FULL-DEPTH RECLAMATION: BRINGING DEVELOPING COUNTRIES’ TRANSPORTATION UP TO SPEED
FULL-DEPTH RECLAMATION: BRINGING DEVELOPING COUNTRIES’ TRANSPORTATION UP TO SPEED

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Abstract

Often, a direct correlation is observed between a country’s transportation network and economic development. Evidence of this is observed all over the world. Full Depth Reclamation (FDR) is a roadway recycling technique that mills and mixes the existing roadway with a stabilizing agent and then re-compacts the mixture to create a thicker, stabilized pavement layer. This method is both cost effective and environmentally friendly, making it a very appealing option as the need to rehabilitate or increase the structural capacity of existing roads grows. In this study, the material characterization of FDR was examined as a composite material of both asphalt concrete pavement and some soil. This was accomplished by comparing different compaction methods utilized for both soil and Hot Mix Asphalt (HMA) compaction. The effects of different compaction methods on the strength of the FDR mixtures were evaluated. The Superpave Gyratory Compactor is typically used for the compaction of HMA samples in the lab, and the Proctor hammer is the most common method of compaction for soil samples. In addition to these two methods, different sized compaction molds and varying amounts of compaction effort were compared as well. Optimum moisture contents for each compaction method were developed by compacting FDR samples at 2, 4, 6, and 8 percent water content and determining the dry density of the samples at each water content. With the exception of two, the slotted mold SGC compaction method and the modified Proctor method, the compaction curves displayed similar trends and could be used to easily identify an optimum moisture content. Two strength tests, the Marshall Stability and Flow test and the Indirect Tensile Strength Test (ITS), were then used to evaluate the effectiveness of FDR samples compacted by each of the methods. For both the Marshall Stability test and the Indirect Tensile test, the SGC samples had higher strengths. The slotted SGC samples had a slightly higher stability and tensile strength than the unslotted SGC samples. The tensile strength ratios, which compare tensile strength of moisture conditioned samples to the tensile strength of unconditioned samples, showed that the strength of the FDR samples was decreased by at least 30% when moisture conditioned. Overall, samples compacted in the gyratory compactor seemed to be stronger and more durable. Future research should be done to observe the effect of optimum moisture content on the strength of an FDR mixture.
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1. INTRODUCTION

Often, a direct correlation can be seen between a country’s transportation network and economic development. Evidence of this can be seen all over the world. For instance, impoverished countries in Africa or South America see much slower economic development than a country like the United States, which has many different modes of transportation in their comprehensive network, including airports, highways, and rails. Unfortunately, these developing countries often do not possess the technology, equipment, or funds to build and maintain the infrastructure used in developed. However, even developed countries’ roadways have experienced an increase in travel needs. Existing roadway pavements are experiencing damage from increased usage in addition to the expected distress and deterioration due to aging.

Due to these needs, significant research is being done to understand how to maintain and rehabilitate existing roadways in a sustainable and environmentally friendly way. In pavement maintenance, the goal is to create a safe and operable pavement at the lowest possible cost. With advances in pavement construction equipment over the last two decades, asphalt recycling and reclaiming has emerged as both a technically and environmentally friendly way of rehabilitating the existing, failed pavements. Asphalt recycling meets these goals of creating a safe and operable pavement at low cost, as well as drastically reducing our environmental impact and energy consumption. One asphalt recycling technique that is being utilized is Full Depth Reclamation.
1.1. What is Full Depth Reclamation?

Full Depth Reclamation (FDR) is a recycling technique in which all of the asphalt pavement section as well as a predetermined amount of underlying base materials are treated, as defined by the Asphalt Recycling and Reclaiming Association (ARRA, 2001). This mixture is pulverized and compacted to produce a thicker, stabilized base course, shown in Figure 1. FDR is typically performed to a depth of 100 to 300 mm, or 4 to 12 inches. Often, due to structural capabilities of this blend of material, it is sufficient to act as the base for a new surface wear course without the addition of stabilizing additives. However, if it is determined that the in-situ material is not adequate in structural strength, three different types of stabilization exist: mechanical, chemical, and bituminous. Mechanical stabilization involves introducing granular materials, such as virgin aggregate, or recycled materials, such as reclaimed asphalt pavement or crushed Portland cement concrete. Chemical stabilization consists of the addition of lime, Portland cement, fly ash, or calcium chloride. Bituminous stabilization is the addition of liquid asphalt, asphalt foam, or asphalt emulsion into the mix. These types of stabilization may also be combined and used in conjunction with one another. (Khandhal and Mallick, 1997)
Full Depth Reclamation has several major advantages and benefits. Some of these, as previously mentioned, are the cost efficiency and environmental benefits of FDR. In addition to being a sustainable option, FDR is also an effective option for rehabilitating a deteriorated pavement section and making it more structurally sound. Full Depth Reclamation allows for the improvement of the structure of the pavement without changing the geometry of the pavement or requiring shoulder reconstruction. Distresses such as wheel ruts, potholes, irregularities, rough areas, alligator, transverse, longitudinal and reflection cracks can all be eliminated using FDR, while also restoring old pavement to the desired profile, crown, and slope. Eliminating these problems can also improve the ride quality. Additionally, the frost susceptibility of the pavement may be improved after using FDR. In particular, Full Depth Reclamation is recommended for use on pavements with deep rutting, load-associated cracks, non-load associated thermal cracks, or pavements with previous maintenance patches. It is also a viable option for pavements with base or subgrade problems (Khandhal and Mallick, 1997).

In terms of cost efficiency, several aspects of FDR contribute to a less expensive option. The cost of a Portland cement concrete road for an interstate is
about $2,630,144 per mile, and for an asphalt cement concrete road, $2,493,568 per mile. Placing only a crushed stone road would cost approximately $300,000 per mile. However, a comparable FDR road would cost only about $127,000 per mile, which is a savings of over 58 percent (RSMeans, 2009). Some of these savings are a result of little to no need for hauling new materials to the site because FDR utilizes in-place materials. Depending on the method chosen for construction, constructing an FDR road may require fewer machines and equipment.

Environmental sustainability is also achieved in numerous ways. By using in-place materials, less new material is used and can be saved for future use. Also, because FDR is considered a cold-recycling technique, there are fewer emissions and less energy consumption during the reclaiming process. A life cycle analysis study done by Chappat and Bilal (2003) found in-situ asphalt emulsion recycling to be the technique that consumed the least energy and contributed least to greenhouse gas emissions. A typical hot mix asphalt concrete road would consume 591 MJ per ton of material. An emulsion in-situ recycled road, however, would use only 139 MJ per ton, which is only about one-fourth of the energy used for hot mix asphalt. This is accomplished by using less heavy machinery, and by placing the new roadway at lower temperatures. Full Depth Reclamation is actually best suited for labor-intensive construction (Asphalt Academy, 2009).

Unfortunately, while FDR has many benefits, there are still several limitations to its widespread use. Because FDR consists of a composite, single layer of both the subgrade soil and flexible pavement layers, it is more difficult to characterize than either soil or asphalt cement mixtures. This makes predicting the
performance of FDR pavements more difficult than that of a typical pavement structure. More research is required to better understand how to model these recycled pavements in the lab and design them for use in the field.

1.2. Material Components

Selecting the type of stabilizing agent to be used depends on several factors, including the composition of the existing structure, the type of subgrade soil, and the objective of the recycled pavement. For instance, if the recycled base is mixed with untreated subgrade soil, then stabilizing additives will be required. Both past and recent experiences show that careful selection of the appropriate additive will result in a better performing pavement. Therefore, understanding the primary function and use of each stabilizing additive is largely beneficial.

As previously mentioned, Portland cement, lime, fly ash, and calcium chloride are all types of chemical stabilization. Portland cement is used to increase the compressive strength of the mixture and is most effective in granular and low plasticity base or subgrade. When compared with other active fillers that have been tested, Portland cement concrete seems to offer the most advantages. Lime lessens the effect of reactive clays in the material by reducing the plasticity and the swelling potential associated with clays. Additionally, it helps the mixture resist water damage and increases both tensile and compressive strengths. Fly ash is primarily used to form a cementitious bond within the soil in the presence of water, as well as increase the impermeability and strength of the mix. Field tests have indicated that fly ash also improves the constructability and moisture sensitivity of the mixture. Calcium Chloride is used to lower the freezing point of the recycled material, which
helps the mixture’s resistance to freeze-thaw problems. Also, adding calcium chloride improves the load-bearing capacity of the mix.

Asphalt materials are the most common type of stabilization used in FDR. Asphalt emulsion is used to increase cohesion of the mixture and the load bearing capacity. It also helps to rejuvenate and soften the aged binder in the existing asphalt material, creating a flexible and fatigue resistant layer not prone to cracking. Emulsion is asphalt dispersed through water and chemically stabilized as shown in Figure 2. Typically, asphalt emulsion contains between 40 and 75% asphalt cement, 0.1-2.5% emulsifier, and 25-60% water. The asphalt cement droplets are 0.1 to 20 microns in diameter once suspended. The droplet size varies depending on the recipe used and the manufacturing plant. The size of the particles influences the viscosity and storage stability of the emulsion. Once the droplets get close enough to one another, they will join together and flocculate.
Asphalt foam, which is becoming increasingly popular for use in FDR, has been shown to increase adhesion properties of the asphalt, making it well suited for mixing with cold or moist aggregates. Due to the foaming capabilities, the asphalt is better dispersed throughout the materials to be recycled. To create the foam, a small percentage of water is added to hot asphalt cement, causing the liquid asphalt to expand in a small-scale explosion, as in Figure 3. The amount of water added controls the rate and amount of foamed asphalt. As a result, a thin film of asphalt with about ten times more coating potential than typical asphalt cement is created (Asphalt Academy, 2009).
Both emulsified and foamed asphalt have many advantages that make them a preferred choice over typical liquid asphalt. One of these advantages is that emulsion and foam have a lower viscosity, allowing them to be constructed at lower temperatures and increasing the paving season. Additionally, the emissions and energy consumed are decreased because they can be used at lower temperatures. In terms of emissions, the greatest contribution during asphalt production comes from drying and heating the aggregates used in the mixtures. This process also requires the greatest consumption of fuel. Using asphalt emulsion and foamed asphalt does not require this significant heating of the aggregate, but rather uses the in-situ material at ambient temperatures. As a result, about half of the energy required for typical Hot Mix Asphalt (HMA) is consumed. Additionally, emulsions and foam do not contain any volatile chemicals that evaporate into the atmosphere,

Figure 3. Diagram of Foamed Asphalt (Asphalt Academy, 2009).
also making them more environmentally friendly options than typical asphalt cement. (Khandhal and Mallick, 1997)

1.3. Construction

There are five main steps in the construction process of FDR, including pulverization, introduction of additive, shaping the mixed material, compaction, and application of the surface course. Although, before any of these steps may be performed in the field, preliminary testing is required to establish such things as the criteria for gradation, the residual asphalt content, and the additive to be used. The first step, which is to rip, scarify, pulverize, or mill the existing pavement to a specified depth, can be done either using in-place methods or involving a central plant. Typically, an in-place method is used, however, the materials can be taken to a central plant to be processed and mixed with recycling agents or virgin materials. The in-place methods, which are generally more economical as they do not require transporting materials, currently utilize one of four different types of sizing and mixing: the multi-step sequence, two-step sequence, single machine, and the single pass equipment train.

As the name denotes, the multi-step sequence involves several different steps and equipment to break, pulverize, and mix the existing pavement with a recycling agent. While this process is thought to be efficient with HMA layers, it sometimes produces large chunks of material that require further processing. Also, because it requires several passes to adequately reduce the size of the material, there may be a lack of uniformity in the depth of the cut and have low production rates. However, the equipment used in this process is typically readily available for use.
In the two-step sequence, the pulverizing steps are combined with the cold milling machine, and the second step includes adding the stabilizing agent and mixing the material. Cold milling machines, as displayed in Figure 4, can pulverize and size the material in just one pass. This allows for less interference with traffic surrounding the construction site, accurate cutting depth at a lower cost, and less damage to underlying material. Unfortunately, the depth of cut is limited in order to maintain such accuracy and oversized aggregate may still result. Additionally, the equipment required for this method is more specialized.

Figure 4. Cold Milling Machine (Khandhal and Mallick, 1997).

Both the single machine and the single pass equipment train are capable of breaking, pulverizing, and adding in the stabilizing agents in one pass. For a single machine, if necessary, virgin material is spread on the existing pavement surface ahead of the recycling equipment. A schematic of the single machine is given in
Figure 5. The single pass equipment train consists of a series of equipment, which each performs a particular operation. Typically, this will consist of a cold milling machine, a portable crusher, a travel-plant mixer, and a laydown machine. High production capacity and simple operation are the greatest advantages of these methods. Again, depth limitation and oversized aggregate are the main disadvantages for these methods.

![Diagram of single pass equipment train](image)

*Figure 5. Single Machine Schematic (Khandhal and Mallick, 1997).*

After the material has been pulverized, sized, and mixed with the stabilizing agent, it must cure to allow for the reduction of the water and volatile content of the recycled mix. This can be done by placing the material in a windrow after mixing and then leveling it to the proper cross slope using a motor grader. The mix can also
be aerated with the motor grader by blading the mix back and forth across the roadway. Curing helps reduce the fluid content of the mix, allowing it to become stable enough to support the weight of the compaction roller. The amount of time required for curing depends on several factors, such as the type of asphalt modifier, the mix water content, the gradation of the aggregate used, the temperature outside, and the humidity. If there is too much water in the mixture, additional curing may be necessary to prevent a loss of stability and excessive moisture retention. In this case, heavy traffic should not be allowed onto the surface during this delay.

Following the curing process, compaction of the recycled material occurs. This can be done with static steel-wheel, pneumatic-tired, vibratory rollers (Figure 6), or a combination of two or all three. The number of passes required for compaction depends on the properties of the mix itself, the type and weight of the roller being used, environmental conditions, and the lift thickness.
The moisture content plays a large role in the compaction of the mix. Having enough moisture can help in compaction; however, if there is too much water in the mix, this can lead to low density and moisture retention in the sealed layers. Typically, an HMA overlay or surface treatment will be placed over the recycled base in order to help prevent raveling of the new surface. This cannot, however, be done until enough moisture has left the mixture. The thickness of this surface course is determined by analyzing traffic data (Khandhal and Mallick, 1997).
2. LABORATORY PLAN

With the limitations of implementing Full-Depth Reclamation in mind, this experiment was designed to further investigate material characterization of FDR pavements. Following is a description of the objectives of this research, the material selection, and the laboratory testing done.

2.1. Objectives

The objectives in performing this research are:

1. Investigate previous work completed toward developing a mix design for FDR, specifically using asphalt emulsion.
2. Using three different compaction methods (Superpave Gyratory Compactor, Standard Proctor Hammer, Modified Proctor Hammer), determine the effect each has on density and optimum moisture content of FDR samples.
3. Create FDR samples stabilized with asphalt emulsion using each of these compaction methods at the determined optimum moisture content.

2.2. Scope

This experiment involved researching past work done with FDR and understanding existing mix design and laboratory testing procedures in order to create representative FDR samples using asphalt emulsion. The mix design procedure followed was given by the research done by Robert Hill at the University
of Arkansas to synthesize an FDR mix design. The samples created were tested for density, moisture content, tensile strength ratio, stability and resistance to plastic flow.

This report will display the results from these tests and discuss the effects of using different compaction methods, one typical for soil and the other for asphalt cement mixtures, on the strength and stability of the mixtures. The optimum moisture contents determined for a six inch slotted gyratory compactor, a four and six inch unslotted gyratory compactor, and a four inch proctor mold using both standard and modified effort will be compared. Table 1 shows the experimental matrix used for this research, with the number of replicates done for each test and with each compaction method.

Table 1. Experimental Matrix.

<table>
<thead>
<tr>
<th>Compaction Method</th>
<th>Compaction-Optimum Moisture Content Determination</th>
<th>Tests</th>
<th>Marshall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ITS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Conditioned</td>
<td>Unconditioned</td>
</tr>
<tr>
<td>Slotted SGC</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4” Unslotted SGC</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6” Unslotted SGC</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Standard Proctor</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Modified Proctor</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

2.3. Material Selection

Making samples that resemble an actual FDR layer in the field is very difficult due to the significant material variability within road sections. Generally, the layers milled in road sections include a HMA surface layer, HMA base layer, granular base course, and the pre-existing soil subbase, as well as any chip seals or
overlays that have been placed on the road. In order to model these materials, samples were created by combining fifty percent “Recycle B” asphalt road millings and fifty percent Class 7 aggregate base course. These materials were obtained from Sharps Quarry nearby, and the proportions used of each were selected based upon typical thicknesses used in the road layers.

The way in which the asphalt stabilization, whether asphalt emulsion or asphalt foam, disperses throughout the mixture is largely dependent on the gradation of the unstabilized, milled mixture. Because emulsion and foam behave differently in this dispersion process, the ideal gradations for each vary slightly. Where emulsion coats the larger particles more completely, the foam only partially coats the larger aggregate. Asphalt emulsion was used to create FDR samples for this research, so the ideal gradation for emulsion given by the Asphalt Academy’s mix design was used for the recycled asphalt pavement (RAP) and Class 7 aggregate mixture. The final gradation selected is displayed in Figure 7 along with the minimum and maximum values for ideal mixtures given in this mix design (Asphalt Academy, 2009).
Figure 7. Final Aggregate Mixture Gradation.

Prior to use, both the Class 7 aggregate and the Recycle B were dried in the oven at 100°F. This temperature was selected so that the asphalt binder in the Recycle B did not melt and become viscous again as that would effect the stiffness of the recycled mix. The aggregate mixture was dried so that the initial moisture content can be assumed to be 0% and to increase the accuracy of target moisture contents in the creation of samples.

The emulsion used, CIR-EE, was provided by Ergon Asphalt and Emulsions, Inc. This emulsion is between 60 percent and 70 percent asphalt cement, 30 to 40 percent water, and less than 3 percent emulsifier. Based upon previous tests performed by Rob Hill with the same Class 7 aggregate and Recycle B mixture, the optimum emulsion content was selected to be 4 percent.
The North Carolina mix design states that for design of FDR samples, only a percentage of this optimum moisture content should be used when actually combining the mixture. The percentage of OMC to be used is based upon the annual average rainfall in that region and the sand equivalent value. Because Class 7 aggregate seems to have almost very little clay, the sand equivalency value was assumed to be greater than 30. Therefore, for an annual average rainfall of greater than 20 inches in Fayetteville, AR, 45 to 65 percent of the OMC is recommended. So for this research 50% of OMC was used when creating the emulsion FDR samples. Table 3 also displays these 50% OMC values used for design.

A mechanical mixing bowl was used to combine all of the components of the FDR mixture together. Initially, the aggregate/RAP mixture is placed in the bowl and the mixer is turned on. The water is then added and mixed for 1 minute, followed by the addition of the emulsion, which is again allowed to mix for 1 minute. This mixture was then placed in the oven at 100°F to cure for 30 minutes before compaction.

2.4. Compaction

Compaction is defined as the use of mechanical energy to achieve the densification of a material by removing air. For both soils and asphalt cement mixtures, compaction is a vital process as it helps increase the strength properties of the materials. By increasing the unit weight, or the weight of material in a given volume, there are fewer air voids, which serve only to occupy space and contribute nothing to the strength of the material. Different methods of compaction are used in the field, including smooth-wheel rollers, sheepfoot rollers, vibratory rollers, paver
screed, steel wheel rollers, or pneumatic tire rollers. Laboratory procedures seek to model these compaction methods used in the field. Unfortunately, particle orientation and compactive effort can vary significantly in the field, making modeling this process very difficult. Because Full-Depth Reclamation layers in pavements include both granular or soil materials as well as recycled asphalt pavement, both soil compaction and asphalt cement compaction methods must be considered.

The degree of compaction of a soil is measured by its dry unit weight at a given water content. Water is important in the compaction of soil materials because it acts as a softening agent on the soil particles, allowing particles to slip over each other and move into a more densely packed position. Initially, increasing the water content of soil and using the same compactive effort also increases the unit weight of the soil. However, after the “optimum” moisture content, continuing to increase the moisture content actually decreases the unit weight of the soil. The Proctor compaction test (ASTM D698 and ASTM D 1557) is the laboratory procedure most commonly used to determine this optimum moisture content and maximum dry density. Using the Proctor test, the soil is compacted by placing it in layers of equal height into a mold and compacting it with a prescribed number of blows by either a 5.5-pound hammer, for the standard method, or a 10-pound hammer, for the modified method. The compaction test is performed on the same soil samples at different moisture contents. The compacted weight of the moist soil is weighed, and a small sample from the center of the compacted specimen is dried in the oven to find the actual moisture content of the soil. Once the actual moisture content has
been determined using the dry weight of the sample, the dry unit weight is found using the following equation. These dry unit weights are then plotted against the moisture contents of the various samples, and the peak of this curve is taken to be the OMC.

\[ \gamma_d = \frac{m_{\text{comp}}}{(1+w)\times V} \]  
(Das, 2006) (1)

Where \( \gamma_d \) is the dry unit weight, \( m_{\text{comp}} \) is the compacted weight of the soil, \( w \) is the water content, and \( V \) is the volume of the proctor mold.

In addition to the moisture content of the soil, the type of soil and the effort of compaction used also majorly influence the maximum dry density. Type of soil includes the gradation of the soil, shape of the grains, specific gravity of the soil solids, and the amount of clay in the soil. Each of these can affect how the particles fit together while being compacted. The compaction effort also significantly affects the maximum dry density. For Proctor compaction, the compaction energy per unit volume is determined by the following equation,

\[ E = \frac{N\times L\times W_h \times h}{V} \]  
(Das, 2006) (2)

where \( E \) is the compaction energy, \( N \) is the number of blows by the hammer per layer, \( L \) is the number of layers, \( W_h \) is the weight of the hammer, and \( h \) is the height of drop of the hammer. As the energy used in compaction increases, the maximum dry density is increased and the optimum moisture content decreases to a small extent. Figure 8 displays this trend for compaction curves caused by increasing compaction energy.
While optimum moisture content is essential for compaction of soil, asphalt concrete samples are compacted to an optimum air void content. The volume of air in asphalt pavements has a large effect on the long-term pavement performance. Generally, lower air void contents in asphalt pavements help to increase the stiffness and strength, decrease rutting and moisture damage potential and increases the durability of the mixture (pavementinteractive.org). Currently in the
United States, the most commonly used mix design method for asphalt cement pavements is the Superpave method. This mix design procedure, which is based on both properties of the aggregate and asphalt binder used as well as the volumetric properties of the mixture, uses the Superpave Gyratory Compactor (SGC) to achieve compaction of laboratory samples. The SGC applies a constant vertical pressure at an angle of gyration and a given rotational speed to the asphalt mixture in order to compact the sample (Anderson et al., 2002). Using the angle of gyration creates a “kneading” effect on the mixture. It is believed that the SGC creates samples with physical-mechanical and volumetric properties that very closely model those of in-situ asphalt cement pavements. Additionally, it closely simulates both the compaction by equipment in construction as well as continued densification that occurs over pavement life from traffic loads (Cerni, 2011). Previous research has even suggested that the Superpave Gyratory compactor and parameters obtained from compaction data can be related to a mixture’s stiffness and rutting resistance and therefore, used in performance testing (Anderson et al., 2002). Two types of molds will be used in the SGC, a slotted mold and an unslotted mold. The slotted mold has small holes in the sides of the mold, which allow for water to be expelled from the sample through these holes during the compaction process. The unslotted mold is the typical SGC mold used for HMA compaction.

Full-Depth Reclamation mills together the subgrade soil as well as the layers of the existing pavement. This layer is thus a composite material of both soil and asphalt cement materials. Compaction is a very important process in material characterization and highly useful in predicting the performance of the pavement.
material. FDR, unlike asphalt cement mixtures, requires some amount of water, so determining the optimum moisture content for use in FDR is necessary. However, FDR cannot be characterized solely using Proctor compaction because it is stabilized using some sort of binder agent, similar to an asphalt cement mixture. Thus, to simulate field compaction, gyratory compaction should be explored as a compaction method.

For both soil and asphalt cement materials, it is important to obtain a densely packed specimen, so it is of interest, for the characterization and creation of laboratory samples of FDR to understand how each method of compaction affects the material. In compacting samples using the Proctor method, the material’s stiffness has a significant effect on the densification because a fixed amount of energy is delivered to the specimen by impact compaction. The Superpave Gyratory Compactor, however, applies a constant shear strain, allowing for the amount of energy put into the specimen to adjust to the stiffness of the mixture (Anderson et al., 2002). According to the North Carolina Department of Transportation, 30 gyrations are recommended for the creation of FDR samples in the lab. Whereas, proctor compaction requires 25 blows with a 5.5-pound hammer over three layers for the standard method or 25 blows with a 10-pound hammer over five layers for the modified method. So not only is the method of compaction very different, but the compaction effort varies between methods as well. With the compaction of FDR, the effect of water on the densification process is also important in understanding the behavior of the material. Cerni and Camilli (2011) found that, when compacting
soil and aggregate mixtures, the most effective method of compaction was that which allowed the greatest expulsion of water.

In this research, Proctor compaction was compared to Superpave Gyratory compaction on FDR samples. Specifically, the factors analyzed were the method of compaction, size of mold, compactive effort, and whether or not water was allowed to leave the sample. The un-stabilized aggregate and recycled asphalt pavement (RAP) mixtures used in FDR samples were combined at varying moisture contents and compacted in one of five ways:

1. Gyratory Compaction in a 6 inch slotted mold
2. Gyratory Compaction in a 6 inch unslotted mold
3. Gyratory Compaction in a 4 inch unslotted mold
4. Standard Proctor Compaction in a 4 inch mold, Method B
5. Modified Proctor Compaction in a 4 inch mold, Method B

For the Proctor Compaction, ASTM D698 and ASTM D 1557 were followed for standard and modified effort respectively. These procedures were also followed for sample preparation and dry density calculations for the samples compacted in the gyratory compactor. From this compaction data, the optimum moisture content to be used in the creation of asphalt emulsion stabilized FDR samples can be found for each method of compaction.

2.5. **Strength & Stability Tests**

Following the determination of optimum moisture contents for use with each of the compaction methods, the strength and stability of the FDR mixtures will be evaluated using the Indirect Tensile Strength Test and the Marshall Stability test. An
FDR layer will act as a base and subbase layer within a pavement structure. These layers serve to help distribute the applied loads down from the surface course to the subgrade soil. The strength of these layers also significantly affects the performance of the surface course on top. Therefore, ensuring that an FDR mixture provides adequate support within the pavement structure is essential to implementing this recycling technique in the field. A positive correlation between density and strength as well as compaction energy is expected for these samples as this is true for both soil specimen and HMA mixtures. These are performance tests associated with HMA. Therefore, comparing the results obtained on FDR samples created with different compaction methods as well as typical values obtained for HMA samples will help further characterize these FDR layers.

2.5.1. Marshall Stability Test

The Marshall mix design method was developed in the 1930’s and is still widely used by many sub-state agencies, such as cities and counties, for airport pavement design, and also for asphalt emulsion mixes. This method uses an impact hammer for compaction of the HMA mixtures. The performance test used to evaluate the HMA mixtures is the Marshall Stability and Flow test, which is an empirical test. The test measures the resistance of the asphalt mixture to plastic flow, which is a measure of the deflection resulting from the load on the sample applied at a rate of two inches per minute up to a peak load. This peak load is used to determine the stability of the mixture. The test specification followed for this procedure is ASTM D6927. The Asphalt Institute (1979), gives minimum stability
requirements as well as an allowable range for flow for roads of varying levels of traffic, which are displayed in Table 2.

Table 2. Typical Marshall Design Criteria (Asphalt Institute, 1979).

<table>
<thead>
<tr>
<th>Mix Criteria</th>
<th>Light Traffic</th>
<th>Medium Traffic</th>
<th>Heavy Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Flow (0.25 mm or 0.01 inch)</td>
<td>8</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>Stability (minimum)</td>
<td>500 lbs.</td>
<td>750 lbs.</td>
<td>1500 lbs.</td>
</tr>
</tbody>
</table>

2.5.2 Indirect Tensile Test

The Superpave mix design was completed in 1993 and was created to replace the Marshall mix design and other older methods. Accounting for traffic loading and environmental conditions as well as having a more mechanistically based evaluation of materials set the Superpave mix design apart from previous design methods. A major way in which this mix design method accounted for environmental conditions was adding a moisture susceptibility evaluation into the process. This test is known as the Indirect Tensile Strength Test (ITS), and it compares the tensile strength of dry specimens to that of moisture-conditioned specimen by use of a tensile strength ratio (TSR). The Superpave mix design moisture susceptibility specification requires a TSR of greater than or equal to 0.80, meaning the tensile strength of the moisture-conditioned samples must be greater than or equal to 80% of that of the unconditioned samples (pavementinteractive.org, 2010). The test specification followed for this procedure is ASTM D4867.

Because FDR layers serve as a base and subbase layer in a recycled pavement structure, they are more likely to experience greater levels of moisture and
saturation than an HMA surface course. This could be from water draining down from the surface course above or a high water table and capillary action up through the subgrade. Observing the effect of moisture on FDR samples is then of particular interest because they may be exposed to prolonged periods of greater moisture. Additionally, comparing the TSR of the FDR samples to the TSR requirements for HMA may help validate the use of FDR instead of an HMA base course layer.

3. RESULTS

3.1. Compaction Results

Compaction data was collected for each of the five methods described previously at target moisture contents of 2%, 4%, 6%, and 8%. The class 7 aggregate and RAP mixture was combined into 2500-gram samples for these compaction tests, which were weighed out and evenly separated with a splitter. The dry weight of the sample was taken, and from this, the amount of water that was required to reach the target moisture content was calculated. The water was mixed thoroughly into the aggregate and RAP blend before compaction began.

For the Proctor compaction tests, the weight and volume of the mold were recorded first. As mentioned previously, and according to the ASTM specification, the correct number of blows and layers were used for both the modified and standard proctor test. Method B was followed for both of these tests because more than 20% of material was retained on a No. 4 sieve and less than 20% was retained on a 3/8” sieve. Therefore, the 4-inch mold was used for both modified and standard Proctor compaction. Following compaction, the weight of the sample was recorded while still in the mold. The compacted specimen was then extruded from
the mold, and a representative sample was taken from the center of the specimen. This representative sample was weighed to obtain the weight of the moist sample and then placed in the oven to dry so that the actual moisture content of the sample could be measured. Once this actual water content had been determined, the moist and dry densities could be calculated. Moist density ($Y$) was found by dividing the compacted weight of the sample by the volume of the mold. The following equation, given in the ASTM specifications was then used to calculate dry density ($Y_d$),

$$Y_d = \frac{Y}{(1+w)}$$

(Das, 2006) \hspace{1cm} (3)

where $w$ is the actual water content of the sample.

A similar procedure was used for the compaction of samples in the gyratory compactors. The water was mixed into the aggregate/RAP blend, the mixture was placed into the compaction mold, and then it was placed into the Superpave Gyratory Compactor. Per the North Carolina Department of Transportation’s mix design procedure for FDR, 30 gyrations were used for all samples compacted by the gyratory compactor. Following compaction, the specimen was extruded from the mold, the sample weighed, and then placed into the oven to dry so that the actual water content could be obtained.

Once samples had been compacted at each of the target moisture contents, a compaction curve of the data was created. This curve plotted the dry unit weight of the samples versus their water content. As discussed previously, the optimum moisture content was then found to be the moisture content at the peak of this curve. Figure 9 depicts the compaction curves for all five methods of compaction used.
Figure 9. Compaction Curves.

From looking at this graph, it appears that there are two groups of curves. This upper group, which includes both 6-inch gyratory molds and the modified proctor test appear to have applied quite a bit more effort to the samples than the methods in this lower group, including the 4-inch gyratory mold and the standard proctor test. None of these curves have the same shapes or slopes, which was unexpected because the same aggregate gradation was used in all types of compaction. Therefore, it seems that the method of compaction may have an effect on the shape of the compaction curve. The method that appears to have applied the most effort to the samples is the Modified Proctor method as this curve is the
furthest up on the graph; however, the 6-inch gyratory compaction curves remain very close to this Modified Proctor curve.

All of the curves behaved as expected in that they gradually increased and then decreased after reaching an OMC peak except the 6-inch slotted gyratory compaction and the Modified Proctor curve. The reason that the Modified Proctor curve behaved in this way is unknown. The 8% target moisture content sample was prepared and compacted twice and the same results occurred each time. The behavior of the 6-inch slotted gyratory compaction curve could be expected. Because this mold has holes in it, if a sample is being compacted at a moisture content greater than its optimum, the water will be pushed out of these holes during the compaction process. In all other compaction methods, there is nowhere through which this excess water can leave, so instead, the water is retained and the sample is not compacted to its maximum density. For the purposes of creating a compaction curve though, the slotted gyratory mold is not ideal because it is unlikely that the curve will be allowed to continue downward after reaching the OMC. From these curves, the OMC for use with each method of compaction was found and is displayed in Table 3. The 50% OMC values used for design of the FDR samples is also shown.

*Table 3. Optimum Moisture Contents.*

<table>
<thead>
<tr>
<th>Compaction Method</th>
<th>Optimum Water Content</th>
<th>50% OMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slotted SGC</td>
<td>6.1%</td>
<td>1.8%</td>
</tr>
<tr>
<td>4&quot; Unslotted SGC</td>
<td>5.6%</td>
<td>2.8%</td>
</tr>
<tr>
<td>6&quot; Unslotted SGC</td>
<td>3.6%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Standard Proctor</td>
<td>5.4%</td>
<td>2.7%</td>
</tr>
<tr>
<td>Modified Proctor</td>
<td>4.0%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
3.2. Strength and Stability Results

For both strength tests performed in this research, 6-inch diameter samples were used, so only the standard and modified proctor methods, and the 6-inch slotted and unslotted gyratory methods were used. All of the samples created using the gyratory compactor were easily extruded from the mold in tact. Unfortunately, the samples compacted using Proctor hammers were much more difficult to remove from the mold. Because only one mold was available for use, the samples were immediately extruded so that additional samples could be compacted. Once asphalt emulsion is mixed with the aggregate, it has to break, or have a separation of the asphalt cement from the water, in order for the asphalt to act as a binder in the mixture and develop its cohesive strength. This break typically occurs once the sample has been fully compacted (Asphalt Academy, 2009). The standard Proctor samples could not be demolded without completely falling apart, so none of these samples were used in the strength tests. This may have occurred because the emulsion had not broken and thus a strong enough cohesive bond had not yet formed between the aggregate and the asphalt cement.

The samples created using the modified Proctor method held together well enough to be initially extruded intact; however, once extruded from the Proctor mold, the samples could not be taken off the extrusion device and placed back into the oven for curing. The extrusion mold, shown in Figure 10, was used to remove all of the gyratory samples from the gyratory mold.
The samples remained in these molds throughout the curing process. Unfortunately, the diameter of the Proctor mold was slightly larger than the gyratory molds, so these extrusion molds could not be used on samples compacted in the Proctor mold. In order to demold the modified Proctor samples, they were compacted in the 6-inch unslotted gyratory mold, which most closely resembled the Proctor mold. Because the base plate of the gyratory mold is not rigidly attached to the rest of the mold as is the Proctor mold, some of the energy from the hammer’s impact on the sample may have been dissipated through movement of the gyratory mold. However, no visible movement could be detected. While this is a significant
deviation from the specification, it seemed to be the most efficient way to ensure that the samples remained in tact after compaction and before curing. If 12 Proctor molds had been available, perhaps the samples could have been left in the mold for the entire curing process and then extracted. Figure 11 shows an example of one of the samples compacted using the modified Proctor hammer in the unslotted gyratory mold after being extruded. These samples were not nearly as tightly compacted as those done in the gyratory compactor.

Figure 11. Modified Proctor Compacted FDR Sample.
Once compacted, these FDR samples then had to cure. The standard curing process for all samples, as per the North Carolina mix design, required that they be placed in the oven at 100°F for a period of 48 hours.

3.2.1. Marshall Stability Results

For the Marshall stability test, three replicate test specimens were created for each compaction method (unslotted gyratory, slotted gyratory, and modified Proctor), making for a total of 9 samples. Unfortunately, upon removing one of the modified Proctor samples from the oven, the sample was found to be cracked and could not be used in the test. The test specification, ASTM D6927, states that after curing, the bulk specific gravity (ASTM D2726) and height of each specimen needs to be found and recorded. Next, samples are conditioned in a water bath at 140°F for 30 to 40 minutes. Unfortunately, when the samples prepared for this test were ready to be tested, the loading frame typically used for the Marshall stability test was not working. This loading frame remained unavailable, so the MTS load frame was used instead. However, for the sake of conserving materials and the need to wait for resources to become available, a modified conditioning procedure was used. Following the 48 hour curing period, these samples were conditioned for 30 minutes and then removed from the water bath and stored at room temperature for another 24 hours. Finally, immediately prior to testing, they were conditioned again in the water bath at 140°F for another 30 minutes.

A loading rate of 2 inches per minute was used on the MTS load frame. A preload of 45 pounds was also used to ensure that the loading ram was making complete contact with the specimen in the mold. The samples were placed in the 6
inch Marshall stability testing head. This configuration is displayed below in Figure 12.

![Marshall Stability Test Configuration](image)

*Figure 12. Marshall Stability Test Configuration.*

Once the test began, the load was increased until a peak load was reached. The MTS software recorded the loading and the displacement of the loading ram. This peak load was determined to be the stability of the mixture. The stability values, bulk specific gravity \( G_{mb} \), and the height found for each sample are expressed in Table 4. The theoretical maximum specific gravity (ASTM D2041) was also needed for each
specimen so that the percent air voids within the specimen could be calculated (ASTM D3203). This calculated percentage of air voids is also displayed in Table 4. Additionally, the average stability was calculated for the samples compacted by the same method for each of the three methods used. The coefficient of variance (COV) was determined for each of these average stabilities by dividing the standard deviation by the mean for each set. The COV is used as a standardized method of comparing statistical deviations.

*Table 4. Marshall Stability Test Data.*

<table>
<thead>
<tr>
<th>Compaction</th>
<th>Gmb</th>
<th>Height (mm)</th>
<th>Air Voids, %</th>
<th>Stability (lb)</th>
<th>Avg. Stability (lb)</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slotted Mold</td>
<td>2.134</td>
<td>71.60</td>
<td>13.96</td>
<td>1966.69</td>
<td>2017.66</td>
<td>7.15%</td>
</tr>
<tr>
<td></td>
<td>2.139</td>
<td>70.30</td>
<td>13.75</td>
<td>2180.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.142</td>
<td>71.20</td>
<td>13.65</td>
<td>1905.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unslotted Mold</td>
<td>2.143</td>
<td>70.20</td>
<td>13.58</td>
<td>2375.58</td>
<td>1957.69</td>
<td>22.21%</td>
</tr>
<tr>
<td></td>
<td>2.137</td>
<td>71.20</td>
<td>13.85</td>
<td>1989.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.138</td>
<td>71.00</td>
<td>13.78</td>
<td>1507.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Proctor</td>
<td>2.056</td>
<td>83.89</td>
<td>17.09</td>
<td>595.34</td>
<td>527.20</td>
<td>18.28%</td>
</tr>
<tr>
<td></td>
<td>2.042</td>
<td>85.53</td>
<td>17.65</td>
<td>459.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The average stability values for samples compacted in the slotted gyratory mold and the unslotted gyratory mold were much more similar than that of samples calculated using the modified Proctor method. Figure 13 displays these average stability values along with the standard deviation that occurred for each compaction method.
The stability of the SGC samples exceeded the minimum requirement for heavy volume HMA roads of 1500 pounds. The modified Proctor samples, however, barely met the requirements for a light traffic road. This was expected, as these samples did not seem to be nearly as solid as the gyratory samples and even had fairly large chunks fall away from the sample through the curing and conditioning processes. These results are interesting due to the fact that the Marshall stability test was designed and originally intended for use with samples compacted using the Marshall hammer, which is also an impact method of compaction, like the Proctor method.

Comparing the stabilities of the samples created with the two gyratory molds, the slotted mold samples would have a higher stability than the unslotted mold samples. This may be due to the fact that during compaction, excess water

Figure 13. Average Stability Values.
was allowed to easily be expelled from the sample in the slotted mold, which may have, in turn, allowed the sample to be even more densely compacted and result in a stronger specimen.

3.2.2. *Indirect Tensile Strength Results*

Like the Marshall stability test, the Indirect Tensile Strength (ITS) test involves a conditioning process. However, in this test, only half of the samples are conditioned, and the conditioning process is significantly longer. Also like the Marshall, the bulk specific gravity of each sample must be determined after the curing process is completed. Additionally, the theoretical maximum specific gravity (ASTM D2041) was used again to determine the percent air voids within the specimen (ASTM D3203). A total of eighteen samples were created for the ITS test, six for each of the three compaction methods used. These eighteen samples were split into two groups, one of which would be moisture conditioned and the other remained unconditioned. The conditioning process involved first partially saturating the sample using a vacuum to a level between 55% and 80%. Then the samples were placed in water at 140°F for 24 hours. The unconditioned samples were simply stored dry, at room temperature. Following this 24 hour conditioning period, the moisture conditioned samples were transferred to water at 77°F to cool to ambient temperature. Unfortunately, one of the moisture-conditioned modified proctor samples cracked before it could be tested, as was the case with the Marshall stability test samples. This prematurely failed specimen is displayed in Figure 14.
The loading used for the ITS test the same as the Marshall Stability test. A 2-inch per minute loading rate was used again, along with a 45-pound preload. The MTS load frame was also used to perform this test as the Pine load frame, which is typically used for both the Marshall Stability Test and the ITS, was still out of service. Figure 15 shows the test configuration used.
Figure 15. ITS Test Configuration.

While running the test, the MTS magnitude of the load and the displacement of the loading ram were recorded. The sample was loaded until it completely failed by fracture. Figure 16 shows an example of the typical fracturing that occurred for these FDR samples.
The peak load recorded was used to calculate the tensile strength of that sample. The specification gave the equation used to calculate both the tensile strength and the tensile strength ratio between the moisture conditioned samples and the unconditioned samples. The equation for calculating tensile strength was given as,

$$S_t = \frac{2P}{\pi td} \quad \text{(ASTM D4867)} \quad (4)$$

where $S_t$ is the tensile strength in psi, $P$ is the maximum load in pounds, $t$ is the height of the sample in inches, and $D$ is the diameter of the sample in inches. Table 5
displays the calculated tensile strength, the bulk specific gravity, and the percent air voids for each of the samples.

*Table 5. ITS Test Data.*

<table>
<thead>
<tr>
<th>Compaction</th>
<th>Conditioned?</th>
<th>Gmb</th>
<th>Air Voids, %</th>
<th>St (psi)</th>
<th>TSR</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGC Slotted Mold</td>
<td>Yes</td>
<td>2.138</td>
<td>13.8</td>
<td>23.0</td>
<td>63.91%</td>
<td>3.03%</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>2.144</td>
<td>13.5</td>
<td>24.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>2.158</td>
<td>13.0</td>
<td>22.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>2.147</td>
<td>13.4</td>
<td>33.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>2.140</td>
<td>13.7</td>
<td>35.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>2.193</td>
<td>11.6</td>
<td>40.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SGC Unslotted Mold</td>
<td>Yes</td>
<td>2.157</td>
<td>13.0</td>
<td>28.9</td>
<td>70.85%</td>
<td>13.79%</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>2.164</td>
<td>12.7</td>
<td>25.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>2.134</td>
<td>14.0</td>
<td>21.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>2.164</td>
<td>12.7</td>
<td>37.1</td>
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<td></td>
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<tr>
<td></td>
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<td>2.147</td>
<td>13.4</td>
<td>38.1</td>
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<td></td>
<td>No</td>
<td>2.128</td>
<td>14.2</td>
<td>32.1</td>
<td></td>
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<tr>
<td>Modified Proctor</td>
<td>Yes</td>
<td>2.017</td>
<td>18.7</td>
<td>2.9</td>
<td>60.56%</td>
<td>58.36%</td>
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<tr>
<td></td>
<td>Yes</td>
<td>2.025</td>
<td>18.4</td>
<td>0.0</td>
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<td></td>
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<td></td>
<td>Yes</td>
<td>2.056</td>
<td>17.1</td>
<td>3.5</td>
<td></td>
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<td></td>
<td>No</td>
<td>2.048</td>
<td>17.4</td>
<td>4.7</td>
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<tr>
<td></td>
<td>No</td>
<td>2.000</td>
<td>19.3</td>
<td>5.8</td>
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</tr>
<tr>
<td></td>
<td>No</td>
<td>2.039</td>
<td>17.8</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is interesting to note that while the modified Proctor samples had the highest stabilities from the Marshall stability test, they were also found to have the lowest tensile strengths. Additionally, the ITS test is intended for use with HMA samples compacted using the SGC, and the FDR samples compacted using both gyratory methods were much higher than the modified Proctor samples. A comparison of the average tensile strengths calculated for samples made using each compaction method in both the conditioned and unconditioned state is displayed in Figure 17.
This calculated tensile strength was used to determine the tensile strength ratio (TSR), which was calculated by simply dividing the average tensile strength of the moisture-conditioned samples by the average tensile strength of the dry samples. A TSR was calculated for samples compacted using the SGC slotted mold, the SGC unslotted mold, and the modified Proctor method, and these values are also displayed in Table 5. The unslotted gyratory samples had the highest TSR of 70.85%, followed by the slotted gyratory samples at 63.9% and least the modified Proctor samples with a TSR of 60.55%. The modified Proctor samples had experienced significant visible degradation following moisture conditioning, so the low TSR for these samples is not surprising. However, the reason for the difference between the TSR of the slotted and unslotted SGC samples is unknown. All of these
TSR’s determined for FDR samples were lower than the recommended value of 80% for HMA mixtures. From this test, it is evident that moisture conditioning causes a considerable decrease in tensile strength for all FDR samples.

In addition to comparing the tensile strengths of the conditioned and unconditioned samples, the tensile strength was also compared to the bulk specific gravity of the sample. The bulk specific gravity is a measure of the density of the material, which is affected by the compaction. Figure 18 shows the relationship between bulk specific gravity and tensile strength.

![Graph showing the relationship between bulk specific gravity and tensile strength. The graph includes data points for both conditioned and unconditioned samples, with R² values of 0.93024 and 0.95417 for Proctor and Gyratory samples, respectively.](image)

*Figure 18. Bulk Specific Gravity versus Tensile Strength.*

From this graph, a positive correlation can be seen between the bulk specific gravity and the tensile strength. The denser FDR samples were compacted by the gyratory
compactor. Thus, stronger FDR samples are created using typical HMA compaction techniques rather than soil compaction.

4. CONCLUSION AND FUTURE WORK

From the two strength tests, it was very evident that the compaction method affects the strength of FDR mixture. The hypothesis that the samples that were allowed to expel the greatest amount of water during compaction would be the strongest was found to be true. Like soil samples, water plays an important role in the compaction of FDR samples. The gyratory compactor, which is typically used for HMA samples that contain no water, proved to be very easy to use for the determination of optimum moisture content. The dry densities obtained for the samples compacted in the 6-inch gyratory molds were comparable to those of samples compacted by the modified Proctor Test; however, the OMCs of the two differed. Further research should be done to determine which of these methods produces the most optimum moisture content for creation of FDR samples. Not only were differences observed between Proctor compaction and gyratory compaction, the strengths of samples created in the slotted mold versus the unslotted mold varied. This would seem to imply that the ability for water to be expelled from the specimen during the compaction process affects the strength of the sample.

A direct correlation was observed between density and tensile strength as well as stability. The gyratory compacted samples were generally denser than the samples compacted by the Proctor hammer, thus they also had greater tensile strengths and stabilities. Soil typically has almost no tensile strength, thus these observed tensile strengths in the FDR mixtures are a material property that is more
similar to HMA. More HMA performance tests should be done on FDR samples to further evaluate the performance capabilities of FDR and compare them to those of HMA.
REFERENCES


Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types. Manual Series No. 2 (MS-2). Asphalt Institute. Lexington, KY


