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Full Depth Reclamation: Compaction and Moisture Content

An Undergraduate Honors College Thesis

in the

Department of Civil Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

by

Alexander Jackson

April 26, 2012

FULL DEPTH RECLAIMATION: COMPACTION AND MOISTURE CONTENT

An Honors Thesis submitted in partial fulfillment
of the requirements for Honors Studies in
Civil Engineering

By

Alexander Jackson

2012
Department of Civil Engineering
College of Engineering
The University of Arkansas

This thesis is approved.

Thesis Advisor:

Thesis Committee:

Abstract

Many times a road will fail and will be in need of both a structural increase and a repair. Full Depth Reclamation (FDR) is a road rehabilitation technique able to offer both. This method also has a lower total cost and significantly lower material usage than traditional overlaying repair methods. FDR is a road repair method which mills up the current road down into the subgrade, and then stabilizes and compacts the milled material. This is also useful for correcting deeper problems in the road structure which are not addressed by traditional methods. In this study, three different suggestions of mix designs for this repair method were observed, and the strengths and weaknesses of each were compared. A consistent problem with the more thorough mix designs was that there is a large amount of equipment required from different fields of engineering: many of the tests required equipment from both a soils and a pavements laboratory. In an effort to streamline testing equipment, the results of a modified Proctor test were compared to the results of densities of samples tested in a gyratory compactor at varying water contents. The Proctor and gyratory compactor both gave similar trends between water content and dry density. The gyratory compactor testing was also much quicker, and the data had a tighter fit line. This is an important step in simplifying FDR mix design in order to make it more widely available. Samples with binder contents of 2%, 3%, and 4% and water contents varying from 2%-6% were created in a slotted gyratory compactor. These samples were tested for density and for compressive strength after N_{design} of 75 Gyrations. It was observed that higher water contents were correlated with higher density, and higher compressive strengths. Higher binder contents had no noticeable bearing on the density of the sample, but did increase the compressive strength of the sample. In the future, the adsorption of coarse aggregate will be observed, and samples will be tested at higher water contents.

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ABSTRACT

1. INTRODUCTION

A consistent problem in the majority of the developing world is a lack of safe and stable roads. Full Depth Reclamation (FDR) has the potential to be a very useful tool in significantly improving the quality of life in many developing nations. Studies have shown that FDR has the capability to cost effectively improve unpaved roads through stabilizing, or FDR can be used along with an overlay to create a paved road (Bushman 2006).

Many times after a natural disaster such as an earthquake, flood or tsunami, the road system of a country sustains a large amount of damage. In these times, there is an increased need for heavy traffic to efficiently move through the areas, which will further damage the roadways. There have been numerous natural disasters around the world in the last five years which have damaged not only the surface of roads, but also created underlying structural problems. A traditional mill and fill repair is insufficient because many times the new surface will often fail prematurely due to a lack of support. FDR is ideal for these types of repairs because it is truly a full depth repair. This makes FDR a very important tool for a damaged country to help restore itself.

1.1 WHAT IS FDR?

FDR is a method for in-place recycling of a road. In this process, the road is milled to a depth between four and twelve inches, and a stabilizer is added to the millings. Virgin aggregate is sometimes added to ensure a proper gradation. The mixture is then compacted and allowed to cure. This results in a stabilized base course, which can then be sealed and overlaid to create a new strengthened road.

FDR is both economically and environmentally beneficial when compared to the traditional mill and fill method of road repair. FDR has significantly lower material production and transportation costs than traditional repair methods. Because it is able to use 100% of the material which is already in place, the issue of hauling away and disposing of existing material is eliminated. (Kearney, 2007)

Many times when a road has failed, there is not only a need for a repair, but also a structural increase from the original design of the road. This happens in newly developed areas where there is a significant increase in population, and consequently more traffic compared to when the road was originally built. FDR offers an increased structure because the stabilized base course has a higher structural number than the original base with which the road was designed. FDR is also able to correct a road grade, and it will repair many subgrade or base coarse problems by the nature of its process. (Kearney, 2007) An example of the FDR process is shown below in Figure 1. The treated material from this diagram will be compacted to create the stabilized base course. This material will then be overlaid to create a new road.

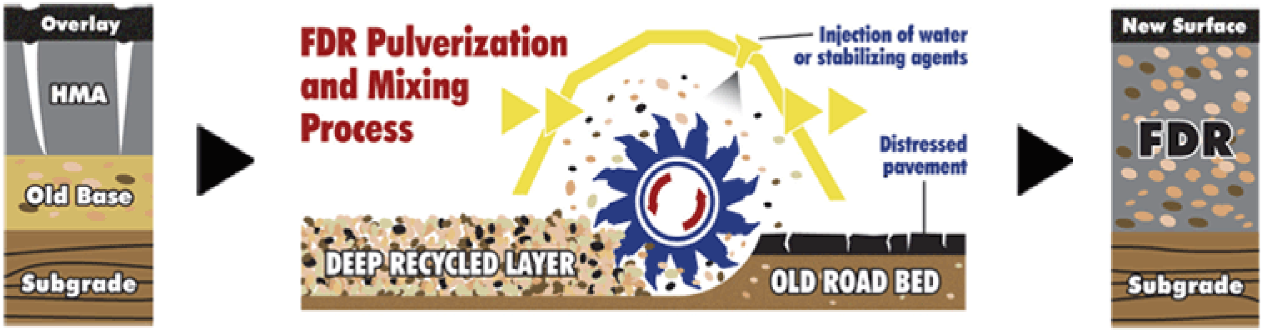

Figure 1. Full Depth Reclamation mill diagram (American Road Reclaimers, 2011).

1.2 EQUIPMENT AND ADDITIVES

FDR is a very broad field, and it has the potential to be used in a large range of situations in regards to current road condition, infrastructure and economy of the area, the materials present in the road, expected traffic loading, and traffic closing time allowed. FDR has many different options for machinery used and stabilization methods. The machinery options can be categorized by how many steps are taken in the process. One option is a multi-step sequence. In this process, different machines are used on the existing road to rip, pulverize, mix crushed samples with stabilizers, compact and level it. A paver is then used to spread an overlay. This process has a lot of potential to be used in developing nations for multiple reasons. The first of which is that there is little initial investment cost in new equipment. The typical equipment required includes a bulldozer, a traveling hammermill (a type of pulverizer), a mixer with the ability to add some type of stabilization input, a compactor, and a paver. Most of this equipment already exists in the majority of places where construction would be conducted. The multi-step process is labor intensive process, which is acceptable in countries where manual labor is inexpensive and where many people are available for work. Many times, this process is not desirable because it takes longer, keeping traffic blocked. It is also a much less accurate procedure when compared to two-step or single machine procedure due to difficulties getting a uniform cut with machinery which was not designed for FDR purposes.

A two-step sequence involves one set of machinery for breaking up and pulverizing the current road and another set for mixing and compacting the pulverized materials. This process is quicker and more accurate. It can also be done in most types of weather. The difficulty with this sequence is that there is a higher initial investment for specialized equipment and specialized training for a crew.

The method with the highest production rate is a single machine, or single pass train. This train is made up of a milling device, a crusher, a pugmill mixer, and a paver, and it can turn a road into a stabilized base course in a single pass. This method requires very specialized equipment, but is desirable for bigger jobs because of its efficiency. As more road systems make the initial investment for this process, it will be more widely accepted.

There are many different stabilizers which are used in Full Depth Reclamation. The main types of stabilizers used are asphalt emulsions, foamed asphalt, cementitious material and mechanically stabilized material. Asphalt emulsions consist of bituminous materials suspended in water. When mixed with FDR, the water evaporates, leaving evenly distributed binder in the sample to increase cohesion and strength. The added moisture content also helps with the compaction of the material. Emulsions are very convenient because the emulsion and the millings are both mixed at room temperature. This makes the process simple and safe. However, emulsions take more time to cure, which slow reopening of roads.

Foamed asphalt is created by injecting hot binder with compressed air and boiling water. This creates a voluminous substance which can mix throughout the sample and form bonds as the binder bubbles deflate. Demonstrations of how emulsions and foamed asphalt stabilizers are created are shown in Figure 2 and Figure 3.

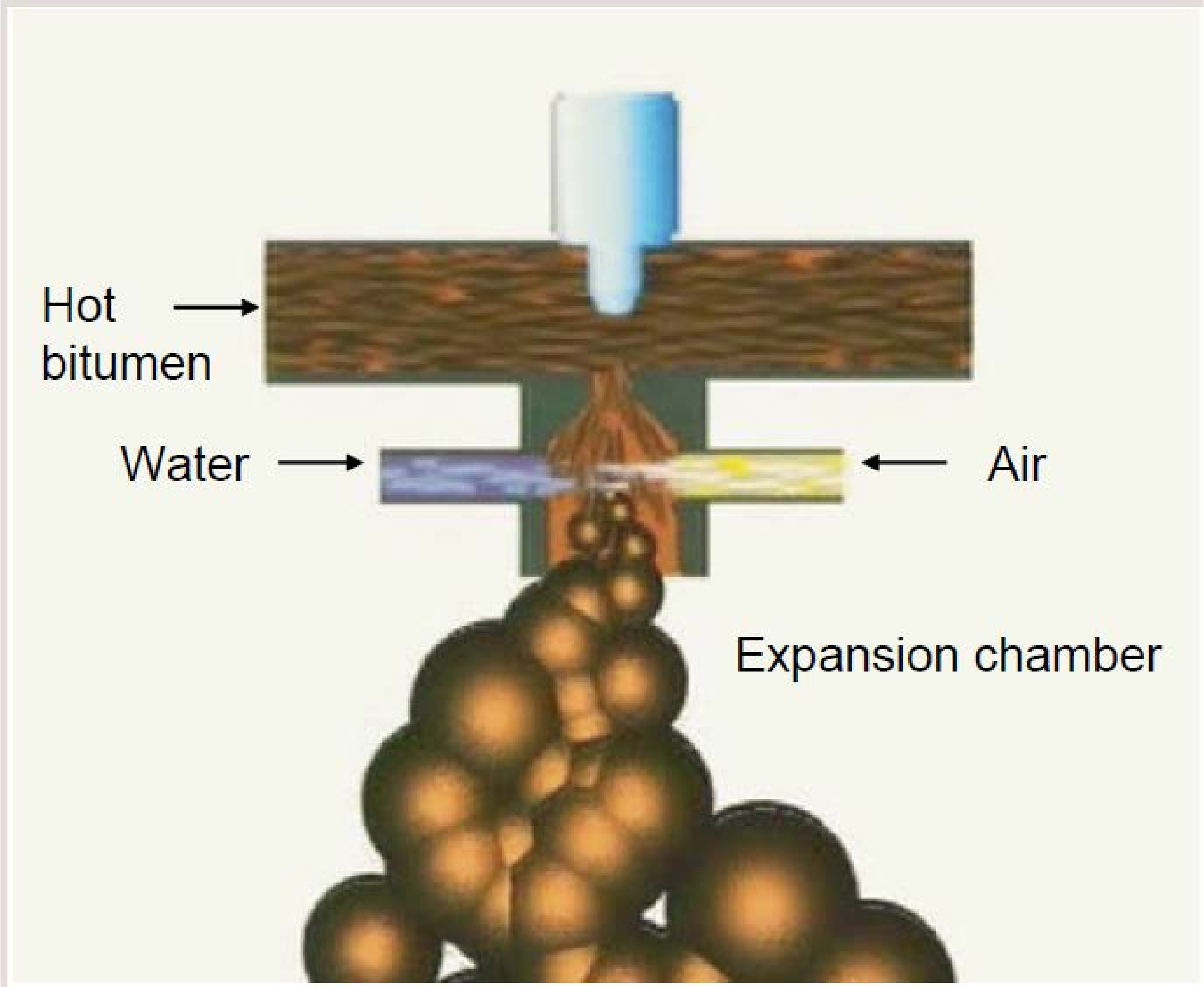

Figure 2. Foamed asphalt diagram (Asphalt Academy 2009).

Mechanical stabilization is used when the milled material is found to have adequate untreated, compressive strength. Sometimes virgin aggregate is added to change the material to a desirable gradation (Asphalt Academy 2009).

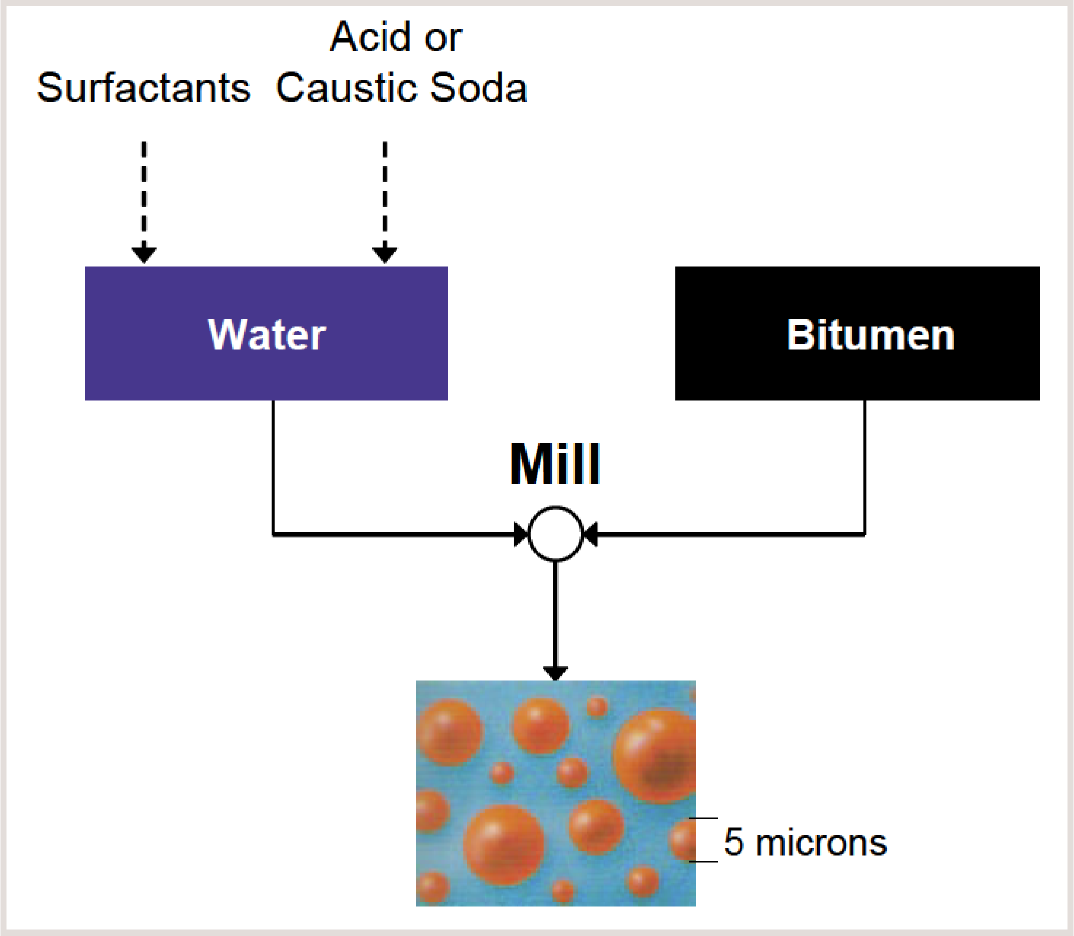

Figure 3. Asphalt emulsion diagram (Asphalt Academy 2009).

FDR involves treating asphalt pavement and part of an aggregate base course to create a stabilized base course. Many times soil is also milled up along with the pavement and base course as a result of an inconsistent road profile. FDR has a wide range of materials used, and therefore, requires a wide variety of testing. These tests require many types of equipment, making the type of laboratory used in FDR to be very complicated and expensive.

There is no established mix design for FDR, and because there are so much variability of the materials and conditions in FDR, it is difficult to create a mix design which is reasonably simple and thorough enough to address the potential issues of this type of technology. In order for FDR to be more accessible globally, there is a need for a simple and efficient mix design procedure. Improving this process is a key to FDR being used for significant global improvement.

1.3 OBJECTIVES

This experiment is designed to:

1. Evaluate different methods of FDR mix designs and select an optimal functional mix design.
2. Test the potential to substitute a Proctor test with a similar test from a slotted Superpave Gyratory Compactor (SGC).
3. Develop correlations between binder content, water content, density and compressive strength of a FDR sample.

1.4 SCOPE

This experiment involved researching different methods of FDR mix design to select a functional and practical design, obtaining aggregate and synthesizing it to create a representative of field conditions for FDR, and creating foamed asphalt samples. The gradation was given through a thorough mix design report (Asphalt Academy 2009). The samples were tested for density, moisture content, compressive strength, and water content.

This paper will show the density, compressive strength, compaction, and water content of a large number of test samples. It will compare Optimum Moisture Content (OMC) determination from a slotted gyratory compactor with OMC determination from a Proctor mold. It will also correlate binder content and water content to compaction and strength.

2. MIX DESIGN SELECTION

There is no standardized mix design for FDR. There is a lot of information published about FDR, but most of the information only discusses the applications and benefits of FDR. There are few articles which go into significant detail for an FDR mix design. Three designs were discovered to have significant detail for mix designs. The three designs observed are as follows:

The first was a mix design from the Asphalt Academy in South Africa (Asphalt Academy 2009). Many parts of this mix design use the Marshall Mix design. This design divides the quality of pavement into three categories based on the amount of traffic expected to travel on the road. The categories are less than 3 Million Equivalent Single Axel loads (MESA), 3 to 6 MESA and over 6 MESA. This design uses different levels and thoroughness of testing based on which category of road is being designed. All samples are tested for gradation, optimum moisture content and Atterberg limits. The first level requires a 100 mm diameter Marshall Briquette to be compacted. A vibratory hammer is used for compaction of all samples in this design. The sample is tested for wet and dry indirect tension and tensile strength retained. The proper type and amount of stabilizer must be identified. Then the gradation and other properties are observed to determine if there is a need for virgin aggregate to be added. The first level tests are required for levels two and three as well, and the second level requires a 150 mm diameter by 127 mm high cylinder to be compacted and cured. The sample is then tested in both soaked indirect tension and equilibrium indirect tension. This data gives information on the moisture susceptibility of the sample. The third level of testing requires that a 150 mm diameter by 300 mm height sample be made for a triaxial test.

This testing requires the more specialized equipment and time than the other methods, but it gives the most reliable data. This mix design report is over 130 pages long, and to fully follow the procedure requires a significant amount of equipment. Much of this design was used to determine the equipment, aggregate sample gradation, and testing methods for this experiment.

Another mix design observed was [Development of a rational and practical mix design system for Full Depth Reclamation (FDR).] This mix design aimed to use a Superpave gyratory compactor and study the different additives used in FDR. This study looked at the potential N_{design} values, and Mallick concluded that while using a Superpave gyratory compactor for FDR testing, the ideal N_{design} is 75. The report stated that there should be a field compaction of 97 percent of these densities achieved, or 91 percent if cement stabilization is used. A CoreLok was used to confirm bulk density (Mallick 2001).

This design also discussed future testing options using a falling weight deflectometer and testing in-place cores. There are many field uncertainties, which cannot be accounted for in the lab. Many of these are related to not knowing exactly what is under a road. It is, therefore, important to observe FDR projects after completion.

The third mix design evaluated was fabricated by the North Carolina Depart of Transportation (NCDOT 612). This design looked at the use of emulsions in FDR. It divided FDR samples into categories Type 1 and Type 2. The division between these categories was determined by the amount of fines (material passing a No. 200 sieve) in the mix. The dividing point was material with greater than 8 percent fines by weight and less than 8% fines by weight. This method also used a gyratory compactor with an N_{design}

of 30 gyrations. The design requires four samples to be compacted at different emulsion contents. The sample sizes are to be 150 mm in diameter and 70 to 80 mm in height. The samples will be tested for Indirect Tensile Strain (ITS), resilient modulus, conditioned ITS and cohesion. The samples must meet the minimum standards given by the design, and the lowest emulsion content which passes will be chosen.

Parts of these mix designs were utilized in this experiment's methods. Much of the Asphalt Academy report was used for gradation, machinery recommendations, and the idea to compact samples at OMC. The same asphalt foaming machine utilized for much of this report was also utilized in this experiment (Asphalt Academy 2009). There was no access to a vibratory hammer, so the Superpave Gyratory Compactor used in the other two reports was utilized (Mallick 2001, NCDOT 612).

3. METHODS

This section gives details for the process of aggregate selection and determination of water content in the foamed binder. It also discusses the binder selected for the experiment. Issues of the difficulty of material consistency, and gradation will also be discussed.

3.1 MATERIAL SELECTION

Samples of a road being excavated in Clinton, AR were considered as source materials. The samples were obtained and examined, but were unusable without a proper milling machine. These samples showed a high variability of materials potentially taken in the milling process. Samples taken from the same depth were clay at one location and base course at another. This would result in uncertainty of FDR in the field. This is one of the main difficulties of FDR. Research must be done to find effective and non-destructive means of knowing the variance of the depth of road layers along the road.

The layers which can be milled from typical road depths include chip seals or other overlays, the hot mix asphalt surface layer, a hot mix asphalt base layer, a granular base course and a soil sub-base. Because of this variance, there is difficulty in trying to create a testing sample which is similar to what would be encountered in the field. The aggregate sources used in this project were obtained from a quarry in order to have certainty in the experiment. In the future it is a hope that field samples can be utilized for testing.

The aggregate used were half inch limestone chip seal, “Recycle B” asphalt road millings and Class 7 base course provided from APAC Asphalt. These materials were selected because they give a representative sample of what is normally milled up in a road sample. Recycle B is a milled section of the paved layer of asphalt, the gradation of the limestone chip seal would be found in any road which has had a chip seal placed and Class 7 material is similar to what is found in the base course of a road. These three sections of road are generally what are milled for FDR, and the weights of each material used are proportionally similar to the thicknesses of each road layer. The gradation and blend of these materials was based on data from the ideal mix of the (Asphalt Academy 2012), as shown in Table 1 and Figure 4.

Table 1. Gradation of sample used in experiment.

PERCENT USED	**%10**	**%25**	**%65**			
Sieve size	**1/2 LM chip**	**Recycle B**	**Class 7**	**Job Mix**	**Recommendation from Asphalt Academy**	
(mm)					**Min**	**Max**
50	100	100	100	100	100	100
37.5	100	100	100	100	87	100
25	100	100	94	96	77	100
19	100	100	87	92	66	99
12.5	100	100	75	84	57	87
9.5	83	96	68	76	49	74
4.75	6	71	54	54	35	56
2.36	2	53	38	38	25	42
1.18	2	41	27	28	18	33
0.6	2	33	21	22	14	27
0.3	2	26	17	18	10	21
0.15	2	18	14	14	7	16
0.075	1.7	11.7	11	10	4	9

The binder selected to use in the FDR was PG 64-22. These numbers signify that this binder will perform well at the temperature range of 64 °C to -22 °C. This pavement is commonly used in Arkansas because there are rarely temperatures which fall outside of these limits. This is also a very common and inexpensive binder. It was provided though Lyon Oil. Another option for binder is polymer modified asphalt. This binder is more durable, but also more expensive.

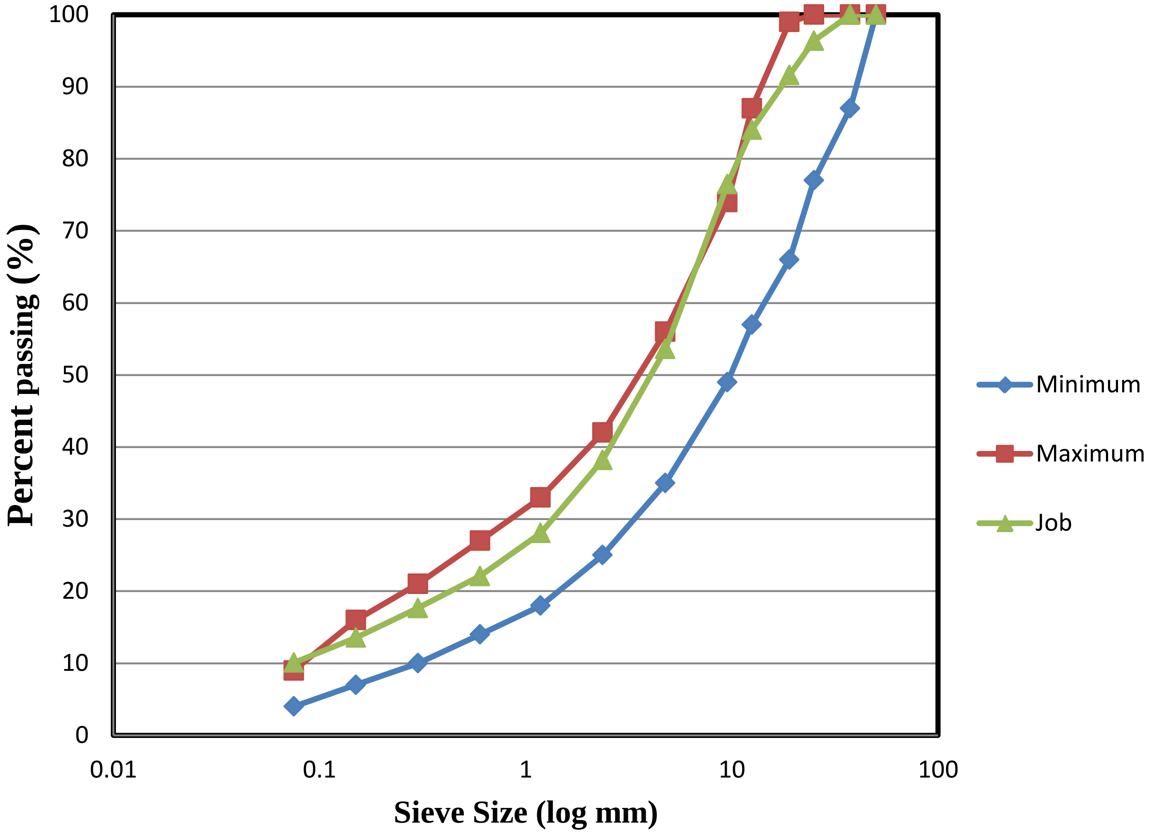

Figure 4. Gradation of job mix and recommendation.

3.2 WATER CONTENT IN FOAM

The water content in the foamed asphalt was determined using the expansion ratio and the half-life of the foam according to the instructions on the Wirtgen foaming machine. The half-life is defined as the time taken for a sample to reduce to half of its volume. The midpoint water content between the minimum expansion ratio and the minimum half-life is taken as the water content. To obtain this value, 500 gram foamed samples is sprayed into a bucket with a measuring rod specifically designed for this test. The measuring device initially reads the total expansion, and a second person records the time from the initial expansion until the sample volume is at half of the original value.

This water content varies with the type of binder used. This process is illustrated in Figure 5.

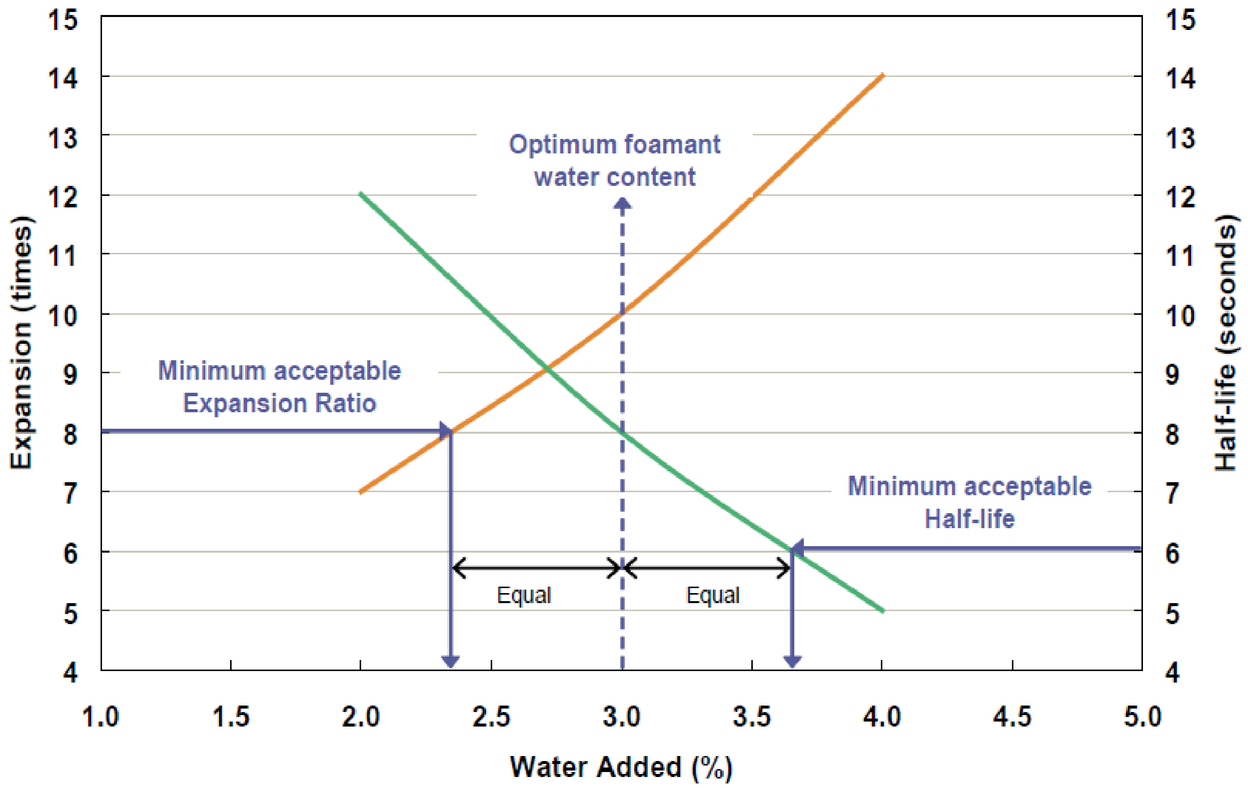

Figure 5. Determination of the water content in the foamed asphalt (Asphalt Academy 2009).

4.0 TESTS AND RESULTS

This section discusses the testing and the results of the experiment with a Superpave Gyratory Compactor and modified Proctor test. It also discusses the testing of samples made in a Superpave Gyratory Compactor at varying binder contents and water contents.

4.1 GYRATORY COMPACTOR AND PROCTOR:

4.1.1 N_{design}

An N_{design} of 75 gyrations was recommended (Mallick 2001). The Transportation Research Record Journal recommends using an N_{design} of 50 gyrations, but it stated that no significant differences were observed using an N_{design} of 75 gyrations (Mallick 2002). Therefore, an N_{design} of 75 gyrations was therefore used in this experiment.

4.1.2 Curing

The use of an SGC causes much of the water to be “squeezed” or drained out of the sample. This moisture reduction causes the curing time to be very short. A time of one week for emulsion samples was recommended by Mallick as being more than enough for the sample to fully cure. Generally foamed asphalt does not require curing, but it was believed that the high water contents used in the samples would have different strength characteristics over time. This same amount is used in this experiment for foamed asphalt samples because it was conducive to the research schedule.

4.1.3 Water Content

A modified Proctor test (AASHTO T-180, 2010) was conducted using Method C described in the manual. According to instruction, only on material passing a 19 mm sieve was used. This required a large amount of material to be sieved. A box sieve was used to separate material needed, and each material was oven dried for 18 hours at 300F, and then allowed to cool for approximately 2 hours. When drying the Recycle B at these temperatures, there was a concern that the binder in the sample would be altered. The same dried material was used for both samples, so even if there was an alteration through drying, it was consistent for both testing methods. In the future, samples with bituminous contents should not be dried as such high temperatures. The materials were then weighed as the proportion of the total mix design, and then they were sieved. The material which passed the sieve was mixed together, creating the same effect as if the whole sample was sieved together. A pugmill mixer was used to mix the sample. All material used in the compaction samples was divided and weighed out using an aggregate splitter to ensure that the gradation would be uniform between each sample and representative of the calculated gradation.

A previous standard Proctor test done on similar material was conducted and the optimum moisture content of material passing a 4.75 mm sieve was determined to be 3.5%. The operator of the Wirtgen foaming machine estimated the optimum moisture content to be approximately 3%. The original water contents which were intended to be tested were 1.5%, 2.5%, 3.5%, 4.5% and 5.5%. Upon testing, it seemed clear that the water content of the material with the aggregate passing a 19 mm sieve, but not a 4.75 mm sieve, was higher than originally estimated. An adjustment was made during testing, and target water contents of 1.5%, 2.5%, 3.5%, 4.5%, 5.5%, 7.5%, and 9.5% were tested in compaction. When the target water contents samples of 9.5% and 5.5% were tested, the actual water contents measured were 7% and 16.5% respectively. These numbers were not used due to this inaccuracy.

The Asphalt Academy report recommended adding the optimum moisture content to the material during mixing (Asphalt Academy, 2009). A potential problem was that the moisture content was calculated using only the weight and properties of the fine material with no information on the adsorption of the coarse aggregate. The coarse aggregates were assumed to have similar properties to fine aggregates tested. This assumption was utilized in the experiment, but further research should be conducted to judge if the optimum water content should be adjusted by the percent of aggregate retained on a 19 mm sieve.

The same material described for the modified Proctor test was tested in compaction at different moisture contents with a slotted gyratory compactor. The moisture contents tested were in a similar range as the Proctor test, but with more uniform spacing. The measured amount of water, foamed binder and aggregate used were mixed in a pugmill mixer with the water content added after the oven dried material was well blended. The mixture was then blended for 60 seconds so the water would be uniformly distributed. This time was recommended during training for mixing samples with both water and foamed asphalt added, so it was assumed that the time would be adequate for only water. Every sample was weighed with water added, and exactly 5000 grams was measured for each sample. The actual water contents of the SGC samples were not measured, the water contents were assumed to be the target moisture contents. The SGC records the final sample height at 75 gyrations. Because the molds all have a fixed cross section and the height is recorded by the machine, the wet density was also easy to calculate. The dry density was found by using the following equation, and the compaction results of the Proctor curve are shown in Figure 6 and the results of the SGC are shown in Figure 7.

$$Ddry = m \times \left(\frac{D}{2}\right)\pi \times h \times (1 - w\%) \times .0022$$ **Equation 1**

Where:
D=Diameter in cm^2 (15 for an SGC)
h=Height in cm. (digitally output by the SGC after test)
m=sample weight in grams (weighed at exactly 5000 g.)
w%=water content as a percent

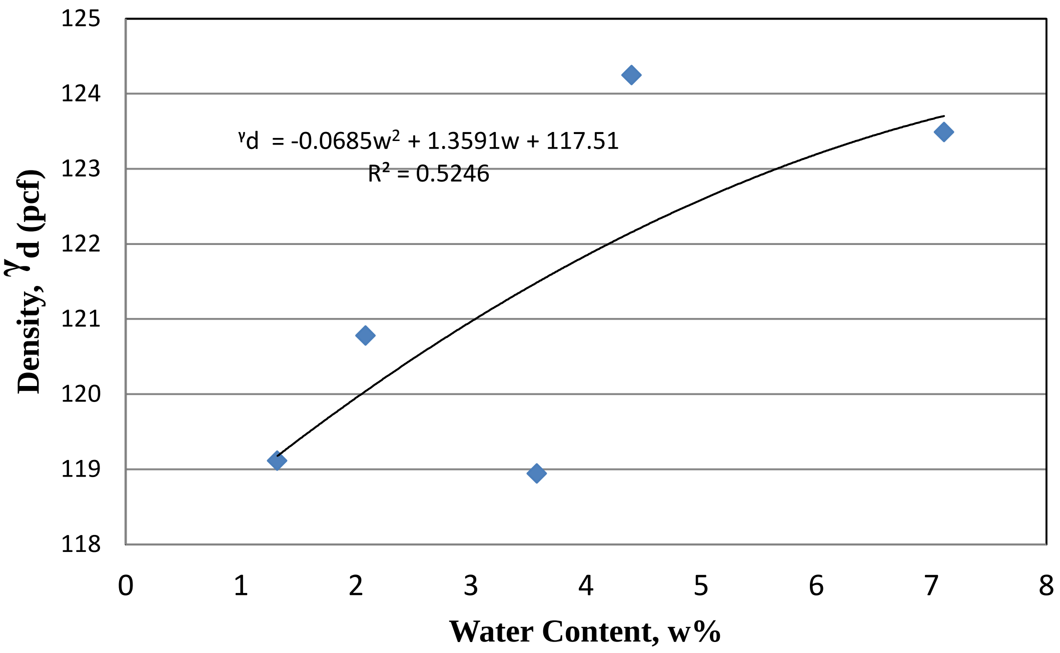

Figure 6. Results of a modified Proctor curve.

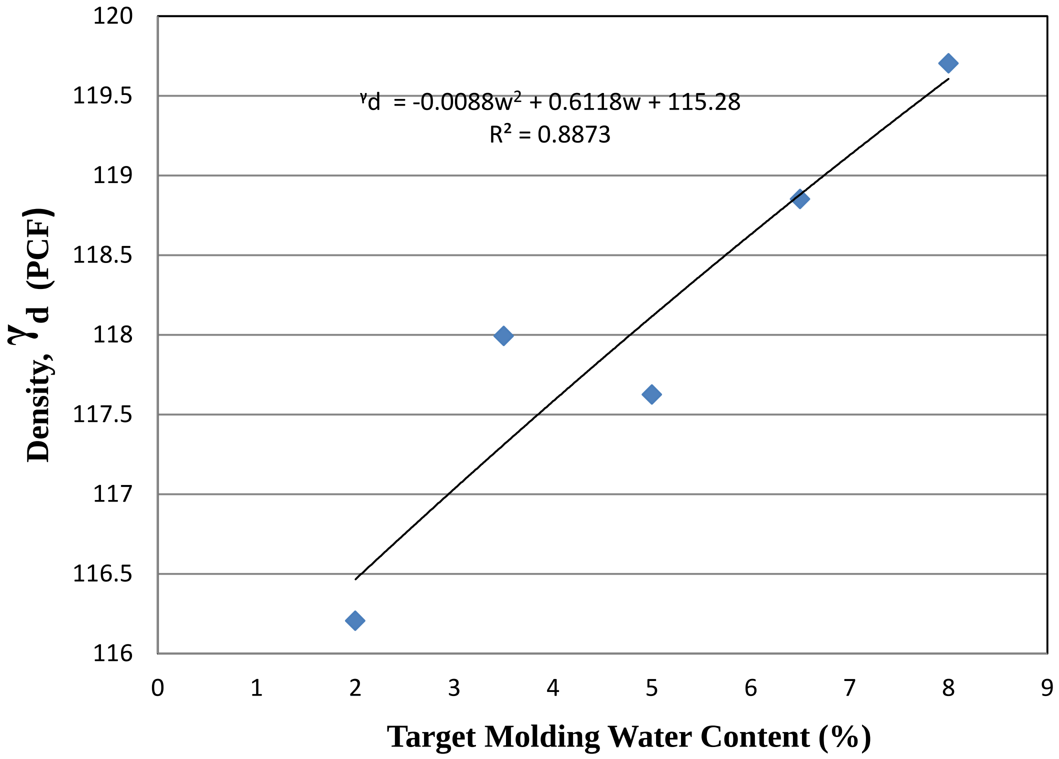

Figure 7. Results of compaction in the SGC at different water contents.

As is shown in these graphs, the results of the Proctor curve and the SGC obtained similar results in relating compaction to moisture content. Both continue to increase until close to 7.5% water content. This was unexpected because previous testing of the material passing a 4.75 mm sieve and previous experience had indicated the OMC to be in the range of 3% to 4%. This is most likely due to the adsorption of the coarse aggregate. More testing must be done at higher moisture contents to observe the data at optimum moisture contents.

The densities recorded through the slotted gyratory compactor were lower than the densities recorded from a modified Proctor test. This is reasonable because a modified Proctor delivers more energy to the material than the slotted gyratory compactor.
The trends of these two graphs are very similar. The results of the SGC had a much higher R^2 value. This is most likely because the compaction process in an SGC is more automated and simpler than a modified Proctor test. Therefore, the SGC compaction has less room for human error, and it can be accurately conducted with less training or experience. The use of a gyratory compactor will therefore also increase the repeatability of the test because the results are less dependent on the person.

4.2 COMPRESSION TEST

This section was conducted to observe the effects of water content and binder content of both compaction and compression. Samples, methods and data are included.

4.2.1 SAMPLES USED

The three materials used for the design mix were oven dried for 24 hours in order to determine the water content in each. The materials were assumed to have uniform water content, and the material used in the mix was adjusted for the moisture weight assumed in each. Eleven samples were created at a weight of 15 kg. A splitter was used to ensure a uniform gradation in each of the samples.

The samples were made using a laboratory scale foaming machine WLB 10 S and a pugmill mixer WLM 30. The amount of water and binder added was calculated by weight. After the samples were mixed, three samples were weighed at 5 kg each. The time between mixing and compaction varied from approximately 10 minutes to an hour and a half. This time difference is a result of the gyratory compactor being much slower than the pugmill mixer, and three samples were made in the gyratory compactor for every one sample made in the pugmill mixer.

4.2.2 RESULTS

The dry density of each sample was calculated using Equation 1 (Page 18). These results are shown in Figure 8.

Each sample from the gyratory compactor was tested in compression by standards outlined in CIP 35 (National Ready Mixed Concrete Association 2003) in a Forney press. There were modifications which had to be made in order to test FDR samples instead of concrete. The first change was that tests falling below the 500 PSI range were not to be used. Since the maximum strength was below 200 PSI, this was unreasonable. Another modification made at the suggestion of a laboratory technician was that the neoprene pad and sulfur caps not be used in testing. This was also due to the difference of the material being tested. It was assumed that the samples were 150 mm in diameter because this was the mold size used in the experiment.

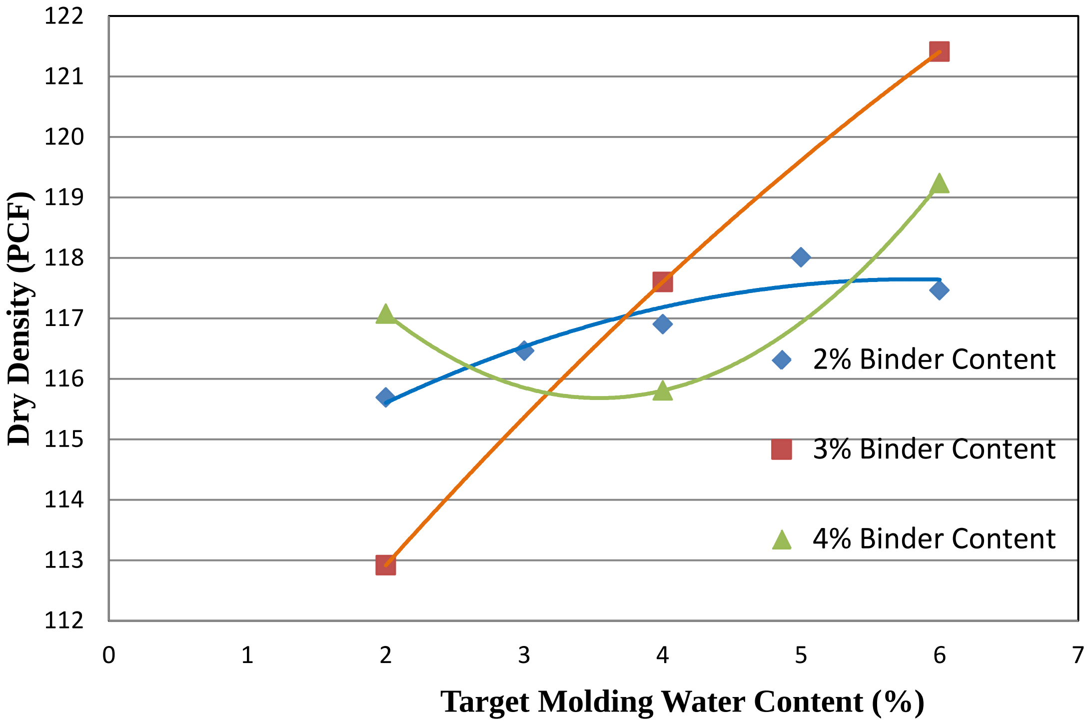

Figure 8. Dry densities obtained using different water content and binder content.

The samples were allowed to cure for a week before being tested. Some of the samples were damaged during extrusion, so the numbers which were gathered for these samples were slightly lower. It was common that the corner of a sample had fallen off. These damaged samples were noted on the data, but still tested with the exception of the sample compacted at 2% water content and 2% binder content. This sample could not support itself after being compacted and was damaged too badly to be used. There is a need to discover a way to successfully extract an FDR sample from a mold without damaging the sample.

Originally the samples were intended to be tested in indirect tension (ITS), but the samples created had approximately a 6 in. height, and the required size for the ITS machine is a 4 in. height. It appeared that the traditional method of cutting samples to an appropriate size with a wet saw would have destroyed the samples. For this reason, these samples were tested in compression. The ultimate compressive strength at failure was recorded and compared with the density of the sample and the water content. The results are shown below in Figure 9 and Figure 10.

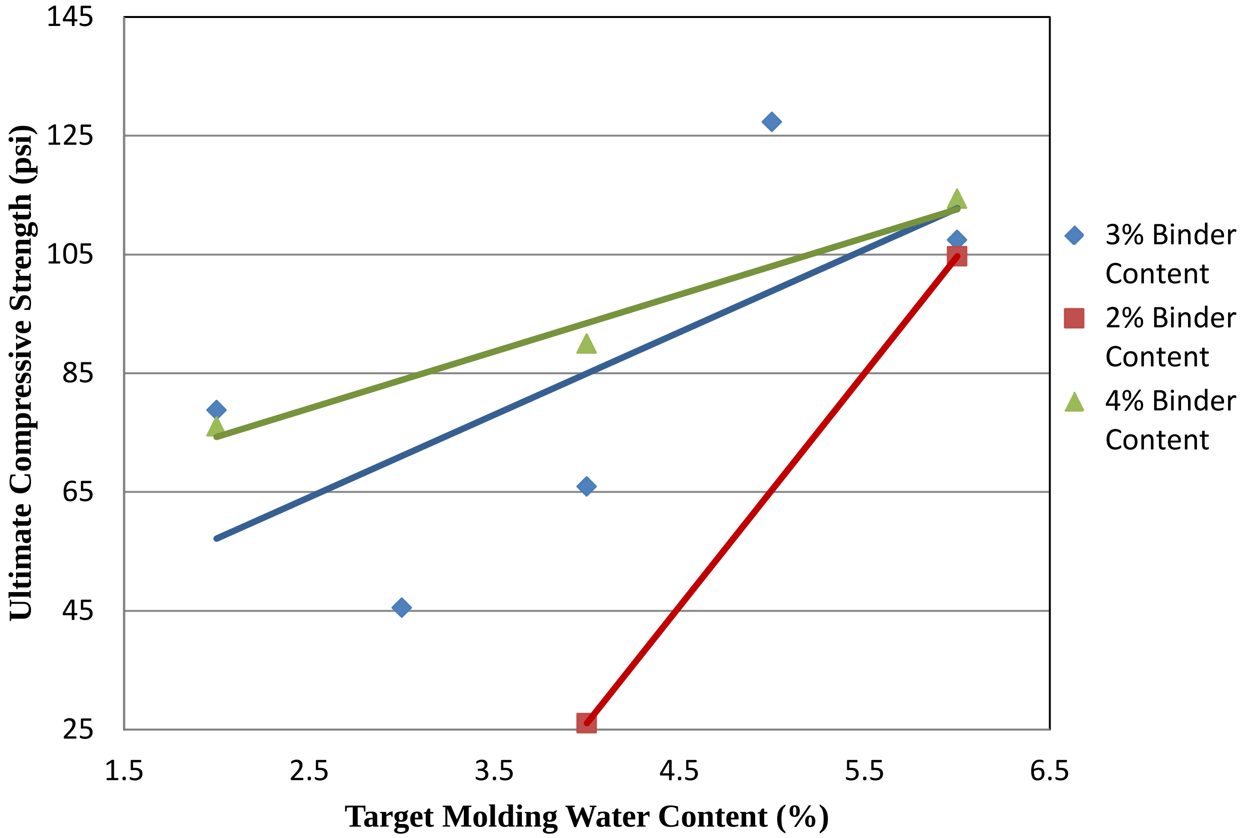

Figure 9. Water content and compressive strength.

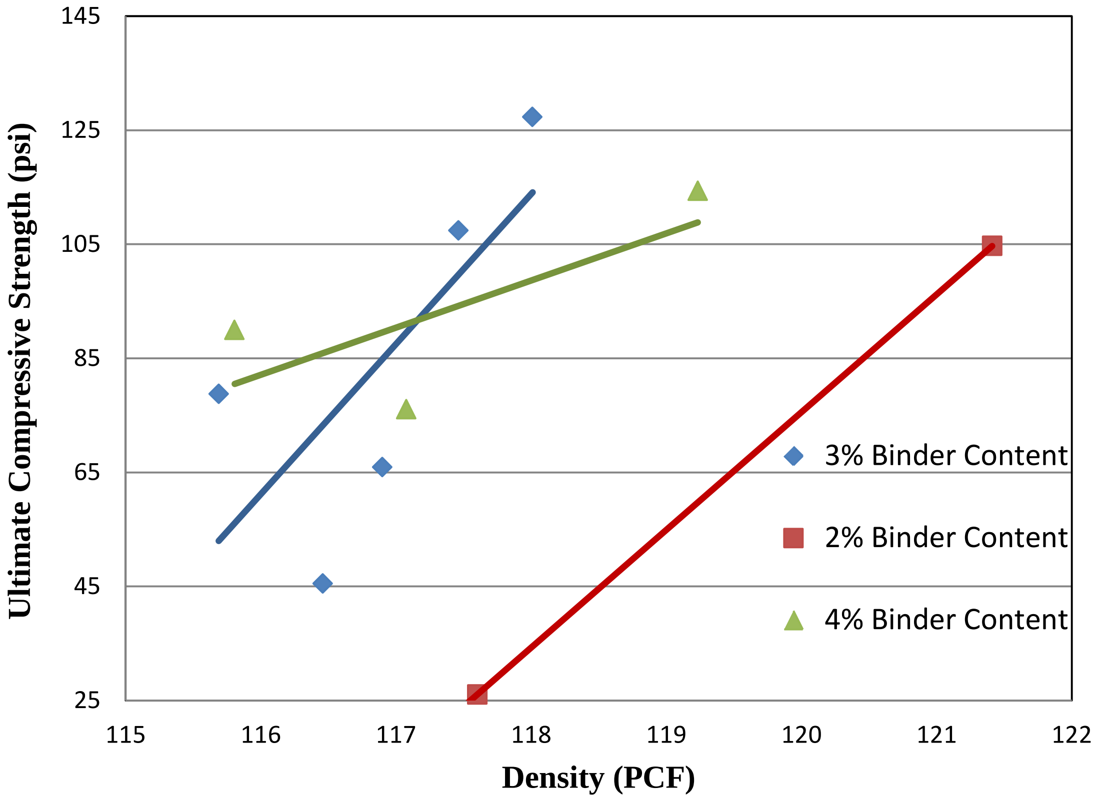

Figure 10. Density and Compressive strength.

These results are not in a very tight line. This is likely due to some of the samples being damaged in extrusion. The general trends are all consistent. They show that higher water contents will produce both higher density and higher compressive strength. If a sample has a higher dry density, it implies that there are fewer voids than a sample of the same material with a lower dry density. These voids will create higher internal stress concentrations in the samples, causing it to fail at lower compressive force. Higher binder contents will also increase compressive strength. Binder is the stabilizing agent used in FDR, so it follows that higher binder content will increase cohesion and compressive strength.

5. OBSERVATIONS

This experiment was able to create observations of trends which will be further explored. Using a slotted gyratory compactor to find the optimum water content of a sample is most likely a useful substitute for a Proctor test in FDR mix design. More research must be conducted to determine the compaction behavior at higher water contents. This will provide the opportunity for a quality mix design to be conducted with less equipment. This enables more effective use of FDR in simpler laboratories.

Adding water significantly increases compaction and compressive strength for a range of binder contents. It is a beneficial practice to find the optimum moisture content of the material used in a project and add this in the field. The following points warrant consideration:

1) Density and compressive strength were observed to be correlated in FDR, even if a sample was made with more water to help with compaction. This is true at a range of binder contents.
2) Testing the densities of material passing a 19 mm sieve at different water contents in an SGC might be a viable alternative to conducting a Proctor test for FDR to find optimum water content.
3) The absorption of coarse aggregate seemed to significantly alter the optimum moisture content.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

The compaction and optimum water content portion of this project only observed the moisture content and compaction behavior of the material passing a 19 mm sieve. The adsorption of the coarse material was not taken into consideration. Previous testing on the material only passing a 4.75 mm sieve gave significantly lower water content.

The mix design used assumed the optimum water content found for only the fine aggregates would have been the same as the optimum water content for the entire mix. This coarse material adsorption should be further examined.

The samples must be tested at higher water contents to understand more of the use of an SGC to find optimum moisture content. The future testing should be conducted with a 6 inch Proctor mold. This will enable the entire sample to be observed.

In the future, the water contents of the samples in the gyratory compactor should be measured after testing.

REFERENCES:

Asphalt Academy, (2009). *Bitumen Stabilised Materials: A Guideline for the Design and Construction of Bitument Emulsion and Foamed Bitumen Stabilised Materials.* Pretoria: Asphalt Academy.

Bushman, William H., Thomas E. Freeman, and Edward J. Hoppe. "Stabilization Techniques for Unpaved Roads." *Transportation Research Record: Journal of the Transportation Research Board* 1963.2005 (2006): 28-33.

"FULL-DEPTH RECLAMATION." *American Road Reclaimers*. 2011. Web. 16 Apr. 2012. <http://www.americanroadreclaimers.com/arrFDR.htm>.

Kearney, Edward J., and John E. Huffman. "Full-Depth Reclamation Process." *Transportation Research Record: Journal of the Transportation Research Board* 1648.1999 (2007): 203-09. Web.

Lewis, Dwane E., David M. Jared, Helga Torres, and Monzy Matthews. "Georgia's Use of Cement-stabilized Reclaimed Base in Full-depth Reclamation." *Transportation Research Record* 1952 (2006): 125-33. Web.

Mallick, B R., Kandhal P. S, Brown E. R, Teto M. R, Bradbury R. L, and Kearney E. J. "DEVELOPMENT OF A RATIONAL AND PRACTICAL MIX DESIGN SYSTEM FOR FULL DEPTH RECLAMATION (FDR)." *Journal of the Association of Asphalt Paving Technologists* 70 (2001): 176-205.

Mallick, Rajib B., David S. Bonner, Richard L. Bradbury, Jamie O. Andrews, Prithvi S. Kandhal, and Edward J. Kearney. "Evaluation of Performance of Full-depth Reclamation Mixes." *Transportation Research Record* 1809 (2002): 199-208. Web.

National Ready Mixed Concrete Association. "CIP 35- Testing Compressive Stregth of Concrete." *Concrete in Practice: What, Why and How? (*2003).

NCDOT, “Section 612 Asphalt Emulsion Full Depth Reclaiming and Stabilization” Wirtgen GmbH, (2010). *Wirtgen Cold Recycling Technology.* Windhagen: Wirtgen GmbH.