aggregates already had a binder content of six percent, the uncoated aggregates required a higher emulsion content to include the six percent binder that the precoated aggregates contained.

Another significant factor to consider is the amount of air voids in CIR. Unlike hot mix asphalt with target air void ranges between 4-6%, CIR consists of a higher air voids range that is typically between 10-12%. One study conducted by the University of Nevada Reno, evaluated two RAP gradations—one using a laboratory jaw crusher and another using milled RAP materials from the field, targeted air voids at 13.0 +/- 1.0% (Sebaaly & Hajj, 2013). A research publication by the Federal Highway Administration targeted 8-10% air voids while looking at two separate methods of incorporation RAP—one with cold mix plant recycling and another with cold in-place recycling (Federal Highway Administration, 2016). In this project, when

using precoated aggregates, the air voids exceeded the 12% and were more in the 20% range for air voids.

Since the preliminary CIR compaction data did not fit into the compaction metrics designed for hot mix asphalt, a redefined set of compaction metrics was proposed for use in cold in-place recycling (CIR). Table 4 shows the equations and significant variables used for calculating the modified compaction metrics.

Table 4. Compaction Metrics for Cold In-Place Recycling

Compaction Metric	Equation
N_{76}	$76\% \text{ Gmm} = \left(\dfrac{G_{mb}}{G_{mm}} * 100\right) * \left(\dfrac{\text{Final Height}}{h_{76}}\right)$
Locking Point	Not available
Gyratory Compactibility Index	$GCI = \dfrac{\text{height}_{n=30}}{\text{height}_{n=15}}$
Compactibility Energy Index	$CEI = \dfrac{\left(\frac{\pi d^2}{4}\right) * P * (h_{76} - h_{88})}{N_{88} - N_{76}}$
Workability Energy Index	$WEI = \dfrac{\left(\frac{\pi d^2}{4}\right) * P * (h_{n=0} - h_{76})}{N_{76}}$
Construction Densification Index	$CDI = \displaystyle\sum_{N=8}^{N76} \%G_{mm}$

1) N_{92} for hot mix asphalt is based off minimum construction air voids, however, for CIR, the air voids are different. The target air voids range for CIR is generally between 10-12%. For purposes of this research, 12% was used and doubled, therefore, the new metric should be N_{76}, the number of gyrations it takes to reach 76% G_{mm}. A comparison of the HMA N_{92} and CIR N_{76} metrics are shown in Figures 18 and 19.
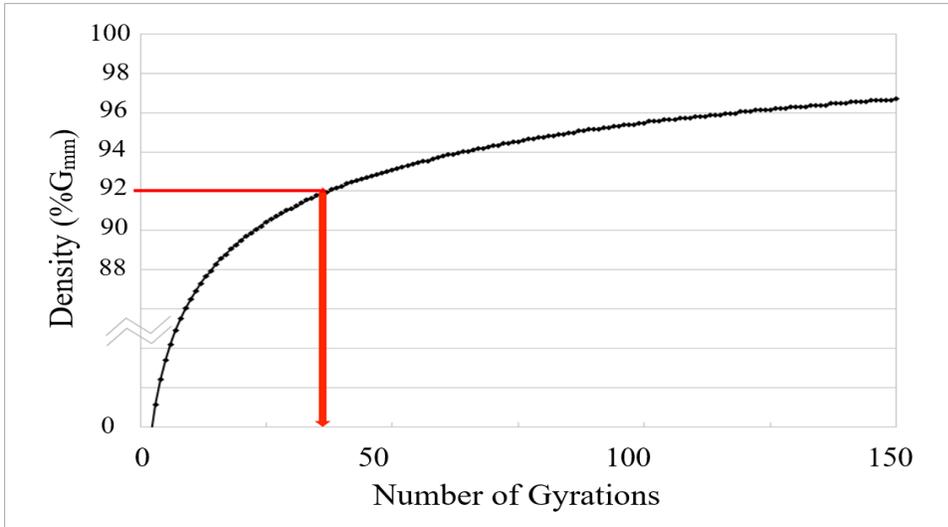
Figure 18. N_{92} metric for HMA
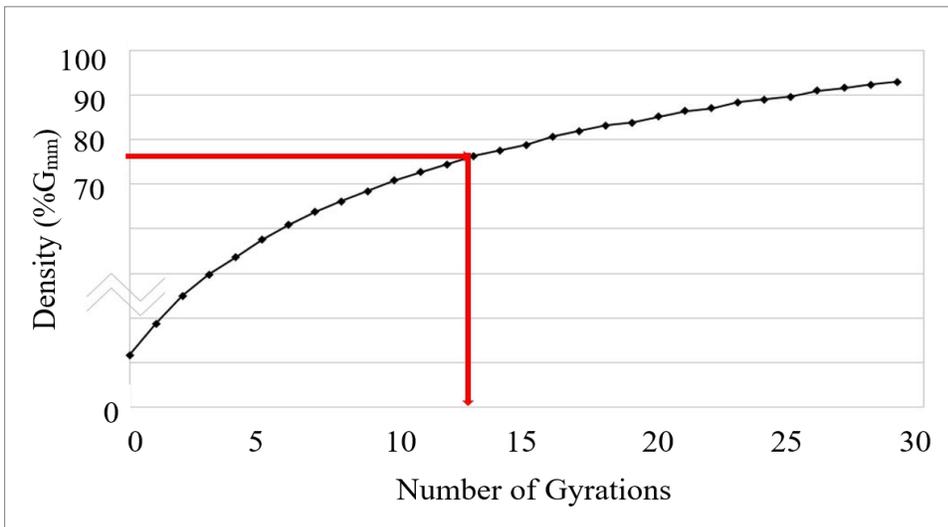
Figure 19. N_{76} metric for CIR

2) The locking point metric did not provide consistent results for CIR samples and it was decided not to move forward with the locking point when examining CIR.

3) Because the air voids were doubled for CIR in the N_{92} to N_{76} metric, a similar approach was used for the gyratory compactibility index (GCI). Since the GCI is based on heights, the heights from the hot mix asphalt metrics were divided by two, and the CIR equation

would consist of modified heights. The comparison between the HMA GCI and CIR

GCI metrics are shown in Figures 20 and 21.

$$GCI = \frac{height_{n=30}}{height_{n=15}}$$
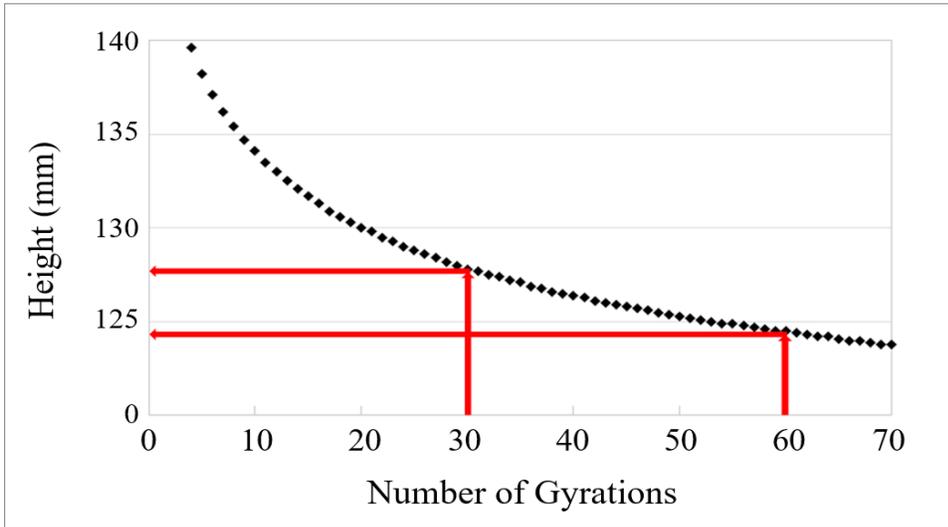
Figure 20. Gyratory Compactibility Index for HMA
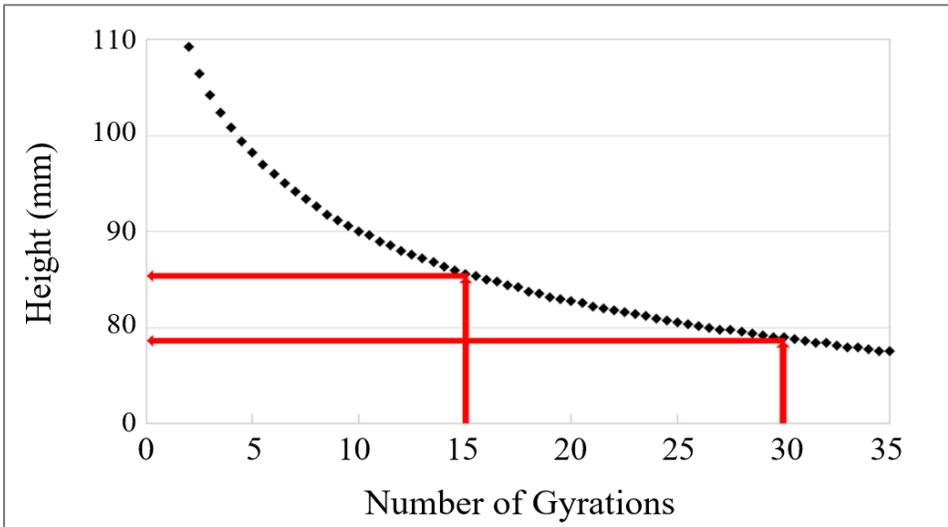
Figure 21. Gyratory Compactibility Index for CIR

4) For the compactibility energy index, the heights and number of gyrations would change

slightly, again based on the doubling principle. The comparison between the two are

shown in Figures 22 and 23.

$$CEI = \frac{\left(\frac{\pi d^2}{4}\right) * P * (h_{76} - h_{88})}{N_{88} - N_{76}}$$
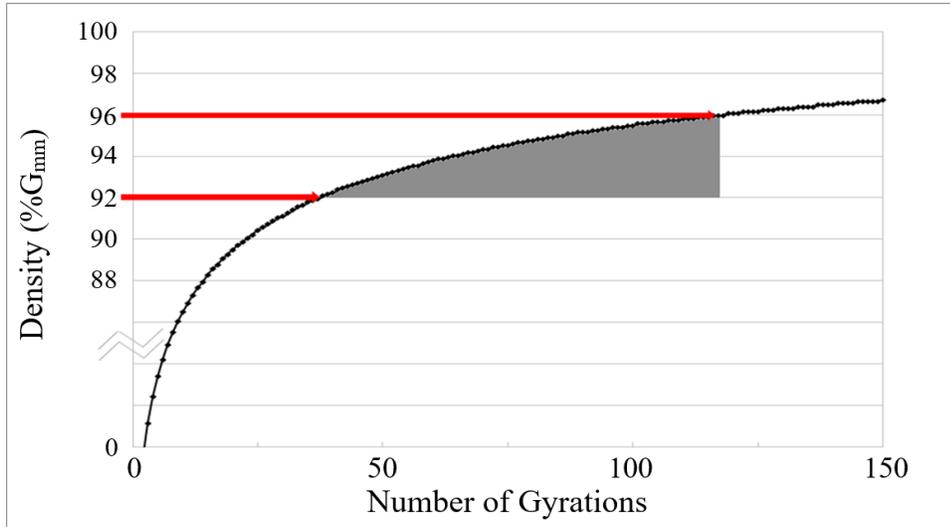
Figure 22. Compactibility Energy Index for HMA
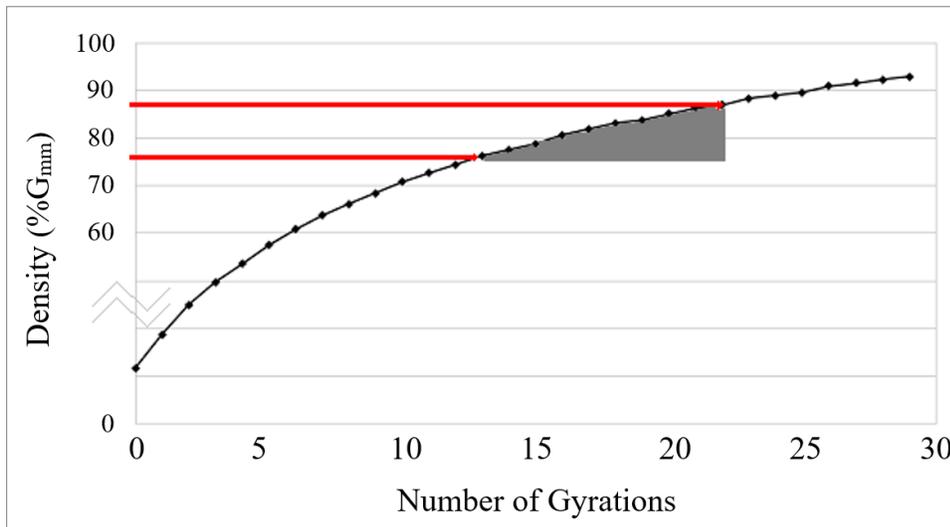
Figure 23. Compactibility Energy Index for CIR

5) The workability energy index would be modified to the height and gyration at 76% G_{mm}.

A comparison between the two are shown in Figures 24 and 25.

$$WEI = \frac{\left(\frac{\pi d^2}{4}\right) * P * (h_{n=0} - h_{76})}{N_{76}}$$

31
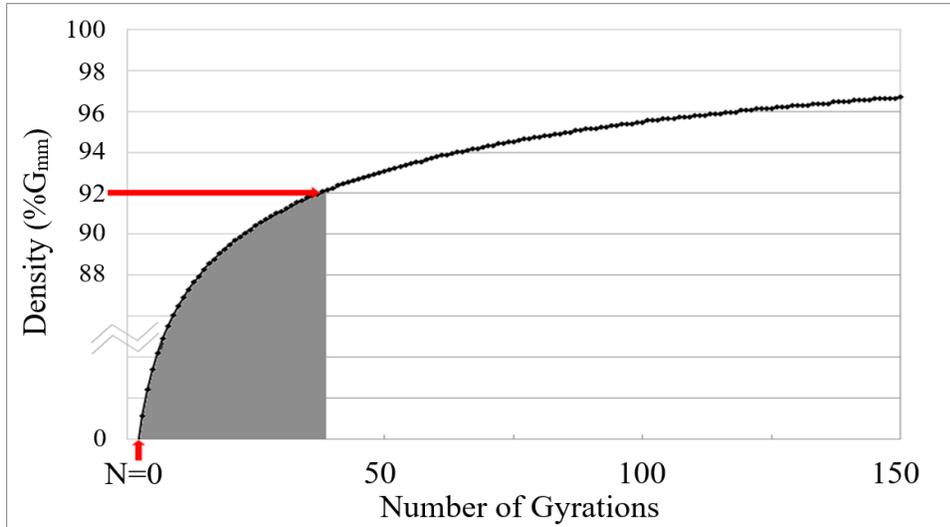
Figure 24. Workability Energy Index for HMA
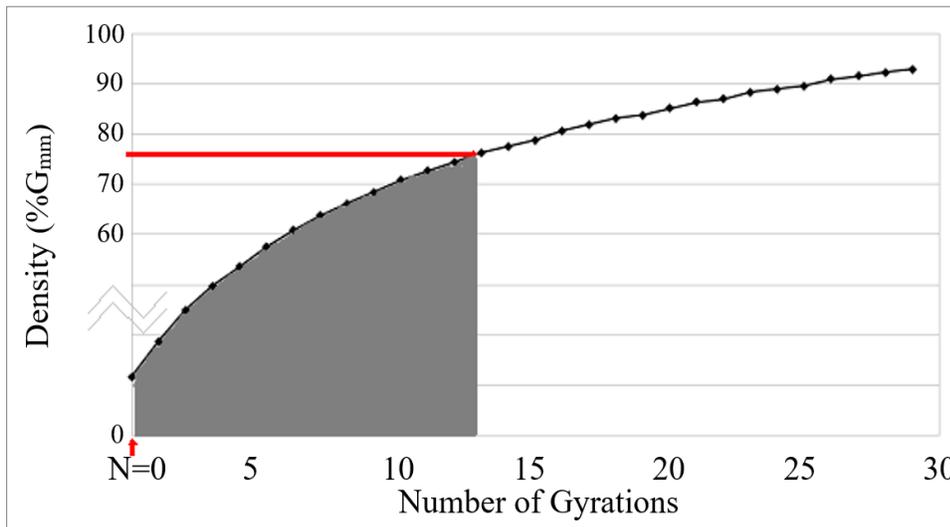
Figure 25. Workability Energy Index for CIR

6) For the construction densification index, the only modification would be to sum up the

$\%G_{mm}$ from zero gyrations to number of gyrations it takes to reach 76% G_{mm}. A

comparison between the two are shown in Figures 26 and 27.

$$CDI = \sum_{N=8}^{N76} \%G_{mm}$$

32
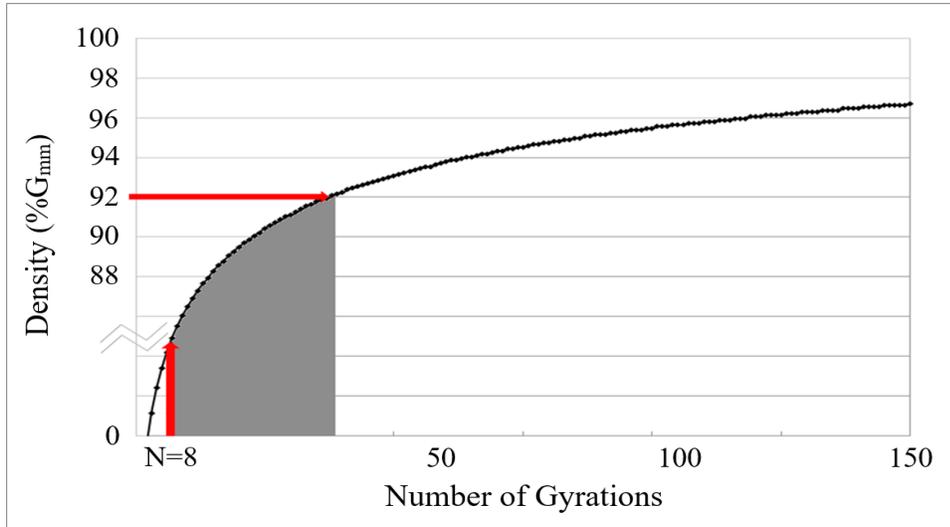
Figure 26. Construction Densification Index for HMA
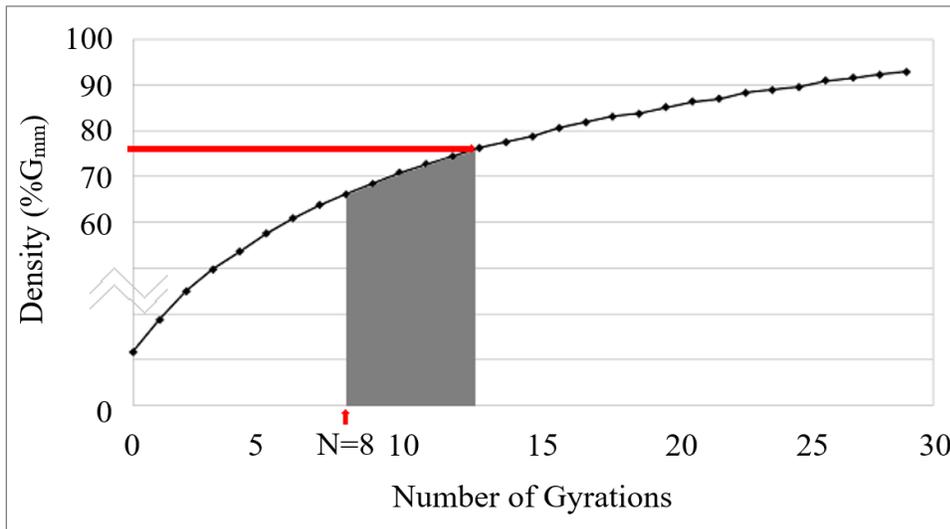
Figure 27. Construction Densification Index for CIR

B. Phase II

After establishing the method for creating lab RAP, the optimal asphalt emulsion content, and a redefined set of metrics specifically for CIR, progress was underway for the final set of data. Three replicates of each aggregate and asphalt emulsion combination were prepared to be crushed and then mixed at time periods of either immediately, one hour later, one day later or one week later before compaction. The samples were then cured at 21°C for 4 hours before running G_{mb} and raveling tests for performance.

33

VI.   Results & Discussion

A summary of the results from the compaction data and the raveling tests are outlined below. The materials used for the compaction samples consisted of three types of aggregates which were limestone, RAP and syenite. The limestone and syenite were both precoated with 6% PG76-22 binder, which is consistent with the field RAP obtained. The aggregates were then mixed with two different emulsifiers, a commodity type and a proprietary type. In addition, crushing times were varied before mixing, starting with crushing and mixing immediately, one hour later, one day later and one week later to explore any surface charge interaction and compactibility with the asphalt emulsions. Compacted samples were cured for 4 hours at 21°C before running G_{mb} and raveling tests.

A. Air Voids

Recall from previously, the amount of air voids in CIR is significant. Unlike hot mix asphalt with target air void ranges between 4-6%, CIR consists of a higher air voids range that is typically from 10-12%. When using precoated aggregates, the air voids seem to fall more in the upper range of 15-20% as indicated in Figures 28 and 29. This is not uncommon since there have been documented ranges of air voids for CIR that are as low as 2.0% and can reach as high as 22.5% (Cox & Howard, 2015).
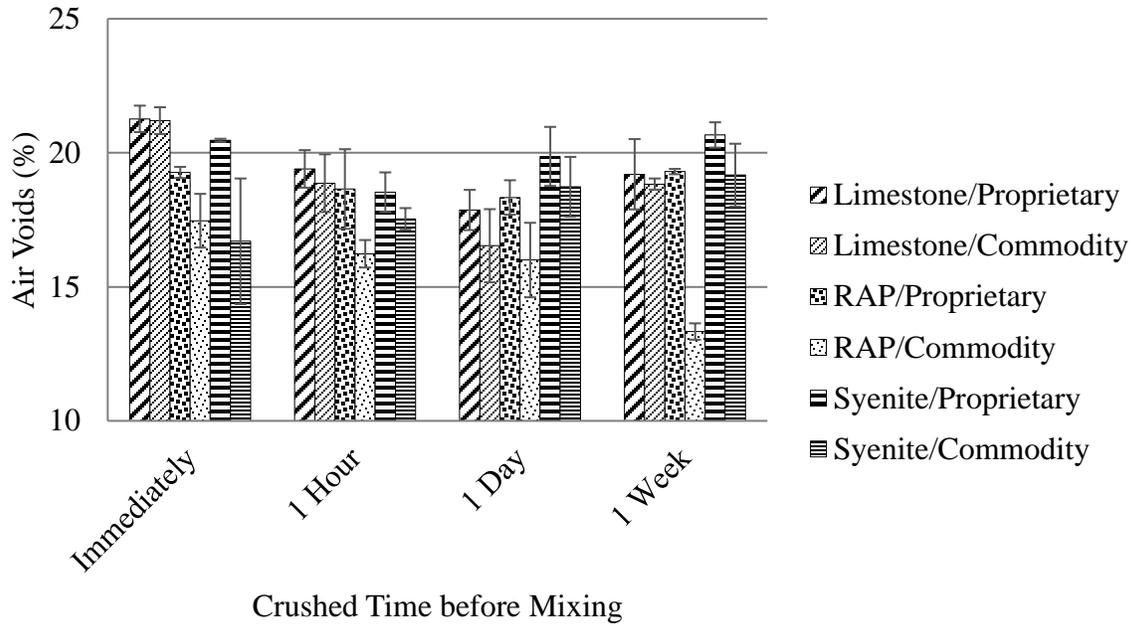
Figure 28. Air voids based on compaction data
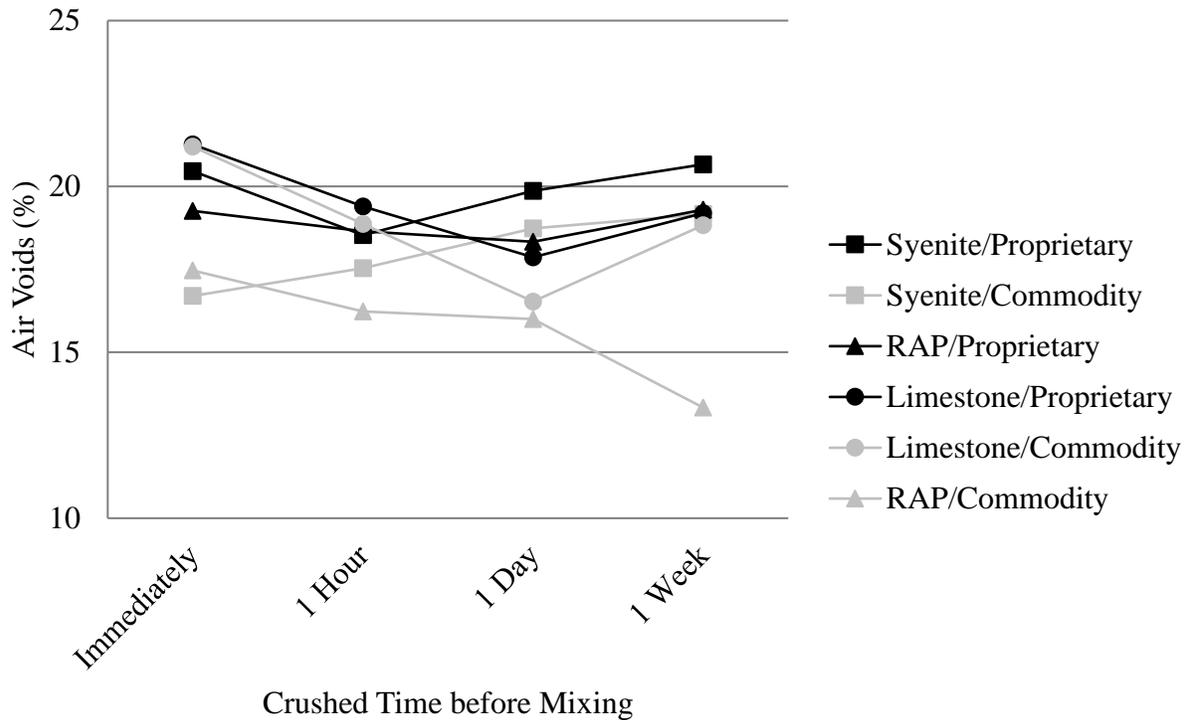
Figure 29. Air voids based on compaction data

B. Compaction Metric Results

Figure 30. Number of gyrations to reach 76% G_mm based on compaction data

Figure 31. Number of gyrations to reach 76% G_mm based on compaction data

Table 5. ANOVA three factor analysis on N_{76} compaction metric

ANOVA

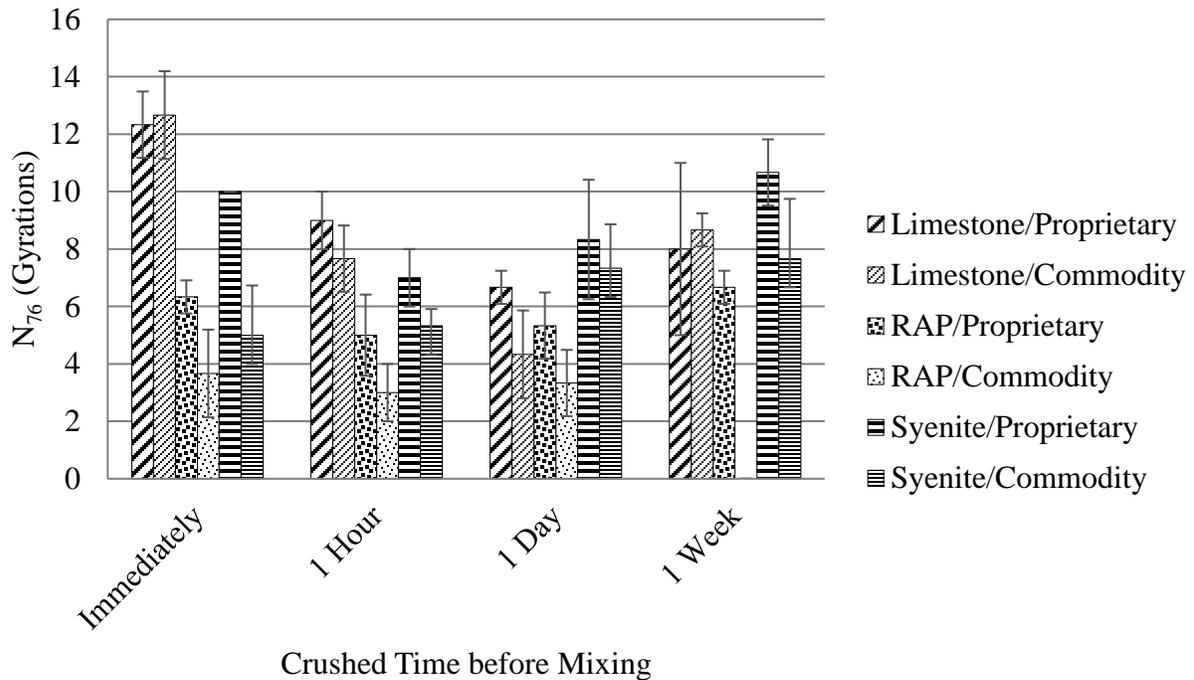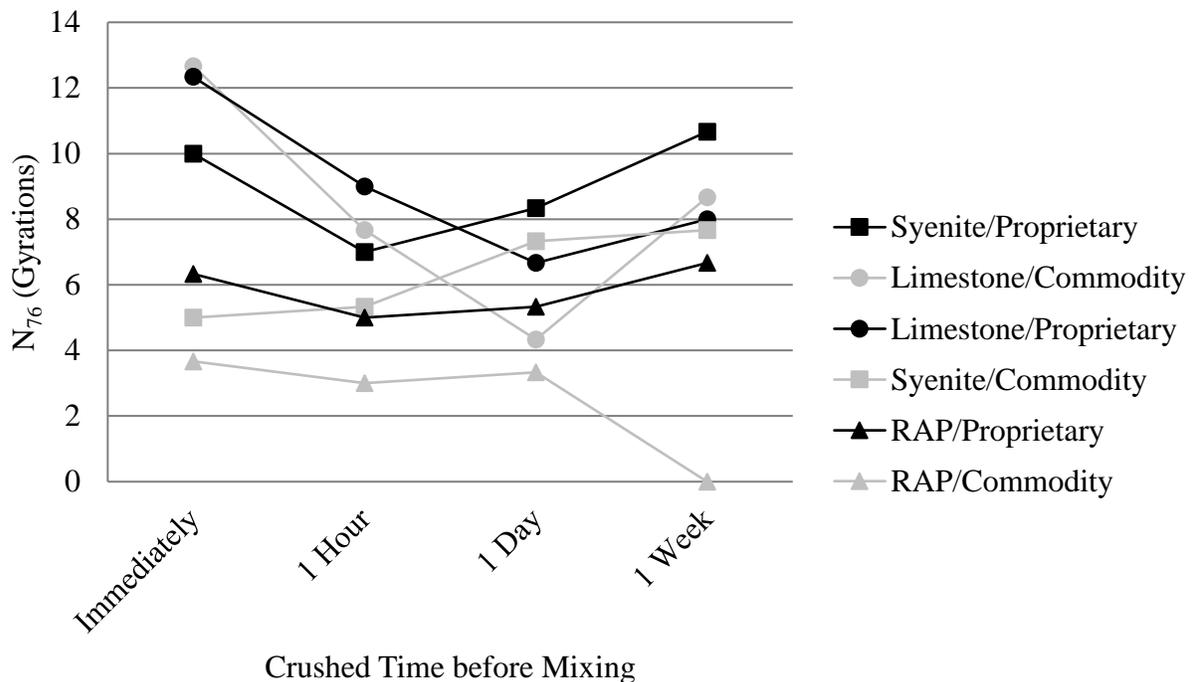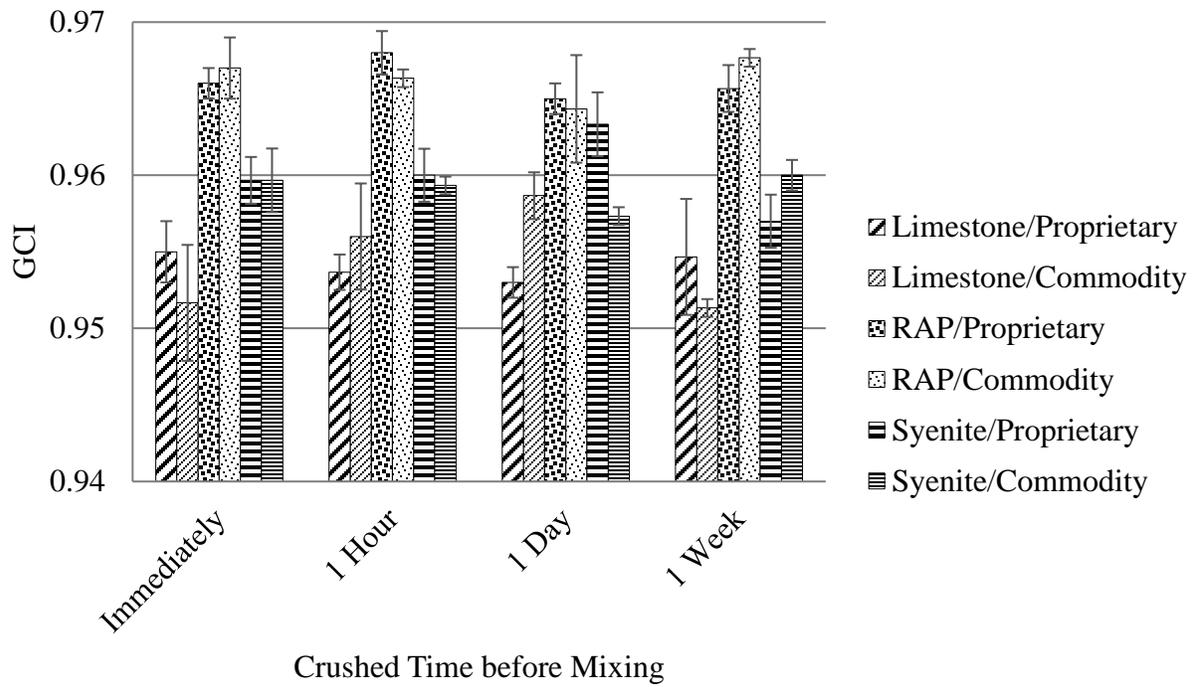| Source of Variation	SS	df	MS	F	P-value	F crit	Significant
Aggregate	268.0000	2	134.0000	77.506	1.3120E-15	3.195	Y
Emulsifier	88.8889	1	88.8889	51.414	4.5113E-09	4.047	Y
Crushing Time	64.7778	3	21.5926	12.489	3.9455E-06	2.802	Y
A x E	23.1111	2	11.5556	6.684	2.7888E-03	3.195	Y
A x C	120.8889	6	20.1481	11.654	5.8966E-08	2.299	Y
E x C	5.2222	3	1.7407	1.007	3.9812E-01	2.802	N
A x E x C	40.4444	6	6.7407	3.899	3.0611E-03	2.299	Y
Error (Within)	81.2582	47	1.7289				
Total	692.5915						

According to Figures 30 and 31, to achieve 76% G_{mm} at lower gyrations, the observed trend points toward crushing and mixing between one hour to one day as optimal times. For the limestone aggregate types, when crushing and mixing immediately, it takes more gyrations during compaction in order to achieve 76% G_{mm}, which may mean it is harder to compact. When compared within each aggregate type in Figures 30 and 31, the proprietary emulsion performed better in most cases than the commodity emulsifier based off the N_{76} metric. Field RAP is also easier to compact compared to lab RAP in the figures. Syenite and limestone lab RAPs seem to have opposite effects caused by crushing times. It may be easier to compact syenite after crushing immediately rather than one week later, but harder to compact limestone when crushed immediately rather than one week later. Based off Table 5, there is statistical significance that the averages between aggregate types, emulsifiers, and crushing times are different. Furthermore, there is also statistical significance in the interaction between aggregates and emulsifiers and also the interaction between aggregates and crushing times. However, there isn't any statistical significance in the interaction between emulsion type and crushing times. There were no RAP/commodity combination samples that reached 76% G_{mm} based off the compaction

data obtained. It is also important to note when compared to other metrics, the N_{76} metric appeared to have the smallest error bars.

Figure 32. Gyratory Compactibility Index (GCI) based on compaction data
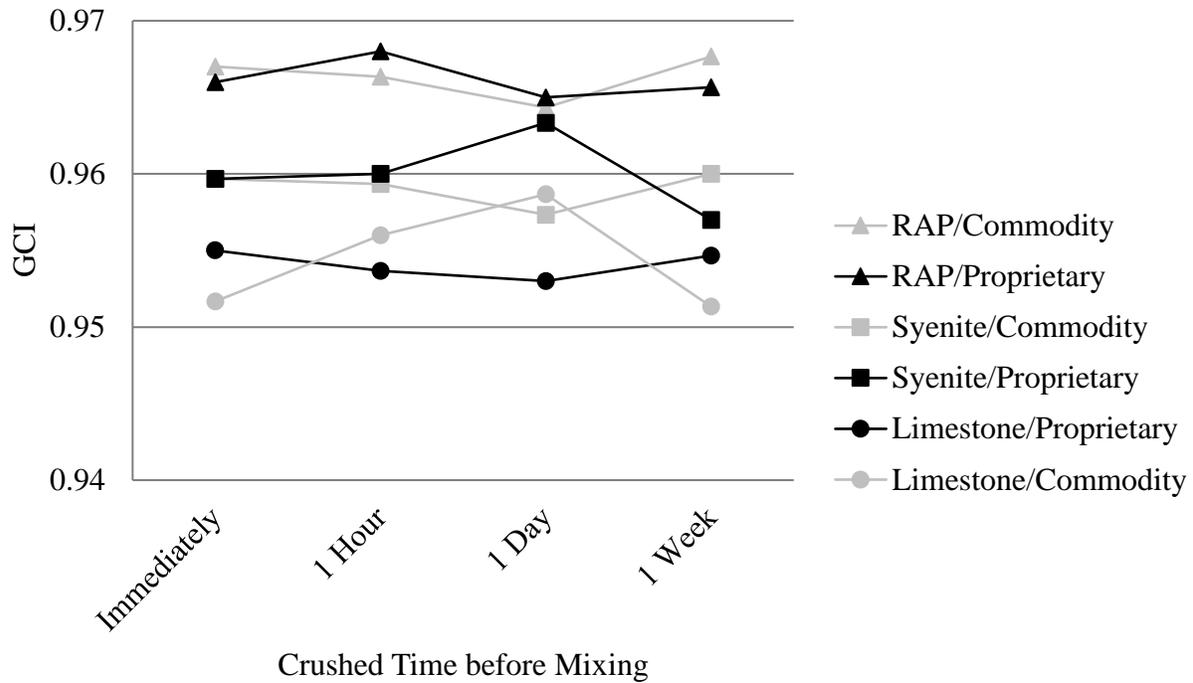
Figure 33. Gyratory compactibility index (GCI) based on compaction data

Table 6. ANOVA three factor analysis on GCI compaction metric

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit	Significant
Aggregate	1.7360E-03	2	8.6801E-04	349.714	6.0128E-29	3.195	Y
Emulsifier	3.4722E-07	1	3.4722E-07	0.140	7.1007E-01	4.047	N
Crushing Time	1.4153E-05	3	4.7176E-06	1.901	1.4239E-01	2.802	N
A x E	5.5278E-06	2	2.7639E-06	1.114	3.3690E-01	3.195	N
A x C	4.9306E-05	6	8.2176E-06	3.311	8.4291E-03	2.299	Y
E x C	4.2639E-06	3	1.4213E-06	0.573	6.3583E-01	2.802	N
A x E x C	1.6003E-04	6	2.6671E-05	10.746	1.7008E-07	2.299	Y
Error (Within)	1.1666E-04	47	2.4821E-06				
Total	2.0863E-03						

Based on Figures 32 and 33, the heights do not lower too much from half of the number of

gyrations to the full amount of gyrations. The GCI was all very similar and within 0.02 of each

other, which indicates that this is not a very good metric to use. The statistical analysis, ANOVA, was used and in Table 6, it can be seen the means are not statistically different between each emulsifier type, crushing time, the interaction between aggregate and emulsifier types, the interaction between aggregate type and crushing time. This adds to the conclusion that GCI is not a good measure to use for comparing compactibility. However, the means are statistically significant between each aggregate type and the interaction between aggregate type and crushing time.

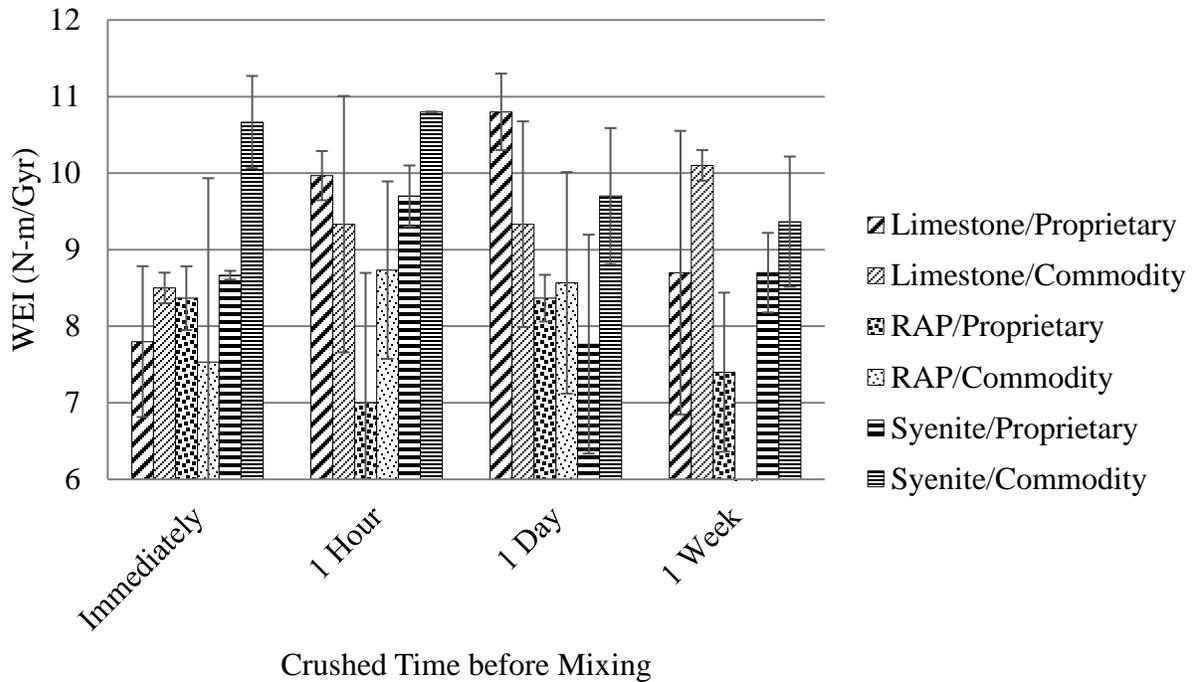**Figure 34. Workability energy index (WEI) based on compaction data**

Figure 35. Workability energy index (WEI) based on compaction data

Table 7. ANOVA three factor analysis on WEI compaction metric

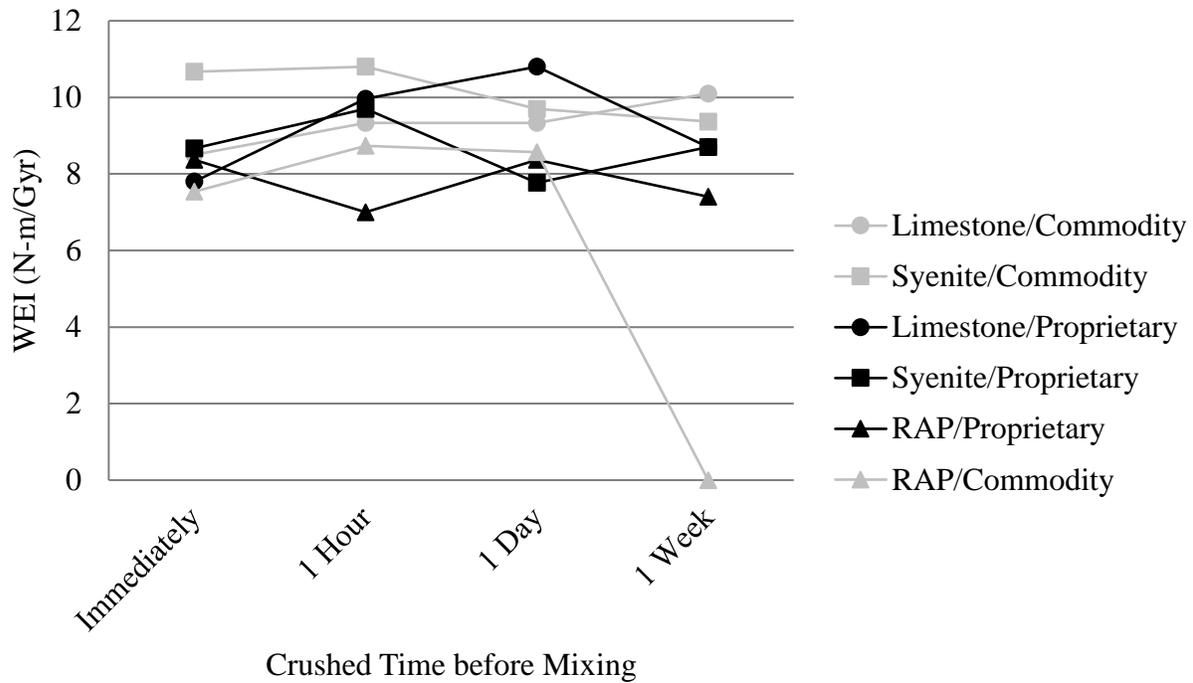ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit	Significant
Aggregate	90.2219	2	45.1110	43.238	2.2247E-11	3.195	Y
Emulsifier	0.0450	1	0.0450	0.043	8.3637E-01	4.047	N
Crushing Time	38.8933	3	12.9644	12.426	4.1533E-06	2.802	Y
A x E	27.0225	2	13.5113	12.950	3.3121E-05	3.195	Y
A x C	69.7492	6	11.6249	11.142	1.0648E-07	2.299	Y
E x C	18.5617	3	6.1872	5.930	1.6205E-03	2.802	Y
A x E x C	63.7108	6	10.6185	10.178	3.3786E-07	2.299	Y
Error (Within)	49.0356	47	1.0433				
Total	357.2400						

In Figures 34 and 35, from observations, WEI show more compaction efforts when crushing and mixing immediately or waiting to mix one day to one week later. This is similar to the results of the N_{76} metric. Based off observed trends, there is also a definite area between one hour and one day where it compacts easiest from a loose state. However, the statistical analysis

ran for this WEI metric shows there the averages are all statistically equal between each crushing time and there is not statistically significant difference between these averages. Field RAP tends to be more difficult to compact according to this metric, and the statistical analysis also shows the averages between aggregate types are not statistically equal. The ANOVA analysis in Table 7 showed the compaction data as being statistically significant for all variables and interactions between variables, except for the emulsifier type, which yielded no statistically significant difference between emulsifiers used. Again, the RAP/commodity for one week of crushing did not reach 76% G_{mm}, which yielded no available data for these samples.

Figure 36. Construction densification index (CDI) based on compaction data

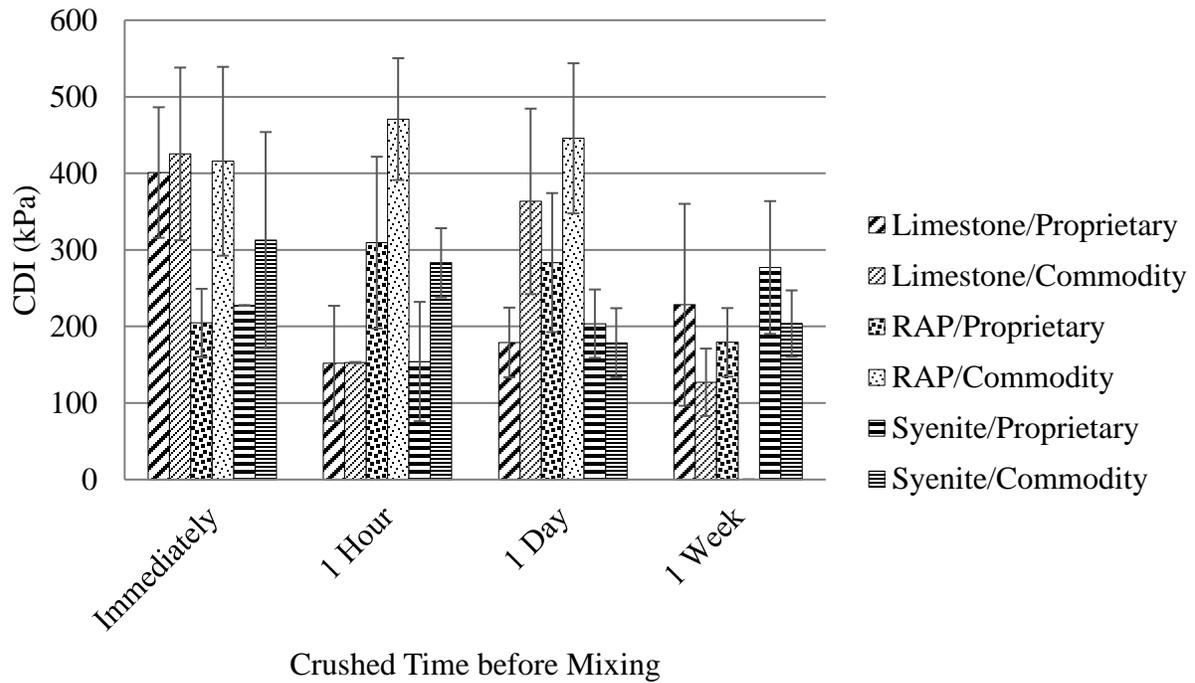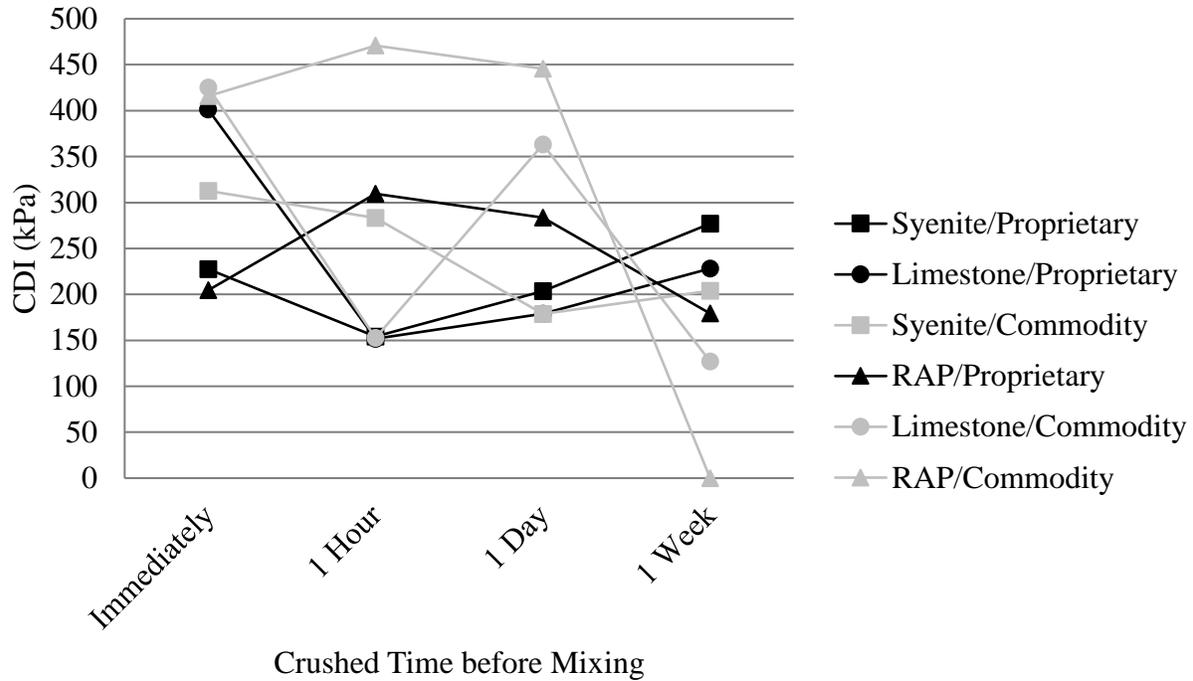**Figure 37. Construction densification index (CDI) based on compaction data**

Table 8. ANOVA three factor analysis on CDI compaction metric

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit	Significant
Aggregate	4.1704E+04	2	2.0852E+04	3.235	4.8256E-02	3.195	Y
Emulsifier	4.2036E+04	1	4.2036E+04	6.522	1.3956E-02	4.047	Y
Crushing Time	2.4418E+05	3	8.1393E+04	12.629	3.5224E-06	2.802	Y
A x E	1.4792E+04	2	7.3961E+03	1.148	3.2614E-01	3.195	N
A x C	3.6374E+05	6	6.0624E+04	9.406	8.8556E-07	2.299	Y
E x C	1.6602E+05	3	5.5339E+04	8.586	1.1876E-04	2.802	Y
A x E x C	8.2617E+04	6	1.3770E+04	2.136	6.6553E-02	2.299	N
Error (Within)	3.0291E+05	47	6.4450E+03				
Total	1.2580E+06						

For Figures 36 and 37, the observed trends show the longer the wait to mix after crushing,

the lower the CDI, which means it becomes harder to compact. This compaction metric agrees

with the previous N_{76} and WEI metrics upon visual inspection. The statistical analysis in Table 8

shows this as well, based on crushing times, the compaction data are not statistically equal and there is significant difference between the averages based off crushing times. Both emulsifiers seem to have a better interaction with crushing aggregate immediately before leveling off after about an hour using this metric. If there is aggregate reactivity like the data suggests, and if the emulsifier interacts with it, the influence appears to leave after about an hour. The ANOVA analysis performed on this compaction metric (Table 8) show that all variables and interactions between variables are statistically significant, except for the interaction between aggregate and emulsifier type. Syenite aggregate is perceived to be the more resistive of aggregate types in compaction based off this metric, and the analysis also agrees there is a statistically significant difference between aggregate types.

The compactibility energy index (CEI) was not reached based off of the compaction data taken from the Troxler compactor. The CEI metric is, once again, used to measure the compactibility and stability of pavement as it is loaded over its service life and is computed using the heights at 76% G_{mm} and 88% G_{mm}. Because the samples never reached 88% G_{mm}, this metric could not be calculated and therefore should not be included for CIR mixes. An alternative to calculating the CEI could be the raveling test, based off of ASTM D7196.

The locking point was also not reached based off of the data from the compactor. The locking point is the second gyration of two consecutive gyrations of the sample at the same height. Because the height of the sample was not repeated in the 20 gyrations used in compaction, the locking point was not calculated.

Overall, the compaction metrics selected and modified for use in CIR application seem to agree with one another, with the exception of the GCI metric. The GCI does not appear to have much significance when used in analyzing these CIR samples. According to the WEI, CDI, and

N$_{76}$ metrics, there seems to be an optimal mixing time that seems to fall between one hour of crushing and one day of crushing. Syenite tends to be the better aggregate and indicates better performance when used with the emulsifiers. Additionally, there is not one emulsifier that seemed to perform significantly better than the other based on the collected data. However, there may be higher interaction between the surface charge and emulsifier when crushed immediately, using the CDI metric. Using stockpiled RAP, or RAP that has been sitting around, may not be representative of RAP formed during a CIR process.

C. Raveling Test Results

Following compaction, samples were cured at 21°C for 4 hours before running bulk specific gravity (G$_{mb}$) tests and then the raveling test. The raveling test followed ASTM D7196, in which it required a specimen height of 70 +/- 5mm, with an initial mix amount of 2700g. The raveling test brought out challenges because using mix amounts of 2700g yielded heights of about 90mm, which could not be tested correctly. After several attempts using different mix amounts, the final mix amount used for all samples was reduced to 2100g in order to produce heights of 70 +/- 5mm. The results are as follow:
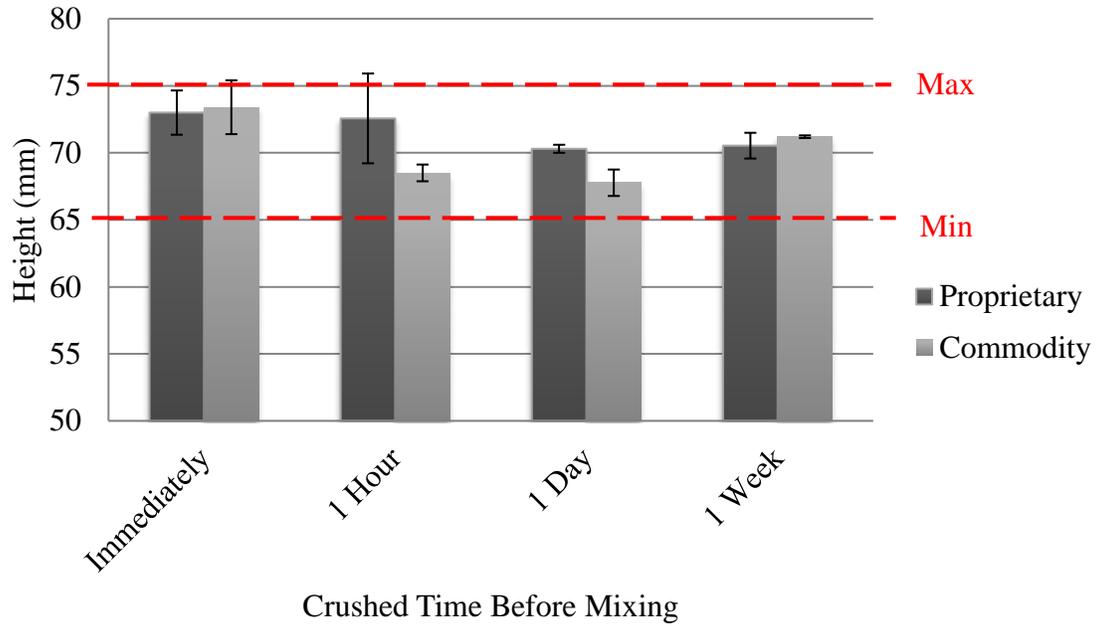
Figure 38. Height (mm) after compaction based on crushing time for limestone aggregate
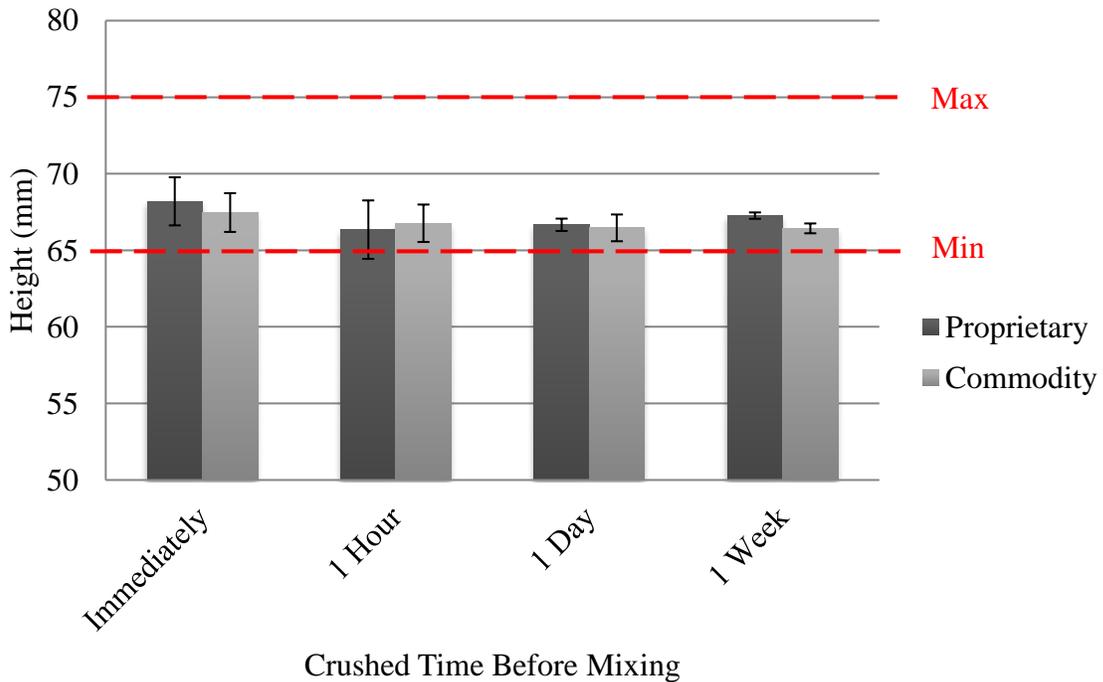
Figure 39. Height (mm) after compaction based on crushing time for RAP aggregate
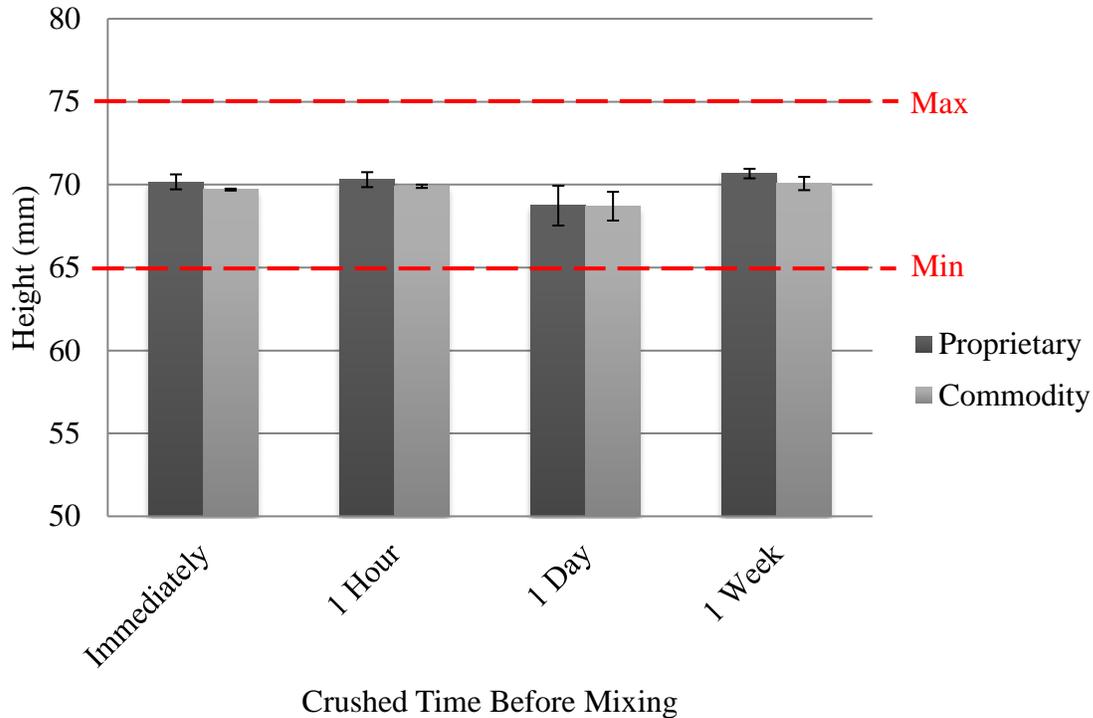
Figure 40. Height (mm) after compaction based on crushing time for syenite aggregate

Table 9. ANOVA three factor analysis on final heights based off compaction data

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit	Significant
Aggregate	199.3547	2	99.6773	85.089	2.3942E-16	3.195	Y
Emulsifier	7.1884	1	7.1884	6.136	1.6897E-02	4.047	Y
Crushing Time	42.5126	3	14.1709	12.097	5.4425E-06	2.802	Y
A x E	5.1605	2	2.5802	2.203	1.2180E-01	3.195	N
A x C	27.0940	6	4.5157	3.855	3.3000E-03	2.299	Y
E x C	2.9534	3	0.9845	0.840	4.7861E-01	2.802	N
A x E x C	23.3148	6	3.8858	3.317	8.3374E-03	2.299	Y
Error (Within)	55.0583	47	1.1715				
Total	362.6366						

According to the heights and crushing times, waiting to mix between one hour to one day after crushing is detected to yield lower heights than mixing either immediately or one week later. This agrees with the observed compaction metrics of N76, WEI and CDI, where it was

easier to compact if waiting to mix after crushing one hour to one day. In addition, according to

Table 9, the ANOVA analysis shows that there is a statistically significant difference between

the variables, as well as the interaction between aggregate type and crushing time. However, the

interaction between the aggregate and emulsifier types as well as the emulsifier type and

crushing time do not have any statistically significant difference. The commodity emulsifier was

observed to produce lower heights which may suggest better compaction, but the interaction

between emulsifier types and variables showed no statistically significant difference. Using field

RAP tends to produce lower heights, which the analysis in Table 9 also agrees with. The

analysis between the aggregate types showed that the averages were not statistically equal and

that there is a statistically significant difference between the aggregate types.
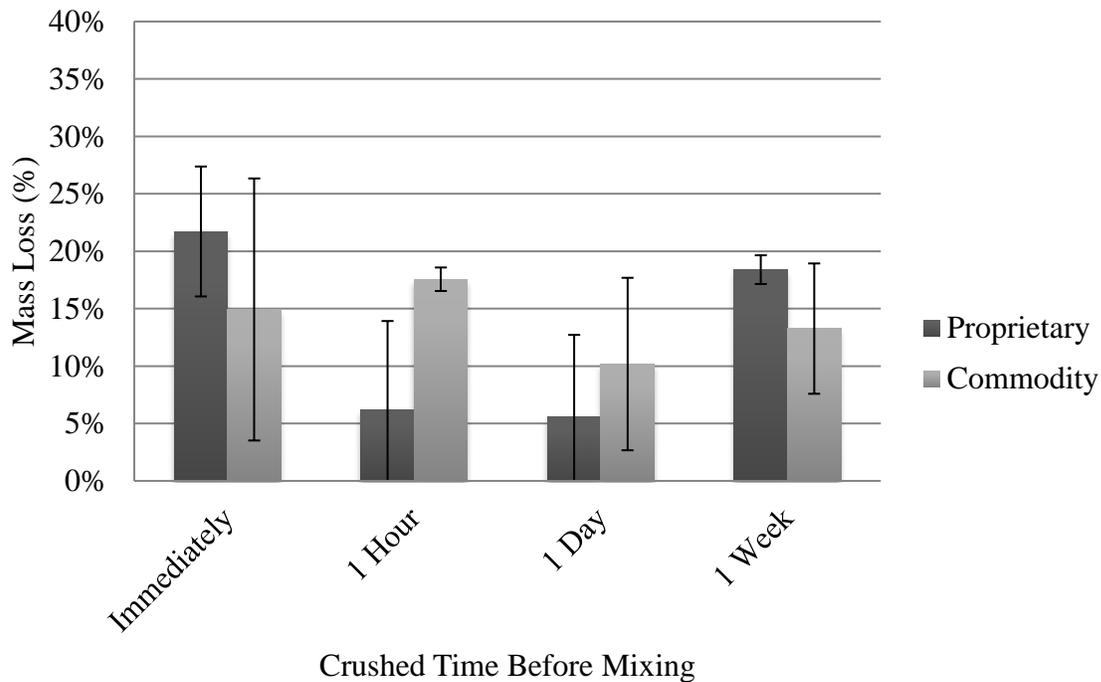
Figure 41. Percent loss for limestone aggregate based on the raveling test
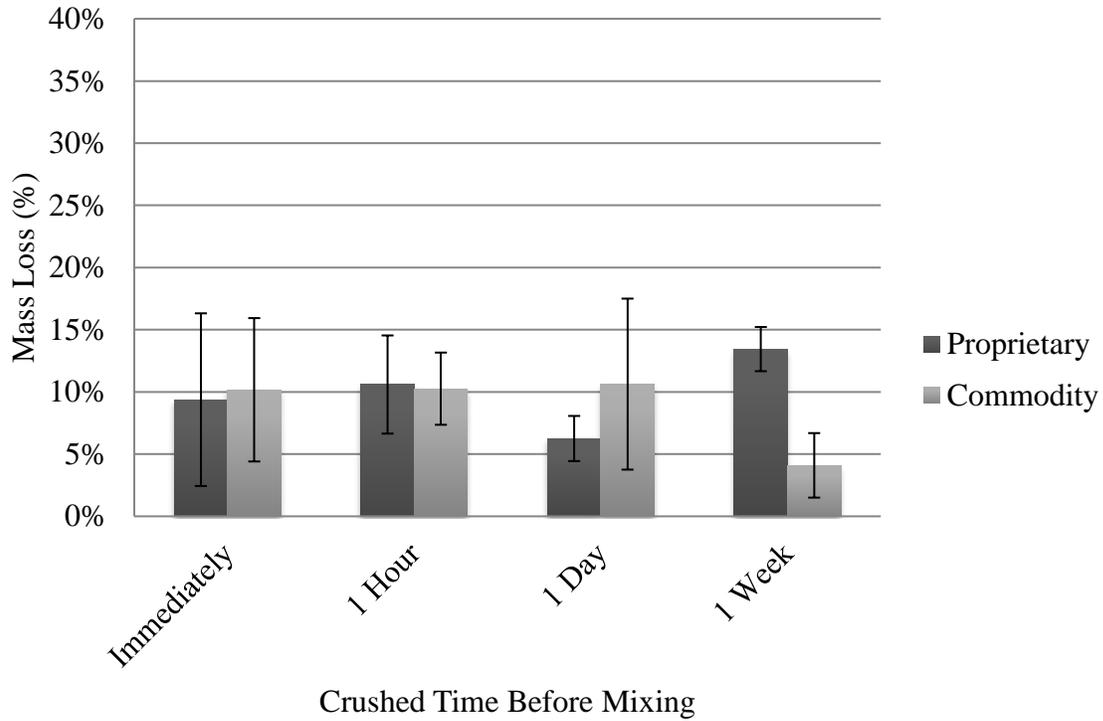
Figure 42. Percent loss for RAP aggregate based on the raveling test
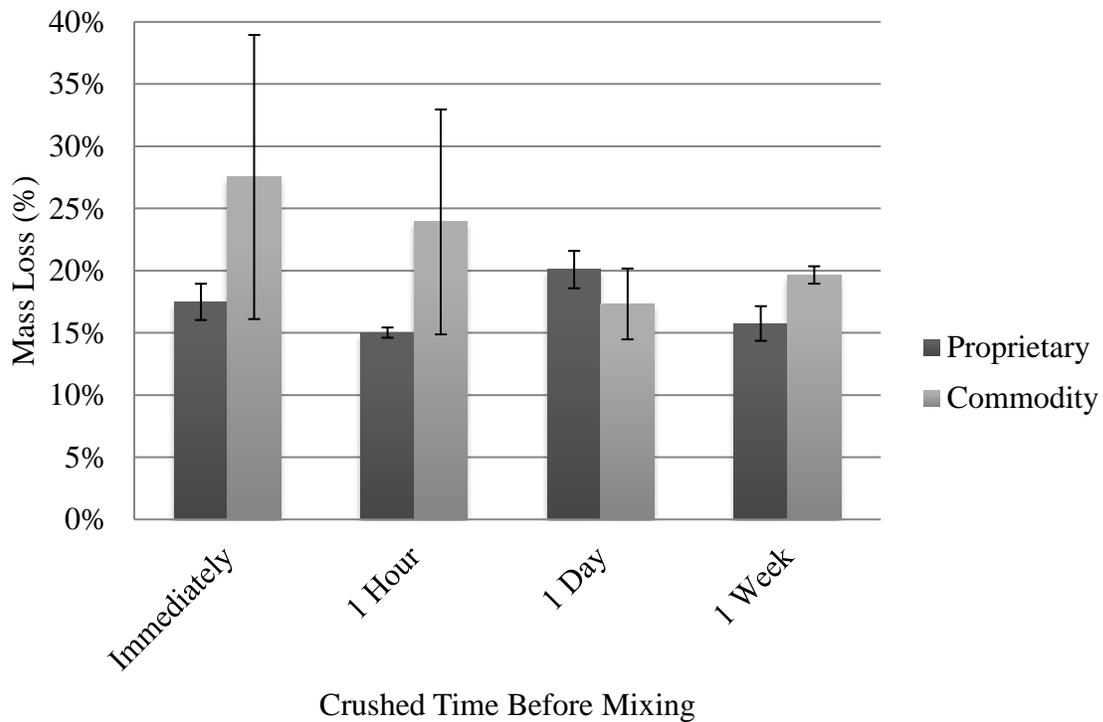
Figure 43. Percent loss for syenite aggregate based on the raveling test

Table 10. ANOVA three factor analysis on mass loss based off compaction data

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit	Significant
Aggregate	0.1275	2	0.0638	20.167	4.7489E-07	3.195	Y
Emulsifier	0.0048	1	0.0048	1.521	2.2364E-01	4.047	N
Crushing Time	0.0244	3	0.0081	2.577	6.4886E-02	2.802	N
A x E	0.0117	2	0.0058	1.848	1.6875E-01	3.195	N
A x C	0.0226	6	0.0038	1.190	3.2811E-01	2.299	N
E x C	0.0234	3	0.0078	2.467	7.3657E-02	2.802	N
A x E x C	0.0401	6	0.0067	2.112	6.9521E-02	2.299	N
Error (Within)	0.1486	47	0.0032				
Total	0.4031						

Based off observed trends, using the combination of RAP and the proprietary emulsifier produces the least amount of mass loss for each sample. RAP still shows the least amount of mass lost even with the commodity emulsifier. The proprietary emulsifier tended to do better than the commodity in most cases between the aggregates. However, the analysis in Table 10 shows that the averages between the variables and interactions among the variables are all statistically equal and that no statistically significant difference is present besides the aggregate type. Generally mixing between the one hour and one day time periods yielded the least amount of mass loss, based on Figures 41-43. However, the analysis in Table 10 disagrees and shows the averages between each crushing time are statistically equal and that there is no statistically significant difference between the crushing times.

VII. Conclusions

Based on compaction and raveling performance results, the effect of surface charge over time combined with asphalt emulsion had an observed difference on the compactibility of cold in-place recycling (CIR). The N_{76}, WEI, and CDI modified compaction metrics for CIR tended to agree that crushing and then waiting to mix after one hour to one day produced easier

compactibility for samples. The commodity emulsifier tended to produce lower heights which may suggest better compaction, but based on the raveling test data, the proprietary emulsifier had less mass loss than the commodity emulsifier within each type of aggregate. The aggregates examined showed less effort in compacting the field RAP as opposed to lab RAP. Within the lab RAP, the syenite aggregate tended to have opposite effects from the limestone aggregates whether it was crushed and mixed immediately or one week later. However, after running ANOVA analyses on the data based on aggregate types, emulsifier types, and crushing times, and the interactions between the factors, many of the observed trends such as emulsifier type and interaction between aggregate and emulsifier types were statistically equal in their averages. This means the crushing technique does not appear to create material sensitive to emulsifier type, but rather in regard to time—after one hour to one day. The one hour to one day window was seen in two completely different forms—compaction and raveling, indicating there may be important behavior changes during this time frame.

Future investigations and recommendations include:

- Modified compaction metrics seem to agree with CIR results but still need more research and possibly exploring other compaction metrics
- Field RAP still performs significantly better than lab RAP—need to examine how to better represent field RAP and use different aggregate types
- More research on commodity versus proprietary emulsifiers—what is performance based on (aggregate type, crushing/mixing time, etc.)
- Investigate commodity emulsifier's particle size distribution
- Investigate between one hour and one day to understand what the optimal time is for crushing and then mixing

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