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Return to Traffic of Full Depth Reclamation Pavements

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RETURN TO TRAFFIC OF FULL DEPTH RECLAMATION PAVEMENTS

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ABSTRACT

Full-Depth Reclamation (FDR) is a cost-effective rehabilitation treatment for deteriorated pavements. However, when using asphalt emulsion based rehabilitation techniques one of the most challenging aspects of FDR is determining when traffic can be returned to the rehabilitated pavement surface. Since asphalt emulsion mixtures need ample time for curing, they cannot be sealed with a surface layer until the water has evaporated from the rehabilitated layer. It is often not possible to keep the road closed until all of the water has evaporated and the surface layer is placed, therefore, at some point the traffic needs to be returned to the rehabilitated surface. Determining when this point occurs, however, is still unclear. A laboratory raveling test run on Superpave Gyratory Compactor prepared samples simulates the raveling that can occur on the newly recycled pavement, and will be used in conjunction with inexpensive, simple tests that can be used in the field by agencies and contractors to determine if traffic can be released without causing damage to the rehabilitated pavement surface. Three mix designs were analyzed and used in conjunction to produce the emulsion and foam samples used in the testing. An optimum emulsion content was found and used to produce all of the samples. Based on a review of literature and an evaluation of practicality, four tests are recommended to be modeled for field use: British Pendulum Tester, Dynamic Friction Tester, a field-scale cohesiometer, and a rebound tester. The in-house testers were put through numerous tests on asphalt emulsion and asphalt foam samples. It was decided that of all of the testers, the one that showed the most potential was the Sweep Tester. Alterations to improve the devices were stated after all of the testing was completed.

This thesis is approved for recommendation

to the Graduate Council.

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DEDICATION

      I would like to dedicate this thesis to my mother and father, Mike and Angie Hill and my younger brother Julian. Without their continuous love and support, I honestly could not see myself at this point in life. Seeing the joy on my parent's faces as I received my bachelor's degree was one of the greatest moments of my life. I remember my brother calling me during the middle of the graduation ceremony to tell me that he was proud of me and that he was sorry he could not make it because he was in the Navy at the time. I remember his voicemail saying, "I'm sorry I can't be there brother, but don't you worry, I'm definitely gonna make it to your next one!" My entire extended family has been instrumental in my growth as a person and as a student. I can honestly say that I am proud to call them my family. Thank you so much for always being there for me and I promise this is the last graduation that you guys will have to attend.

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Chapter 1

1.0 Introduction

1.1 Overview

In the late 1970's and throughout the 1980's recycling became an integral part of hot-mix and cold mix asphalt construction and rehabilitation (Dai et al. 2008). Full Depth Reclamation (FDR) is a pavement rehabilitation technique in which the full flexible pavement section and a predetermined portion of the underlying materials are uniformly crushed, pulverized or blended, resulting in a stabilized base course; further stabilization may be obtained through the use of available additives (Asphalt Recycling & Reclaiming Association 2001). All pavements, over the time of their use, under traffic loads and the elements, wear out. A traditional approach to dealing with deteriorated pavements is to remove the surface layer and cover with, new, additional layers or material which extends the service life of the pavement. Eventually, a road deteriorates to a point where conventional maintenance techniques will become expensive and ineffective due to the distresses in the underlying layers of the road. In this stage the pavement would typically be completely reconstructed to address its deficiencies. With the advances in high horsepower road reclaimers with the state of the art additive systems, FDR is one of the fastest growing rehabilitation techniques being specified by pavement engineers around the world (Asphalt Recycling & Reclaiming Association 2001). FDR conserves previous investments on the in place material by reutilizing it.

FDR sets itself apart from other rehabilitation techniques such as Cold Planing, Cold In-Place Recycling or Hot In-Place Recycling by always reclaiming completely through the

asphalt section and into the underlying base layers. This not only corrects the pavement distresses, but also addresses the distress mechanisms which will cause the recurring distresses and increases the structural capacity of the road. Current rotomills and stabilization equipment can effectively process to depths > 8 inches (Thompson et al. 2009). With today's innovative equipment and vast range of stabilizing additives, FDR can be utilized to depths exceeding 12 inches, although it is typically performed at 6" to 9" (Asphalt Recycling & Reclaiming Association 2001). Since they are specifically designed to recycle thick pavement layers in a single pass, modern recyclers tend to be large powerful machines, mounted either on tracks or high flotation pneumatic tires (Wirtgen GmbH 2010). The then pulverized layers become one homogenous material with improved structural characteristics. From a structural perspective, a single 300 mm thick layer of stabilized material has a far higher load-carrying capability than two separate 150 mm thick layers constructed one on top of the other (Wirtgen GmbH 2010).

FDR allows for the opportunity to add a stabilizing agent to the new base material. This can be done with a specific additive or a combination of additives. Through the use of additives many of the structural characteristics of the base can be improved. For example, when either asphalt foam or emulsion is used as an additive, the pavement behaves as a flexible bound material which achieves fatigue resistance. Through the addition of Portland cement or fly ash, added compressive strength can be achieved. In areas where freeze/thaw cycling is severe, calcium chloride can be added to reduce the freezing point of the new base. Where plasticity is a concerned the addition of lime can be used to mitigate the effects of swelling. When the overall structural capacity of the material in question is inadequate, virgin material can be brought in to increase the capacity.

This report is separated into five chapters. Chapter 2 is a literature review related to FDR. It details the applicability of FDR and all of its benefits. The process of FDR is explained in detail along with the materials that comprise it. Chapter 3 summarizes the mix design process of FDR and a detailed description of the testing required. Three separate mix design were analyzed to produce the final mixture used for all of the samples tested. Chapter 4 presents background information on five different testing methods to addressing the surface properties of pavements. From these five established test methods, in-house testing devices and methods were developed specifically for surface characterization of FDR pavements. Each of the devices was put through number of tests relating to the curing time of the samples and different methods of curing. Chapter 5 details the conclusions made from the research conducted.

1.2 Objectives

The objective of this research is to determine the ability of inexpensive and simple testing devices to quantify FDR pavement's resistance to raveling. FDR pavements are susceptible to raveling when they are released to traffic too early. There is currently no way to quantify the time at which traffic can be let onto the road after construction to prevent this. The devices will be built from parts obtained at a local hardware store. The idea to keep the cost of the devices minimal and use readily available parts is to allow DOT's and contractors to construct and operate the devices themselves.

A mix design will be followed to produce the samples to be tested in the laboratory by the in-house testers. Samples will be tested at different curing times and conditions in the attempt to identify a trend associated with the curing time. This trend will be used to evaluate

the effectiveness of the device that was used to produce it. It is believed that the resistance to raveling will increase as the pavement cures and this will be identified by one or more of the devices developed in this research.

Chapter 2

2.0 Literature Review

2.1 Overview

This chapter summarizes findings from the technical literature related to full depth reclamation. Specifically, this review will focus on the different types of full depth reclamation and a description of the construction process. Also discussed will be the material components of each type of stabilization and the properties and functions of the stabilizing agents used.

2.2 Material Components of FDR

The choice of stabilizing agent depends on several factors including the composition of the existing structure, the type of subgrade soil, and the recycling objective. If the recycled base material is mixed with untreated subgrade soil, then additives required for stabilization are used. Past and recent experiences have shown that a better-performing recycled pavement can be obtained by careful selection of the suitable type of additive. The terms additive and stabilizing agent are used interchangeably throughout this review. Different types of additives such as asphalt emulsions, foamed asphalt and chemical agents such as calcium chloride, portland cement, fly ash, and lime and combinations of these additives are added to obtain an improved base.

Asphalt emulsion is used to help increase cohesion and load bearing capacity of the mix. An emulsion is a dispersion of small droplets of one liquid in another liquid. Oil-in-water (O/W) emulsions are those in which the continuous phase is water and the disperse

(droplet) phase is an "oily" liquid. Water-in-oil (W/O) "inverted" emulsions are those in which the continuous phase is an oil and the dispersed phase is water (James et al. 2006). Figure 2.1 shows and example of the different types of emulsions.

| (a) | (b) | (c) |
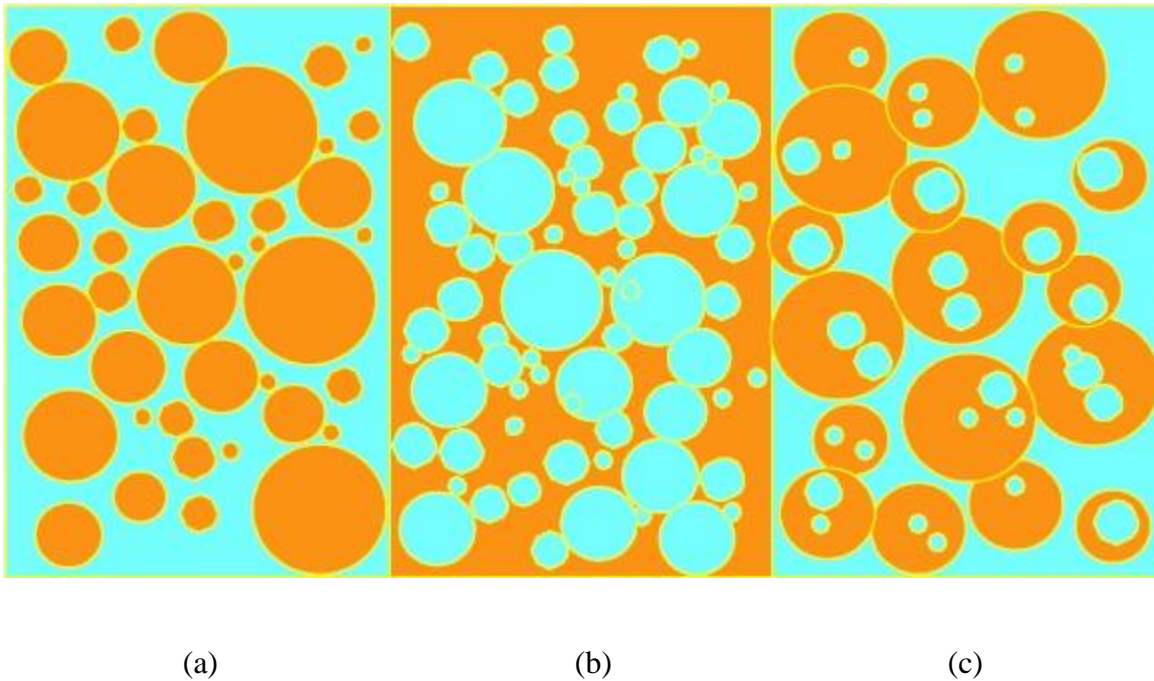
Figure 2:1: Types of emulsion: (a) O/W emulsion, (b) W/O emulsion, and (c) multiple W/O/W (James et al. 2006)

Standard asphalt emulsions are normally considered to be of the O/W type and contain from 40% to 75% bitumen, 0.1% to 2.5% emulsifier, and 25% to 60% water (James et al. 2006). Emulsion provides a lubricating action in the mixes which facilitates better compaction and packing of materials (Mallick et al. 2002). It also helps to rejuvenate and soften the aged binder present in the existing asphalt material. Cationic emulsion is generally used for FDR to ensure breaking without compromising mixing and compaction (Wirtgen GmbH 2010). The tem "breaking" refers to the evaporation of the water within the emulsion,

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leaving only the asphalt cement behind. An emulsion-stabilized base is flexible, fatigue resistant, and not prone to cracking. Emulsion treatment, with or without a small percentage of cement, has become a somewhat popular option to provide increased strength while retaining some flexibility (Sebesta et al. 2011).

Foamed asphalt is beginning to be increasingly used in FDR. Foaming of the asphalt reduces its viscosity considerably and has been shown to increase adhesion properties, making it well suited for mixing with cold and moist aggregates (Romanoschi et al. 2004). Due to the foaming capabilities there is a better dispersion of the asphalt into the materials to be recycled. A small amount of water is added to hot asphalt cement and when the two mix, the liquid expands in a small scale explosion. This expansion is approximately 15 to 20 times the volume of the original asphalt (Romanoschi et al. 2004). Figure 2.2 is an illustration of how foamed asphalt is created in an expansion chamber.
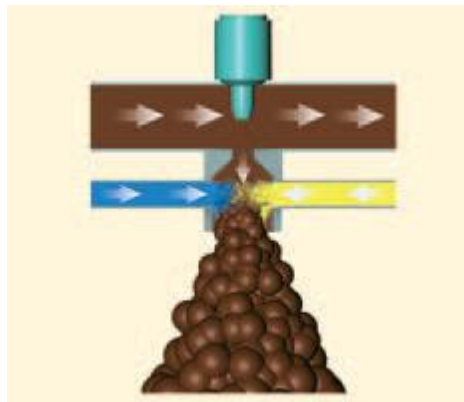
Figure 2:2: Foamed Asphalt Production in Expansion Chamber (Wirtgen GmbH 2010)

Portland cement is used to increase the compressive strength of the mixture. The addition of cement is most effective in granular and low plasticity base or subgrade. FDR with cement stabilization is especially appropriate when resurfacing is not sufficient for

rehabilitation, the existing distresses extend into the base and subgrade layers, 15 to 20 percent of the surface area necessitates full-depth patching, or the existing pavement is inadequate for projected traffic levels (Guthrie et al. 2007). When using emulsion, a small percentage of cement is sometimes added to "destabilize" the emulsion and trigger the break (Wirtgen GmbH 2010). A dual-treatment approach combining cement with asphalt stabilization can provide strength gain comparable to chemical stabilization without shrinkage cracking (Sebesta et al. 2011).

Lime is used as an additive to lessen the effect of reactive clays in the material. It reduces the plasticity within days and brings down the swelling potential associated with clays. It also serves the purpose of resisting water damage and increasing tensile and compressive strengths of the recycled mix. Lime can permanently stabilize submarginal base materials (such as clay-gravel, "dirty" gravels, limestone, caliche) that contain at least 50 percent coarse material retained on #4 screen (National Lime Association January 2004). Results indicate that the use of hot lime slurry resulted in an improvement in material properties that affect the performance of Cold-in-place-recycled (CIR) pavements, regardless of the emulsion used, and that CIR with lime could be an alternative to the use of fly ash (Cross 1999).

Fly ash is mainly used to form a cementitious bond in soil while in the presence of water and decrease permeability and strength of the mix. Previous field test sections have indicated that fly ash improves constructability and moisture sensitivity (Cross and Young 1997). The American Coal Ash Association recommends FDR with self-cementing fly ash as

an option for pavements with granular material beneath the wearing surface that are too thin, contaminated, or unstable (American Coal Ash Association 2008).

Calcium chloride is used to lower the freezing point of the reclaimed material which helps to combat against freeze thaw problems. This additive has produced results that proved its versatility and effectiveness in reducing frost heaves as well as aiding in compaction (Brown 1995). The use of calcium chloride as the stabilizing additive can facilitate compaction and improve strength relative to untreated aggregate (Morian et al. 2012). Load-bearing capacity of the base can also be improved through the addition of calcium chloride.

Table 2.1: Function of stabilizing agents

Additive	Function
Asphalt Emulsion	Increase cohesion & Load bearing capacity
Asphalt Foam	Increase adhesion
Portland Cement	Increase compressive strength
Lime	Reduces plasticity
Fly Ash	Increase strength and impermeability
Calcium Chloride	Lower freezing point

Stabilizing agents all have their specific general function and usefulness, and can be used in conjunction with one another to achieve desired results. Laboratory testing should be

carried out to determine the type and amount of stabilizing agent to be used on any specific project.

2.3 Full Depth Reclamation Process

FDR consists of four major categories that include: pulverization, mechanical stabilization, asphalt stabilization, and chemical stabilization. These four categories are discussed below.

2.3.1 Pulverization

The initial construction activity is the pulverization of the existing pavement with reclaiming machines. This includes the blending of the pavement layers and a specified amount of the underlying material. During this step is when the specific grading size is accomplished. This is controlled by the reclaimer operator, who controls the actions of the reclaimer such as: speed, cutting speed, etc. The rotating drum that rips and blends the pavement can be seen in Figure 2.3.

Figure 2:3 Cutting Tools on Milling Machines and Recyclers (Asphalt Academy 2009)

Once the material has been pulverized to the specified depth and blended successfully, water may be added to adjust the moisture content for improved compacting (Kearney and Huffman 1999). Recyclers are equipped with at least one pumping system for adding fluid (e.g. water) to the recovered material (Wirtgen GmbH 2010). By adding the water in this fashion as opposed to adding water from the surface, the moisture is consistent throughout the reclaimed material cut depth.

Breakdown compaction takes place immediately behind the reclaimer to achieve a more consistent material density throughout the reclaimed mat prior to any shaping with the motor grader (Asphalt Recycling & Reclaiming Association 2001). Shaping of the material follows the compaction to establish proper grade and cross slope to the new base course. Figure 2.4 shows the shaping of the material with a motor grader immediately after it is reclaimed.

Figure 2:4: Initial shaping with motor grader (Morian et al. 2012)

Due to drying that may occur during the shaping, water may need to be added to the surface of the material. During this step, intermediate rolling is generally done with a pneumatic roller to knead, or a heavy smooth drum vibratory compactor to seat, any loose aggregates generated by the motor grader. Following this, a finishing rolling can be done to finalize the compacting process. A fog seal of asphalt emulsion or a specific sealer is generally applied to help bond any of the loose particles and to protect from traffic and the environment before the new surface course can be installed.

Because there is no stabilizing agent added, the pulverization is best suited for structures like parking lots, where age and lack of preventive maintenance, not insufficient base thickness, is the reason for failure (Asphalt Recycling & Reclaiming Association 2001).

2.3.2 Mechanical Stabilization

This type of FDR requires the addition of imported granular material during the pulverization or the mixing pass of the reclaimer. This will require additional equipment such as dump trucks and a stone spreader to haul and spread the granular material. The material can either be spread in front of the reclaimer or mixed in during a separate blending pass. Mechanical stabilization is a fairly cost-effective alternative to simple pulverization when more structural strength is needed. The structural integrity can increase through mechanical stabilization by the addition of missing fractions of gradation sizes. When a project contains a high concentration of bitumen, mechanical stabilization can be used to thin out the concentration. Through the addition of virgin materials, the extra bitumen has more surface area to coat and thus decreases the in-place content and increases the structural stability (Asphalt Recycling & Reclaiming Association 2001). Widening and increased pavement elevations can also be achieved through mechanical stabilization. Many of the common mechanical stabilization additives are crushed aggregates, asphalt grindings (RAP) and crushed concrete (RPC) (Asphalt Recycling & Reclaiming Association 2001).

2.3.3 Asphalt Stabilization

This type of FDR requires the addition of asphalt stabilizing additives. The two types of asphalt additives are asphalt emulsion and foamed asphalt. The emulsion or foam is added during the pulverization process through the machine's integrated liquid additive system. This can be done in a single pass or in a mixing pass.

Asphalt stabilization has been in use for many years and is used to improve the strength of the reclaimed material, along with reducing the effects of water. This type of

stabilization with either foamed bitumen or emulsified bitumen as binders, behave like granular materials with retained inter-particle friction but increased cohesion, and stiffness (Wirtgen GmbH 2010).

There are many types and compositions of emulsion that have been produced to increase the performance of pavements. Through the use of core samples and laboratory mix designs of the in place material, a proper emulsion can be selected for a specific project.

After the material is blended with the asphalt emulsion, there is a period of time where the emulsion breaks. Figure 2.5 shows a side shot of the application system integrated with many of the reclaimers used in FDR construction.
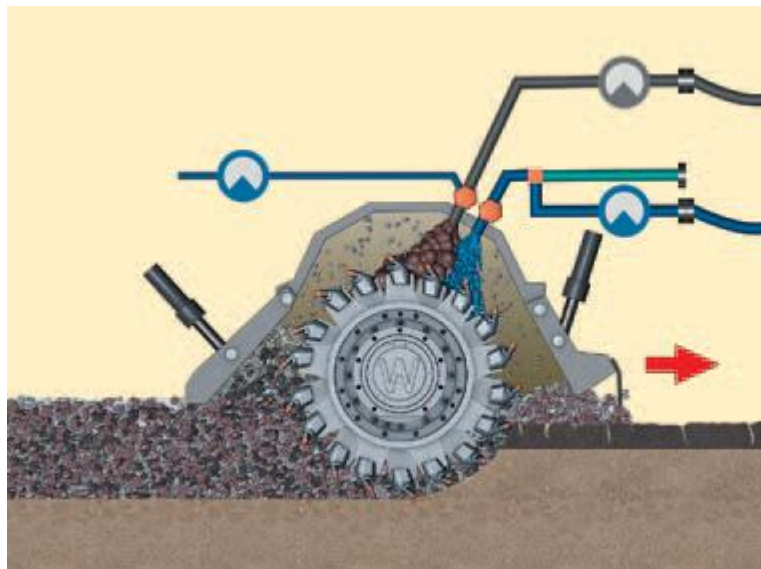
Figure 2:5: Dual application of asphalt and water (Wirtgen GmbH 2010)

The breaking of emulsion is the period of time when the asphalt particles flocculate back together and essentially squeeze out the water, leaving only the asphalt behind to coat the reclaimed material.

The break point of an asphalt emulsion can be affected by many things such as

- Environmental conditions.

- Chemical composition.

- Water evaporation or loss of water through reclaimed material absorption.

- External pressures from mixing and compaction processes.

- Chemical catalysts such as Portland cement (Asphalt Recycling & Reclaiming Association 2001).

Typically an emulsion tanker will travel in front of the reclaimer connected by a delivery hose using the reclaimer's integrated additive injection system to apply the emulsion. The emulsion tanker can be seen in Figure 2.6.

Figure 2:6: Emulsion truck connected to the reclaimer (Morian et al. 2012)

Breakdown compaction should be done immediately after the emulsion break and followed by motor grader shaping. Depending upon layer thickness and curing acceleration, final or finish rolling shall proceed following the establishment of proper grade and cross slope elevations (Asphalt Recycling & Reclaiming Association 2001). Emulsion stabilized materials can be trafficked a few hours after compaction, after the emulsion in the upper layers breaks.

Another bitumen technique gaining popularity is the use of foamed asphalt. Foamed asphalt is produced by injecting water into hot asphalt, resulting in spontaneous foaming (Asphalt Academy 2009).

One of the advantages of using foamed asphalt is that there are no manufacturing costs like there are with asphalt emulsion. Emulsion has to be manufactured off site and then hauled in to be used. With foamed asphalt the initial investment of the foaming apparatus is the only cost incurred other than the asphalt itself. Foamed asphalt stabilized material can be placed, shaped, compacted and open to traffic immediately after mixing and remains workable for extended periods of time (Asphalt Recycling & Reclaiming Association 2001). Figure 2.7 Show a side by side comparison of a emulsion mixture and a foam mixture.

Figure 2:7: Observation behind the recycler: (left) emulsion, (right) foam (Asphalt Academy 2009)

When looking at Figure 2.7, the material is sticking to the tires of the reclaimer on the right. This is either due to the asphalt not foaming or insufficient fines and represents a poor mixture. One disadvantage of using foamed asphalt is that a material with insufficient fines does not mix well with foamed asphalt. For this reason, the minimum requirement normally specified is 5% (by mass) passing the 0.075 mm sieve (Asphalt Academy 2009). When it is discovered that there are insufficient fines, importing and spreading the missing fractions is necessary. Unlike asphalt emulsion stabilized materials, the large aggregates are not coated by the asphalt foam. The asphalt foam binds to the finer materials and then acts as a mortar between the larger aggregates to bind them together.

Portland cement or lime can also be added to supply the missing fraction of fines concerning foamed stabilized materials. Also, in both types of stabilization, these materials can help increase early and retained strength, shorten the curing time and improve stripping problems (Asphalt Recycling & Reclaiming Association 2001).

2.3.4 Chemical Stabilization

This type of stabilization involves the use of dry or wet chemical additives to stabilize the base material. Portland cement, lime, fly ash and calcium chloride are some of the chemical stabilization additives used mostly for their cementitious effects on the mixture. Strength is gained through the cementing of material particles and aggregates in the reclaimed layer. The strength gain is governed by the type of material being reclaimed and the type and amount of stabilizers being used. Too much strength gain can occur when too high a percentage of stabilizers are used, adversely affecting the flexibility of the treated material. This reduces its ability to withstand repeated loading without producing cracks. The proper amount of a specific stabilizer should be determined through laboratory testing prior to construction.

The additives previously mentioned can be added in two separate forms. They can either be spread in their dry form ahead of the reclaiming machine with calibrated spreading units or in a slurry form.

Figure 2:8: Bulk Spreader (Wirtgen GmbH 2010)

The slurry form can also be distributed ahead of the reclaimer as in Figure 2.8 or it can be introduced through a spray bar that is integrated into the reclaiming machine's mixing chamber.

2.4 Conclusion from the Evaluation of the Literature

Many studies have been performed on specific full depth reclamation projects around the world looking at the long term performance of the pavement. With the large amount of variability from project to project, precedence should be put on the development of a standardized mix design so that the cost effectiveness of this rehabilitation technique can be fully utilized. Also the literature reviewed did not provide strong evidence of research being conducted in the area of returning traffic back to the FDR pavements. All that was found was

the placing of a slurry seal would be required if the pavement would need to be returned to traffic before the final surface layer could be placed.

Chapter 3

3.0 Full Depth Reclamation Mix Design

3.1 Introduction

Due to the large variability concerning materials, there is no current standardized mix design process as of yet nor is there a standardized mixture. The results of structural characterization and life-cycle cost analysis vary greatly, making it difficult to implement the results of previous studies directly as typical values for future pavement designs. Due to the increase in traffic, the deterioration of our nation's infrastructure and the push for sustainability, FDR seems to be a very strong candidate for the future of transportation.

3.2 Mix Design Requirements

Full Depth Reclamation (FDR) is a roadway recycling process in which the entire pavement and some of the underlying material is pulverized and treated with an additive to produce an improved, stabilized base. Through altering the mix proportions of aggregate, asphalt and filler material it is possible to produce a mix that behaves similar to granular materials, cemented materials or hot-mix asphalt. There are two main failure mechanisms that that need to be taken into consideration in the mix design process: Permanent Deformation and Moisture Susceptibility.

Permanent deformation is the accumulated shear deformation with loading and is dependent on the material's shear properties and densification achieved. Resistance to permanent deformation is improved by:

- Improved aggregate angularity, shape, hardness and roughness.

- Increased maximum particle size.

- Improved compaction.

- Reduced moisture content.

- Addition of a limited amount of asphalt, usually under 3.5% to decrease rutting.

- Addition of active filler, usually limited to a maximum of 1% to decrease brittleness.

The presence of water in FDR as well as the partially coated nature of the aggregate makes moisture susceptibility an important consideration in the evaluation of material performance. The presence of water in the lower layers of the FDR pavement does not allow for the emulsion to break and gain enough strength. Moisture susceptibility is the damage caused by exposure of a FDR to high moisture contents and pore-pressures, caused by traffic. This results in the loss of adhesion between the asphalt and the aggregate. Moisture resistance is enhanced by:

- Increased asphalt content, taking into consideration the cost implications and potential for permanent deformation.

- Addition of active filler, usually limited to 15% by mass of dry aggregate.

- Improved compaction

- Smooth continuous grading of aggregate

Permanent deformation and moisture susceptibility are the two main failure mechanisms associated with FDR (Asphalt Academy 2009)and need to be focused on when the optimum mixture is being developed in the lab. The problem at hand is determining what tests and specifications should be set to determine this final mixture and how to relate lab data to performance data in the field.

3.3 Comparison of current mix designs

Through a literature review of numerous FDR mix designs, it was apparent that there is no single adopted mix design. The absence of a rational mix design procedure hinders the full cost effective use of this technique and, hence, prevents the savings that can be attained by use of this procedure (Mallick et al. 2001). In earlier designs the Marshall hammer or the California kneading compactors have been used (James 2002). As laboratories in the USA move away from the Marshall compactor for hot mix design, there is a demand to use the Superpave gyratory compactor (SGC) to prepare FDR samples (James 2002). Most of the literature found pertaining to FDR was not necessarily focused on the mix design procedure. It seemed that most of what was found was project specific and focused on performance of the FDR project in question or specific additives. One example would be a study of trial sections in Virginia where the amount and types of additives were stated, but there was no procedure stated as to how the values were determined (Diefenderfer and Apeagyei 2011).

Another would be a laboratory study of FDR mixes which states that by using peak density and resilient modulus, optimum amounts of asphalt emulsion and water can be determined (Mallick et al. 2001). While this may be true, there is more to a mix design than just the selection of the asphalt emulsion. The mix design of FDR is particularly challenging due to the number and types of ingredients that comprise these materials.

Three mix designs were chosen as references to potentially synthesize into a streamlined version. The most comprehensive of the three were from the Asphalt Academy in South Africa, "A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials" (Asphalt Academy 2009). This report is based off of an extensive study done in South Africa with the SGC not being the main method for compaction. Instead the use of vibratory or Marshall Compaction is used. The report is very in depth and comprehensive. This report will be used in various ways as a reference for the overall mix design. Another of the mix designs that will be referenced was comprised by the North Carolina Department of Transportation (NCDOT), "Asphalt Emulsion Full Depth Reclaiming and Stabilization". This mix design is based on the compaction method using the SGC. Similarly the third report is the "Development of a Rational and Practical Mix Design System for Full Depth Reclamation (FDR)," also utilizing the SGC. This report seems to encompass the evaluation and development of a mix design and will be used to help synthesize the recommendations for a new one. All of these mix designs will contribute in the development of a new mix design.

3.3.1 Similarities and differences of the three mix designs

It became apparent that since all of the mix designs in question were different, that they would need to be separated into separate sections to compare. After analysis, separating them into Pre- and Post-compaction was the easiest way.

3.3.2 Pre-Compaction

It was stated in all of the designs that there needed to be some sort of sampling of the in-place material initially. Only the NCDOT mix design states an actual minimum sample size to be obtained, which is 350 pounds (NCDOT 2012). Once the sample was obtained, gradations were on the material. A gradation envelope is only given in the South African mix design while the NCDOT mix design gives one for the recycled asphalt gradation only. When determining the max aggregate size to include in the mix designs the sizes range from the largest being 50mm to 19mm. Washed gradations to determine fines content are also specified in some form in each mix design. The NCDOT mix design also asks for the sand equivalent values to be determined. The Mallick mix design states that an extraction of the asphalt binder be performed while the other two do not. Only the NCDOT mix design does not test for the plasticity of the base course materials. The South African mix design calls for the Durability Mill Index (DMI) to be run and the others do not. All of the mix designs call for finding the Optimum Moisture Content (OMC), but not necessarily through the same specific test. The South African design asks for OMC in three different forms: Unmixed, modified AASHTO compaction with emulsion added and vibratory compaction with the emulsion added (Asphalt Academy 2009). The NCDOT also selects the water content, without the asphalt emulsion, based on average annual rainfall (NCDOT 2012). The Mallick mix design determines the

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OMC through means of the gyratory compactor and then selects to add 2 percent water based on the 1:2 ratio of base course and asphalt bound materials used (Mallick et al. 2001). Mixing of the material is done by hand in the Mallick mix design while the other two use mechanical mixers. Once the samples are mixed, the NCDOT mix design states that the loose mix should be allowed to cure for 30 minutes while the other two designs state no pre-compaction curing.

There may be a few slight variations that differ between the three designs, but the main pre-compaction differences are listed here in Table 3.1.

Table 3.1: Pre-compaction comparison of mix designs

Pre Compaction			
Mix Designs	**Mallick**	**NCDOT**	**Asphalt Academy**
Sampling Size	No	Yes	No
Gradation Envelope	No	No	Yes
Max Aggregate Size	37.5 mm	31.25 mm	50 mm
Washed Gradation	Yes	Yes	Yes
Asphalt Binder Content	Yes	No	No
Plasticity	Yes	No	Yes
Durability Mill Index (DMI)	No	No	Yes
Optimum Moisture Content (OMC)	Yes	Yes	Yes
Mixing Method	Hand	Mechanical	Mechanical

3.3.3 Post-Compaction

One thing that is immediately apparent when comparing the three mix designs is the compaction method. The NCDOT mix design and the Mallick mix design both use the Superpave gyratory compaction method. This is convenient for most labs who have switched over to the SGC as opposed to Marshall or Vibratory hammer compaction, on which the South African report is based off of. While the other two use the SGC, they specify a different number of gyrations. Mallick compacts to 75 gyrations while the NCDOT design compacts to 30. Only the NCDOT design calls for early strength testing by the Modified Hveem Cohesiometer. Each mix design states a different curing time and method. The Mallick design calls for the samples to be cured at 40C and taken out every 24 hours to test for Resilient Modulus and mass. The South African and NCDOT mix designs both call for the samples to be cured for 72 hours at 40C before any further testing is done. The Mallick and NCDOT mix designs both use a vacuum sealing type of test to determine the bulk specific gravity of the compacted samples. The NCDOT design also calls for a max specific gravity to be calculated while the other two do not. The Mallick mix design relies heavily on resilient modulus testing and uses that as the main basis for selecting asphalt emulsion and water content. The resilient modulus test is also done in the NCDOT mix design along with the Indirect Tensile Strength Test (ITS). The South African mix design relies heavily on the ITS and uses it in several forms. Another difference in the South African report is that it uses monotonic triaxial testing and the Moisture Induced Sensitivity Test (MIST) while the other two do not call for them. Conveniently, the South African report and the NCDOT mix design are both split up into mix design categories. The South African report is split into three levels based off of traffic levels while the NCDOT mix design is split into two levels based off of the amount of fines in the

mixture. The Mallick design does not have designated sections for fines content nor traffic levels. When considering the types of test run in each of the designs the South African design differs by using TMH1, Standard Methods of Testing Road Construction Materials, and specified methods developed by the Asphalt Academy. The other two designs both specify the use of ASTM's. The Mallick design never specifies the compacted sample sizes needed for the testing while the other two do. The dimensions are not exactly the same, but they are fairly close. The South African and NCDOT mix design both give target values for the results from the tests while the Mallick design is more project specific and uses relationship curves. These findings are summarized in Table 3.2.

Table 3.2: Post-compaction comparison of mix designs

Post Compaction			
Mix Designs	**Mallick**	**NCDOT**	**Asphalt Academy**
Compaction	SGC	SGC	Marshall or Vibratory
Number of Gyrations	75	30	n/a
Early Strength Testing	No	Yes	No
Curing Time	10 Days	72 Hr	72 Hr
Curing Temp	40 C		
Bulk specific gravity	Vacuum	Vacuum	
Resilient Modulus	Yes	Yes	No
ITS	Yes	Yes	Yes
Triaxial Testing	No	No	Yes
Design Levels	No	Yes	Yes
Testing Methods	ASTM	ASTM	TMH1
Targeted Values	No	Yes	Yes

3.3.4 Pros and cons of the three mix designs

The South African mix design is very complete and thorough. Traffic levels are specified and values are given for each level of design that the mix design is split up into. This is very valuable and attractive when considering FDR as a potential candidate for a project. The gradation envelope is helpful when formulating the amounts of raw materials to use. The major concern with the mix design would be the main method of compaction and the testing methods. The SGC is widely used in the world now, while the Marshall and Vibratory compaction methods are not being used as much anymore. The testing methods from TMH1 are not widely used in the U.S. where the ASTMs and AASHTO are the primary testing standards. These two factors will cause contractors and DOTs from utilizing it.

The NCDOT mix design is thorough and easy to follow as well. The main method of compaction is the SGC, which almost every mix design lab has available to them. The design is split into two design alternatives based off of the amount of fines present in the mix. While this does help, it seems that having a design similar to the South African report, based on of traffic levels, would be valuable. The fact that all of the tests required are based on ASTMs is beneficial due to the familiarity that contractors and DOT's have with them. One concern is the use of the resilient modulus test. This is a test that was actually withdrawn in 2003 from the ASTMs due to its low repeatability.

The Mallick mix design also uses the SGC as its main compaction method and testing is based on ASTMs. While the method of compaction is preferred, convincing DOT's to special order the perforated type of mold specified will not be an easy task. This would also require a special type of SGC fitted to allow water to escape the mold. As stated previously

the resilient modulus is an outdated test and this mix design relies heavily on it when determining optimum levels of asphalt emulsion to be added. This was more of an investigation of a mix design so it is somewhat difficult to follow from beginning to end. There is no distinction between either traffic levels or amount of fines like the other two mix designs to base the design off of. There is also no specified gradation envelope to follow. Table 3.3 summarizes the pros and cons of the three different mix designs, and clearly shows that there is no single mix design available for FDR pavements.

Table 3.3: Pros and cons of mix designs

Pros and Cons			
Mix Designs	**Mallick**	**NCDOT**	**Asphalt Academy**
Design Levels	Con	Pro	Pro
Gradation Envelope	Con	Con	Pro
Compaction	Pro	Pro	Con
Testing Methods	Pro	Pro	Con
Easy to follow	Con	Pro	Pro

3.3.5 Unknowns of the three mix designs

The South African mix design presents so much information that there are very few unknowns to be found throughout the report. The only question that is pending is, can the mix design be adapted to the SGC and to using ASTMs and still be as effective?

When considering the NCDOT mix design one question comes to the surface. Where were the minimum target values obtained from and what level of traffic is the mix design applicable to. There is also no test to determine plasticity of the base material which can have a significant impact on the overall mixture. Again, with the use of the resilient modulus test, how heavily does this mix design depend on this test? Also there is no specified gradation other than the removal of larger aggregates and a fines content of more or less than eight percent. This should be explained further in the mix design.

The Mallick mix design also has no specified gradation envelope to base the mix proportions off of other than a maximum amount of larger aggregate. It seems as if this design is strongly based off of the resilient modulus testing and dry density to determine the optimum total fluid content. Is the resilient modulus testing accurate enough to deliver a quality mix design? It is stated that a slotted gyratory mold was used in the development of the mix design.

3.4 Producing a FDR Mixture

To continue with the overall goal to produce an acceptable FDR mixture, it was decided to follow very closely to the NCDOT mix design due to its simplicity and method of

compaction. Parts of each mix design were followed to ultimately finalize a mixture to be used in the laboratory for testing.

3.5 Pre-Compaction

3.5.1 Material Selection

By not having a FDR project nearby or one that could consistently supply material for samples, materials from a local quarry were used. The materials that were chosen for the mixture were Arkansas Highway and Transportation Department (AHTD) Class 7 base course and Recycled B RAP. Due to the amount of testing that was being proposed, these two materials were readily available and in no shortage of supply.

3.5.2 Gradation

When analyzing the three mix designs, the most thorough gradation specified was given by the South African Report and thus it was chosen to move forward. Attempts were made to try and blend the materials to fit inside of the gradation envelope specified. The gradations of the material were given by the supplier. While the mix designs call for gradations to be run on all of the material, it was deemed unnecessary because the materials gradation was later altered. The materials were all coming from the same place so the assumption was made that all of the material would generally fall in to the gradations given. To double check this assumption, gradations were run on the Class 7 base course, (ASTM C 117 and C 136), and the results were fairly close to the gradations given by the supplier. The gradations for the Class 7 base course and RAP can be seen in Table 3.4.
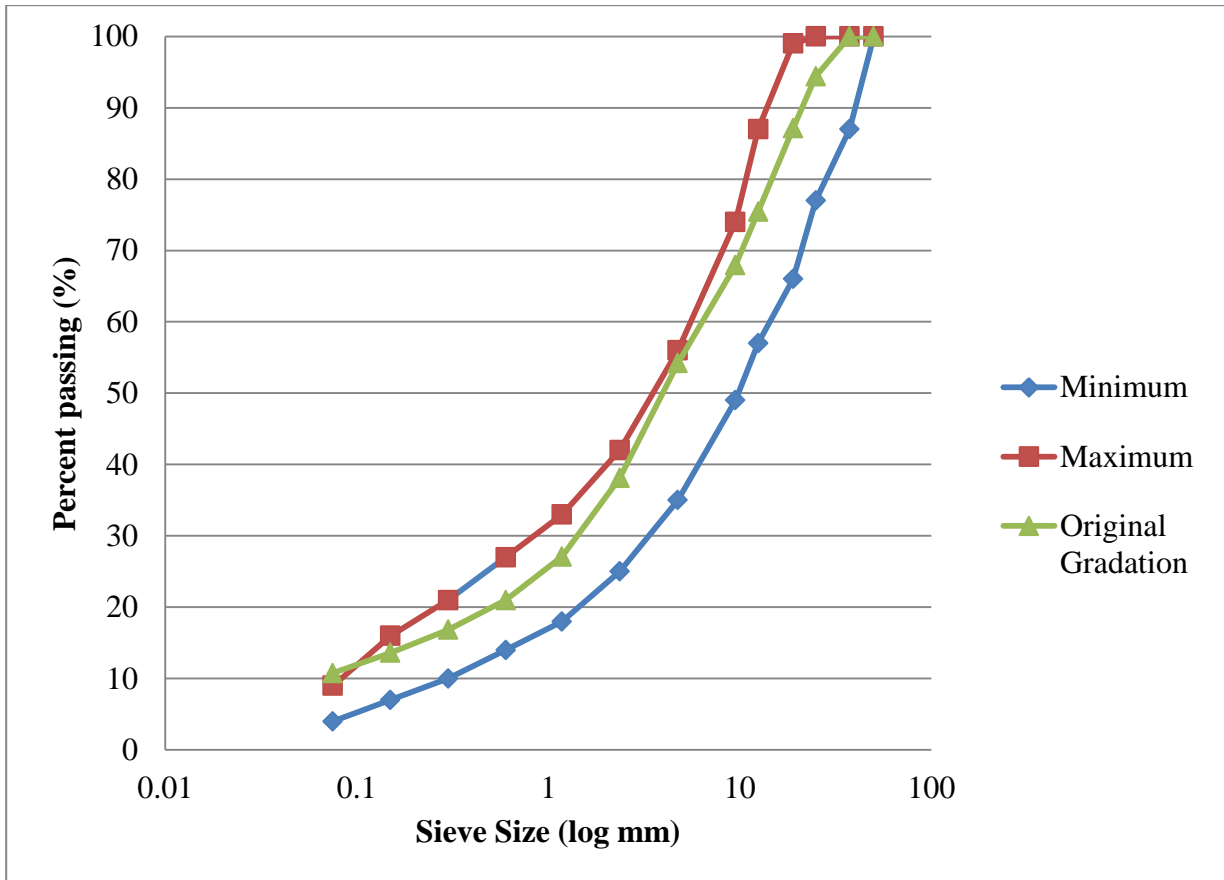
Figure 3:1: Initial Gradations and Gradation Envelope

Since most FDR mixtures would be comprised of only the Recycled Asphalt Pavement (RAP) layers and the underlying base course, only these two materials were used to form the mixture. With the gradations that were given, it was very difficult to proportion these materials in any way to achieve a gradation that fit inside of the specified gradation envelope. Therefore the decision to alter the Class 7 base course's gradation was made. The RAP gradation was not changed due to the inability to sieve the material for fear of gumming up the sieves that are used by more than just one specific research group. For simplicity the materials proportions were chosen to be 1:1, Class 7 to RAP. When mixed in a 1:1 ratio the gradation did not fall within the envelope specified and this can be seen in Figure 3.1. The

altered Class 7 and the Job Mix gradation can be seen in Table 3.4. With this altered gradation

and proportioning, a job mix was created that fit within the gradation envelope specified by

the South African mix design shown in Figure 3.2. Each of the sizes of the Class 7 material

was sieved and separated into individual buckets. Each sample was batched by adding the

necessary percentages of Class 7 to achieve the altered gradation.

Table 3.4: Final gradations and job mix

Sieve Sizes		Gradation			
(in)	(mm)	Recycle B	Class 7$_{\text{Original}}$	Class 7$_{\text{Altered}}$	Job Mix
1.969	50.0	100	100.0	100.0	100.0
1.476	37.5	100	100.0	100.0	100.0
0.984	25.0	100	94.4	*90.0*	95.0
0.748	19.0	100	87.1	*80.0*	90.0
0.492	12.5	100	75.4	*50.0*	75.0
0.374	9.5	96	67.9	*35.0*	65.5
0.187	4.8	71	54.2	*20.0*	45.5
0.093	2.4	53	38.1	*18.0*	35.5
0.046	1.2	41	27.1	*11.0*	26.0
0.024	0.6	33	21.0	*9.0*	21.0
0.012	0.3	26	16.8	*7.0*	16.5
0.006	0.2	18	13.6	*5.0*	11.5
0.003	0.1	11.7	10.8	*2.0*	6.9
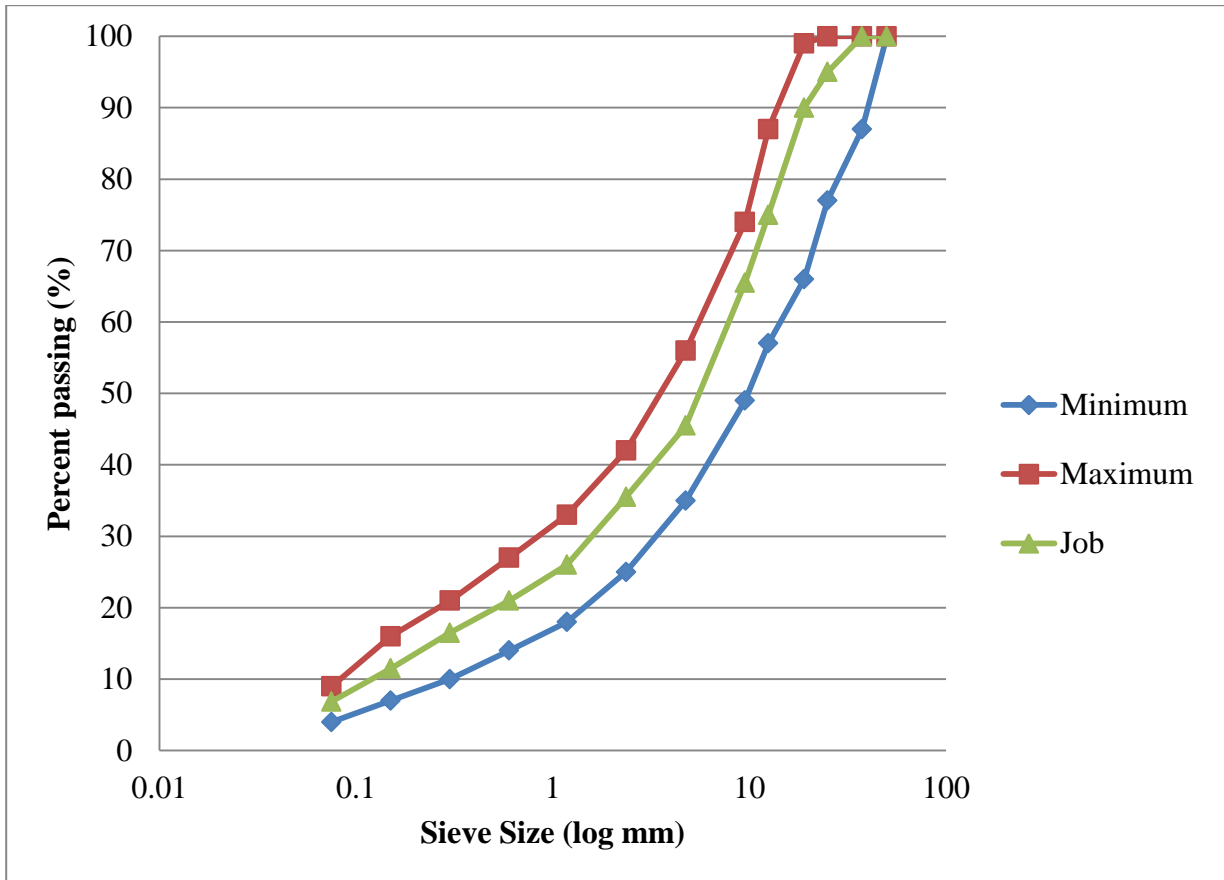
Figure 3:2: Gradation Envelope with job mix

The NCDOT mix design then stated that a Sand Equivalency (SE) (ASTM D 2419) test was to be run on the material. This test was not run on the material. Therefore we assumed that our SE would be a lower value since we were only using Class 7 and RAP in our mixture which contain little to no claylike particles.

3.5.3 Selection of Optimum Moisture Content

A modified proctor test (ASTM D 1557, Method B) was conducted on the materials chosen to make up the mixture. The NCDOT mix design states that Method C should be used,

but from the aggregate blend we created, the material fell under Method B, therefore Method B was run. According to the specification, only material passing the 3/8" (9.5-mm) sieve was used in the test. The moisture contents used to conduct the test were, 2%, 4%, 6%, 8%, and 10%. It should be noted that when the test was performed, at 10% moisture, water was seeping out of the mold. This seemed to be a fairly excessive amount of water and produced a very large density value, therefore it was discarded and only the four lesser water contents were plotted in Figure 3.3. The results from this test found that at approximately 5.375% water content, the highest density was achieved at around 111.1 lb/ft^3. This value was determined to be the optimum moisture content and was used throughout the rest of the testing as such.
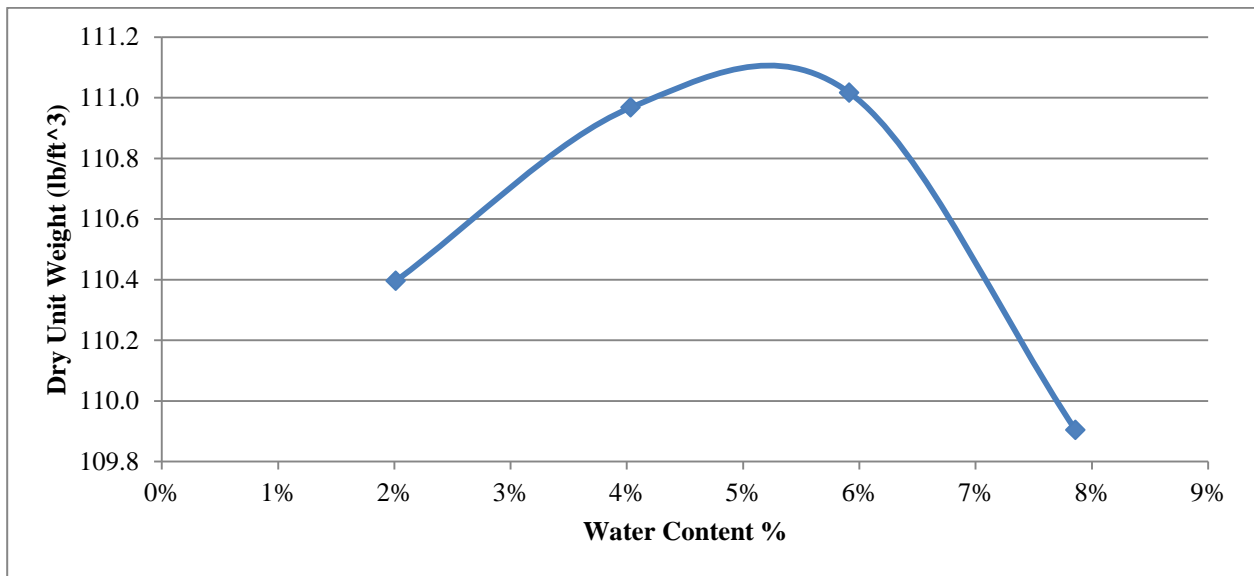
Figure 3:3: Results of modified proctor test

When selecting the water content for design, the NCDOT mix design uses a percentage of the OMC based on average annual rainfall and sand equivalency value. It splits

it up into two sections, greater than or less than 20" and a SE of greater than or less than 30. The assumption was made that the area in question would be Fayetteville, AR, which has an average annual rainfall of 46" and since we were unable to run a SE test we were unable to attain a SE value. The NCDOT states the selection of water content for design as follows;

For average annual rainfall > 20 in.

- 60 – 75% OMC if SE ≤ 30

- 40 – 65% OMC if SE > 30

We did not have a SE value so we chose a design water content that was 50% of the OMC because we assumed that we had little to no claylike particles in our materials which would give us a value greater than 30.

3.5.4 Preparation of Samples

With the gradation and moisture content now set, we could begin creating samples for testing. The NCDOT mix design calls for three mechanical tests and two volumetric tests to be run. All of these tests require specimens to be 70 to 80 mm tall. From the proctor curve the material required to produce samples of this height was found. The sample size consisted of 1250 grams of the Class 7 blend and 1250 grams of RAP, producing a total sample size of 2500 grams. The samples were all batched individually and the altered Class 7 gradation was added in each specific sieve size. The RAP was split into the appropriate amount for each sample.

The mixing of the samples calls for a mechanical mixer with a bowl of 10 to 12 inches and rotates 50 to 75 revolutions per minute. The mixer should also have a mixing paddle that makes contact with the side and bottom of the bowl. The mixer used can be seen in Figure 3.4.

Figure 3:4: Mixing Bowl

The mixing of the samples was done in two parts. The water was introduced into the sample for 60 seconds and then the emulsion was introduced for an additional 30 seconds. The emulsion used was supplied by ERGON Asphalt & Emulsions, Inc. The chemical name of the emulsion is CIR-EE. A residue test was conducted on the emulsion and it was found to

contain 60-70% asphalt as detailed in the ingredients. All of the samples were mixed at room temperature.

With an unknown target emulsion content, a large range of emulsion percentages were tested. The samples were mixed at emulsion contents of 1%, 2%, 4%, 4.25%, 4.75%, 5.5% and 6%.

3.5.5 Curing before Compaction

Once the samples had been mixed they were allowed to cure in plastic containers that were 6 inches in diameter and 12 inches in height. The samples were cured in the plastic concrete cylinders due to the large number of samples that were being made. There were many concrete cylinders available which made it easier to prepare large numbers of samples. The mix design actually called for the containers to be 4 to 7 inches in height and 6 inches in diameter. It was assumed that the taller cylinders had minimal effect on the curing of the samples. The same amount of surface area was exposed for each sample during the curing, the only deviation from the specified containers was the height. This was not tested. The samples were set in an over at 40°C for 30 minutes according to the NCDOT mix design.

3.6 Compaction

Specimens were compacted in a specially design slotted gyratory mold obtained through Troxler Electronic Laboratories. This was used as opposed to a closed mold to better represent the compaction of the recycled mixture in the field. When the mix is compacted

with a roller in the field, water is allowed to escape, and therefore the mix loses moisture as and when it is compacted (Mallick et al. 2001).With a closed mold there would be no way for the water to escape and pore pressures would build up. The mold can be seen in Figure 3.5.

Figure 3:5: Slotted gyratory mold

According to the NCDOT mix design, samples were compacted to 30 gyrations, at 600 kPa, and an internal angle of 1.25°. The only deviation from the mix design was that the 600 kPa pressure was not applied for 10 seconds after the last gyration. The Model 5850 Superpave™ Gyratory Compactor was used to compact all of the samples and is shown in Figure 3.6. This specific compactor differed from normal SGCs because it was designed to handle the water that was present in the samples. All of the samples were compacted at room temperature.

Figure 3:6: Troxler Gyratory Compactor

3.7 Post Compaction

3.7.1   Sample extrusion cell

Once the specimens had been compacted they were removed from the mold to cure. However, samples made with recycled material and with emulsion may not be sufficiently stable to allow extrusion immediately after compaction, as it takes time for the emulsion to fully cure. The samples were very easily disturbed during the removal process so a sample extrusion cell was developed. The device can be seen in Figure 3.7. The cell was placed over the sample as it was extruded from the gyratory mold and then used to move the sample.

Figure 3:7: Extrusion cell, top and bottom

3.7.2 Curing

Immediately after compaction samples were transferred to an oven and cured for 72 hours at 40°C. The samples were not removed from the extrusion cells for fear of them falling apart. The extrusion cells were perforated in the same manner as the gyratory mold used so that the sample would not be entirely enclosed on the sides and bottom. The Mallik mix design also stated the use of an extrusion cell to aid in the handling of the samples. After the samples had cured for 72 hours they were allowed to cool at 25°C for 24 hours before any tests were conducted.

3.7.3 Volumetric Measurements

After cooling to ambient temperature, all of the samples were tested for bulk specific gravity according to ASTM D 6752. The samples were not tested according to ASTM D 2726 for fear that they would fall apart once immersed in water. The samples were vacuumed seal

using the Corelok® method shown in Figure 3.8. Maximum specific gravity was determined

for each of the emulsion contents that were tested according to ASTM D 2041. The values for

each emulsion content can be seen in Table 3.5.

Table 3.5: Volumetric measurements

Emulsion Content	1.0%	2.0%	3.5%	4.0%	4.3%	4.8%	5.5%	6.0%
Average G_{mb}	2.04	2.06	2.04	2.10	2.08	2.09	2.12	2.14
Average % Air Voids	19.36	17.89	17.69	14.76	15.68	14.60	13.22	11.72
G_{mm}	2.53	2.51	2.48	2.47	2.47	2.45	2.44	2.43
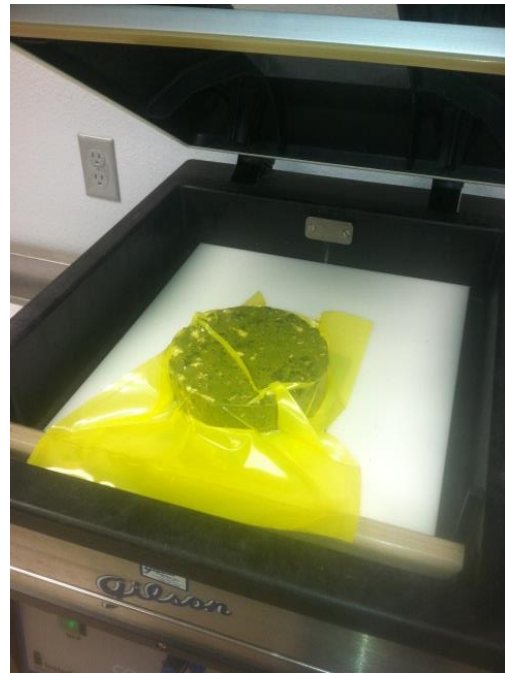
Figure 3:8: Corelok® Machine and Sealed Sample

3.7.4 Mechanical Measurements

After samples had cured for 72 hours they were prepared for strength testing according to ASTM D 4123. The samples were separated in to two sets for Indirect Tensile Strength (ITS). One set was placed in an oven and cured for another 24 hours at 25°C. The other samples were then partially saturated between 55% - 80% before being submerged in a water bath at 60°C for 24 hours. Immediately after the 24 hours, the unconditioned samples were set out at ambient temperature while the conditioned samples were transferred to a water bath set at 25°C. The samples were then tested with the Pine ITS loading machine in Figure 3.9. From the conditioned and unconditioned samples, the average tensile strength of the dry subset (S_{td}), and the average tensile strength of the moisture-conditioned subset (S_{tm}) was determined. The data obtained from the testing is displayed in Figure 3.10 and Table 3.6. The two dashed lines on Figure 3.10 display the minimum and maximum values suggested from the NCDOT mix design.

Figure 3:9: ITS loading machine
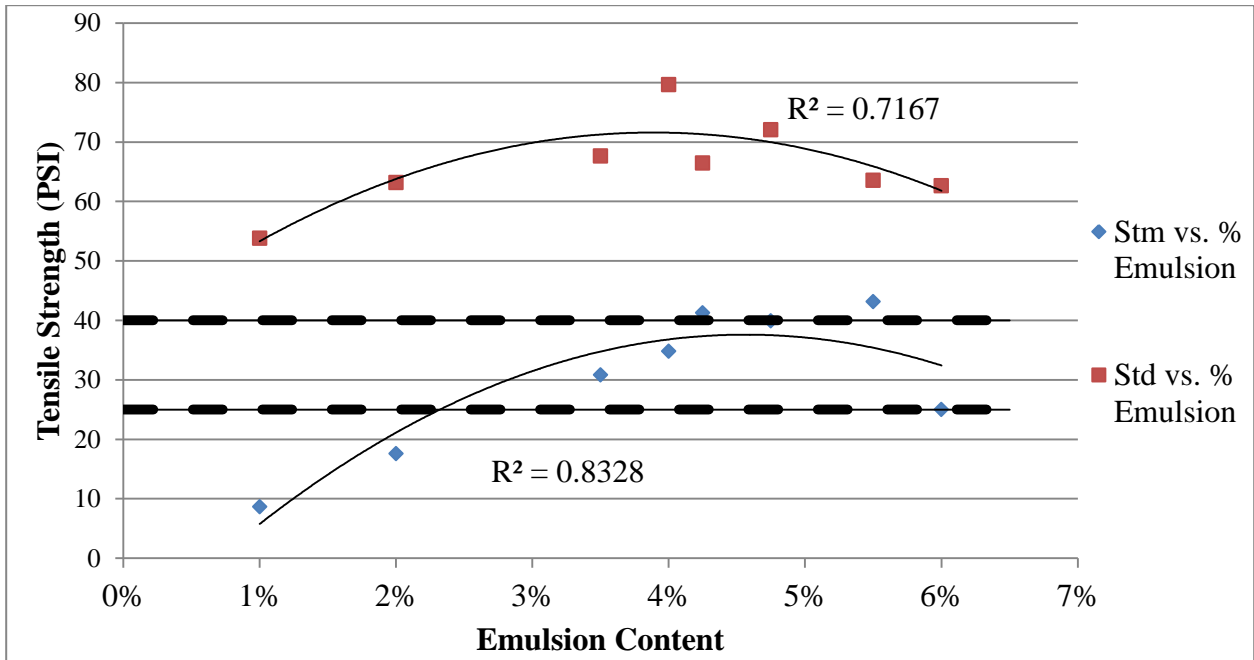
Figure 3:10: ITS vs. Emulsion Content

Table 3.6: ITS data

Emulsion Content %	1.00	2.00	3.50	4.00	4.25	4.75	5.50	6.00
Avg S_{tm} (psi)	8.62	17.59	30.81	34.79	41.24	39.94	43.15	24.99
Avg S_{td} (psi)	53.83	63.16	67.62	79.62	66.47	72.07	63.52	62.65
Coefficient of Variance S_{tm}	11.80	2.21	11.88	6.11	12.72	5.25	4.69	11.93
Coefficient of Variance S_{td}	5.98	14.71	4.42	3.65	3.22	3.69	5.93	8.82

From the trend line in Figure 3.10, the optimum tensile strength comes from an emulsion content of 4%. This can be said with confidence because of the low coefficient of

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variance that is associated with the average dry tensile strength. The NCDOT mix design calls for a minimum conditioned ITS strength of 25 psi and a minimum unconditioned ITS strength of 40 psi. At 4% emulsion, the average conditioned ITS was 34.79 psi and the average unconditioned ITS was 79.62 psi, both values well above the minimum values specified.

3.8 Conclusions

While the simplest mix design was chosen to move forward, it is recommended that further testing be carried out. The early strength testing as well as the resilient modulus test was not performed. Despite the fact that those specific tests were not run, the main goal was to follow a mix design as close as possible to produce a mixture that could be tested for an early return to traffic, which will be discussed in Chapter 4. Even with the mix design, it was difficult to perform properly due to the frailty of the samples immediately after compaction. It was nearly impossible to pick the sample up without the development of an extrusion cell. There were many learning experiences throughout the process of determining an optimum emulsion content that the mix design did not cover. Future mix designs should be extremely detailed and not leave so much grey area that unfamiliar researchers will have to deal with.

Chapter 4

4.0 Full Depth Reclamation Surface Raveling

A problem that is currently being experienced with FDR projects in the field is that the reclaimed surface is susceptible to raveling when being released to traffic too early. Raveling is the progressive disintegration of a pavement layer from the surface downward as a result of the dislodgement of aggregate particles. This is occurring before the surface wear course is being applied. The surface wear course cannot be immediately applied due to the possible trapping of water in the lower areas of the stabilized layer. Therefore, there is a time window of when the reclaimed surface is exposed to traffic because it is very costly to keep the road shut down. The stabilized FDR base should be cured before placing the surface for at least 7 days after the completion of construction. Heavy trucks and construction equipment should not be allowed or at least should be limited during curing, to prevent structural damage to the base, such as flexural cracking (Kearney and Huffman 1999). The friction between the vehicle tires and the reclaimed surface is one of the causes of the raveling problems. Since the asphalt emulsion does not have time to form a strong enough cohesive bond to the aggregate, the aggregate may come loose from the surface of the reclaimed layer when the friction force is applied and thus raveling occurs. For asphalt emulsion stabilized base, a tack coat of diluted slow-setting emulsion is usually applied to ensure good bonding of the HMA or cold-mix overlay (Kearney and Huffman 1999). Currently there is no field test to quantify when the traffic should be released onto the FDR section. It is typically based on engineering judgment and many projects are being opened to traffic too early, causing raveling, or too late, causing

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costly user delays. Due to the variability with each project, there is no established method to determine the optimal return to traffic timing to avoid raveling. Contractors are asking for a cheap and portable tester to fill this void in the construction process. This research reviewed four different portable lab tests to determine if they are capable of establishing a test method that precisely identifies the optimal return to traffic time.

4.1 Testing Procedure

To determine if a test could be suitable for lab testing and also be adapted to test in the field, four in-house testers were constructed. Each tester was constructed for a fairly small amount of $100 or less and was made of material available at a local hardware store. These testers were then used on lab produced emulsion and asphalt foam FDR samples. The emulsion samples were tested with all four of the testers, including the raveling test after curing at ambient temperatures over a period of two days. Three samples were tested at each designated curing time and the data was averaged. The initial data was then evaluated and experience from utilizing the testers was then used to determine the two most promising of the in-house testers. These testers were then tested on emulsion samples cured in the oven at 40C for two days and on asphalt foam samples cured at ambient temperature. The asphalt foam samples were tested to determine if the testing devices were suitable for foam treated FDR pavements as well. Tables 4.1 and 4.2 show the experimental matrix used during this study. Round one testing involved all of the testers and emulsion samples cured at ambient temperature. Three samples were tested by each device at each curing time. The second round of testing involved emulsion and foam samples being tested by the raveling, rebound and

sweep testers. The emulsion samples were cured in the oven at 40C and the foam samples were cured at ambient temperature. Two samples were tested by each of the testers at the specified curing times.

Table 4.1: Experimental Matrix Round 1

Factor	# of Levels	Levels
Curing Times (Hours)	10	0,0.5,1,1.5,2,3,4,12,24,48
Testers	5	Rebound, Sweep, Torque, Pendulum, Raveling

All of the samples tested in Round 1 were stabilized with emulsion. The curing was carried out at ambient temperature and there were three replicates tested at each of the curing times for a total of one hundred and fifty samples.

Table 4.2: Experimental Matrix Round 2, Part 1

Factor	# of Levels	Levels
Curing Times (Hours)	10	0,0.5,1,1.5,2,3,4,12,24,48
Curing Procedure	2	Ambient, 40° C
Testers	3	Rebound, Sweep, Raveling

Round 2, Part 1 testing involved two emulsion stabilized replicates tested at each of the curing times for a total of sixty samples.

Table 4.3: Experimental Matrix Round 2, Part 2

Factor	# of Levels	Levels
Curing Times (Hours)	10	0,0.5,1,1.5,2,3,4,12,24,48
Testers	3	Rebound, Sweep, Raveling

Round 2, Part 2 testing involved two foam stabilized replicated tested at each of the curing times. The samples were cured at ambient temperature for a total of sixty samples.

4.2 Preparation of samples

The asphalt emulsion and foam samples were all cured while sitting in the extrusion cells (see Chapter 3.7.1). This was due to the frailty of the samples throughout the duration of

the cure time and allowed them to be moved easily without disturbing them. The extrusion cells all had air holes drilled in the outer walls and the base so that the sides of the samples were not sealed. The surface of the sample was the area that the testing was to be performed on and the extrusion cells worked very well for that. Many of the tests were carried out with the sample never leaving the extrusion cells until it was time to discard.

The emulsion samples were prepared according to the modified NCDOT mix design in the same manner as was described in Chapter 3. All of the steps taken to find the optimum emulsion content were performed through the compaction of the samples. Post compaction curing was the only step that was altered.

A mix design was not performed on the asphalt foam samples. The optimum asphalt foam mix was not necessary for the tests that were going to be performed. The emulsion used in the mixture contained between 60-70% asphalt. Therefore it was decided that the amount of foam used for each sample would be approximately 70% of the total amount of asphalt emulsion used. According to the Asphalt Academy, 65-85% of the Optimum Moisture Content (OMC) should be selected for the mixing moisture of foamed asphalt mixtures (Asphalt Academy 2009). The water content selected for the foam samples was 75% of the OMC.

The samples were not mixed in the bucket mixer like the emulsion samples. The samples were prepared using the WLB 10S Wirtgen Foamer and the WLM 30 pugmill attachment. Figure 4.1 shows the two machines used.

Figure 4:1: Wirtgen WLM 30 Pugmill Mixer and WLB 10 S Asphalt Foamer

Samples were mixed with water for 60 seconds and then the foam was added and mixed for another 30 seconds (Asphalt Academy 2009). The samples were compacted in the same manner as the emulsion samples.

4.3 Laboratory Raveling Test

Currently there is one laboratory scale raveling test being used to evaluate the resistance to raveling of Cold In-Place Recycled (CIR) mixtures. This test, from the slurry surfacing area, has been adapted by Koch Materials as a cohesion test for cold mix, ASTM D7196. The test involves abrasion of partly (4 hours) cured, compacted cold mix specimens

(150mm) with the Wet Track Abrasion Tester used in slurry testing. The test is run dry for 15 minutes and simulates raveling, which could occur from too early trafficking. According to the author, a properly cured mix ready for traffic should exhibit less than 2% abrasion loss in the test (James 2002). The laboratory raveling test is shown in Figure 4.2.

Figure 4:2: Raveling Tester

This device was used on both the emulsion samples and foam samples to try and find a correlation between the curing time and method, and the resistance to raveling of the samples. Unlike ASTM D7196, which is used for CIR pavements, there is no current testing method adapted to this device to determine the raveling characteristics of FDR samples. This device

was used in a similar manner as is done for CIR samples. The data obtained from this device was to be used as more of a control for the research performed with the in-house testers. This was decided because of the precision with which this machine can operate, as compared to the other testers that were built. If a tester showed a similar trend of data, like the data gathered from this device, it would then be further evaluated.

4.3.1 Quantification

Initially the emulsion samples were tested after curing at ambient temperatures. The test was originally intended to follow the CIR testing guideline and run for fifteen minutes and measure the mass loss of each sample. This quickly proved to be impossible due to the lack of early strength that the emulsion samples had at early curing times. Since FDR has much larger aggregate than CIR, the raveling head would simply catch one piece of aggregate and once that happened, the sample would practically explode. After making this observation the quantification by mass loss was abandoned. The samples would be quantified based on the amount of time that they were able to last in the tester, a point where the sample had been destroyed. Determining the point when the sample was destroyed was done by the same individual for every test that was run. The test was performed on each sample until it was determined that the sample had been destroyed. This stopping point was determined through visual inspection. As was the case many times, the raveling head would displace the surface material enough to then catch one of the larger pieces of aggregate and abruptly pull it from the sample. After this occurred the rest of the sample quickly began to fall apart and the test was stopped. The test was stopped once the raveling head was no longer coming into contact

with the original surface of the sample. This stopping point was defined as when the raveling head began to exert more of a lateral force on the sample and was no longer exerting a downward force. Once this point was reach the test was stopped and the time recorded. A maximum time of ten minutes was set for the test to run.

4.3.2 Round 1, Raveling Test Results

The data presented in Table 4.4 shows the results obtained from the emulsion samples tested after curing at ambient temperature without a draft. The samples were cured in a closed room that experienced no consistent air flow during curing. The samples cured between time 0 and 4 hours still seemed to be moist and were very difficult to hold once they were taken out of the molds. The only samples that managed to make it through the full ten minutes of testing were the samples that cured for 48 hours. The Coefficient of Variance (COV) is very high for all of the testing times except for time zero. Three replicates were tested for each of the specified curing times. The samples were still so wet that they hardly had enough strength to be placed into the tester base. Figure 4.3 shows the average time lasted versus the cure time that the samples were tested at. Figure 4.3 only includes the data up to four hours because the data points from twelve to forty eight hours are too far away to accurately form a trend. This shows the extreme variability of the samples themselves because the raveling test was performed the same way each time. The upper and lower bounds of the COV are graphed on each data point. A linear trend line was fitted to the data because regardless of the variability, the data did tend to follow a linear trend.

Table 4.4: Raveling data for emulsion samples cured at ambient temperature

Cure time (hr)	0	0.5	1	1.5	2	3	4	12	24	48
Avg time lasted (sec)	16.7	12.7	20.7	44.3	24.0	42.0	25.0	69.7	129.0	600.0
COV (%)	17	56	45	63	64	54	35	51	59	0
% Mass Loss	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.3%
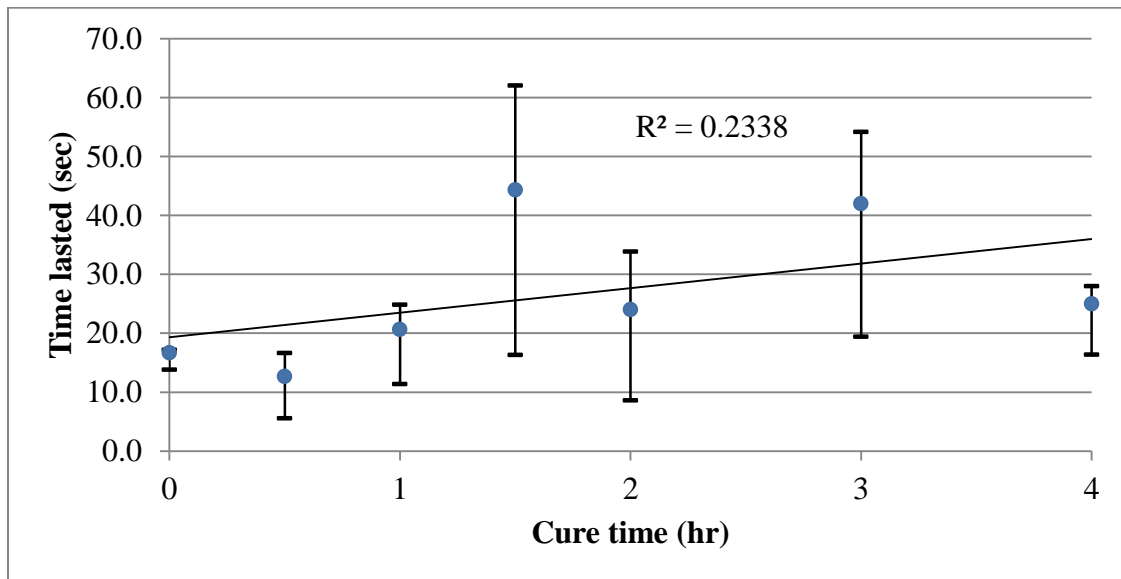
Figure 4:3: Time lasted (0-4 hours) vs. cure time of emulsion samples, cured at ambient temperature

When analyzing the twelve through forty eight hour data points a large increase in stability of the sample occurs between twenty four and forty eight hours shown in Figure 4.4. This does not follow a linear trend but more of an exponential trend. The sample should be

able to last throughout the entire test at some time between the twenty four and forty eight hour marks. Since the test concludes after ten minutes the trend would stop and then a percent mass loss would need to be calculated instead of the time lasted.
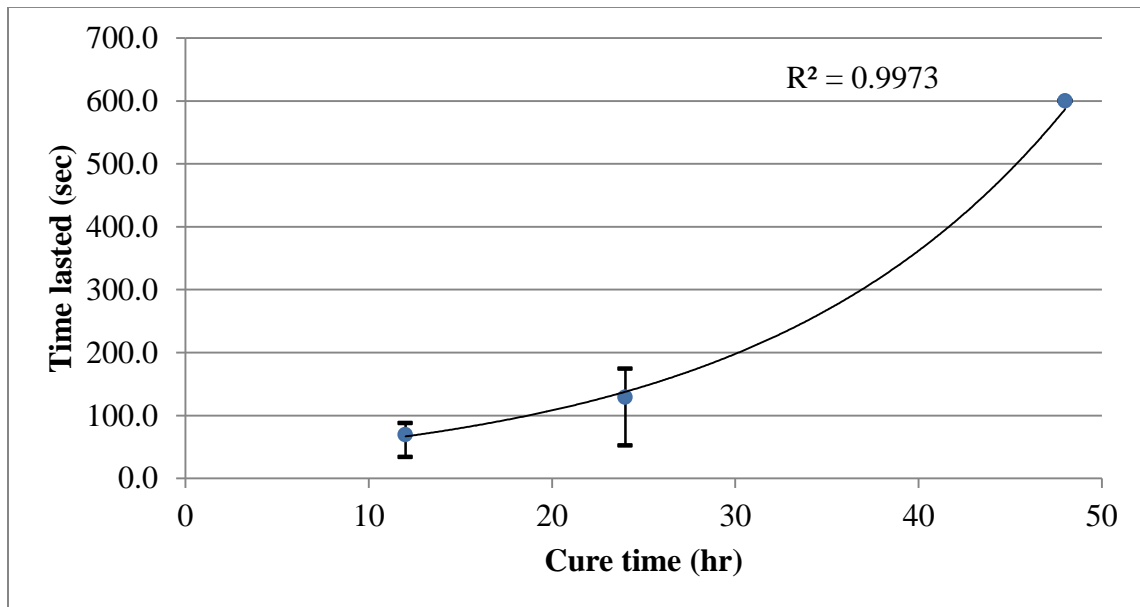
Figure 4:4: Time lasted (12-48 hours) vs. cure time of emulsion samples, cured at ambient temperature

4.4 Return to Traffic

Four tests were identified as having the potential application in the return to traffic areas of FDR. These four tests are the British Pendulum Tester, the Modified Cohesion Test, the Dynamics Friction Tester, and the Falling Weight Deflectometer (FWD). Each of these test were analyzed and the concepts were to be closely duplicated by developing cheap and inexpensive tests that use the same concepts that the original testers were developed upon.

The four draft specifications are located in the Appendix. Each summarizes how to construct and run the tests.

4.5 British Pendulum Tester

Also known as the Portable Skid Resistance Tester, ASTM E303, the BPT was originally designed to measure the slip resistance of floors in government buildings. The instrument was later adapted to measure the frictional resistance of pavements by the Transport Research Laboratory. The device is shown in Figure 4.5.

Figure 4:5: British Pendulum Tester

4.5.1 In-house Pendulum Tester

The University of Arkansas had acquired a British Pendulum Tester (BPT) which was purchased through a separate study a few years back. The BPT was assembled and analyzed to acquire a better understanding of its mechanics. The friction of the surface in question was greatly dependent upon the deviation in the single level asperities, mainly the height of the highest asperities above the above the mean line of the surface profile. Asperities would be represented as single pieces of aggregate in the mix.

When two nominally flat surfaces are placed in contact, surface roughness causes contact to occur at discrete contact spots (junctions). When two surfaces move relative to each other, the friction force is contributed by adhesion of these asperities and other sources of surface interactions (Bhushan 2002). Repeated surface interactions and surface and subsurface stresses, developed at the interface, result in the formation of wear particles and eventual failure (Bhushan 2002). When raveling is brought into question, tribological terms can add significant value. Because pavements are considered a non-homogeneous material it is difficult to relate to tribological terms because they are based on homogeneous materials, such as metals. Single pieces of aggregate are separated from the pavement surface by a force, friction, overcoming the cohesive strength of the bonding agent. This tester will apply the force to those asperities and determine the cohesive strength built up over time.

From the analysis of the British Pendulum Tester, a similar tester was fashioned. The objective was to base the design on the principles that the BPT operates, but to apply them in

a different way. All of the parts used to assemble this tester were purchased from the local hardware store and cost around eighty-five dollars in total. Similar to the rubber hose used in ASTM D7196, a pipe bender was fitted with the hose to act as the abrasive material which contacts the road surface. The frame of the tester was constructed from 2x4" lumbers and was especially difficult to assemble due to the nature of lumber to not necessarily be straight. Once this was overcome the apparatus was fairly easily assembled and operated. Initially it was uncertain as to how a measurement was going to be taken as the tester was put into motion. The four feet on the tester were adjustable so that the tester could be leveled by a bubble level. It was determined that this would be a problem due to the amount of leveling that would be required and the difficulty to do so, so the bubble was removed along with the feet.

4.5.2 Quantification

Instead of swinging the arm one time and recording the distance that the arm traveled once the hose struck the pavement surface, it was proposed that the arm be swung multiple times. The apparatus was be set at a certain height so that the arm would be set at a certain angle when at rest and touching the pavement. This was intended to eliminate the leveling process assuming that the road surface will be relatively flat over the short distance that the tester covers. With the fixed height of the tester, the arm would be swung and come into contact with the road surface multiple times. Using this method, the tester could be operated to determine two different values. One value could be if the tester was swung a set number of times and the amount of debris created could be collected and measured. The other use was to

record the number of swings that it takes for the tester to record a complete swing that is unaffected by the pavement surface. Preliminary field evaluation did not provide data, but provided insight that was evaluated in the lab.

It was soon realized that swinging the device multiple times and collecting the debris created was not a viable option for quantification. A fixed angle was used in the operation of the device, but not to the degree where it would take multiple swings to make a full swing. Meaning that the smaller the angle the arm was set at, the less amount of contact would be made with the sample. If the angle was too great, the arm would not be able to make a complete swing. The final measurement used was more of a combination of both of the initial ideas.

The device was set on a portable pallet jack that was able to be raised and lowered in very small increments. It was extremely difficult to level the device with the adjustable feet that were initially on the device. The device was centered over a sample and raised up and down until the desired angle of the arm was achieved. A cheap rubber car mat was placed under the sample to keep if from sliding forward when struck. The sample was transferred from the three inch tall mold into a smaller two inch mold so that the head of the device would not strike the edge. Once the height was achieved the arm was raised perpendicular to the surface of the sample and released. The rubber house fitted into the head would scrape back and forth across the top of the sample until it came to a stop. The number of times that the head passed over the sample was recorded as the first swing. The arm was then lifted again, in the same fashion, and dropped into the same place as the first swing. This was

recorded in the same way. The idea was that after the first swing, the head would have displaced some of the material so that when it was swung a second time it should have achieved a higher number of swings. The logic was that the more the sample had cured closer the ratio of the first swing to the second swing would be to a value of one. Figure 4.6 shows the device from a few different angles.
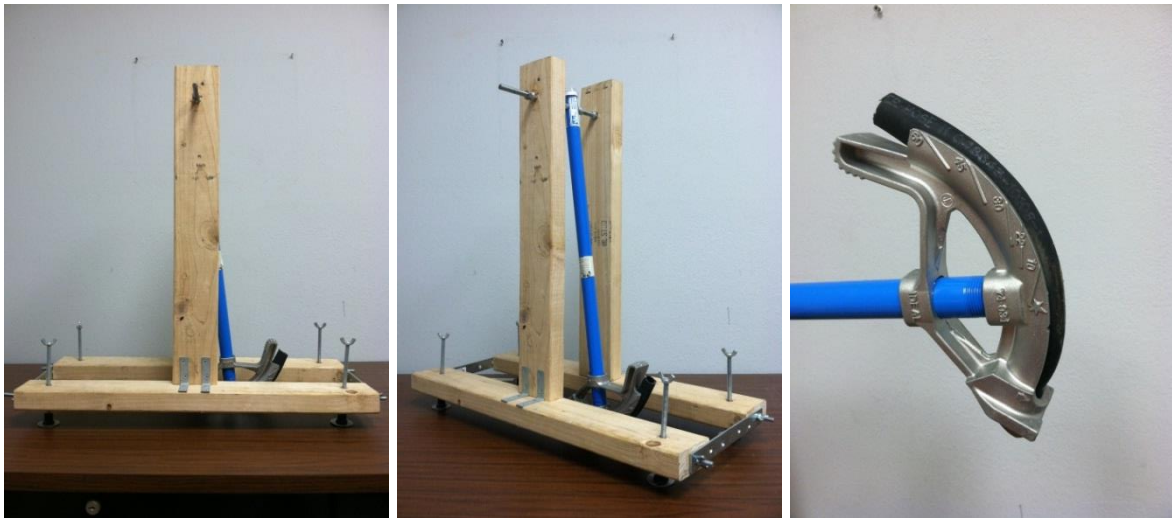
Figure 4:6: In-house Pendulum Tester

4.5.3 Round 1, Pendulum Tester Results

Three emulsion samples, cured at ambient temperature, were tested at each designated curing time. The results of the tester can be seen in Table 4.5.

Table 4.5: Pendulum data for emulsion samples cured at ambient temperature

Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg # 1st Swings	8.0	7.0	6.0	6.0	5.3	6.3	6.7	3.0	3.3	4.7
COV 1st Swing (%)	25.0	49.5	16.7	16.7	28.6	32.9	22.9	0.0	17.3	44.6
Avg # 2nd Swings	8.7	6.7	7.3	7.3	5.7	6.3	7.0	3.3	4.3	4.7
COV 2nd Swing (%)	24.0	31.2	20.8	20.8	50.9	32.9	28.6	17.3	35.3	61.9
Avg Ratio	0.9	1.0	0.8	0.8	1.0	1.0	1.0	0.9	0.8	1.1
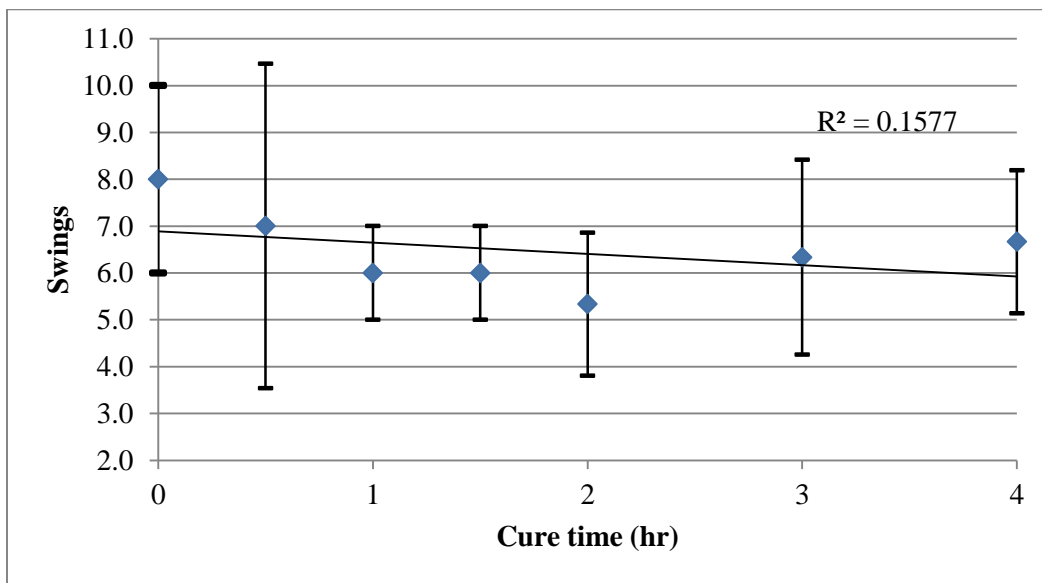
Figure 4:7: 1st swing vs. cure time (0-4 hours) of emulsion samples, at ambient temperature

When looking at the average number of first and second swings, the number is shown with a decimal. The swings were measured in whole numbers, no partial swings were recorded. This illustrates which whole number of swings that the actual average number was

66

closest to. The COV is fairly high when considering the low number of swings that occur. There is a somewhat linear decrease in the number of swings as the cure time increases in both the first and second swings showing that the samples were gaining strength. Figure 4:7 only illustrates the first swing because the second swing data is nearly identical, but translated up approximately one swing.
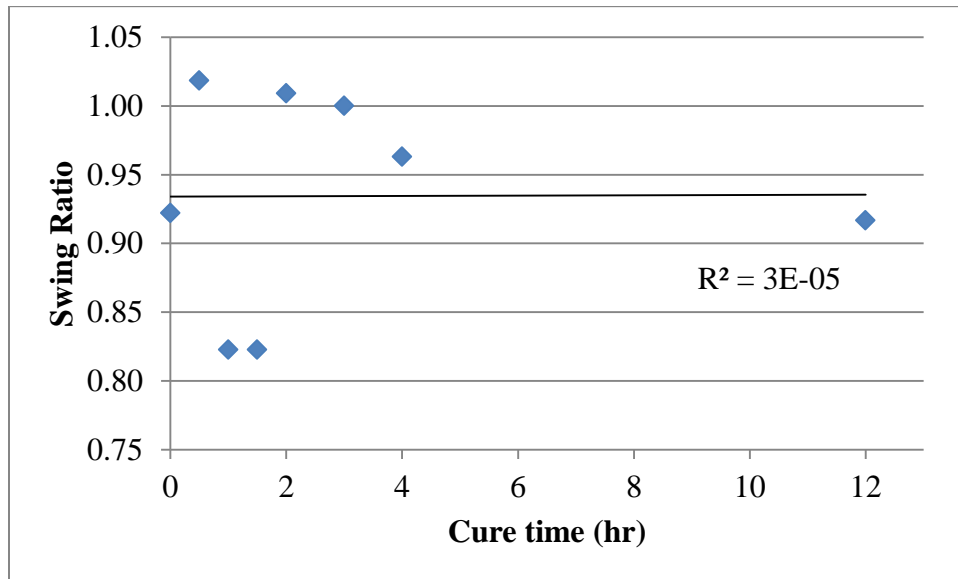
Figure 4:8: Swing ratio vs. cure time (0-12 hours) of emulsion samples, at ambient temperature

When analyzing the ratio approach to quantification, there seems to be no developing trend and the data did not come out as expected. At forty eight hours the ratio actually goes above a value of one, meaning there were more swings averaged on the second swing than the first. Which is completely opposite from what was expected.

4.5.4 Problems/Recommendations

Inconsistency was the main problem that was faced with this device. With the varying height of the specimens, it was extremely difficult to have the device set at the same angle repetitively. Figure 4.9 illustrates how the device was used throughout the testing. The device was also not solid enough to handle the force generated from the swinging arm when it struck the sample. The device itself was just not able to be built to the level of precision that would be required for this test. This was due to a lack of expertise in the area of construction and fabrication.

Figure 4.9: Pendulum tester set up

When around professionals in the field, it has even been stated that the BPT is very difficult to use and has a tendency to produce unreliable data. It is recommended that this test, be reanalyzed and used in a different way. One possibility might be to have a quick drying epoxy and adhere a vertical bracket to the top of the sample. Then the device could be swung and strike the bracket with a specified amount of force. The time at which the device does not detach the apparatus could be recorded and possibly correlated with another tester. This specific tester would require a complete reconstruction, due to many of its inconsistencies.

4.6 Cohesiometer

The third test that was examined was based on the Modified Cohesion Test (ISSA TB 139), which is a laboratory test designed to quantify the cohesion of slurry seal. In the slurry seal test, a torque pressure of 200 kPa (29psi) is applied to small patties of slurry that have reached an initial set. Every thirty minutes, the torque required to rotate a neoprene foot in contact in the specimen is recorded. From the resulting plot of torque versus time, a slurry seal mix can be classified in terms of set times and return to traffic.

While examining the modified cohesiometer another test was discovered that was used to determine the curing rate of asphalt emulsions used in chip seals known as the TTI Cohesion Test. In the "Investigation of Laboratory Test Methods to Determine Curing Rate of Asphalt Emulsion" the Texas Transportation Institute developed a test very similar to the modified cohesiometer, but on a larger scale (Estakhri et al. 1991). Instead of a one inch diameter rubber pad the TTI tester uses a three inch diameter rubber pad. The larger pad was needed to account for the larger aggregate used in chip seals. With the larger aggregate in FDR a three inch pad was thought to be adequate. When getting more in depth into the requirements of this homemade tester, problems began to arise concerning the amount of force that needed to be applied to the surface of a sample. Torque is the tendency of a force to rotate an object about an axis, or pivot.

Torque = r*F,

where r is the length of the lever arm and F is the magnitude of the force applied. The idea is that the torque will begin to increase as the mixture begins to set. The amount of force that would need to be applied to the pad would be unreasonable in the field.

4.6.1 Torque Tester

This type of tester was analyzed and the concepts were utilized and implemented in the homemade cohesion tester. The idea was to create a tester that had the ability to apply pressure to a pad that would rest atop a gyratory sample. This pad would then be rotated and the torque required to disturb the surface of the sample would be recorded.

Initially it was decided to make the pad out of 1"x5.5" board by cutting out a circular piece. Spikes were added to the bottom of the pad by driving 1-1/4" shank nails through the top to where just the tips were protruding from the bottom side. The idea of using the spikes as opposed to a pad came from a cohesion tester that was viewed during visits to Jackson, Mississippi. The spikes were also being considered due to the constraint of the amount of pressure that can reasonably be applied to the pad in the field. It quickly became apparent that using wood for the pad was not going to work. Because of the tendency of wood to warp, assumed that the nails would begin to slip back out when pressure was applied from the top. A wooden shaft was also initially chosen, but for the same reason was abandoned. The decision was then made to switch to metal parts to be more reliable and sturdy. The wooden shaft was replaced with a ½" rigid conduit pipe. The end of the pipe was threaded so it would be easy to attach to a base plate that was also threaded. This led to the choice of a 4" diameter

junction box to be used for the base. The open end of the junction box was closed in with a stainless steel box cover. The cover then had 7 holes drilled through it, 1/8" in diameter. The holes were drilled 1.25" from the center of the plate, where a center hole was drilled, and were spaced at 60° apart. These holes were then filled with 6x1/2 stainless steel screws. The screws protrude 3/8" out of the bottom of the plate. The base plate assembly can be seen in Figure 4.10.

Figure 4:10: Torque tester base

Once the base plate and the shaft we completed, how to apply the pressure was to be addressed. The idea of adding weights to the shaft was abandoned because it seemed impractical to carry into the field. The pressure was chosen to be applied by springs. A 2x4 inch lumber was cut to 2 feet long and a 1.5 inch hole was drilled through the center of it. This was to allow the board to slide over the shaft. A ¼ inch hole was then drilled through the

center of the shaft so that a bolt could be placed in for the board to rest on. A washer was used to distribute the force evenly to the bottom side of the board. On the underside of both ends of the board, a screw eye was inserted. This screw eye is used to hook the springs to. The springs hang from the screw eyes and a chain was formed in the shape of a stirrup for the tester to step into to apply a uniform force. Regardless of the weight of the person using the tester, the same amount of force will be applied. The springs and chains can be seen in Figure 4.11.

Figure 4:11: Torque tester with springs and chains

The idea was to have the person performing the test step into the stirrups and perform the test. When this was tried it was noted to be fairly difficult and very awkward. It was also noted that with a relatively small amount of pressure applied that it was difficult to keep the tester held down. To combat this problem 2, 2x4" lumbers were cut to length of 4' with a notch cut into the middle of each to allow for the chain to rest in. The boards are to be stood

on from both sides. This means that the test will require two individuals to operate it. This was found to be much easier and safer. It was also noted that with the addition of the boards it was very easy to apply the force to the base plate. It was decided that more holes should be drilled in the shaft so that the tension in the spring could be increased, thus increasing the force applied to the base plate. Holes were drilled 20, 22, 24, and 26" from the bottom of the base plate. This allows for variable amounts of pressure to be applied with the simple switching of a bolt. The complete tester can be seen in Figure 4.12.

Figure 4:12: Torque tester with base boards

4.6.2 Quantification

A beam torque wrench was purchased in the hopes that it would be sufficient to measure the torque applied to the shaft. When reviewing the modified cohesion test it is noted

that a pressure of 200 kPa (29 psi) is used and the maximum torque value around 21 kg-cm (26 in-lbs). The TTI cohesion tester exerts a pressure of 35-45 psi and torque values from 35-45 in-lbs. With the larger aggregate sizes in FDR pavements it would seem that the testers would need to be closer to the values used by the TTI cohesion tester. Table 4.6 displays the data that was measured from the in-house torque tester.

Table 4.6: Torque tester specs

Height from Base(in)	Force (lb)	PSI (base plate, no screws)	PSI (screws)	PSI (per screw)	lb (per screw)
20	52	4.14	605.33	86.48	7.43
22	92	7.32	1070.98	153.00	13.14
24	132	10.50	1536.62	219.52	18.86
26	*172*	*13.69*	*2002.26*	*286.04*	*24.57*

The increase in pressure from one height to the next followed a linear pattern and increased 40 lbs every 2 inches that the tester was raised. Once the force was recorded the PSI was calculated for the base plate without the screws and also with the screws. The data for the 26 inch height is the expected data. The actual data at that height could not be determine because the scale used maxed out at 150 lbs. The maximum PSI that could be achieved with just the base plate is expected to be 13.96. This is well short of the values used in either of the cohesion testers mentioned earlier. This is why the screws were added to possibly add more

grip to compensate for the lower pressure that this tester can achieve. The idea behind the tester is that the torque will begin to increase as the mixture begins to set.

4.6.3 Round 1, Torque Tester Results

The tester was used on emulsion samples that were cured at ambient temperatures for the first round of testing and then was deemed unreliable. Table 4.7 shows the data that was obtained through the use of this tester.

Table 4.7: Torque data for emulsion samples cured at ambient temperatures

Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg Torque (lb/ft)	13.3	15.0	13.3	15.0	17.3	15.0	15.0	16.7	26.0	19.2
COV (%)	21.7	0.0	21.7	0.0	23.3	0.0	0.0	17.3	6.7	19.9
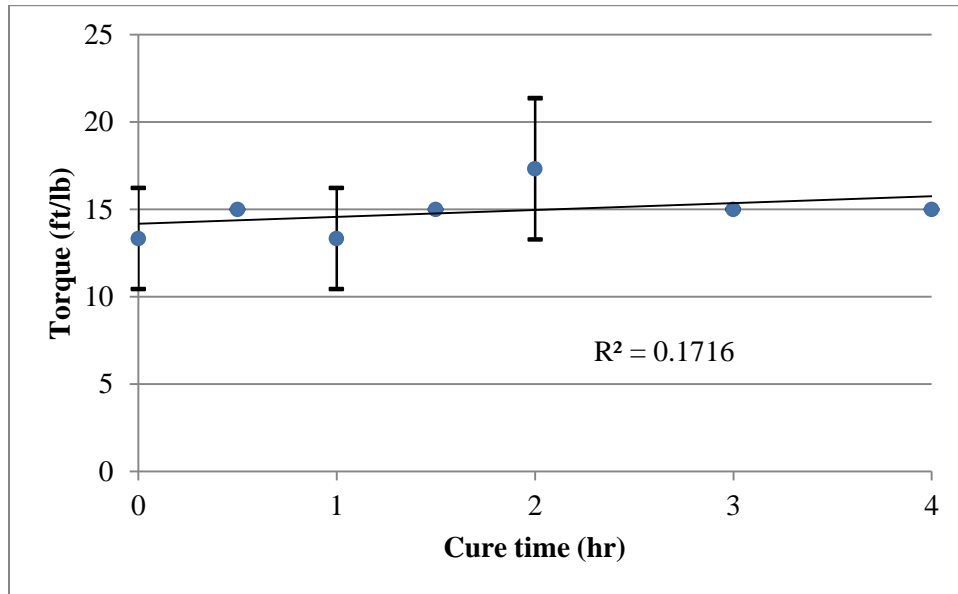
Figure 4:13: Torque vs. cure time (0-4 hours) of emulsion samples, at ambient temperature
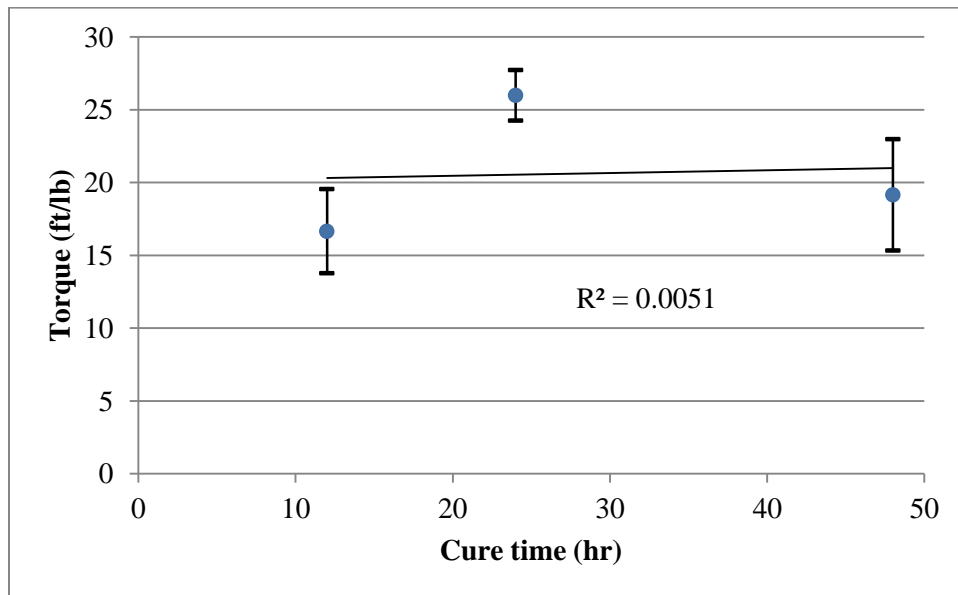
Figure 4:14: Torque vs. cure time (12-48 hours) of emulsion samples, at ambient temperature

The data that was obtained with this tester was highly inconsistent and showed little variation between different curing times as can be seen in Figure 4.13 and 4.14. It seemed as if there was an increase in the torque as the cure time increased, but it was very hard to determine accurately. A beam torque wrench was used to measure the torque. Every specimen tested could have had a higher torque value depending on the amount of force that was put into the torque wrench. It was very dependent on the individual who was controlling the torque wrench. No further testing was done with tester because of its inconsistency.

4.6.4 Problems/Recommendations

The main problem with this tester was the inability to safely apply enough force to the top of the sample. The springs were maxed out on the tester and it began to get somewhat hazardous to apply the maximum amount of load that the tester was capable of. The samples would begin to deform as the load was applied because they had no confining pressure to stabilize them. This was combated by placing a sleeve around the sample made from a six inch PVC pipe so that it could provide a little support. Once that was taken care of another problem arose. The entire sample would spin when the torque was applied instead of just the top shearing off. The samples were moved to a rough patch of concrete in the lab to try and mitigate this. The twisting was reduced, but not eliminated. The measuring devices that were available were a beam torque wrench and a digital torque wrench. The beam torque wrench was the only one that could be used because the digital torque wrench was in in/lb. and would max out before the total amount of torque could be applied. The problem with the beam torque wrench was that it wasn't able to record the maximum torque applied. This meant that

someone had to judge the maximum torque that was achieved by staring at the needed as the torque was applied. The difficulty to operate this testing device proved to be the main problem.

4.7 Dynamic Friction Tester

The Dynamic Friction Tester (DFT), ASTM E1911, is a portable device used to measure the dynamic coefficient of friction and can be seen in Figure 4.15. The instrument is comprised of a measuring unit and a control unit; an x-y plotter or laptop can be used to record data. The measuring unit consists of a disc made to rotate horizontally at a specified velocity before being lowered onto a wetted test surface. The torque generated by the resistance between the test surface and spring-loaded rubber "sliders" attached to the underside of the rotating disc is continuously monitored and converted to a measurement of friction.

Figure 4:15: Dynamic Friction Tester (fhwa.dot.gov)

When examining the dynamic friction tester the idea to use something to scrape across the surface in a spinning motion was realized. One of the main forces of pavement friction is adhesion. When two solid surfaces are brought into contact, adhesion or bonding across the interface can occur which requires a finite normal force, called adhesive force, to pull the two solids apart. A normal tensile force must be exerted to separate the surfaces. At higher temperatures, softening of the surfaces results in greater flow, ductility and a larger real area of contact which results in stronger adhesion (Bhushan 2002). This situation might be present during the hotter summer months when most of the construction projects are done. Adhesion is affected by real area of contact. Adhesion force generally increases linearly with an increase in the normal load.

With heavier traffic there will be in increase in the adhesive force. Adhesive forces significantly increase if a shear displacement (force) is added in addition to the normal load. The shear force would be applied by the spinning aspect of the DFT. When a tangential force is applied to the loaded specimens, there is a growth in the real area of contact by plastic flow under the influence of combined normal and tangential stresses. This would increase the chance of debris being created and test the cohesion force of the mix over time.

4.7.1 Sweep Tester

Concepts from this tester were utilized in the construction of the sweep tester. A wooden mop handle was used as the shaft for the sweep tester. The mop handle was chosen because with it, multiple brush heads can be attached and swapped out for testing. The handle

on the mop was cut to a shorter length because the full length of the mop handle would be difficult to control and also be prone to not being completely straight. A drill bit was glued into the end of the mop handle so that a drill could be attached to the shaft. A common traffic cone was then cut to a height of approximately 5 inches from the bottom. Being able to hold the drill at the same height for an extended period of time was thought to be impractical. To fix this, a mount was made out of 1x5.5" lumbers for the drill to sit in so that it would be able to be held at a constant height through the duration of the test. The testing apparatus can be seen in Figure 4.16.

Figure 4:16: Sweep tester

4.7.2 Quantification

The idea was to attach a handheld drill to the end of the mop handle which had a brush attached to the mop head. The mop would then be lowered into the middle of the traffic cone.

The walls of the traffic cone were used to contain the debris that will be generated. The drill spun, creating a circular sweeping motion for a specified amount of time. The material would then be collected and weighed.

4.7.3 Round 1, Sweep Tester Results

The sweep tester proved to be one of the more reliable testers created during this experiment based on its ease of use and potential. Its use was slightly different than what was originally intended. The samples stayed inside of the extrusion cells during the testing. The sample was initially weighed while still in the extrusion cell. Then the sample would be placed in the center of the drill mount while sitting on another inexpensive car mat to keep it from spinning. The traffic cone was place around the sample to keep any debris from flying off. The head of the brush was placed in the center of the sample and then the drill was run at full speed for forty five seconds. After the allotted time, the sample was weighed again to determine the mass loss. Table 4.8 displays the data that was recorded from the emulsion samples that were cured at ambient temperature.

Table 4.8: Sweep data for emulsion samples cured at ambient temperature

Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg % Mass Loss	0.36	0.56	0.30	0.27	0.52	0.65	0.31	0.22	0.15	0.03
COV (%)	54	28	31	44	28	34	12	46	60	42
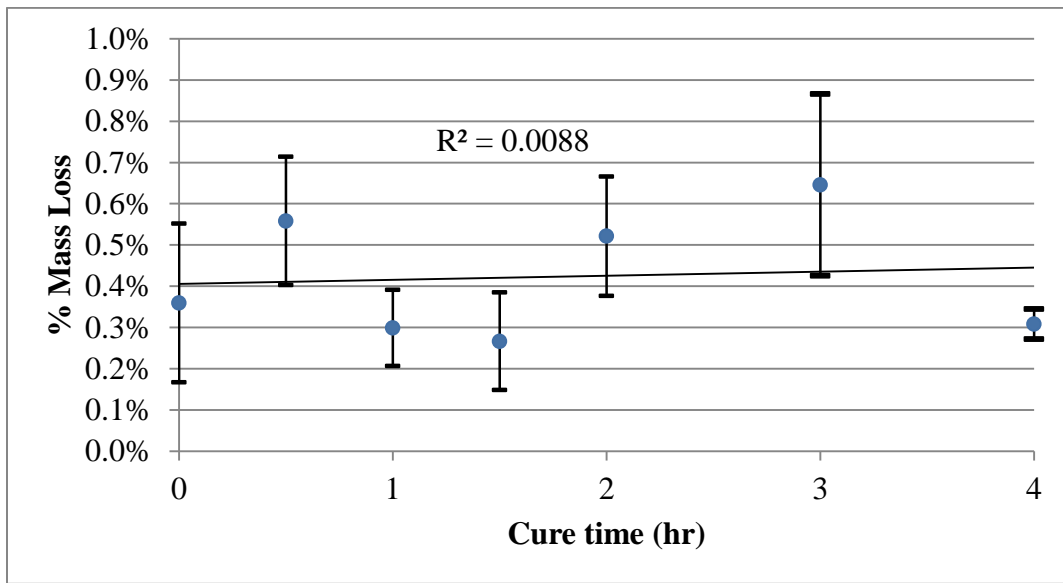
Figure 4:17: % mass loss vs. cure time (0-4 hours) of emulsion samples, at ambient temperature
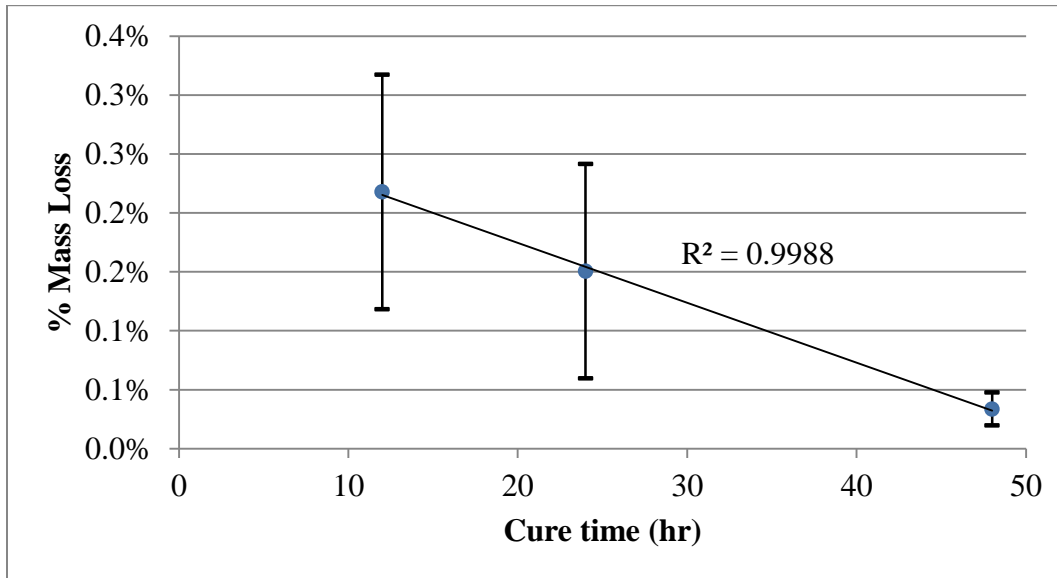
Figure 4:18: % mass loss vs. cure time (12-48 hours) of emulsion samples, at ambient

temperature

Surprisingly Figure 4.17 actually shows a linear increasing trend. This was not expected and did not follow the trend that it should have. Figure 4.18 show the downward linear trend that developed as the samples cured over the twelve through forty eight hour periods. The last three data points fit very nicely into the linear trend. If the test were continued after forty eight hours the data would most likely decrease slightly, but there would be no significant changes in the percentage of mass lost. There was less mass loss overall as the curing times increased. With such small values there were very large COV's for this initial test run on the emulsion samples. The variation can also be attributed to the design of the device itself.

4.8 Rebound Test

A golf ball was being bounced on the tile floor and then bounced on a nearby asphalt sample, being used as a door stop. There was a noticeable difference in the rebound height of the ball by bouncing it on the two different surfaces. With this discovery a way to quantify this was identified.

4.8.1 Quantification

Initially PVC pipes with an inside diameter of two inches were cut to lengths of four, three and two feet lengths. A slit was cut down the length of the pipes and they were marked off in inches. The idea was to drop the golf ball from a constant height and be able to record the maximum height that the golf ball rebounds. Two types of golf balls were used: Callaway Solaires and Titleist DT Solos. Each golf ball was dropped three times each and an average was taken for each time increment. An initial test was done on six inch Hot Mix Asphalt (HMA) samples from the time of compaction to an hour and a half later where it was determined that there was no noticeable change in the rebound height. HMA samples were used because of the ease of making the samples and material availability. From this initial test, the two foot pipe was thrown out due to the short drop height and having more difficulty in being precise with the measuring of the rebound height. The final version of the device is shown below in Figure 4.19.

Figure 4:19: Rebound tester

After this initial round of testing the two inch diameter pipes were replaced with three inch diameter pipes because it was observed that the golf ball was hitting the insides of the pipes, affecting the final height. A four foot pipe was fashioned in the same way as the two inch diameter pipes. The addition of a flexible coupling allowed for the pipe to easily sit on top of a gyratory sample and stand on its own. The test was repeated again with two, six inch tall samples and one, four inch tall sample. There wasn't a very noticeable difference in the rebound height from the six inch sample and the four inch sample. The four and six inch tall samples were both tested using the four foot tall tester. Some of the initial data for the six inch tall sample can be seen below in Table 4.9.

Table 4.9: HMA rebound data, 4' tube, 6" sample

Callaway Solaire						Titleist DT Solo					
T (min)	H (inches)			Avg	Std Dev	COV (%)	T (min)	H (inches)			Avg	Std Dev	COV (%)
0	12	13	15	13.3	1.5	11	0	13	17	15	15.0	2.0	13
5	15	18	15	16.0	1.7	11	5	18	16	15	16.3	1.5	9
10	15	14	16	15.0	1.0	7	10	16	14	16	15.3	1.2	8
15	15	16	19	16.7	2.1	12	15	16	16	18	16.7	1.2	7
20	17	19	18	18.0	1.0	6	20	20	19	17	18.7	1.5	8
25	27	21	22	23.3	3.2	14	25	21	22	23	22.0	1.0	5
30	21	22	22	21.7	0.6	3	30	21	21	25	22.3	2.3	10
60	28	29	32	29.7	2.1	7	60	30	30	31	30.3	0.6	2
90	32	32	36	33.3	2.3	7	90	34	35	34	34.3	0.6	2
120	33	31	34	32.7	1.5	5	120	35	33	32	33.3	1.5	5
150	36	38	36	36.7	1.2	3	150	36	37	38	37.0	1.0	3
180	34	35	38	35.7	2.1	6	180	32	31	34	32.3	1.5	5
1440	34	35	36	35.0	1.0	3	1440	35	39	36	36.7	2.1	6
				Sum	94						Sum	81
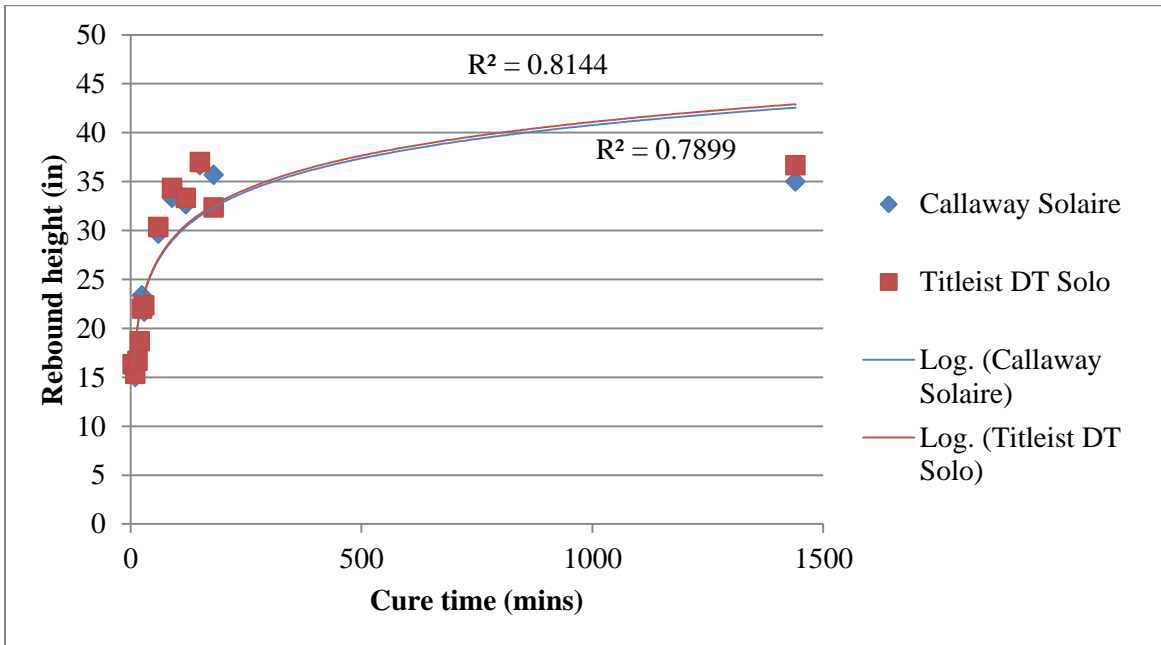
Figure 4:20: Rebound height vs. curing time (0-1,440 mins) of HMA sample

Analyzing the newly constructed testers and the increased testing period, the logarithmic trend was more apparent in Figure 4.20. At a certain point around the ninety minute mark, the data with the four foot tester began to fluctuate and plane off. The three foot tester gradually continued to increase with time. The difference in sample height did not provide any significant difference in rebound height.

It was decided that the four foot tester would be used to continue with this research and that the Titleist DT Solo would be the ball of choice because it had a lower total COV than the Callaway Solaires.

The rebound tester was, by far, the most simplistic and easiest to operate out of all of the testers. One person was able to operate the test efficiently with the simple use of a video camera. The rebound heights were videoed and then reviewed once the testing was completed. The samples were left in the extrusion cells during this test. The tester was moved to a different spot on the sample after each drop so that if any impression was made on the sample after a drop the next drop would not land in the same place.

4.8.2 Round 1, Rebound Tester Results

Due to its ease of use and practically no destructive nature, the rebound test was performed in both rounds of testing. This included the emulsion and foam samples cured at ambient temperatures and the emulsion samples cured at 40C. For efficiency and less material use, the rebound test was performed on either the sweep test or the raveling test samples before either test was performed.

The initial round of testing was performed on the emulsion samples cured at ambient temperature. The data from this round of testing can be viewed in Table 4.10 and Figures 4.21 and 4.22. The data gathered from the FDR samples was quite different than the data gathered from the HMA samples. There was not near as much of a distinction in rebound height over the testing times as there was with the HMA samples.

Table 4.10: Rebound data for emulsion samples cured at ambient temperature

Cure Time (hr)	0	0.5	1	1.5	2	3	4	12	24	48
Avg Rebound Height (in)	28.56	28.33	29.67	29.89	32.56	31.67	30.00	33.22	33.00	32.56
Std Dev	2.40	2.00	1.73	3.33	1.24	2.18	2.50	1.99	2.60	1.01
COV (%)	8.42	7.06	5.84	11.15	3.80	6.88	8.33	5.98	7.87	3.11
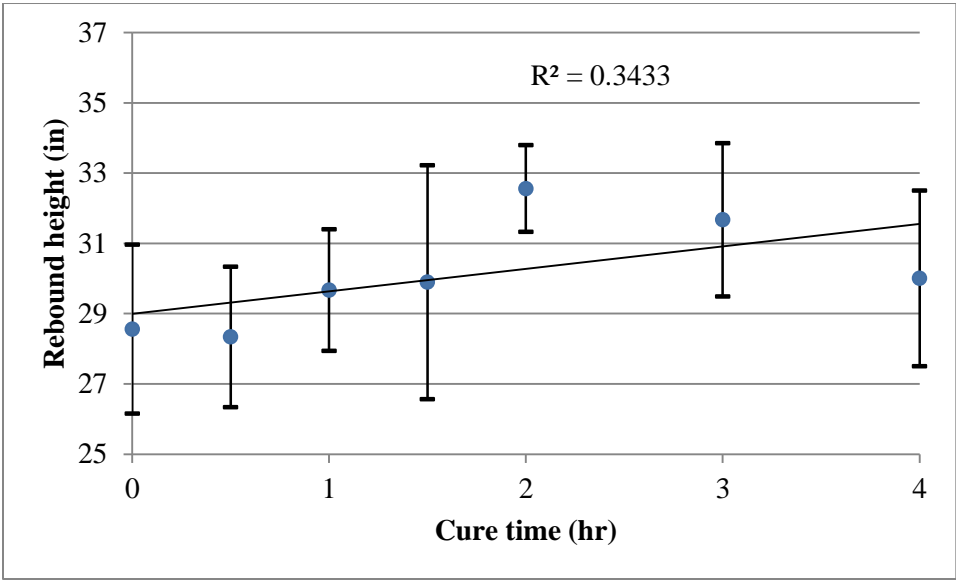
Figure 4:21: Rebound height vs. cure time (0-4 hours) of emulsion samples, at ambient temperature

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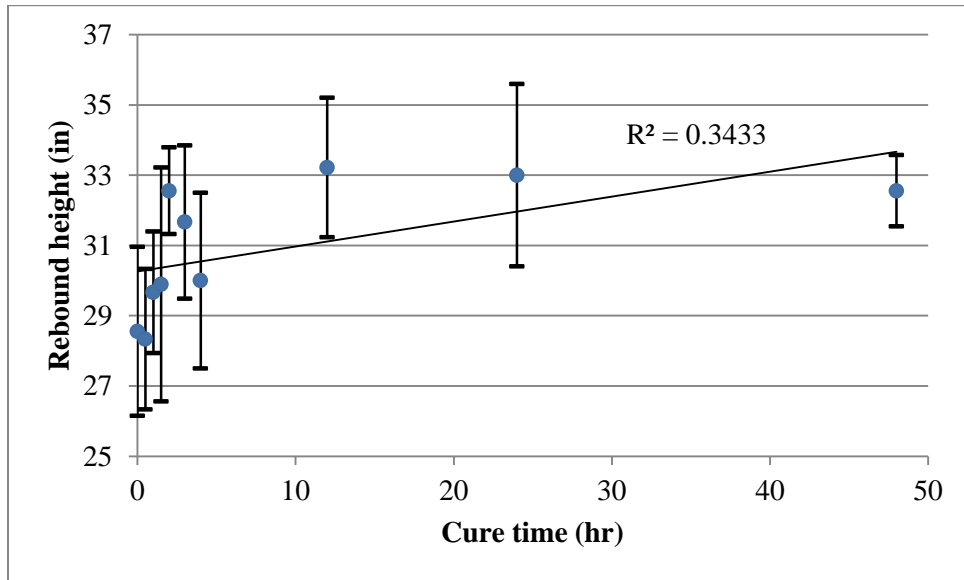
Figure 4:22: Rebound height vs. cure time (0-48 hours) of emulsion samples, at ambient

temperature

When the data was analyzed it was apparent that there was a very small difference between the rebound heights at time zero to four hours. There was a four inch difference between the two and basically the same difference was noted for the entire round of testing. This was a very small window to distinguish between and showed that the stiffness of emulsion samples did not respond well to the rebound tester. One of the positives taken from this round of testing was the relatively small COV for each of the times tested.

4.9 Round 1, Conclusions

The purpose of Round 1 of was to determine which of the testers exhibited that the curing time was a significant factor based off of the data gathered. A single factor analysis of variance (ANOVA) was performed on the data obtained from each of the testers and can be seen in Table 4. 11.

Table 4.11: P-values from ANOVA of the cure time significance on emulsion samples cured

at ambient temperature

Tester	P-value
Raveling	5.31E-15
Rebound	6.79E-07
Sweep	0.00031
Torque	0.00013
Pendulum	0.54803

From analyzing the data produced from the ANOVA, it was apparent that since the P-value was not less than 0.05 for the Pendulum tester. The tester did not show significant differences in the result based on the curing time, therefore, it was considered not appropriate to continue for testing in Round 2. While the data for the Torque tester showed that there was a significant change due to the curing times of the samples, it was also chosen not to be included in the second round of testing. A Least Significant Difference (LSD) was calculated for the torque tester and the data obtained backed up the idea that the device was inconsistent and flawed. The two hour testing period was grouped with the forty eight hour period which is not a reliable statistic. The decision to discontinue the use of this tester was based off of the many flaws that the device exhibited during the testing procedures and the LSD.

The Sweep tester showed that there was significant overlap between the testing periods from time zero up until twelve hours. The real change came around the twenty four to forty eight hour mark and shows that that would be when the test would begin to plane off

with the mass loss. When the Raveling test was analyzed the data showed that there was no significance in testing anywhere between the zero to four hour marks because there was so much overlap in the results. The definite strength change began at twenty four hours and continued to increase up to forty eight hours suggesting that the most increase in strength happened somewhere in that range. The Rebound tester showed that up to the four hour mark there was not much of a change and from the twelve to forty eight hour marks there were also no significant changes.

4.10 Round 2, Raveling Test Results

Once the first round of testing was completed on the ambient cured samples, the test was repeated with foamed asphalt samples cured at ambient temperatures as well. Only two samples were tested at each curing time instead of three to save material. The foam samples were even more fragile than the emulsion samples when subjected to the same curing conditions. Table 4.12 shows the data obtained from the foam samples tested.

Table 4.12: Raveling data for foam samples cured at ambient temperature

Cure time (hr)	0	0.5	1	1.5	2	3	4	12	24	48
Avg Time lasted (sec)	2.0	6.5	10.0	7.5	10.0	9.5	11.5	12.5	13.5	43
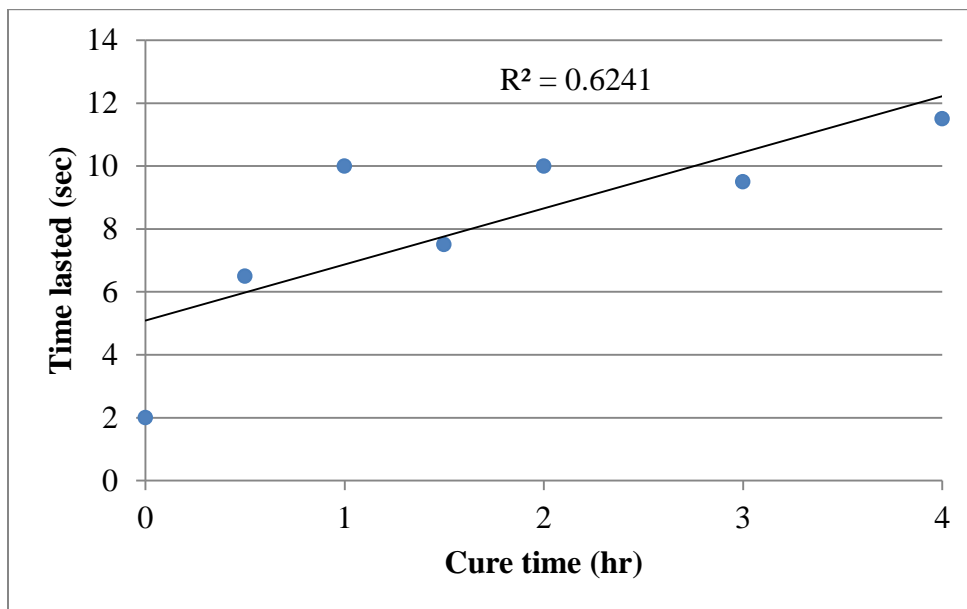
Figure 4:23: Time lasted (0-4 hours) vs. cure time of foam samples, at ambient temperature
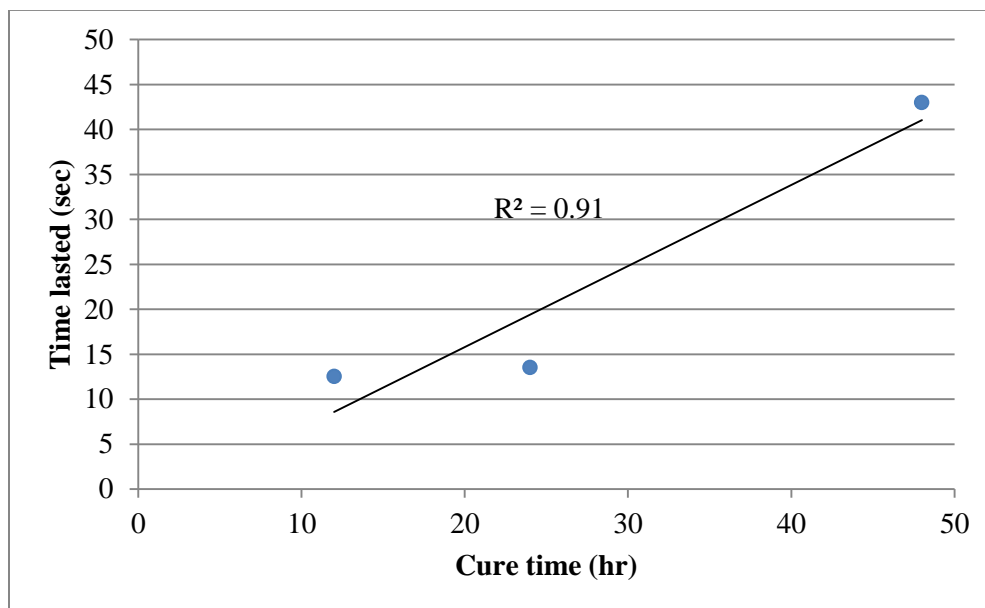
Figure 4:24: Time lasted (12-48 hours) vs. cure time of foam samples, at ambient temperature

When looking at both the foam and the emulsion samples, the variability of each of the stabilizing options is very high. Even so, there still seems to be a linearly increasing trend

with both sample types. From Figure 4.23 and 4.24 it can be seen that the foam samples seem to have a more linear increase in strength than the emulsion samples. The times are much smaller for the foamed asphalt when compared to the emulsion, but this is most likely due to not having the optimum mixture for the foamed asphalt samples.

To determine if the type of curing had a significant effect on the emulsion samples, another round of emulsion samples were tested after curing in a draft oven at 40°C. The data from the tests that followed can be seen in Table 4.13.

Table 4.13: Raveling data for emulsion samples cured at 40C

Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg Sec	17.5	24.5	39.5	41.0	58.0	36.5	49.5	600.0	600.0	600.0
% Mass Loss	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.6%	4.9%	3.9%
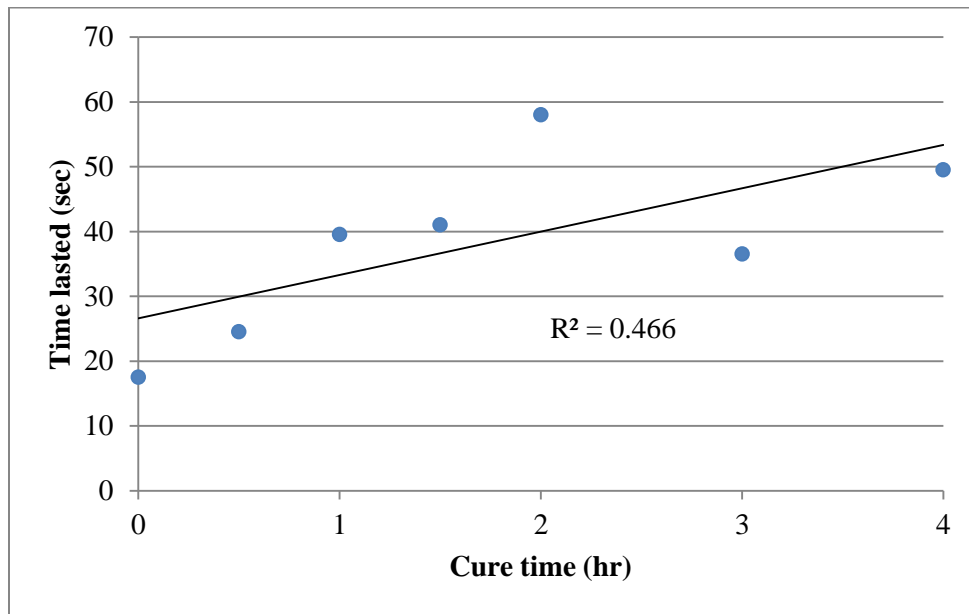
Figure 4:25: Time last (0-4 hours) vs. cure time of emulsion samples, 40C draft oven
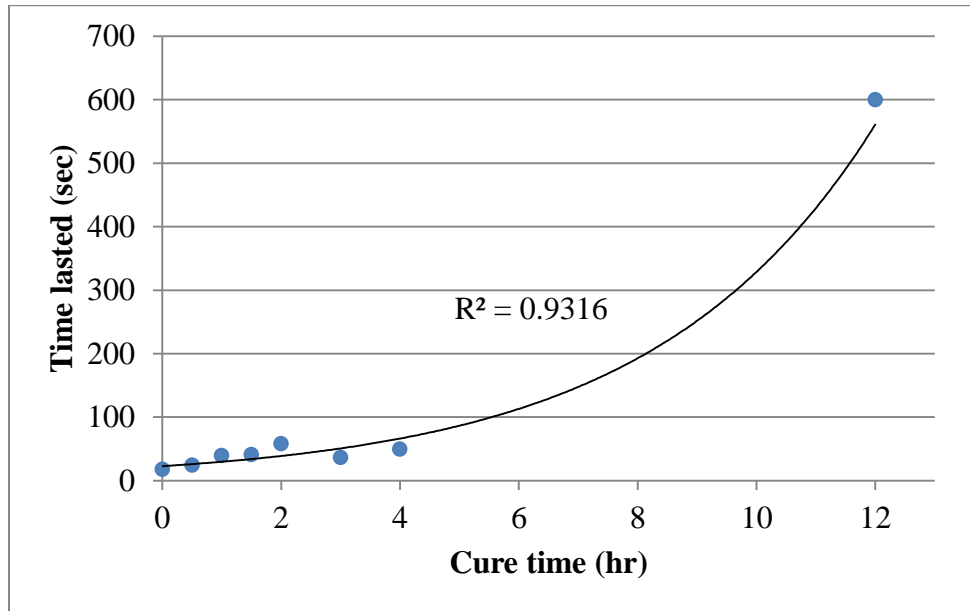
Figure 4:26: Time lasted (0-12 hours) vs. cure time of emulsion samples, 40C draft oven

From looking at Figure 4.25, it seemed that when curing in an oven there was more of a linear trend in the strength gained by the samples up until four hours. From four hours to twelve, there seems to be a large increase in the resistance to raveling. From Table 4.13 the data shows that there is a slight linear trend upward until the four hour mark, but then the trend begins to illustrate a much steeper increase in strength as can be seen in Figure 4.26. When curing in the draft oven, the samples cured much faster and the twelve hour sample was able to make it throughout the duration of the test. There was no need to graph the full forty eight hours because the twenty four and forty eight hour tests both went the duration as well. There was a linear decrease in the mass loss that is experience in the samples which seems as if it would continue to slowly decrease after the forty eight hour mark. Figure 4.27 shows an emulsion sample before the test begins and after the sample has failed.

Figure 4:27: Raveling test before and after

4.10.1 Problems/Recommendations

One of the problems with this test was the samples in their early curing stages. If a section of FDR surface were to be subjected to traffic in the field it would have a sort of confinement pressure around it. With the samples produced in the lab, there was no way to have any sort of confinement while this test was being run. The samples began to fail immediately after the raveling head would sweep over the edge and catch a larger aggregate. This is not representative of what would necessarily happen in the field. It is recommended that for this to accurately correlate with data gathered from the field, some sort of slab compaction would need to be utilized so there could be more of a true representation of the samples resistance to raveling. Also the increase in strength could not be determined from the four hour mark to the twelve hour mark because no testing was done. It is suggested that this testing be carried out for at least every two hours between the four and twelve hour marks

4.11 Round 2, Sweep Tester Results

Because of the ease with which this test was performed and the fairly repeatable data obtained, it was chosen to move forward with to test the foam and emulsion samples. Table 4.14 shows the data obtained from testing the asphalt foam samples, curing at ambient temperature.

Table 4.14: Sweep data for foam samples cured at ambient temperature

Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg % Mass Loss	5.1	1.8	1.4	0.9	1.6	2.0	1.5	0.4	0.5	0.3
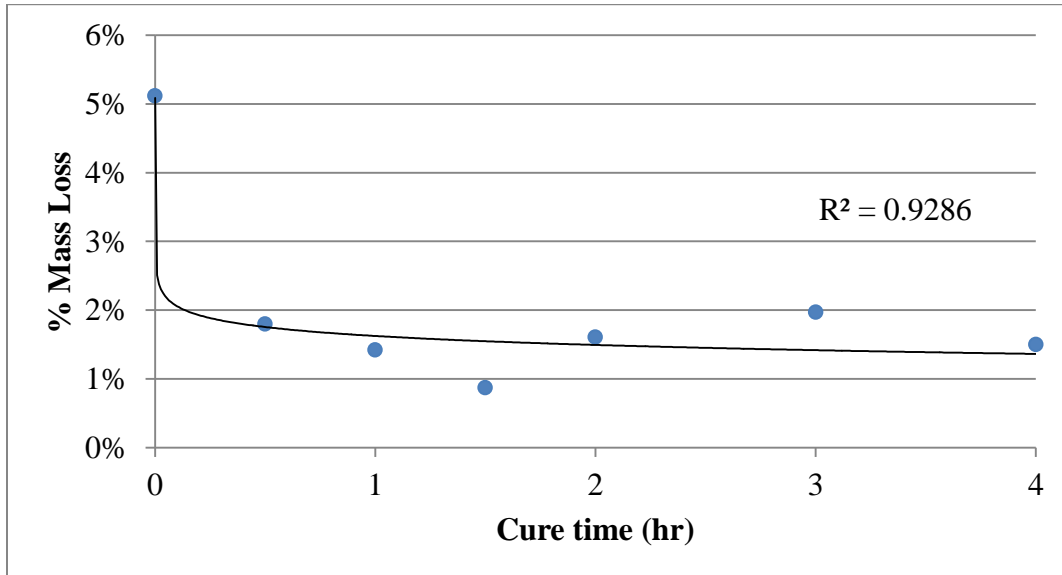
Figure 4:28: % mass loss vs. cure time (0-4 hours) of foam samples, at ambient temperature

The foam samples tended to react differently to the tester by producing more of a logarithmic trend seen in Figure 4.28. There was a large drop in percent mass lost from the time zero to the thirty minute mark. This shows a fairly significant increase in the strength of the sample early on. After thirty minute mark there was not a noticeable difference in the strength of the sample up until the twelve hour mark. The data planed out after the one hour mark and the sample continued to gain strength up to twelve hours. The data still slightly decrease beyond that point, but it is very slight. There is not a very large range of mass loss to distinguish from between time zero and forty eight hours and with such small quantities the data is hard to interpolate. The emulsion samples cured in the draft oven were finally tested with this device and the data is displayed in Table 4.15.

Table 4.15: Sweep data for emulsion samples cured at 40C

Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg % Mass Loss	0.36	0.52	0.22	0.07	0.09	0.06	0.05	0.08	0.04	0.06
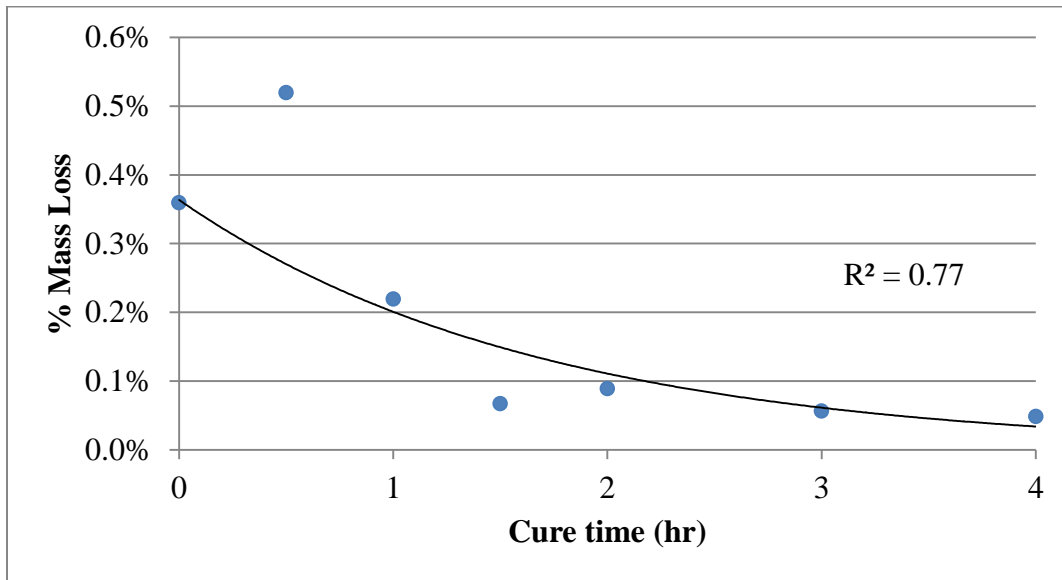
Figure 4:29: % mass loss vs. curing time (0-4 hours) of asphalt emulsion, at 40C

When looking at the Table 4.15 and Figure 4.29 there is a noticeable decrease in the percentage of mass from time zero to one and a half hours. The percent mass loss begins to plane off after then and stays at a fairly low amount from there on out. This set of data tended to follow an exponential curve, differing from both the asphalt foam and the asphalt emulsion samples cured at ambient temperature. Similar to the criteria for ASTM D7196, once the samples begin to experience a percent mass loss under a certain amount, the specification deems them acceptable. This could be specified for this test or one similar to it in the future.

4.11.1 Problems/Recommendations

One of the problems faced with this tester was the differing heights of the samples. The samples varied in height anywhere from 68-75 mm, which would mean some samples were getting more pressure from the brush than others. This could have caused more or less mass loss throughout the testing procedure. Another problem was the instability of the entire apparatus. It was very difficult to hold onto the drill throughout the duration of the test. Also because of the instability of the drill, the test had to be carried out at the top speed that the drill could operate. This was because the drill was impossible to control at slower speeds and only at the highest speed was it able to be held in place. This also posed a problem because the brush was spinning so fast that it actually heated up the top of the samples. This could have caused the binder to soften and cling to the fines that were present on the surface that would have otherwise been expelled by the brush head. The problems could all be addressed with a more robust design of this same apparatus, but it will most likely cost a considerable amount.

4.12 Round 2, Rebound Tester Results

Next, the foam samples were tested after being cured at ambient temperature. Two replicates were tested at each curing time specified. The data is shown in Table 4.16 and Figures 4.30 and 4.31.

Table 4.16: Rebound data for foam samples cured at ambient temperature

Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg Rebound Height	19.67	22.33	20.33	21.67	22.83	21.00	22.17	25.33	29.83	32.83
Std Dev	1.86	1.37	0.82	1.63	1.17	2.68	1.94	1.63	1.72	0.41
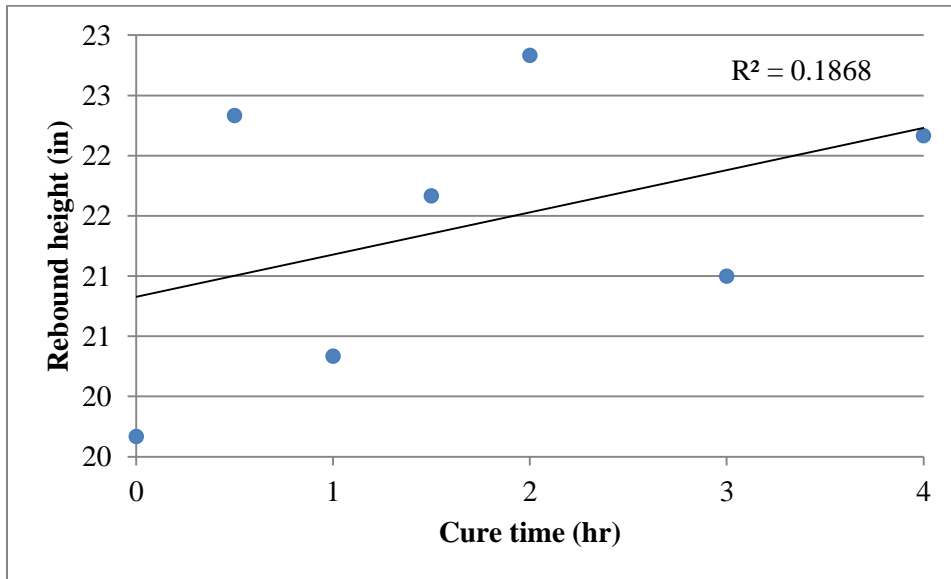
Figure 4:30: Rebound height vs. cure time (0-4 hours) of foam samples, at ambient temperature
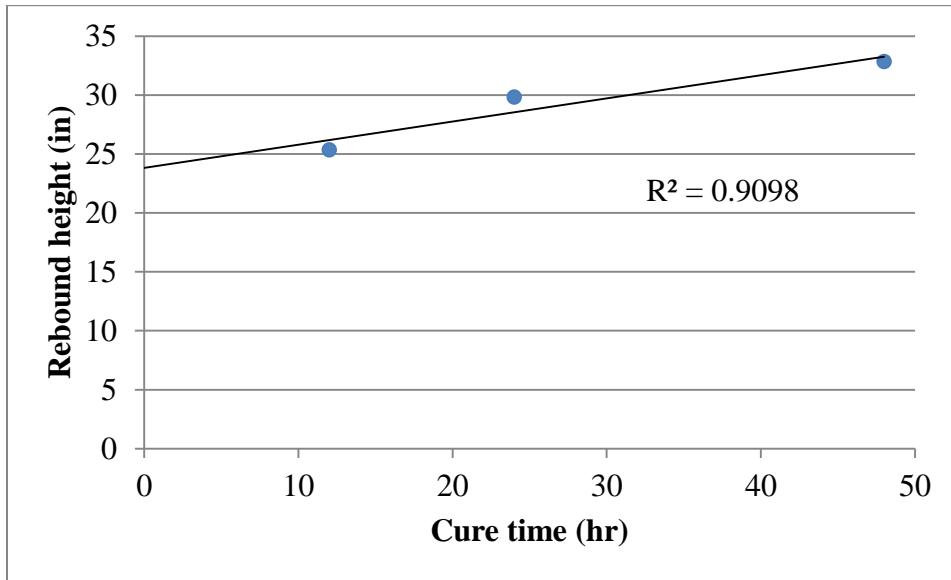
Figure 4:31: Rebound height vs. cure time (12-48 hours) of foam samples, at ambient

temperature

When analyzing the data obtained from the foam samples, it was apparent that there

was a much more linear trend over the entire span of testing. From the zero to four hour test

the data was very random and didn't tend to follow any pattern. The later three testing times

exhibited much more linear characteristics than the earlier times. There was also a low COV,

similar to that of the test performed on the emulsion samples. There was a fairly large range

of rebound heights when compared to the emulsion samples. Approximately thirteen inches of

difference separated the initial drop from the final drop at forty eight hours.   When

considering the entire testing time the data displayed a linear increase in rebound height.

Another discovery was the initial rebound height of the foam samples. A nearly ten inch

difference was recorded from the initial drop height of the emulsion samples. Regardless of

the initial rebound height, the foam samples, at forty eight hours, had nearly the same rebound

height as the emulsion samples. It is not believed that the rebound heights will increase in any significant manner when tested past forty eight hours.

The final rebound tests were carried out on emulsion samples cured at 40C in a draft oven. The data is shown in Table 4.17 and Figures 4.32 and 4.33. It appears that there was relatively no difference in the rebound height from the ambient cured samples and the oven cured samples. The data was nearly identical in both instances. The difference is so small between time zero and forty eight hours that it would be hard to discern between the curing times that were being tested if tested at random.

Table 4.17: Rebound data for emulsion samples cured at 40C

| Cure Time	0	0.5	1	1.5	2	3	4	12	24	48
Avg Rebound Height (in)	29.00	27.83	31.00	30.17	29.00	30.17	30.67	30.50	32.83	33.50
Std Dev	2.90	1.17	2.45	1.17	1.41	0.98	0.82	1.05	1.33	1.76
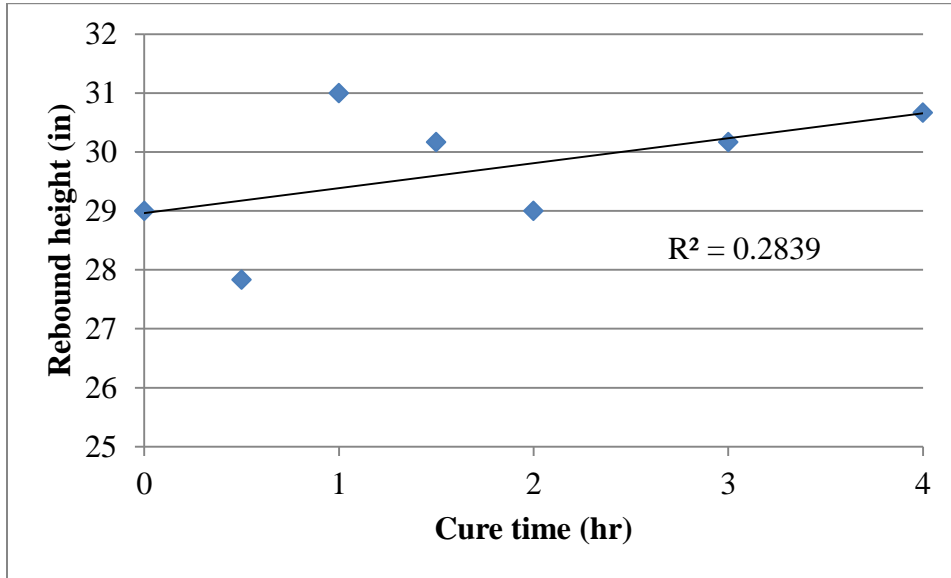
Figure 4:32: Rebound height vs. cure time (0-4 hours) of emulsion samples, at 40C
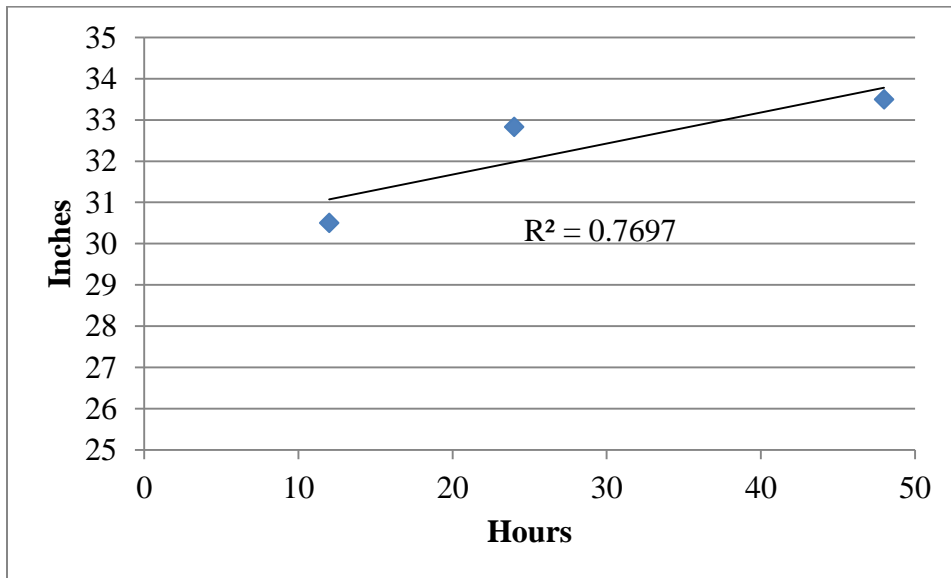
Figure 4:33: Rebound height vs. cure time (0-48 hours) of emulsion samples, at 40C

4.12.1 Problems/Recommendations

While this test was fairly accurate, there were a few problems. One of the problems with the test was achieving a consistent rebound. Many times the golf ball would strike the top of the sample and then bounce straight into the side of the PVC pipe. When this occurred it would affect the rebound height and that drop would be abandoned and not added into the average. This problem could have been attributed to the manner in which the ball was dropped from the top. The delivering device at the top was fairly accurate, but would not drop the ball in the exact same spot every time. This problem also could be credited to the ball striking the edge of a larger piece of aggregate. Another problem associated with the bounce was that on occasion, the ball would land directly onto a single larger aggregate and the rebound height would be much more exaggerated than the rest of the bounces. This would slightly skew the data to a large average drop. The main problem with the device was that, with FDR samples, the device did not give data in a large enough range to distinguish a specific time during curing. The rebound height consistently increased, but with such a small window to look at, there really wasn't enough room to distinguish a specific height to assign a curing rate to. It is recommended that if used, a new dropping method should be fashioned and maybe a different type of ball should be used that is more responsive to the curing rate of the FDR samples.

4.13 Round 2, Conclusions

Round 2 testing consisted of the testing of a different stabilizing agent, asphalt foam to determine whether or not the testers could be used on more than just the emulsion samples. Another ANOVA was run on the foam samples to determine the significance of the curing time when tested with the remaining three testers. The data is presented in Table 4.18.

Table 4.18: P-values from ANOVA of the cure time significance on foam samples cured at ambient temperature

Tester	P-value
Sweep	0.04939
Raveling	0.00408
Rebound	3.4E-20

All of the P-values represented significance in the cure times of the asphalt foam samples. The sweep tester was close to being insignificant. The raveling and rebound testers showed that the results were significant based on the cure time.

When checked by the LSD method, the Sweep tester showed that up to the two hour mark the data had no significant change. After the two hour mark the data had quite a bit of overlap in level of significant change and was very similar. The Raveling test showed a similarity in the data grouping one and a half hours to twenty four hours. There was a significant change from twenty four hours to forty eight, suggesting a noted increase in the

resistance to the tester. The rebound test showed that the twelve, twenty four, and forty eight hour marks all exhibited a significant increase in rebound height.

The second part of Round 2 involved the testing of emulsion samples that were cured in a draft oven at 40C. The idea was to determine whether or not the curing temperature had an effect on the data that was obtained from the testers. The data from this part of the testing was compared with the data obtain in Round 1 to determine the curing temperatures significance. Table 4.19 shows the results of the ANOVA test run on the differing curing procedures.

Table 4.19: P-values from ANOVA of the curing type and time on emulsion samples at 40C and ambient temperature

Tester	P-value $_{Type}$	P-value $_{Time}$
Sweep	1.40E-07	3.17E-08
Raveling	4.08E-22	4.50E-39
Rebound	0.160906	0.000134

From the data, the Rebound test showed to not be significantly affected by the differing curing methods. This was expected when the rebound test was conducted and is represented by the largest P-value of the three testers. The curing type and time had a significant effect on the Raveling test and the Sweep test. This could have been attributed to the tests similarities.

When the LSD method was applied to the sweep tester data it showed that after the two hour mark, the change in percent mass loss contain much overlapping. This showed that after the two hour mark the test had minimal change to the surface of the sample. The Raveling test showed a slight increase in strength leading to the four hour mark. Between the four and twelve hour marks where when the samples had a significant increase in resistance to the test. The Rebound test had quite a bit of overlap in the significant change of the data up until the twelve hour mark. The test did show a significant change at the twenty four and forty eight hour marks.

4.14 Conclusions

When taking all of the devices into consideration, none of them, in their current state, are suitable to test in the field. All of them were built to be used in the lab and in the field. There would have to be a few adaptions made. Every tester would be able to be used with the exact same quantification method except for the sweep test. This test would have to be quantified by the mass of the debris generated and not as a percentage of the total mass. Another possible type of quantification could be achieved by performing a sand patch test (ASTM E965) on the area immediately before and after the test was run. This would measure the texture of the surface which would be believed to increase in roughness after the test was completed.

There are many improvements that could be made to the device to achieve more accurate results. If this research were continued, it is recommended that the testing be done in

one hour increments through twelve hours and then every twelve hours after through seven days. This would give a broader range of data to more accurately record the curing process of the FDR pavements. Also finding the difference between using different types of emulsions could lead to discovering if the devices would be applicable in different circumstances.

Information received while attending the International Symposium of Asphalt Emulsion Technology (ISAET '12) conference shed light on a device that is much like a hybrid of the sweep test and the raveling test. The information was about a modified Hobart mixer that had been designed, but never fully tested in this manner. This is one of the main reasons that further testing was carried out with the sweep tester. It basically works the same as ASTM D7196, but with a modified N-50 Hobart mixer and abrasion head (including hose) used in the Wet Track Abrasion of Slurry Surfaces Test. The device can be seen in Figure 4.34.

Figure 4:34: Modified Abrasion Tester

This tester seems to address all of the downfalls that were described between the sweep test and the raveling test. It provides the user with the accuracy of the Hobart mixer and the ability to operate at one specific speed. It also gives the mobility to take to the field as well as test samples in the lab. It is believed that this tester would be able provide accuracy in the testing procedure itself without much variability, regardless of the person performing the test. While this is an option, it does not fit into the category of being an inexpensive tester. The Hobart mixer itself is in the $2000-$3000 range.

Chapter 5

5.0 Conclusion

The research objective of this study was to develop and validate new testing approaches to characterize an early return to traffic for FDR pavements. This report includes a description of the construction, methodology, operation and results from four in-house developed testing devices. These include the pendulum tester, torque tester, sweep tester and the rebound tester. They were each built with very simplistic parts that were acquired from a local hardware store. All of the testers were built at the Engineering Research Center (ERC) of the University of Arkansas by a graduate student.

These testers, along with the raveling test, were used on emulsion and foam stabilized FDR samples. The samples were mixed on a 1:1 ratio of RAP and Class 7 base course. Mix designs were evaluated and run to determine the optimum emulsion content for the samples to mass produce for testing. The samples for testing were cured at ambient temperatures and in a draft oven at 40C for a period of forty eight hours. Over this time period the samples were tested at specific time intervals with each device to determine the devices capability to measure the resistance to raveling of the FDR samples. Thirty emulsion samples, cured at ambient temperature, were tested by each tester in Round 1 of testing, 150 samples being tested in total. Round 2 of testing involved twenty foam samples, cured at ambient temperature, to be tested by the three most promising devices, the sweep tester, the rebound tester, and the raveling tester. Round 2 also included the testing of the same three devices on

emulsion samples, cured a 40C in a draft oven to determine what significance the differing curing methods had on the samples.

5.1 Tester Results

The data obtained from the testers themselves was not very consistent. Trends were made with each device, but the inaccuracy of the data showed that there was much to be improved upon by each device. The idea was to build cheap and simple testing devices. If one of them happened to work then that would have been great. The true purpose of the devices was to analyze their potential to characterize FDR pavements in the area of return to traffic. They were based off of many devices that measured different fundamental properties such as friction, torsion, stiffness and abrasion in hopes of finding a correlation to susceptibility of an FDR pavement to ravel if traffic was released on it too early. With the simplistic nature of the devices, expecting consistent data was somewhat unrealistic. The more money and resources that are put into a test, usually translate into more accurate data acquisition. Aside from the inaccuracy of the testers, FDR is an extremely variable type of pavement. The range of aggregate sizes and different options for stabilization make it an ever changing variable from job to job.

The testers that showed the most potential were the raveling test and the sweep test. The sweep test proved to be the more reliable of the two when the data was analyzed. ANOVAs to determine the significance of the curing times for the emulsion and foam samples cured at ambient temperature as well as to determine the significance of the different

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curing methods that were used. In each of these analyses the sweep tester proved to give a ninety five percent probability of significance. This was a good sign because if significant data can be obtained from a simple device such as the sweep tester, then it could be possible to further develop it to obtain even better data. A current device, stated at the end of Chapter 4, might be the most accurate way to quantify the raveling characteristics of an FDR pavement. It is a combination of the sweep tester and the raveling tester. It seems that it would provide more accurate data based off of its slower rotational speed and its ability to exchange abrasion heads.

5.2 Recommendation for Future Research

Research in FDR is ongoing throughout the world. Here in the United States, there are many Departments of Transportation (DOTs), private contractors and universities that are trying to hone the process. Recycling of asphalt pavements is an effective way to reuse resources, and agencies are recommending its use, with the Federal Highway Administration (FHWA) issuing a policy statement that "recycling should be one of the options considered at the design stage on all rehabilitation projects." Due to the large variability concerning materials, there is no current standardized mix design process as of yet, nor is there a standardized mixture. The results of structural characterization and life-cycle cost analysis vary greatly, making it difficult to implement the results of previous studies directly as typical values for future pavement designs. Due to the increase in traffic, the deterioration of our nation's infrastructure and the push for sustainability, FDR seems to be a very strong candidate for the future of transportation.

Many different testing methods were used during this research to try and find a correlation between FDR raveling and curing time. A definite trend was not established with any of the testers, but ground has been broken for future research. If this subject were to be pursued further, it is recommended that a device similar to that of the raveling tester and the sweep tester be given top priority. Their relative ease of use and ability to be adapted to lab testing as well as field testing makes them the optimal choice. Future lab work should encompass the use of different setting emulsions tested with different mix designs and with different combinations of aggregate. Also if the nominal maximum aggregate size in the samples could be reduced and similar data could be obtained, the devices might prove to be more accurate. The time period that was tested was split into periods that might have been too far apart from one another to develop a definite trend. The data showed that FDR pavements within the first four hours of curing do not show a significant increase in strength. With that being discovered, it would be suggested that future testing be conducted at larger curing increments of two hours or more. This would allow for the gap in data from four hours to forty eight to be filled in and allow for a better trend to be formed. With that gap filled in, the data could be reanalyzed and then a more specific time window could be honed in on for future testing.

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Appendix

6.0 Pendulum Tester

6.1 Materials

- 2, 26" 2x4" Lumbers

- 2, 24" 2x4" Lumbers

- ½" Pipe Bender

- 5/8" ID Heater Hose

- 6, 3/8" Hex Lock nuts

- 1' of 3/8" All Thread

- 1' of 5/16" All Thread

- 4, 5/16" wing nuts

- 2, 10" Mending Plates

- 4, 2" L Brackets

- 4, 2" Wood Screws

- Softtouch Leveling Glides, 4, 1 1/16"

- 16, 1" Wood Screws

- 1.5" x 3/8" Steel Sleeve

- Wood Glue

6.2 Construction

1. Cut 2x4" boards to lengths specified above.

2. Drill a ½" diameter hole through both of the 24" lumbers 2.5 inches from the end, in the center of the widest part of the lumber.

3. Drill a hole, long ways, and in the center, of the 26" boards approximately 2" deep.

4. Cut the 1' of 5/16" All Thread into 3" segments and place them inside of the holes that should be pre-coated with Wood Glue and let dry.

5. Cut handle on the pipe bender to a length of 25" from bottom.

6. Drill a ½" hole centered ¾" from the end that was cut, perpendicular to the pipe bending end.

7. Drill holes onto the bottom sides of the 26" lumbers 3" inches from both ends. Holes shall be drilled as the Leveling Glides instructions read.

8. *Center the 24" lumber onto the 26" lumber by laying the 26" lumber flat and standing the 24" lumber up and flush with the edge of the 26" lumber. Forming an "L" shape. The holes should both be at the top.*

9. Once centered drill 2, 2" wood screws at an angle through the 24" lumber and into the 26" lumber to secure them.

10. Once secured, place 2 L brackets where the lumber meet and using 3 of the 1" wood screws for each bracket, screw them in to add further support.

11. Now if sitting flat, you should have to "L" shaped pieces. Turn the pieces back to back, where the foot of the "L's" are pointing away from one another.

12. Place the 3/8" sleeve through the hole in the pipe bender and then place the 3/8" All Thread through the sleeve.

13. Screw a 3/8" Lock nut from each side so that the sleeve and the pipe bender are centered on the All Thread. DO NOT TIGHTEN UP AGAINST THE SLEEVE ON EITHER SIDE.

14. Place 2 more of the Lock nuts onto each side of the All Thread so that they are less than an inch away from the Lock nuts previously place on.

15. Put each end of the All Thread into the holes drilled at the tops of the 2, 24" lumbers

16. With the remaining 2, 3/8" Lock nuts tighten the lumbers to where they are 5.25" apart and centered on the All Thread.

17. Now reverse the two previous 3/8" Lock nuts up against the lumbers from the inside to lock the All Thread in place.

Once wood glue has had sufficient time to dry

18. Place the 10" mending plates over the All Thread coming out of the ends of the 26" lumbers on the inside holes and tighten with the 5/16" wing nuts.

19. This should give the dimension of 5.25" between the lumbers.

20. Place feet into holes drilled into the bottom of the 26" lumbers according to manufacturer's instructions.

21. Cut a sufficient length of Heater Hose to place in the end of the pipe bender where the pipe would actually be.

6.3 Operation

1. Secure pallet jack in place.

2. Place rubber floor mat in the middle of the pallet jack.

3. Set pendulum tester on each side of the pallet jack, centered above the rubber mat.

   a. Make sure that pendulum tester can complete full swing

4. Center sample underneath pendulum tester.

5. Adjust pallet jack so that back of pendulum arm is even with the edge of upright 2x4 lumbers.

6. Once the angle is set, raise the head of the device to the peak of its rotation, perpendicular with the ground.

7. Release the head and record the number of times that the head passes over the sample.

8. Whenever the head stops, that last number does not count. The number recorded with be the 1st swing.

9. Repeat this process, taking care to not move the device so that it will strike the same position on the sample.

10. Again, record the number of swings until the head has stopped. This number with be your second swing.

6.4 Calculation

$$\frac{1^{st}\ Swing}{2^{nd}\ Swing} = Pendulum\ Swing\ Ratio$$

7.0 Torque Tester

7.1 Materials

- 1/2" Rigid Conduit

- **7** 6x1/2 Stainless Steel Flat Phillips Sheet Metal

- **2** 4x2-3/16 Screw Eye – Zinc

- 1" Flat Washer SAE-Zinc

- ¼" All Thread Bolt

- 2x4 Lumbers at least **10'** required

- ½" Round Box 5 Holes

- Fixture Box 4" Octagonal Cover

- Craftsman Beam Torque Wrench ½" Drive

- 21mm ½" drive socket

- 2/0 Straight Link Coil Chain

- Hex bolt that will slide inside of ½" rigid conduit

7.2 Construction

1. Drill 1/8" Holes in base plate at 60° spacing approximately1 ¼" from center

2. Attach base plate to fixture box with screws pointing outward

3. Cut 2 2x4 Lumbers to 4' lengths

4. Notch the center of each board on the flat side ½" deep and 1" wide

5. Cut two lengths of chain to 28" or 22 links

6. Cut ½" pipe to length of 4'

7. Drill 5/16" holes through the pipe at lengths of 18.5", 20.5", and 22.5" from the bottom

8. Screws stick out 3/8"

9. 1" hole through center of 2, 2x4

10. Slide bolt into top of conduit

11. Weld bolt into the conduit

12. Screw screw eyes into the flat side of the 2', 2x4 approximately one inch from ehte end and in the center of the board.

7.3 Operation

1. Place sample on a rough surface, such as unfinished concrete

2. Place a bolt through the desired holes, depending on how much pressure you want to apply

3. Slide washer down onto the bolt from the top of the conduit

4. Slide the 2', 2x4 with the hole in the middle down over the top of the conduit so that it sits on the washer

5. Attach springs to the screw eyes

6. Attach chains to the other end of the springs

7. Place base plate onto the top of the sample

8. Slide the 4', 2x4's through the chains so that the chain rests in the notch

9. Have one person stand on both boards on one side and hold the conduit

10. After they are settled, the other person steps onto the boards one at a time

11. Adjust as needed so that the conduit is centered over the sample

12. Take torque wrench and attach to the bolt welded at the top

13. Apply torque while the other person watches the sample

14. When the surface of the sample begins to give way, record the torque.

8.0 Sweep Tester

8.1 Materials

- 8' - 1 x 5 ½" lumbers

- 1 – Jackson Safety 28" Reflective Cone

- Quickie - Professional Acid Brush

- Janitor Mop Handle

- 3 ½" Phillips Power Bit

- Wood Glue

- 6 – 2" Exterior Screw

- Porter Cable 7.0 AMP Drill PC700D

- Rubber car mat

8.2 Construction

1. Cut top of traffic cone off approximately 5" from the cut to the ground

2. Cut 2 boards to 16.25" lengths

3. Cut 1 board to 15.75"

4. Cut a 2.25" diameter whole in the center of the 15.75" board

5. Once boards are cut to the dimensions above, place three screws through the flat side of the shorter board, lengthwise, into the two longer boards, which will be acting as legs. Make sure that the legs are flush with the sides.

6. Cut the brush to a length of 6", 3" length on each side of center

7. Cut a notch ¾" across the width of the broom and 3/8" deep

   The following dimensions will be variable

8. Cut mop handle to a length of approximately 4.5" long. This is the handle only.

9. Drill a hole that is 9/32" in diameter into the middle of mop handle. Make sure hole is the right depth so that the drill can still attach to the drill bit.

10. The drill bit should sit 1 1/8" into the drill when attached.

11. The mop handle length and the depth of the hole to be drilled can vary. The objective is to have the brush sit flush on the ground once sitting in the base and attached to the drill.

12. Once the lengths are determined, wood glue the drill bit into the mop handle and let dry for the time specified by the type of wood glue used.

13. Attach the brush to mop handle, setting the notch into the mop

14. Tighten down on the brush

8.3 Operation

1. Get an initial weight of sample

2. Place sample on rubber mat

3. Place traffic cone around sample

4. Place drill base over the traffic cone, centered above the sample

5. Attach mop head to the drill through the hole in the drill base

6. Tighten the drill bit into the drill

7. Center the brush head over the sample

8. Get drill up to full speed

9. Firmly lower brush head onto the top of the sample and process to brush the sample for 45 seconds.

10. After the 45 seconds is up, take another weight of the sample

8.4 Calculations

$$\left(1 - \frac{final\ weight}{initial\ weight}\right) * 100 = \%\ Mass\ Loss$$

9.0 Rebound Tester Specs

9.1 Materials

- 3" Diameter PVC Pipe at least 4 ft. Long

- 3"x3" Flexible Coupling

- 3" PVC Spigot Flange

- 3"X1.5" PVC Coupling

- Titleist DT Solo Golf Balls

- Callaway Solaire Golf Balls

- Spray Paint – Any Color besides White

- Marker that Contrasts with chosen paint color

9.2 Construction

1. Cut PVC pipe into 3' long segment

2. Cut a 1" slit down the length of the pipe

3. Place the 3"x3" Flexible Coupling and the 3" Spigot Flange together and tighten

4. Slide the PVC pipe into the top of the 3"x3" Flexible Coupling

5. Measure from the bottom of the 3" PVC Spigot Flange to the top of the PVC pipe

6. Mark the pipe at the left or right edge of the slit in Inches to the top

7. Place 3"x1.5" PVC Coupling on top of the pipe to where it slides over the top of the pipe

9.3 Operation

1. Place sample on flat surface

2. Place bottom of tester onto the top of the sample surface

3. Place Spigot Flange on top of the tester

4. Either have someone watch or take a video of the side of the tester marked in inches

5. Drop ball through the spigot flange and record the rebound height

6. Repeat step 5 three times, each time moving the tester slightly so as not to drop the ball in the same exact spot

7. Take an average of the three rebound heights. That is the final measure