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Laboratory Comparison of Full Depth Reclamation Stabilization Techniques Using Arkansas Field Materials

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Laboratory Comparison of Full Depth Reclamation Stabilization Techniques Using Arkansas Field Materials

Laboratory Comparison of Full Depth Reclamation Stabilization Techniques Using Arkansas Field Materials

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

by

Chase Henrichs
University of Arkansas
Bachelor of Science in Civil Engineering, 2013

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Abstract

Full depth reclamation (FDR) is a flexible pavement recycling technique that has not been explored in the state of Arkansas. FDR is unique in that it incorporates the entire flexible pavement section as well as a predetermined portion of the underlying base and sub-base materials with a stabilizer to create a new, stronger stabilized base course. Common stabilization techniques include the addition of asphalt emulsion, asphalt foam, or cement. Using the North Carolina emulsion FDR mix design, the Wirtgen foam FDR mix design, and the Portland Cement Association cement FDR mix design, field materials from four Arkansas highways in the Fayetteville Shale and Brown Dense Shale areas were gathered and used to produced laboratory stabilized FDR samples to determine the potential future use of these mix designs in Arkansas. Initial testing to determine mix properties were performed, which included determination of gradation, Atterberg limits, and sand equivalency testing. Optimal stabilizer contents were determined using the indirect tensile strength test for asphalt emulsion and asphalt foam stabilization and the unconfined compressive strength test was used for the cement stabilized samples. Once the mix designs were validated and optimal contents were determined, performance testing began on new samples produced at optimal stabilization contents from two of the highways to determine material characteristics and to determine if the performance tests are valid for use with FDR materials. For the asphalt emulsion and asphalt foam samples, performance testing included dynamic modulus in indirect tension mode, creep compliance, semi-circular bend, and indirect tensile strength. The cement stabilized samples were tested using the tube suction test and the semi-circular bend test. Results indicated dynamic modulus is a viable testing indicator for rutting and low temperature cracking, while creep compliance may not be suitable for FDR materials. The semi-circular bend test indicated that it is a testing option

when using asphalt stabilized materials but another option may be needed for cement stabilization. The indirect tensile strength and tube suction tests are quantifiable moisture susceptibility tests that worked well with the FDR materials.

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Also, a special thank you to Dr. Andrew Braham who decided to take me on as a graduate student even though I had not performed any research prior.

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To the Arkansas State Highway and Transportation Department, thank you for sponsoring this research. Without your support, this would not have been possible. To Ergon Asphalt and Emulsion, thank you for providing the emulsions used for the research. To Lion Oil Company, thank you for donating the asphalt binder used for foaming.

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Table of Contents

List of Figures

List of Tables

1.0 Introduction:

The United States is faced with an aging infrastructure in much need of repair. The American Society of Civil Engineers (ASCE) released its 2013 Infrastructure Report Card, which rated the overall infrastructure as a D+ and roads as a D. Even with capital investments reaching $91 billion annually for Federal, state, and local governments, it is estimated that $170 billion in capital investments would be needed on an annual basis to significantly improve road conditions in the United States [1].

Pavements will fail for a variety of reasons, but some of the most common reasons for failure are due to age, increased traffic and loads, and weather. Figure 1.0.1 highlights the different periods of a typical pavement’s life and the need for timely maintenance procedures. When a pavement is recently constructed, the ride quality is performing as expected at a high level. However, at a certain point, some maintenance, such as resurfacing, must be performed to extend the pavement’s life in order to stay above the terminal ride quality and meet the required structural design. The goal of resurfacing is to maintain the flexibility and durability of the pavement, but it only addresses deterioration due to the environment. Distresses from loading cannot be effectively treated from these surface maintenance techniques and require some form of structural rehabilitation. The goal of the structural rehabilitation is to offer a lasting solution by bringing the pavement to a level ride quality that is deemed usable for the required structural design. If a pavement is left unmaintained or unrehabilitated, the rate of deterioration will increase, which is shown by the ride quality on Figure 1.0.1. The lower the riding quality of pavement, the greater the measures required to remediate the pavement as well as the greater the costs. Often, the choice of when to take remedial action is dictated by the budgetary constraints of the responsible governing agency [2].

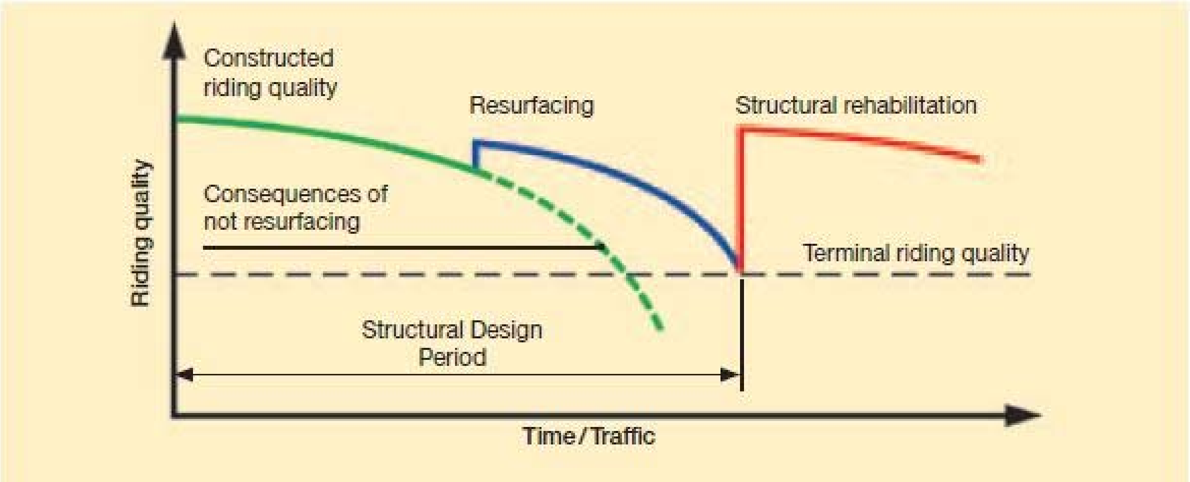

Figure 1.0.1 – Pavement Life Span [2]

The challenge of maintaining a high quality pavement network with dwindling resources is a national wide problem, as indicated by ASCE, and the state of Arkansas is no exception.

1.1 The Arkansas Problem

The Arkansas State Highway and Transportation Department (AHTD) maintains nearly 16,400 miles of roadway in its state highway system, the 12th largest highway system in the nation. ASCE rated Arkansas roadways as a D+, the same as the national average [3]. Many of the state highways in Arkansas, particularly in the Fayetteville Shale and Brown Dense Shale areas, have seen an increased rate of deterioration in recent years due to increased logging and heavy natural gas fracking equipment being transported on roads that were not designed to withstand such loads. This increased deterioration is a concern for AHTD, as these roadways are failing prior to reaching their structural design lives. There are five conventional methods for addressing pavement distresses in Arkansas: chip sealing, crack sealing, overlaying, mill and in-laying, and complete reconstruction. While chip seals, cracks seals, overlays, and mill and in-laying often provide an initial smooth ride, they may not provide a lasting solution, especially in the shale areas discussed above. By addressing only the distresses in the surface course of the pavement system, many of the conventional methods fail prematurely because the pavement structure is inadequate. Often, the root of the problem is below the surface course, in the base course or subgrade layers, which may require structural rehabilitation, such as complete removal and reconstruction of the existing roadway.

The problem Arkansas is facing is how can AHTD upgrade its existing pavements to meet the new traffic demands in an economically and environmentally friendly manner? Full Depth Reclamation is one such technique which could offer a lasting solution by addressing the surface and sub-surface distress, while also providing a “greener” solution to Arkansas pavement distress problems.

1.2 Full Depth Reclamation

Full Depth Reclamation (FDR) is a pavement rehabilitation technique in which the full flexible pavement section and a predetermined portion of underlying materials are crushed, pulverized, and blended with a stabilizing agent to create a stabilized base course [4], as seen in Figure 1.2.1. The reclamation depth generally occurs at depth from 4 to 12 inches through a singular reclaiming machine. Stabilization typically occurs through three primary forms: mechanical, asphalt, or chemical stabilization. Mechanical stabilization is achieved through the use of aggregates and is often used in junction with one of the other forms. Asphalt stabilization typically uses asphalt emulsion or asphalt foam. Chemical stabilization treats the mixture with pozzolans such as cement, coal fly ash, hydrated lime, or a mixture of these pozzolans [5]. FDR without stabilizers is also possible, but reserach suggests that FDR tests sections perform better with either asphalt or chemical stabilization [6]. Careful consideration should be given when selecting a stabilization method; considerations include the in-situ material properties, the objective of the rehabilitated pavement, expected traffic loading, the environmental conditions, and availability [7].

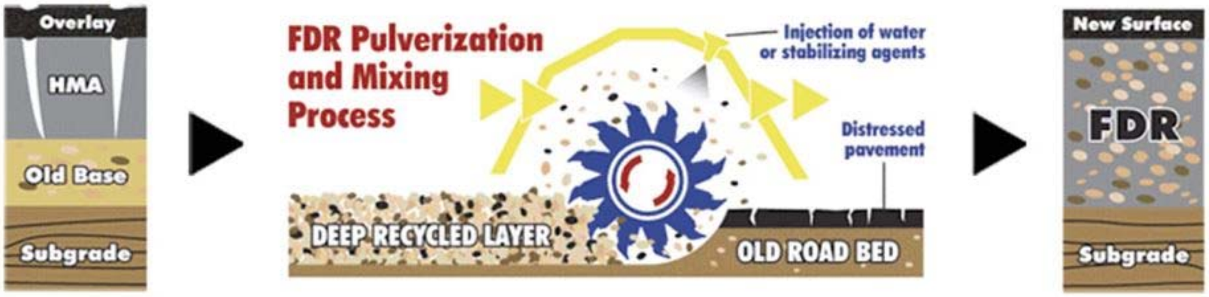

Figure 1.2.1 – Full Depth Reclamation Overview [8]

FDR has numerous benefits, the greatest of which stems from the physical recycling of materials in place. Recycling materials in place reduces costs and environmental impacts. Recycling savings associated with FDR can reach a cost reduction of 50% compared to removal and replacement of a pavement at the end of its service life [9]. FDR has also been shown to reduce energy consumption by up to 70% compared to the complete removal and reconstruction [10] of a deteriorated pavement structure. FDR promotes quarry and landfill life extension by reusing aggregates and reduced fuel consumption from transportation; it also allows for the improvement of pavement structure, geometry restoration, and thinner surface courses [11-12].

Many state agencies have already seized the opportunities to place FDR sections and have reported positive results with few problems. Nevada has placed nearly 900 centerline miles of FDR since 1985, which has increased their load-carrying capacity and structural uniformity as well as saving them an estimated $600 million compared with complete reconstruction costs [13]. Minnesota constructed three trial FDR sections in 2008 on Interstate 94 using emulsion, with early field testing (roughly one year) results indicating little rutting and no cracking [14]. Georgia explored using FDR with cement in Columbia County, with results from falling weight deflectometer indicating that deflections were significantly less than the original pavement and the pavement section treated with only an overlay. Georgia did report minimal rutting as well as isolated cracking after one year of use, which was thought be attributed to excessive cementing of the FDR layer [15]. Several other states have successfully demonstrated FDR, which include Kansas, Louisiana, Maine, Texas, Utah, Wisconsin, Virginia, and Pennsylvania [16-17].

Although many agencies have adopted the use of FDR, there is no universal mix design nor a generally accepted approach used to describe the structural capacity of FDR materials. Different mix designs require different compaction methods, performance tests and criteria to characterize the FDR material in the lab. In addition, there has not been a strong effort to relate laboratory performance tests to potential field performance, in the form of rutting and cracking.

2.0 Research Objectives and Laboratory Plan

Arkansas has yet to explore the FDR process and AHTD has shown interest in potentially pursuing FDR as an option if shown to be viable. AHTD’s Transportation Research Committee (TRC) authorized project TRC 1405 to investigate FDR using Arkansas field materials in order to produce a draft FDR construction and testing specification and handbook. The objectives of this research were to verify three FDR mix designs using Arkansas materials and to determine which performance tests are suitable to evaluate different FDR mix design technologies and potential predict field performance.

Using materials from four locations within Arkansas, laboratory testing was performed to validate three potential FDR mix designs and related performance tests. The FDR mix designs verified were the North Carolina Department of Transportation asphalt emulsion mix design, the Wirtgen asphalt foam mix design, and the Portland Cement Association mix design, which are detailed below in Section 2.2. Laboratory testing performed included material characterization (Section 2.1), optimum moisture content testing (Section 2.3), optimum stabilization content testing (Section 2.4), and performance testing (Section 2.5).

2.1 Materials

Materials were collected at four locations with varying pavement thicknesses, two in the Fayetteville shale and two in the Brown Dense shale areas. Figure 2.1.1 shows the locations of the four locations and estimate of the shale locations. A depth of eight inches was assumed for all locations, which yielded a spread of recycled asphalt pavement (RAP) to subgrade ratios (R:S). The four mixes are presented in Table 2.1.1.

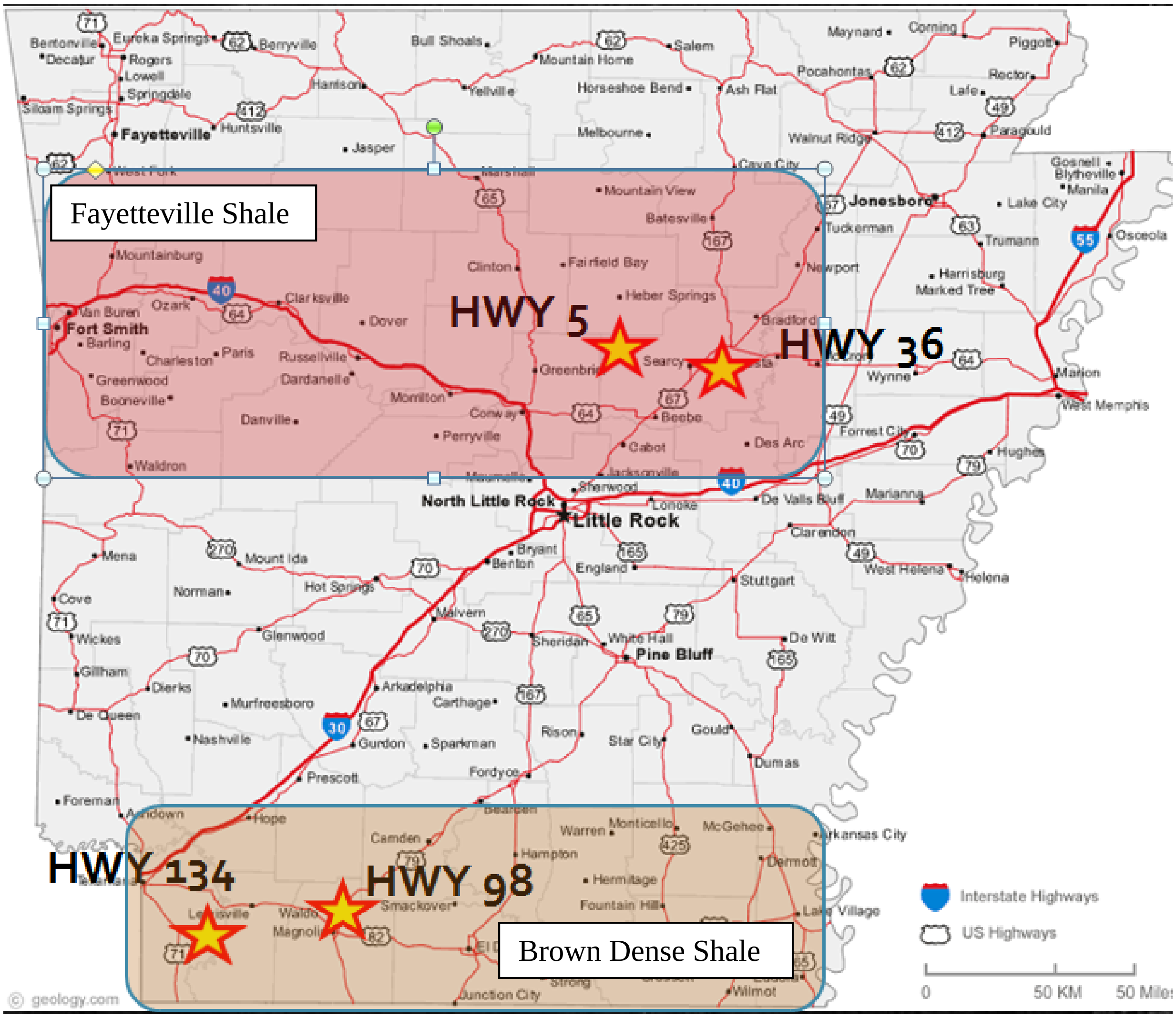

Figure 2.1.1 – Highway and Shale Locations [18]

Table 2.1.1 – Selected Arkansas Highways

Arkansas Highway	Highway Designation	Relative Location
AR 98	HWY 75S:25R	Columbia County, east of Magnolia, AR
AR 134	HWY 62S:38R	Miller County, east of Texarkana, AR
AR 36	HWY 38S:62R	White County, in West Point, AR
AR 5	HWY 25S:75R	White County, in Rose Bud, AR

Once the materials were in the lab, the first step was to process the material. First, each section's materials were dried to constant mass and then reduced using a soil tumbler for the subgrade and a jaw crusher for the RAP. The RAP needed to be crushed in order to better simulate the gradation that occurs in a milling head. Most of the RAP material collected in this study was taken off the surface in larger chunks, which is not representative of the milling head gradation. Therefore, the RAP needed to be crushed. However, initial crushing caused the RAP to warm and activate the asphalt binder, making crushing highly ineffective. In order to make the RAP more brittle, it was frozen using liquid nitrogen prior to crushing.

After the material was processed, testing for material characterization began and is summarized in Table 2.1.2. The gradations, Figure 2.1.2, were established using the ideal range given by the Asphalt Academy [19] for all three stabilization techniques. Due to having a limited supply of materials and to simulate the variability of gradation in the field, the gradations were not altered to fit Asphalt Academy's maximum and minimum suggested range. In general, all four sections had a finer gradation than the suggested gradation.

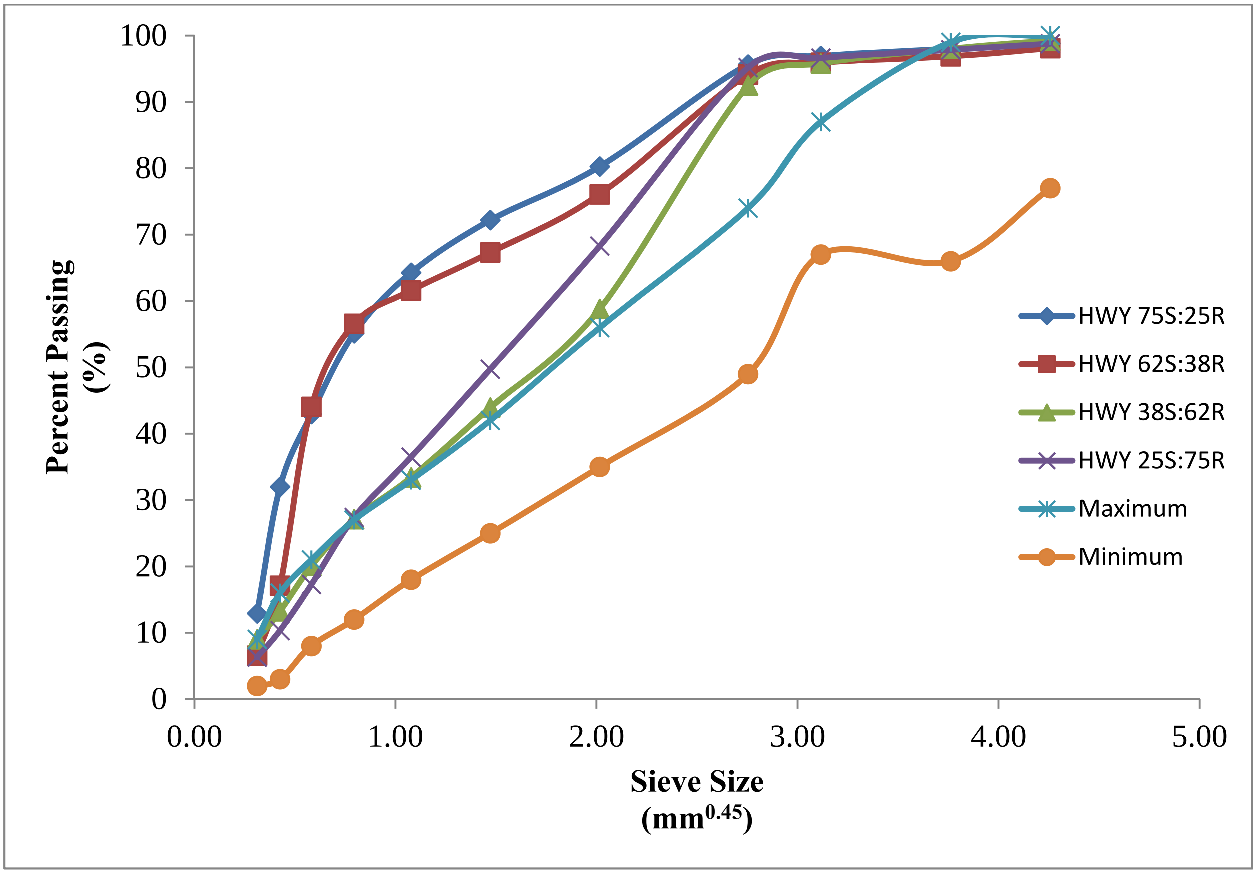

Figure 2.1.2 - Gradations

Table 2.1.2 – Material Properties

Highway (S:R)	**75:25**	**62:38**	**38:62**	**25:75**
P200 (%)	13	7	8	6
Plastic Limit	16.2	13.5	15	16.7
Liquid Limit	26	20	27	28
Plasticity Index	9	6	12	12
AASHTO Soil Classification	A-2-4	A-2-4	A-2-6	A-2-6
AASHTO Description	Silty or Clayey Gravel and Sand			
AASHTO Rating	Good			
Average Sand Equivalent	8	13	21	22
Absorption (%)	N/A	3.42	3.6	N/A

Once the gradations were determined, further testing included Atterberg limits, American Association of State Highway and Transportation Officials (AASHTO) soil classification, and sand equivalency [20-21]. These tests are a blend of traditional soil characterization tests from the geotechnical field and the transportation field. All initial testing was run on samples "as received," therefore no alteration to the original gradations were performed (aside from sieving) to ensure that ratios of subgrade to RAP were representative of the entire mix ratios. Therefore, it is likely that the ratios for each mix were altered because large portions of RAP were retained on the sieves while much of the subgrade passed, increasing the ratio of subgrade to RAP. This was determined to be justified through section 8.1.1 of ASTM D 4318, which states "Where a mixture of materials will be used in construction, combine the various components in such proportions that the resultant sample represents the actual construction case [20]."

With the initial testing performed on the soil and RAP material, focus turned to the stabilizing agents. Three technologies were explored: asphalt emulsion, asphalt foam, and Portland cement. The asphalt emulsion used was "CIR-EE" (Cold In-place Recycling Engineering Emulsion) and was provided by Ergon, Inc. of Jackson, Mississippi. The residue of the emulsion was approximately 63%, meaning the about 63% of the emulsion was asphalt binder and 37% was water, with trace amounts of chemical. The foamed asphalt, a PG 64-22 asphalt binder, was foamed in the Wirtgen WLB 10 S foamer. The asphalt foam was injected into the aggregate and mixed in the WLM 30 pug mill mixer. The virgin binder was provided by Lion Oil Company of El Dorado, Arkansas. The cement used was Type I/II Portland cement that can be found at most hardware stores. The optimum moisture content (OMC), optimum emulsion content (OEC), optimum foam content (OFC), and optimum cement content (OCC) were selected based upon the mix designs described in section 2.2. Once all of the material properties were established, and all of the materials were ready for testing, the mix design process for the three technologies began.

2.2 Mix Designs

For this research, three different mix designs were explored, with each mix design utilizing a different FDR stabilization technology. The three stabilization technologies explored were asphalt emulsion, asphalt foam, and Portland cement. The North Carolina Department of Transportation (NCDOT) mix design for asphalt emulsion stabilization was selected as this is one of the few publicly available FDR asphalt emulsion mix designs available in the United States [22]. For the foamed asphalt stabilization, the 2012 Wirtgen mix design was used [2]. Finally, for the cement stabilized samples, the Portland Cement Association (PCA) mix design was followed [11]. These mix designs were chosen because they have been historically used at the University of Arkansas, are thorough yet easily followed, have overlap in testing procedures, and are similar to the procedures seen in the literature [23]. For the two asphalt based stabilization mix designs, the fabrication of samples and testing are similar, this allowed for an easier comparison of performance samples. Cement samples were also fabricated in similar manner to allow for easier comparison as well. More details on specimen fabrication can be found in Section 2.4.

There were five separate phases for this research used to compare the three stabilization techniques. The first phase consisted of determining the OMC of two of the four sections in Arkansas. The second, third, and fourth phases encompassed determining the OEC, OFC, and OCC of the two sections. These first four phases were used to validate the potential for the three selected mix designs in Arkansas. The final phase involved executing various performance tests to determine the qualities of each mix to validate each performance test for FDR use.

2.3 Optimum Moisture Content (OMC)

Moisture is important in soil compaction, acting as a lubricant to allow the soil particles to pass each other to form a more dense orientation. Compaction at OMC helps to limit the shrink-swell potential and ensures low compressibility of a soil. It is at OMC where a soil reaches it maximum dry density. Density is also a requirement on most, if not all, road construction sites; this helps ensure a strong pavement structure.

The moisture in the FDR samples interacts with the stabilizer used and affects the FDR layer differently depending on the stabilization agent used. For asphalt emulsion stabilized FDR, the moisture reduces the water absorbed into the aggregate from the emulsion preventing the emulsion from breaking, where the asphalt binder drops from suspension in the water, prematurely. By preventing the emulsion from breaking prematurely, curing times are extended and a more cohesive material is formed. For asphalt foam stabilized FDR, the water helps transport the foam during the mixing process, as well as suspends the fines. The suspension of the fines allows the foamed asphalt droplets to more easily access them, creating the “spot-weld” action essential for foamed asphalt stabilization. Finally, the addition of water causes the hardening of cement through the process of hydration, giving the FDR its strength.

Following the NCDOT and Wirtgen mix designs, OMC was determined using the modified Proctor test in a 150 mm mold, method C [24]. The PCA design called for the OMC determination using the standard Proctor test. However, it was decided to follow the same procedure, modified Proctor, for all three stabilization technologies for consistency and conservation of materials [25]. The results from the modified Proctor test, like the standard Proctor test, compares the dry densities achieved at uniform compaction energy to the moisture content of the compacted specimen. Four moisture contents were selected and three replicates at each moisture content were created. OMC was determined as the peak of the dry density versus moisture content curve.

2.4 Optimum Stabilization Content

2.4.1 Optimum Emulsion Content (OEC) and Optimum Foam Content (OFC)

The procedures outlined in both the NCDOT and Wirtgen mix designs overlap one another in the testing, which allows for easier comparison between the results. The Indirect Tensile Strength (ITS) test was used to determine the OEC and OFC [26]. The ITS test evaluates moisture susceptibility of asphalt mixes by comparing tensile strengths of moisture condition and unconditioned samples. The ITS tests was also highlighted in both mix designs. One variation from section 8.6.3 in ASTM D 4867 was to saturate conditioned samples for 20 minutes under a vacuum with no vibration and an additional 10 minutes with vibration and under a vacuum. This method was chosen because the conditioned samples were losing a significant amount of material and not reaching the minimum required saturation point. Saturation is determined by overall mass, therefore the more material that was lost, the lower the measured saturation. More than 30 minutes under the vacuum was detrimental to the conditioned samples, as large sections of the sample would disintegrate. Due to the detrimental effects of the moisture conditioning on the FDR samples, this step may not be suitable for FDR applications and should be further investigated.

Similar to OMC determination, the average of triplicate ITS results were plotted against the stabilizer contents. The OEC and OFC contents were selected as the minimal content that met both the requirements for conditioned and unconditioned ITS, or the peak of the wet conditioned curve.

Samples were created for both OEC and OFC in as similar method as possible, with some exceptions. Per NCDOT, the emulsion samples were created in a bucket mixer, allowed to cure for 30 minutes at 40°C, and compacted in a SUPERPAVE gyratory compactor (SGC) for 30 gyrations. One deviation from the NCDOT mix design was the use of 150 mm slotted SGC mold, which allows any excess water and pore water pressure to escape. The OFC samples were created using the Wirtgen WLB 10 S foamer in conjunction with the Wirtgen WLM 30 pug mill mixer. After the mixing and foaming process was completed, samples were split and quartered [27]. OFC samples were compacted exactly the same as the OEC samples. All OEC and OFC samples were then allowed to cure for 72 hours at 40°C. The minimum ITS requirements, outlined in the NCDOT mix design were 35 psi for dry conditioned samples and 20 psi for moisture conditioned samples [22].

In addition to the ITS testing, volumetric properties were also collected for each sample, which is required by both mix designs. The volumetric properties collected were:

- Theoretical maximum specific gravity [28]
- Bulk specific gravity [29]
- Percentage air voids [30]

Two samples were collected at each stabilization content for theoretical maximum specific gravity, which were averaged for a final value. For bulk specific gravity, the automatic vacuum sealer method was used because FDR samples are highly absorptive. Using these two properties, the percentage air voids was able to be determined. As mentioned, the mix design procedure was very similar for the asphalt emulsion and asphalt foam stabilization techniques, but quite different for the Portland cement.

2.4.2 Optimum Cement Content (OCC)

The OCC was determined from unconfined compressive strength (UCS) test for soil cement cylinders [31]. The range given from the mix design suggested a range of 2.1 MPa to 2.8 MPa (300-400 psi), with the goal of creating a stabilized base that was strong but not too stiff. OCC was selected as the minimum cement content that fell within this range, or the lowest content that exceeded the range. The OCC samples were mixed and compacted in the same manner as the OEC samples, with the exception the OCC samples were compacted in a 100 mm un-slotted SGC mold. The 100 mm mold was selected because it conserved material but allowed for a tall enough sample to create a shear plane for UCS. The mold was un-slotted because a 100 mm slotted SGC mold was not available. OCC samples were then allowed to cure capped for 24 hours in a moist cure room, followed by 6 days uncapped curing. The moist cure room was maintained at 50% relative humidity and 21°C. Prior to performing the UCS, the OCC samples soaked in a room temperature water bath for four hours.

Upon completion of the mix designs for the two sections and three technologies (for a total of six mix designs), it was decided the three mix designs were suitable for Arkansas materials and performance testing began on samples stabilized at optimum contents.

2.5 Performance Testing

Pavement design is moving away from the empirical design standards of the 1993 AASTHO Pavement Design Guide toward Mechanistic-Empirical Design Guide (MEPDG) in the attempt to produce long lasting and higher performance pavements in a cost efficient manner [32]. In order to characterize the material properties, some of which are MEPDG inputs, a series of performance based tests were completed. The performance tests chosen were outlined by AHTD as current tests used to characterize pavement distresses in Arkansas. Distresses that AHTD has indicated as significant problems include rutting and low temperature cracking. The goal of the performance tests, aside from gathering material characteristics, was to evaluate the test themselves as potential FDR tests in Arkansas. These tests were run on new samples produced using the optimum stabilization content (OEC, OFC, and OCC). The performance tests, summarized in Table 2.5.1, can be broken into several categories, which broadly described are:

- Mechanistic properties
- Cracking characteristics
- Moisture damage and strength

Table 2.5.1 – Performance Testing Summary

Test	Test Method	Asphalt or Cement	Use
Dynamic Modulus	AASHTO TP 62; Kim *et al* 2004	Asphalt	Stiffness, MEPDG input
Creep Compliance	AASHTO T 322	Asphalt	Rutting Characterization
Semi-Circular Bend	AASHTO TP 105	Both	Fracture Energy & Cracking Characterization
Indirect Tensile Strength	ASTM D 4867	Asphalt	Strength Moisture Susceptibility
Tube Suction Test	TTI Report 0-4114-2	Cement	Moisture Susceptibility

2.5.1 Mechanistic Properties

Dynamic modulus is one of the primary inputs into MEPDG and seeks to quantify the fundamental linear viscoelastic characteristics of asphalt concrete [33-34]. Dynamic modulus (E*) is a measure of the stress/strain behavior of a material and is linked to rutting characteristics of a material in MEPDG. The E* test applies a load to the specimen at various frequencies and temperatures. As the load is applied to the sample, the displacement is measured by extensometers, which is used for the analysis of the stress/strain characteristics of the material. For this research, E* tests were performed on asphalt stabilized samples in indirect tension, shown in Figure 2.5.1.1, which has been shown to correlate well with the axial loading of E* tests and conserves material [35]. In general, the higher the E* value at the higher frequencies and lower temperatures indicates a stiff sample, which ideally is resistant to rutting but more susceptible to thermal cracking. Conversely, at the high temperatures and low frequencies, a lower E* value indicates rutting potential. If the change in values on the master curve, plotted using time-temperature superposition, produces a flatter line, the sample can be said to be less susceptible to frequency and temperature changes.

Creep is the time-dependent portion of strain resulting from stress, creep compliance is the time-dependent strain divided by the applied stress. Tensile creep compliance is another property of asphalt used to predict low temperature thermal cracking, load magnitude, and creep loading time [36]. For this reason, creep compliance is also a primary input into MEPDG. Creep compliance is determined by applying a vertical load and measuring the deformations near the center of the specimen away from the localized stress concentrations caused by the loading head. The loads are determined to keep the material in the linear viscoelastic range [37]. It has been found that creep compliance typically increases with an increase in temperature, which shows a greater resistance to thermal cracking [37-38]. Creep compliance testing was performed on only the asphalt stabilized samples in the same configuration as E*.

Figure 2.5.1.1 – Dynamic Modulus and Creep Compliance Testing Configuration (Photo Credit – Chase Henrichs)

2.5.2 Cracking Characteristics

The Semi-Circular Bend test [SC(B)] is a three-point bend test, as seen in Figure 2.5.2.1, used to measure low temperature fracture energy of a sample, which is correlated to low temperature cracking resistance [38]. The greater the fracture energy of a specimen, the less susceptible the sample is to thermal cracking [39]. This test is performed on a semi-circular shaped specimen, cut from a cylindrical specimen. A notch is cut into the flat side of the half-disc to facilitate the crack and the load is applied so that the crack mouth opening displacement (CMOD) is held at a constant rate of 0.0005 mm/s. A cracked specimen is shown in figure 2.5.2.2. The CMOD is measured throughout the test and is used to calculate the fracture energy, or the area under the load versus load line displacement curve divided by the ligament area. For this test, the temperatures tested were -24°C and -12°C and were run on all stabilization methods.

Figure 2.5.2.1 – Semi-Circular Bend Test Configuration (Photo Credit – Chase Henrichs)

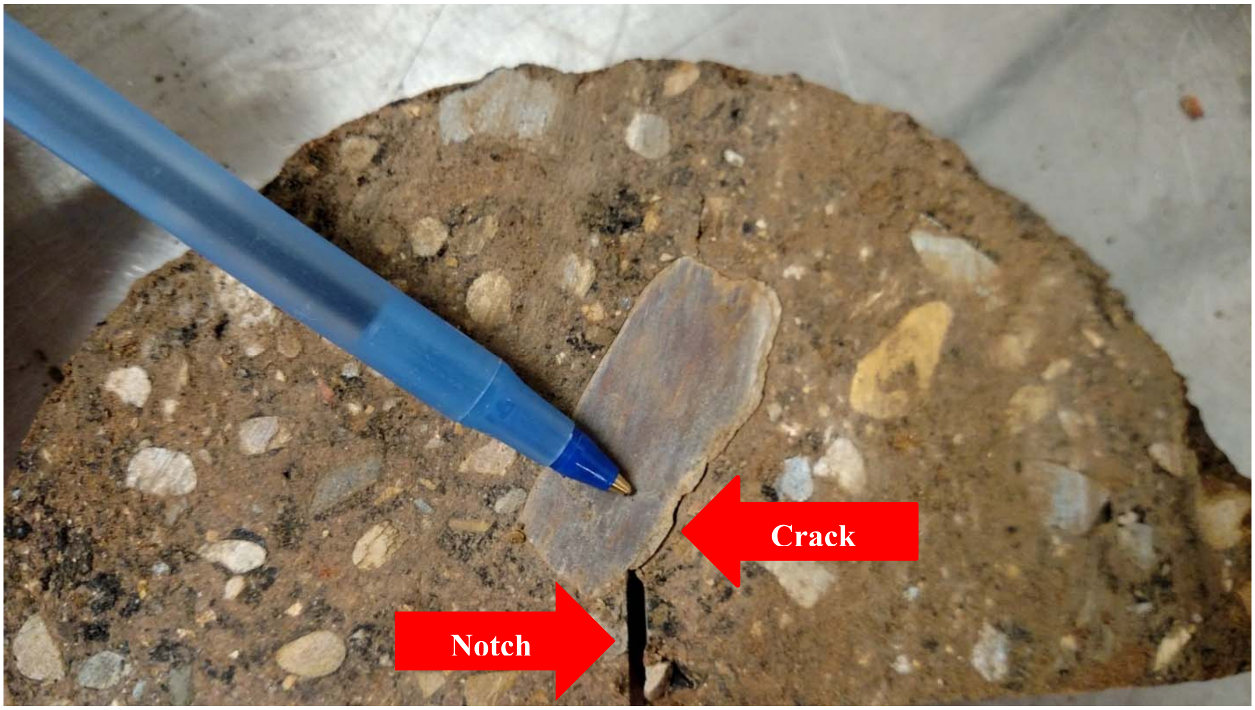

Figure 2.5.2.2 – Cracking from Semi-Circular Bend Test (Photo Credit – Chase Henrichs)

While some researchers believe that the SC(B) can be used for intermediate fracture testing, which is an indication of fatigue properties, the viscoelastic properties of FDR are not well enough understood in order to ensure that the tests were being run in the plain strain region. A plain strain condition is necessary in order to obtain proper fracture properties [40].

2.5.3 Moisture Damage and Strength

Moisture damage testing aims to quantify the detrimental effects of water on a sample, which is highly salient for FDR, as the samples may contain soils that are highly susceptible to changes in moisture, such as clays. Samples that contain soil that are highly susceptible to moisture changes could negatively affect the overall strength of the FDR samples due to the shrink-swell potential of the soil. For this research, two tests were explored to determine the moisture susceptibility of

FDR samples. The two tests performed were:

1. Indirect Tensile Strength (ITS)
2. Tube Suction Test (TST)

The ITS test, described in Section 2.4 and pictured in Figure 2.5.3.1, which was used to determine the optimum asphalt stabilization contents, was rerun to verify the tensile strengths.

Figure 2.5.3.1 – Indirect Tensile Strength Test (Photo Credit – Chase Henrichs)

The TST, developed by the Finnish National Road Administration and the Texas Transportation Institute (TTI), is used to determine moisture susceptibility of granular base materials. Samples are ranked based on a 10 day performance reading of dielectric values. The test places cylinders in a shallow water bath, allowing for capillary action of the material to draw the water into the sample. Dielectric values are measured prior to submersion and during the 10 day soak, then plotted over time. According to TTI, final 10 day average dielectric values less than 10 for base material are considered good, while values between 10 and 16 are marginal, and values greater than 16 are poor. The dielectric value of air is equal to 1 while water is 81 [41]. This test was performed on cement stabilized samples only. Figure 2.5.3.2 and Figure 2.5.3.3 show the TST samples prior to and during the soak period, respectively.

Figure 2.5.3.2 – Tube Suction Test Setup (Photo Credit – Chase Henrichs)

Figure 2.5.3.3 – Tube Suction Test (Photo Credit – Chase Henrichs)

With a comprehensive and unified understanding of the mix design procedures and performance tests, material from Arkansas was tested in order to determine the suitability of the findings to local material.

3.0 Mix Design Results

In this research, the results from HWY 62S:38R and HWY 38S:62R are presented. The objective of this section to validate the use of NCDOT emulsion, Wirtgen foam, and PCA cement FDR mix designs for use on local material from Arkansas.

3.1 Initial Testing: Atterberg Limits

The results from the Atterberg Limits, presented in Table 2.1.2, provide information regarding the characterization of the in-situ properties. The Atterberg Limits test is designed to help characterize the fine grained fraction of construction materials. Typically, soils with a high plasticity index (PI) tend to be clayey and more plastic, while those with lower PI's tend to be silty and non-plastic [42]. The samples displayed consistent values for the Atterberg Limits tested, which indicates that the materials gathered are relatively consistent from the four locations. The consistency of the materials allowed for the closer examination of increased RAP content on performance testing.

3.2 Optimum Moisture Content (OMC)

Using the modified Proctor test in a 150 mm mold, method C, OMC was determined for both highway mixtures [24]. For HWY 38S:62R the OMC was 4.8% and for HWY 62S:38R the OMC was 6.0%, which occurred at the maximum dry density for each mixture. As the subgrade content increases, there is an observed increase of approximately one percent in the OMC. Since the RAP was mostly non-absorbent it was anticipated that HWY 38S:62R, which had the lower absorption, would have an OMC that was lower than HWY 62S:38R. This expected trend was observed, as seen in Figures 3.2.1 and 3.2.2.

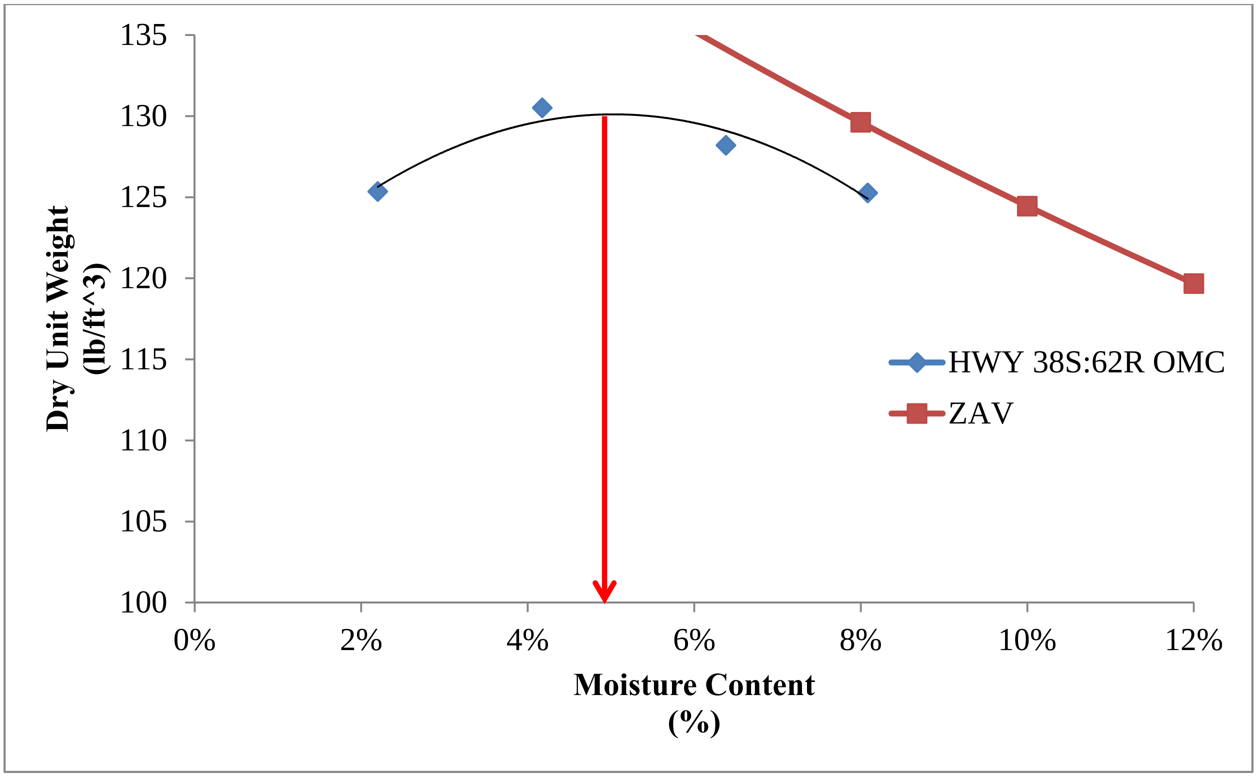

Figure 3.2.1 – HWY 38S:62R Optimum Moisture Content

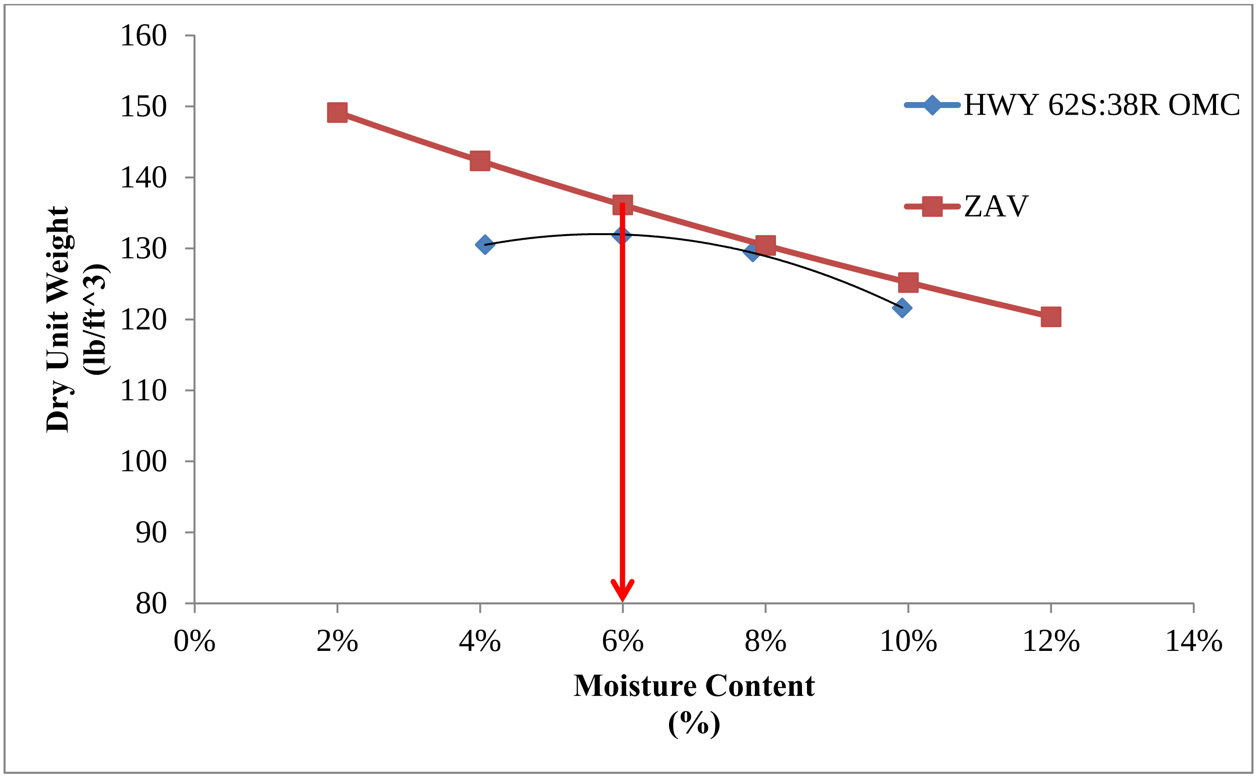

Figure 3.2.2 – HWY 62S:38R Optimum Moisture Content

Once the optimal moisture content for each section was determined, the optimal content of asphalt emulsion, asphalt foam, and Portland cement stabilization techniques were determined.

3.3 Optimum Emulsion Content (OEC)

Optimum emulsion content (OEC) was determined following NCDOT specification. Moisture was reduced to 67% of OMC to account for the water present in the emulsion based on the average annual rain fall for the area and the SE value, per the NCDOT specification. Specimens were mixed, compacted, and allowed to cure for 72 hours before being subjugated to volumetric and ITS testing. Similar to OMC, OEC was selected as the peak of the wet tensile strength curve shown in Figures 3.3.1 and 3.3.2. The OEC for HWY 38S:62R was 6.0%, while OEC for HWY 62S:38R was 5.0%. HWY 38S:62R OEC content was selected to be 6.0% instead of 4.0% because it was the peak wet tensile strength as well as it had the lower standard deviation and coefficient of variation, providing the more consistent samples. Total asphalt content for both highways is around 4.0%, which accounts for the water in the emulsion (approximately 37%). It should be noted that no wet tensile strength for either highway achieved minimum strength of 20 psi, indicating that the samples were susceptible to moisture damage when saturated.

There are multiple reasons why the minimum moisture conditioned strengths were not met. First, the sample gradations fell outside of the maximum suggested range, indicating that the material was too fine for the testing. Second, the ITS test was designed for Hot Mix Asphalt (HMA), a material that displays much higher levels of cohesiveness, so the test may have been unnecessarily robust for use on FDR samples. This is the first of multiple instances where the data indicates that typical HMA tests may not be appropriate for FDR mixtures. Therefore, it is recommended that samples that fall within the gradation band should be tested to further understand the effects of moisture damage on Arkansas materials.

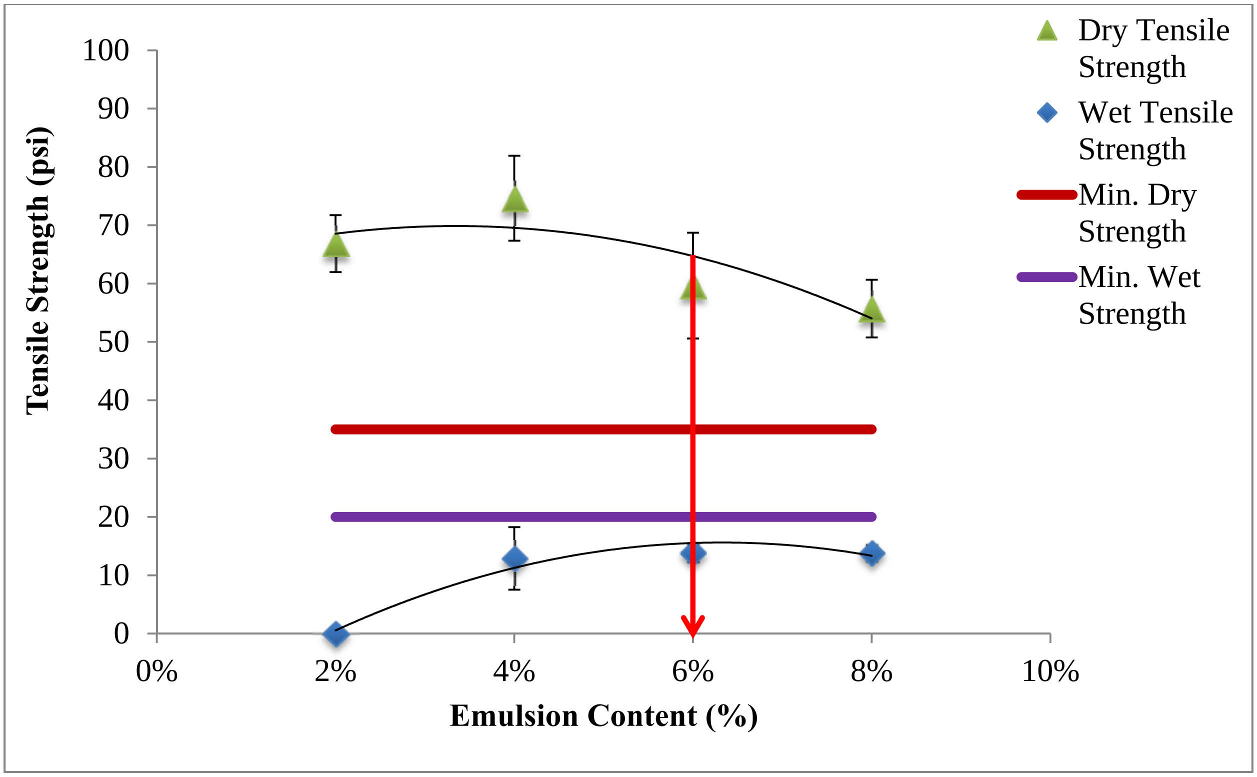

Figure 3.3.1 – HWY 38S:62R Optimum Emulsion Content Indirect Tensile Strength Results

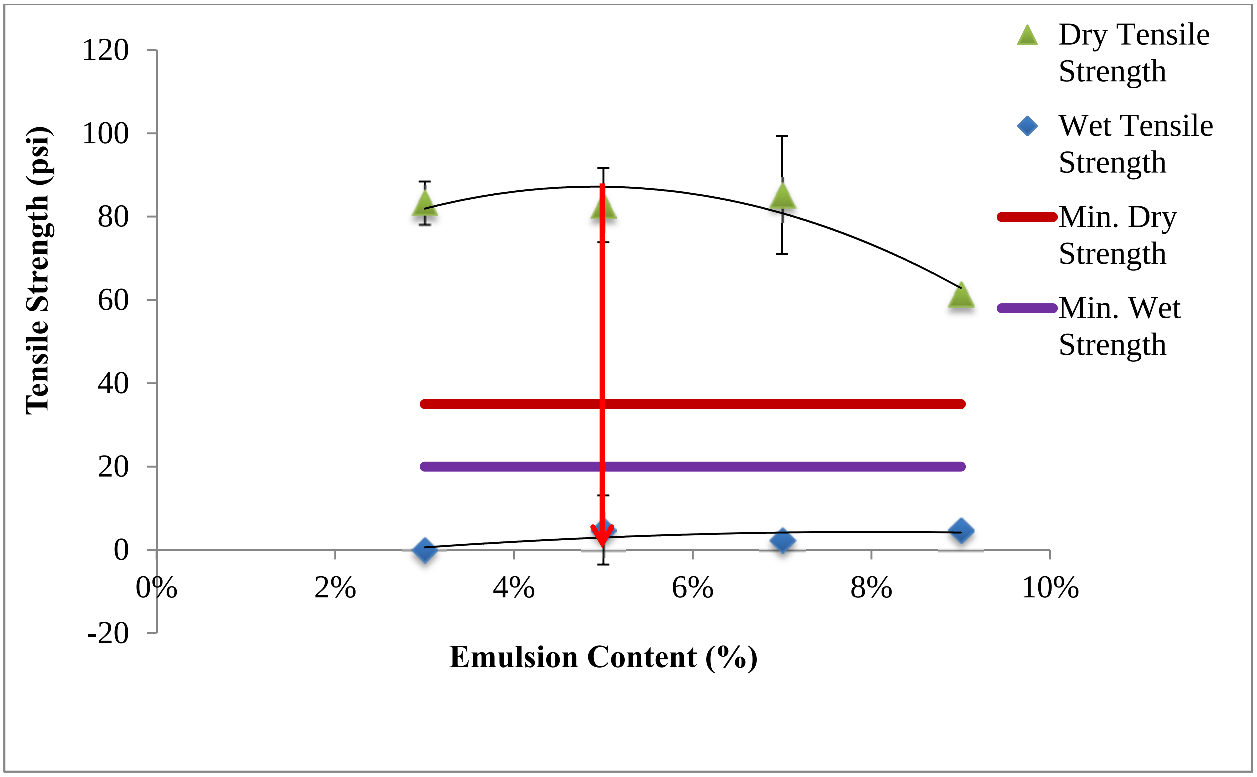

Figure 3.3.2 – HWY 62S:38R Optimum Emulsion Content Indirect Tensile Strength Results

3.4 Optimum Foam Content (OFC)

Using a similar process to the OEC samples, the OFC was determined by using the ITS test as well. Figures 3.4.1 and 3.4.2 display the OFC results for HWY 38S:62R and HWY 62S:38R, respectively. Once again, the peak of the wet tensile strength curve was selected as the optimum, which for both highways was at 8.0% foam. Similar to the OEC samples, the majority of the wet strength samples fell below the minimum requirement, but each highway managed to meet strength at the last content tested. Each highway reacted similarly to the increasing of the foam content, with dry tensile strengths never peaking, but actually decreasing. This may indicate that the OFC for dry tensile strength was lower than the 2.0% tested, but this was no concern since moisture damage of the highways is more critical than dry strength.

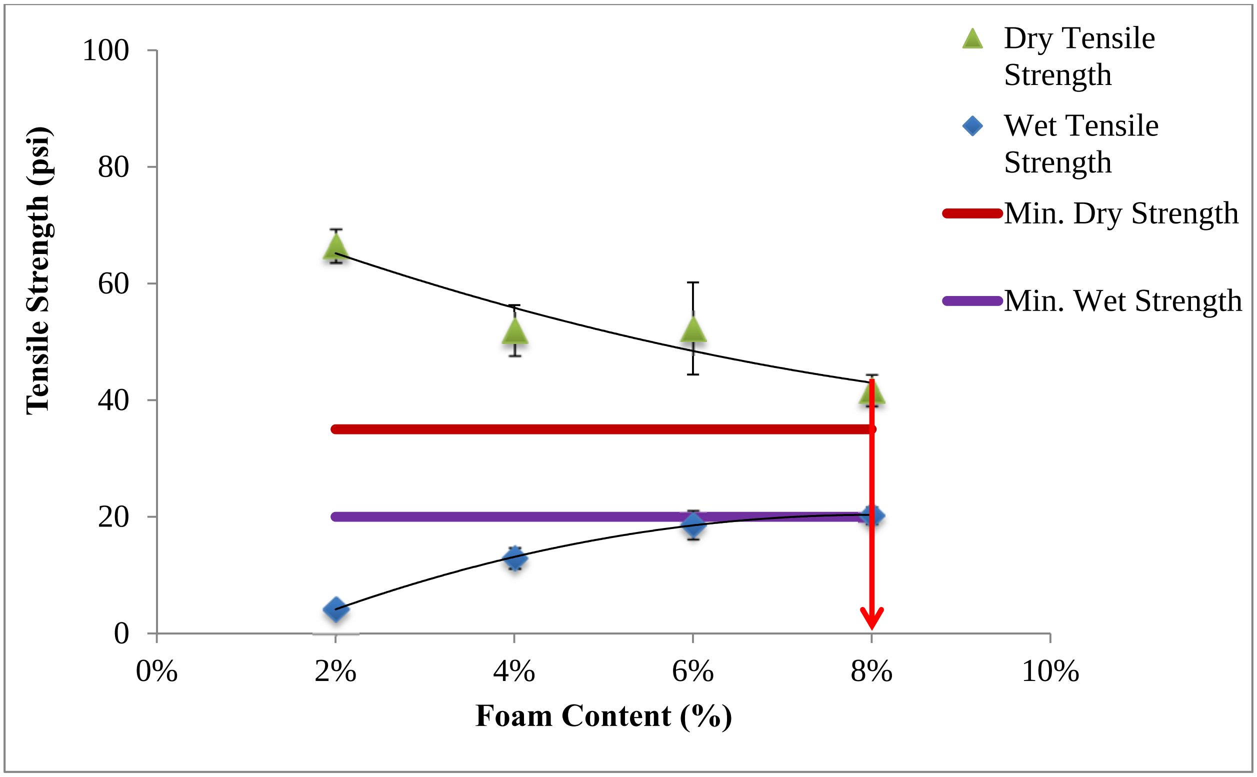

Figure 3.4.1 – HWY 38S:62R Optimum Foam Content Indirect Tensile Strength Results

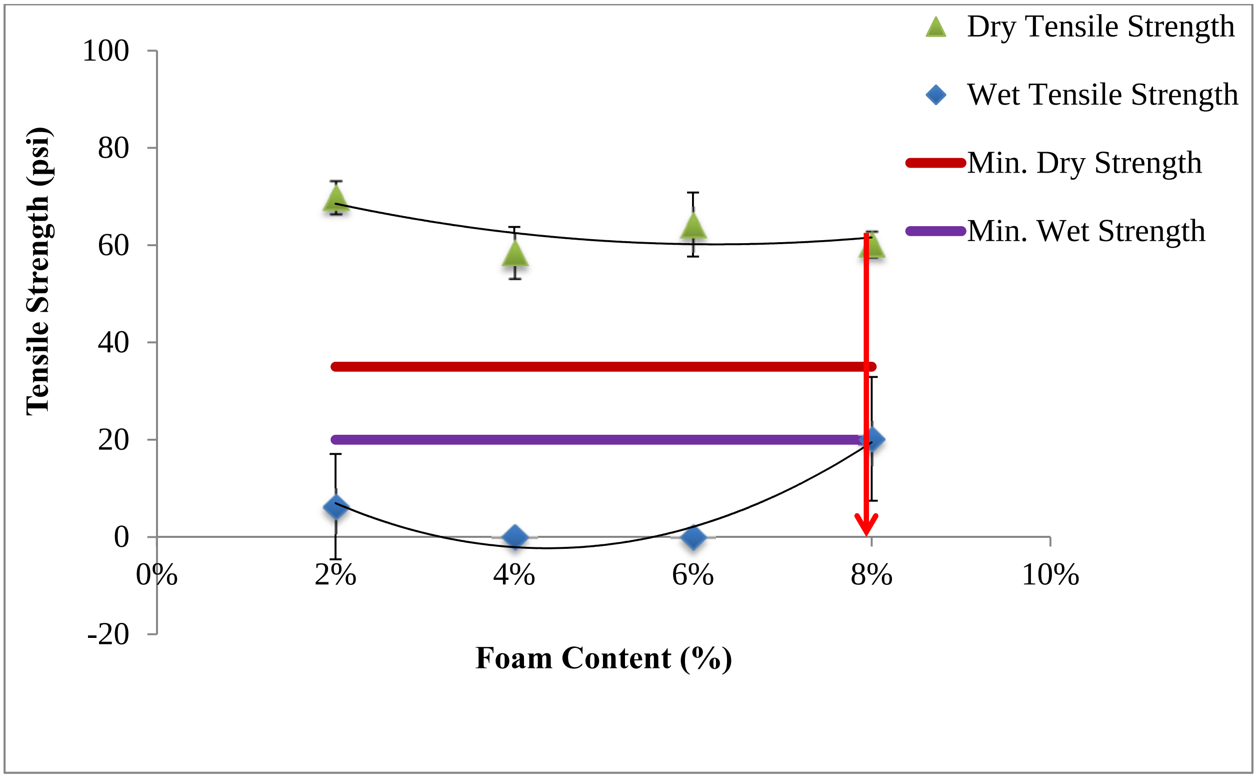

Figure 3.4.2 – HWY 62S:38R Optimum Foam Content Indirect Tensile Strength Results

Table 3.4.1 displays the post moisture condition saturation results from the OEC and OFC determination. Section 8.9.1 of ASTM D 4867 states that a degree of saturation exceeding 80% is acceptable, but not all samples met this requirement. This was deemed acceptable because of the detrimental effects of the moisture conditioning on the FDR samples, causing the samples to lose mass, which resulted in lower measured saturation. Samples in Table 3.4.1 with a degree of saturation recorded as "N/A" did not survive the moisture conditioning. Other alternatives to inducing moisture into the sample should be explored, or this method may need to be altered, as it may not suitable for FDR applications.

Table 3.4.1 – Post Moisture Condition Saturation Results

HWY 38S:62R				HWY 62S:38R			
Emulsion Content (%)	**Post Moisture Condition Saturation (%)**	**Foam Content (%)**	**Post Moisture Condition Saturation (%)**	**Emulsion Content (%)**	**Post Moisture Condition Saturation (%)**	**Foam Content (%)**	**Post Moisture Condition Saturation (%)**
2	N/A	2	21	3	N/A	2	32
4	100	4	57	5	N/A	4	N/A
6	54	6	56	7	131	6	N/A
8	50	8	49	9	108	8	78

3.5 Optimum Cement Content (OCC)

Optimum cement content (OCC) was determined using ASTM D 1633 using specimens that were approximately 100 mm diameter and 150 mm tall. Each specimen was allowed to cure at room temperature in a cure room with a relative humidity of 50% for one week, which is typical of FDR with cement, prior to testing [9,11,15]. Each specimen, according to ASTM D 1633, was subjected to a 4 hour soak prior to performing the UCS tests. The soaking period allowed for the infiltration of water into the specimen although it did not allow for complete saturation of the sample. The PCA mix design suggested a range of 300-400 psi for most FDR applications, which would result in a stabilized base course, yet one that is not so stiff that shrinkage cracking is an issue. The lowest cement content tested was 3.0%, which proved to be excessive for HWY 38S:62R, as seen in Figure 3.5.1. Since HWY 38S:62R had strengths well above the suggested range, 3.0% was selected as its OCC as 3.0% was the lowest suggested cement content by the 1992 PCA Soil-Cement Laboratory Handbook [43]. HWY 62S:38R OCC, Figure 3.5.2, was selected at 5.0% since it was the lowest content tested that was at least as strong as the suggested range.

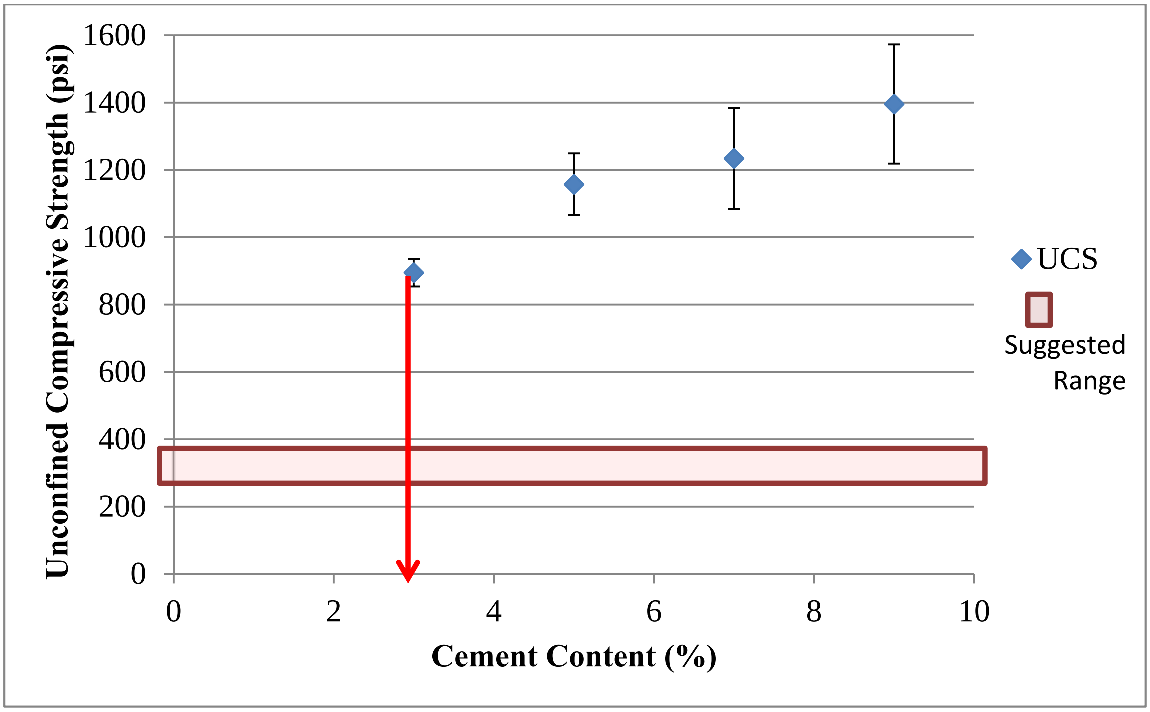

Figure 3.5.1 – HWY 38S:62R Optimum Cement Content Unconfined Compressive Strength

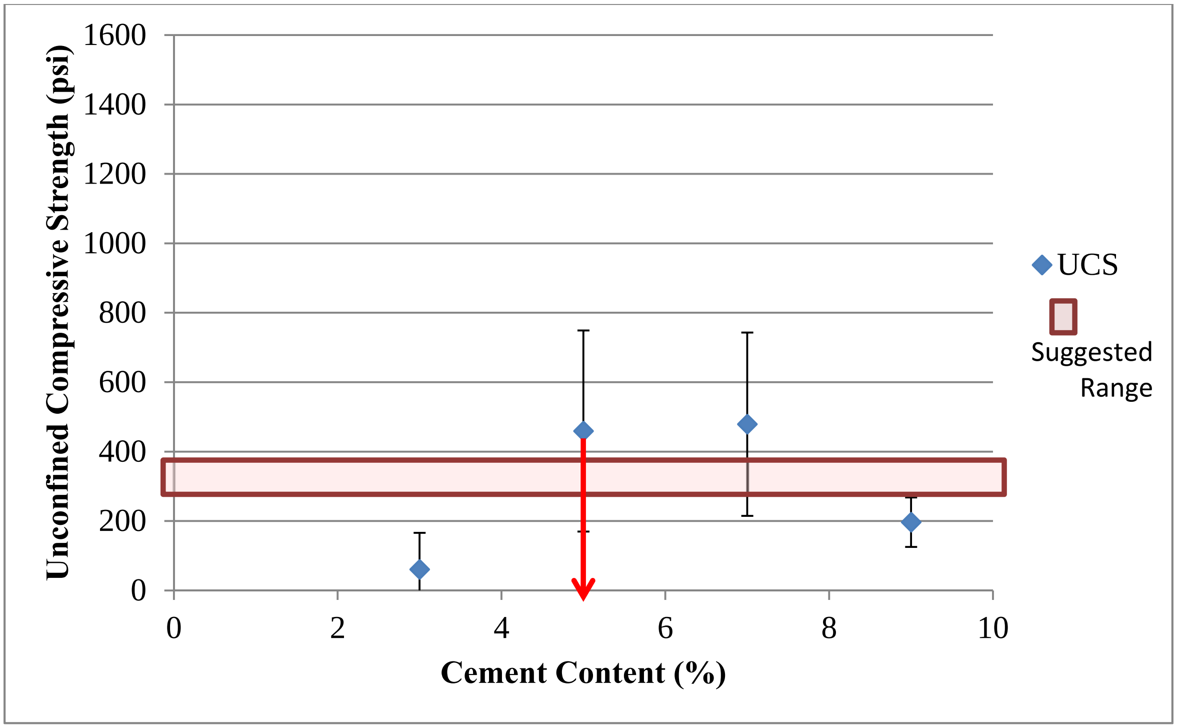

Figure 3.5.2 – HWY 62S:38R Optimum Cement Content Unconfined Compressive Strength

3.6 Mix Design Discussion

Following the testing of the optimum stabilization contents, it was determined that all three mix designs were suitable for Arkansas materials. Each mix design was able to be correctly performed and gave reasonable results that fell in the general ranges of stabilized material compared to other state's experiences. Although aspects, such as moisture conditioned ITS samples, did not always meet the minimum requirements, it was determined that the mix designs themselves provided acceptable quantities. Further investigation into preparing samples that fall into the suggested maximum and minimum gradation ranges may provide different results and should be explored in future work. With the mix designs deemed suitable for the Arkansas materials, performance testing was conducted on samples stabilized at optimum stabilization contents.

4.0 Performance Testing Results

After completing the mix design for the three stabilization technologies, performance testing began to determine which performance tests were appropriate for FDR materials and the material characteristics from each mixture. The moisture tests were chosen by AHTD as potential tests for FDR that would indicate rutting, low temperature cracking, moisture damage, and strength. As each test was completed, it was evaluated as a potential tests for FDR in Arkansas.

4.1 Dynamic Modulus – Performance Emulsion Samples (PEC E*)

Dynamic modulus was utilized to explore both rutting and potential low temperature cracking susceptibility. Using the indirect tension (IDT) configuration outline by Kim *et al* 2004, dynamic modulus (E*) testing was performed [35]. One advantage of performing the E* testing in this configuration is the reduction of material and the ability to reuse the sample for creep compliance and ITS testing since E* and creep compliance are both non-destructive tests.

When comparing the highways to one another, it is clear that the PEC samples from HWY 62S:38R PEC, Figure 4.1.2, are stiffer than HWY 38S:62R PEC, Figure 4.1.1. This result indicates that HWY 62S:38R PEC should be more resistant to rutting but more susceptible to low temperature cracking than HWY 38S:62R PEC. HWY 62S:38R, with its higher subgrade content, is performing more like a non-plastic granular material than an asphalt concrete.

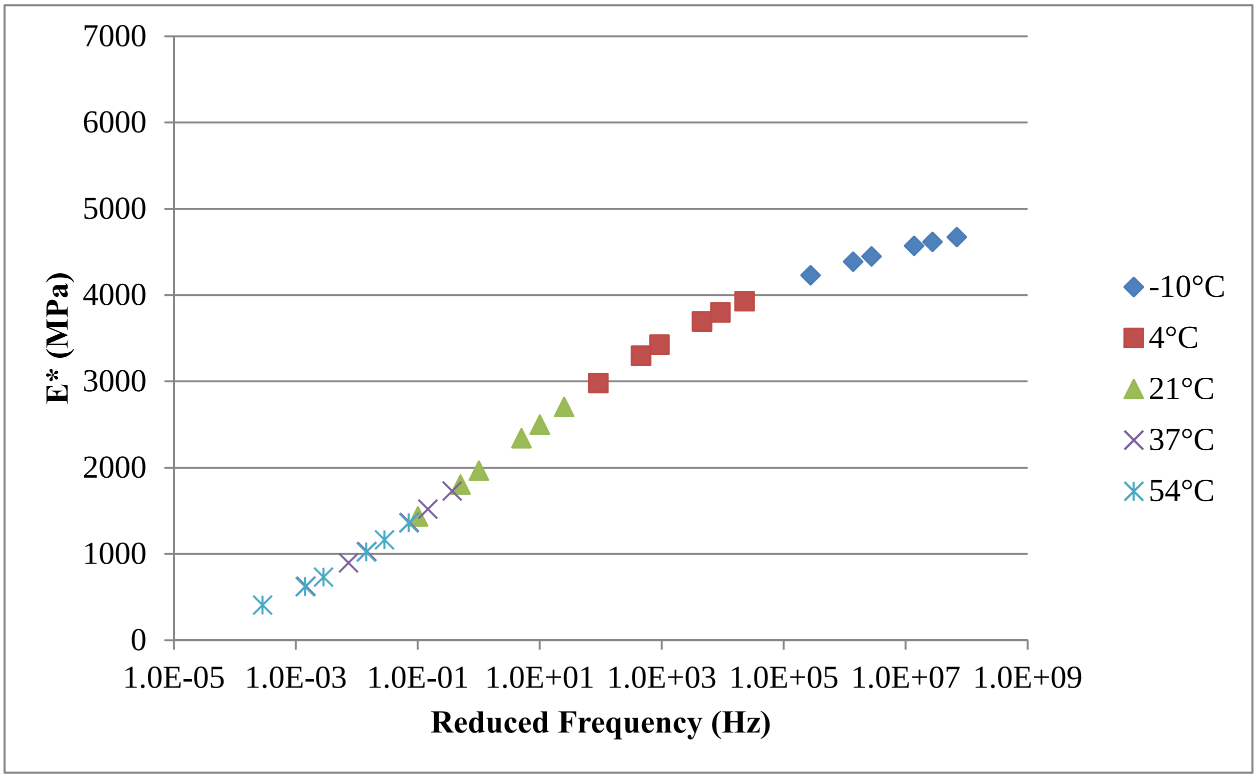

Figure 4.1.1 – HWY 38S:62R Performance Emulsion Content Dynamic Modulus Results

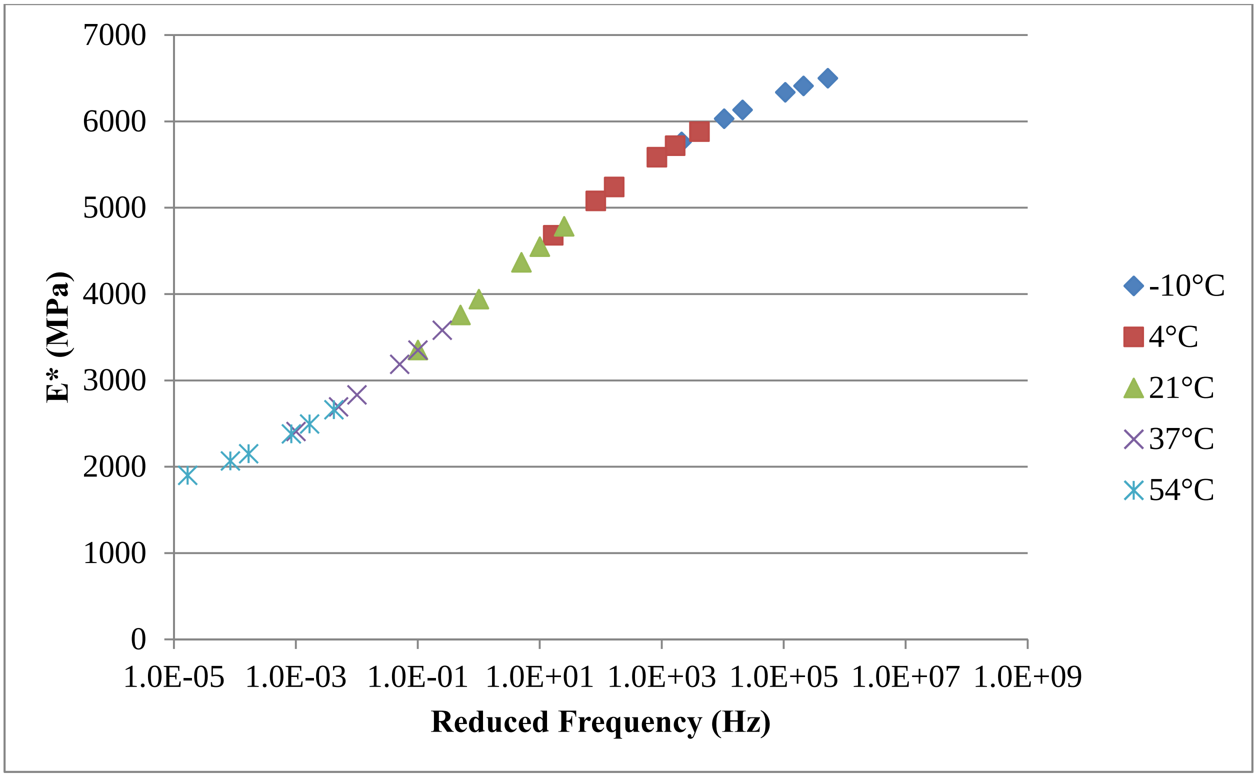

Figure 4.1.2 – HWY 62S:38R Performance Emulsion Content Dynamic Modulus Results

4.2 Dynamic Modulus – Performance Foam Samples (PFC E*)

Unlike the PEC samples, the PFC samples performed similarly in the E* testing. This indicates that the percentage of RAP in FDR mixtures has a higher influence with asphalt emulsion stabilization than asphalt foam stabilization for the two highways examined in this study. However, HWY 62S:38R PFC, Figure 4.2.2, had slightly higher modulus values than HWY 38S:62R, Figure 4.2.1, showing that the subgrade once again provided stiffness, acting like a granular material when loaded.

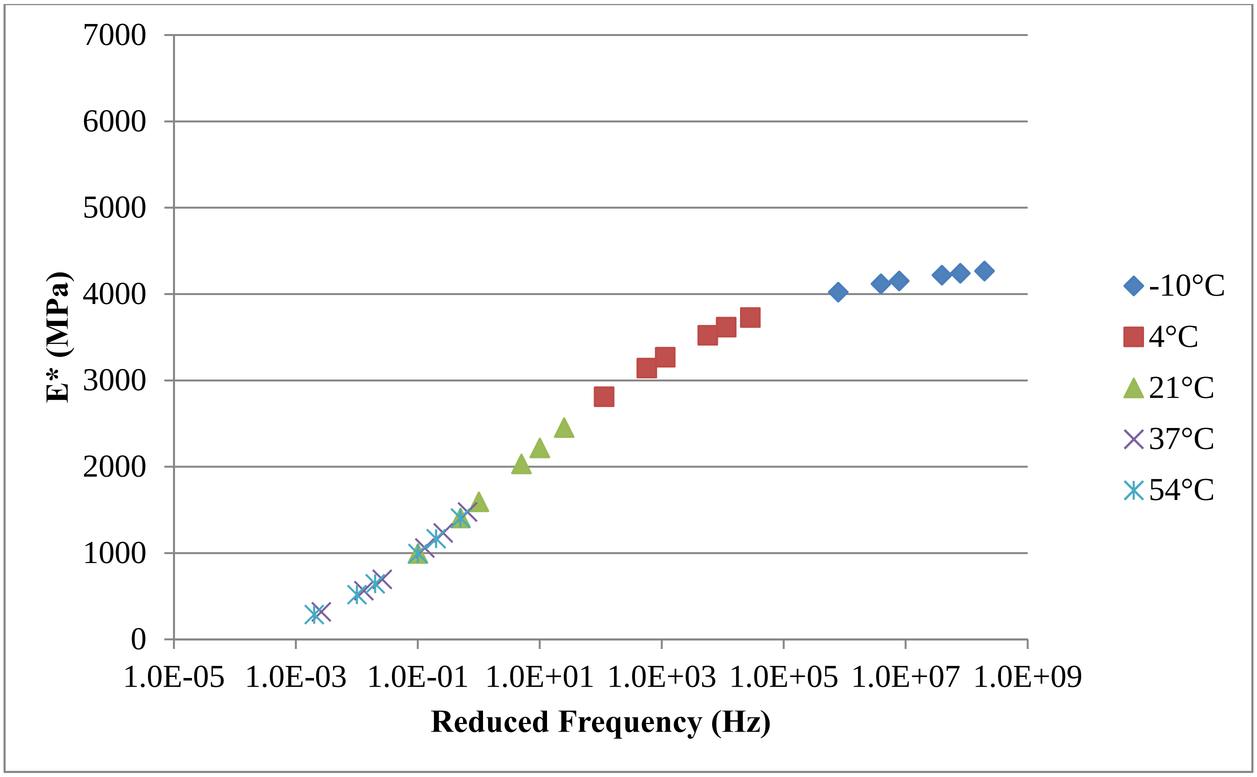

Figure 4.2.1 – HWY 38S:62R Performance Foam Content Dynamic Modulus Results

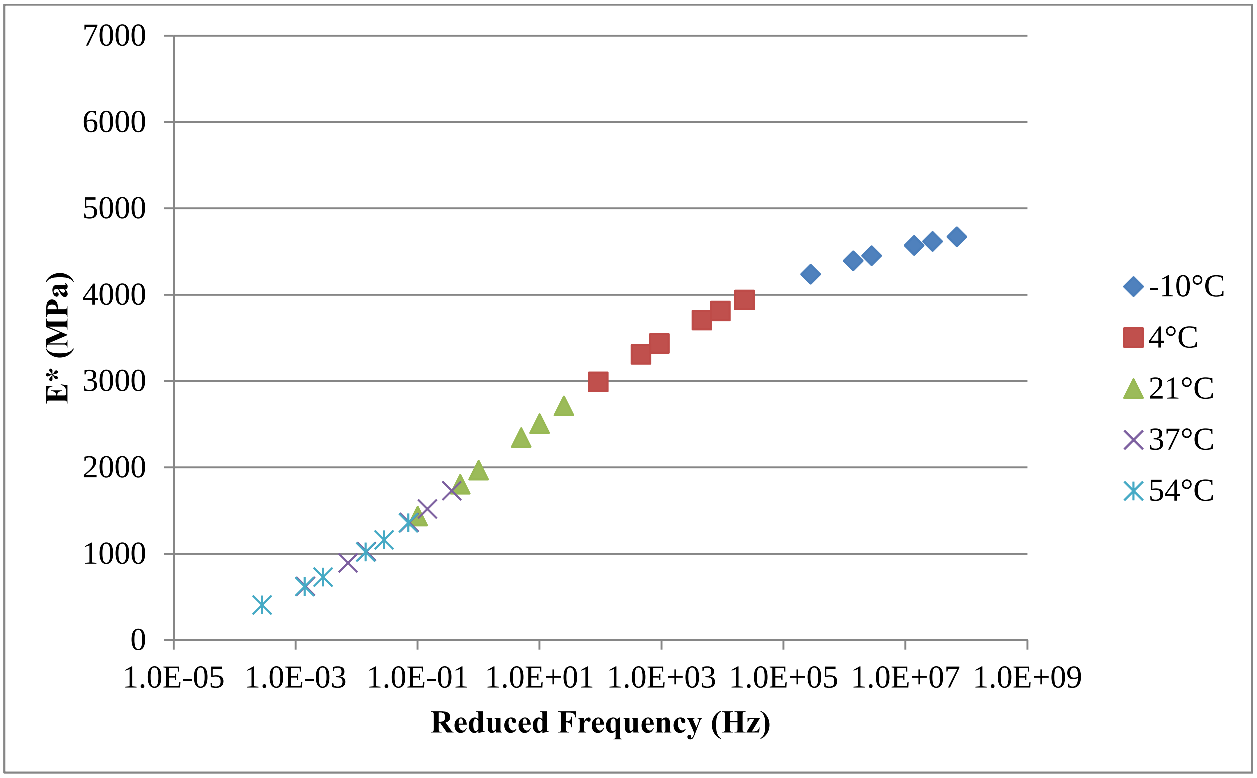

Figure 4.2.2 – HWY 62S:38R Performance Foam Content Dynamic Modulus Results

Comparing the two asphalt technologies to one another, as shown in Figure 4.2.3, two points can be inferred. The first is attributed to the effect of the RAP on the sample. In all instances, as the RAP proportion is increased, the modulus values decrease. This signifies that the subgrade and RAP ratios influence the behavior of the mixture and will influence rutting behavior. As noted above, HWY 62S:38R acted more similarly to a non-plastic, granular material than did HWY 38S:62R. From this data, one could expect HWY 38S:62R to be more susceptible to rutting than HWY 62S:38R. The second inference from the dynamic modulus testing is the emulsion stabilized samples providing higher modulus values. The coating action of the emulsion stabilization, versus the spot weld action of foam stabilization, allowed for the asphalt binder to better stabilize the samples.

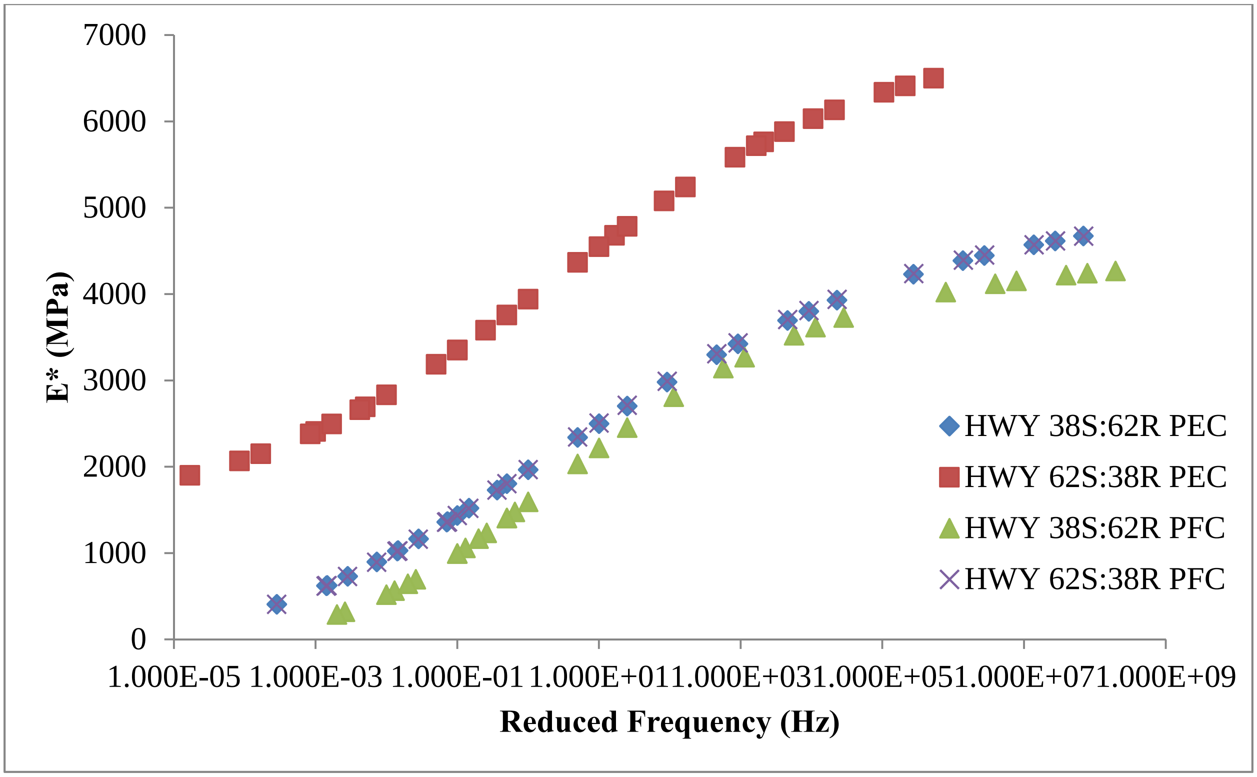

Figure 4.2.3 – Combined Dynamic Modulus Results

Compared to FDR E* values found in the literature, the two highways have lower E* values at the low temperature, high frequency loading rates but are similar at the high temperature, low frequency loading. Thomas and May explored FDR samples stabilized with two emulsions in 2007. One mix was 25% limestone and 75% RAP with a SE value of 72. The second mix was 75% limestone and 25% RAP with a SE value of 39. In the E* testing performed by Thomas and May, similar trends are seen as the samples where increased RAP contents tended to have lower modulus values [23]. Although Thomas and May used limestone instead of subgrade and tested in uniaxial compression, it is interesting to notice the trend that increased RAP content leads to lower modulus values applies to HWY 38S:62R as well. It should be noted however, this is only two studies and dynamic modulus is sensitive to nominal aggregate size, binder type, and loading

[44].

Table 4.2.1 – Dynamic Modulus Overview

	HWY 38S:62R		**HWY 62S:38R**	
	Emulsion	**Foam**	**Emulsion**	**Foam**
Average Air Voids	11.8%	9.9%	13.3%	10.6%
Reference Temperature °C	21	21	37	21
Predicted Versus Measured E* Σ(error)^2 (SSE)	0.038	0.128	0.010	0.038
Agreeableness	Good (SSE<0.05)	Moderate (0.05<SSE<0.15)	Good (SSE<0.05)	Good (SSE<0.05)

Table 4.2.1 highlights the results from the dynamic modulus testing, in particular the agreeableness of the modulus results to the predicted results. Sum of the error squared values less than 0.05 were determined to be good, which deems the test a good fit for FDR. Values between 0.05 and 0.15 were considered moderate, which suggests the test could be appropriate in determining FDR properties. With the majority of the tests falling into the “Good” threshold, it was determined that the dynamic modulus test, which in this form was designed as an HMA test, was an appropriate test for these two FDR materials from Arkansas and could be used in future applications.

4.3 Creep Compliance

Creep compliance, the time-dependent strain divided by the applied stress, is used to predict thermal cracking in asphalt. It is determined by measuring the deformations near the center of a loaded specimen, away from the localized stresses of the load ram. The higher the creep compliance value, the greater the resistance to thermal cracking can be expected [45]. Typically, creep compliance increases as the temperature increases in HMA mixtures [46], but only HWY 62S:38R PEC, Figure 4.3.2, exhibited this trend for all three test temperatures. Overall the creep compliance data didn't show any consistent trends, but HWY 38S:62R had higher creep values for both stabilization methods.

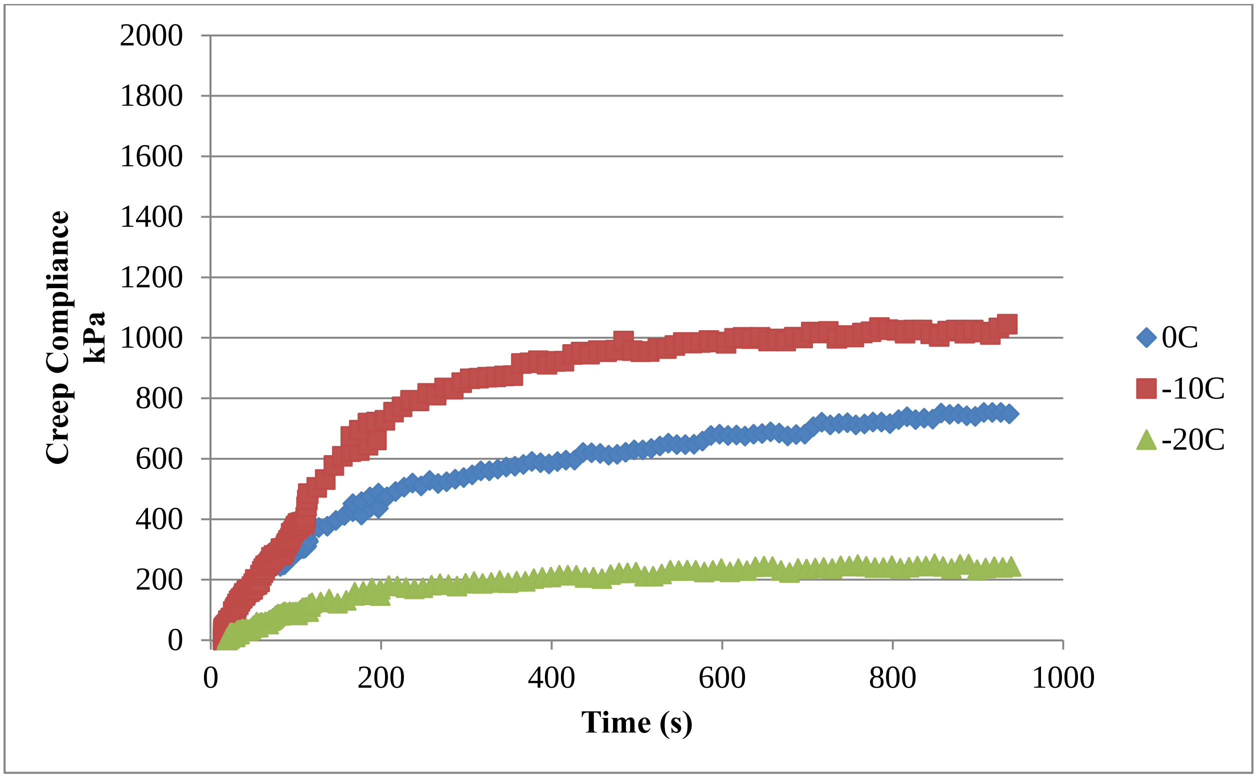

Figure 4.3.1 – HWY 38S:62R Performance Emulsion Content Creep Compliance Results

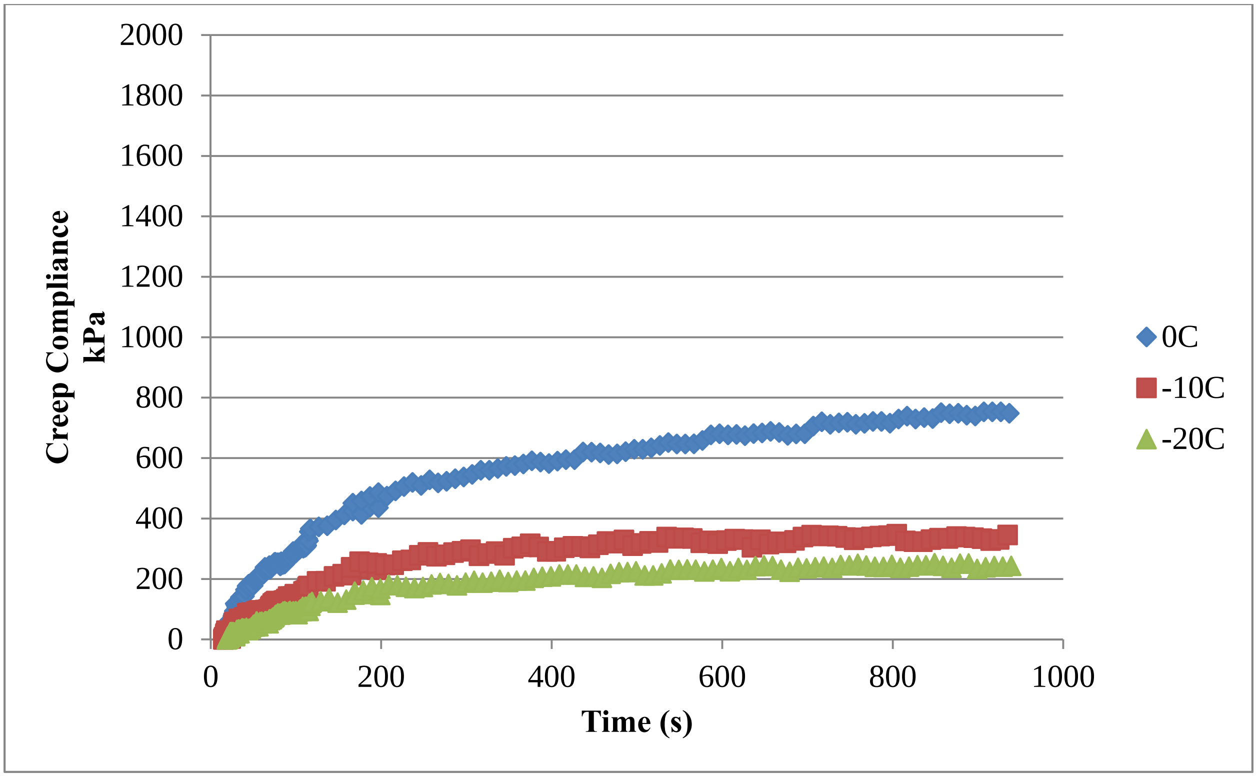

Figure 4.3.2 – HWY 62S:38R Performance Emulsion Content Creep Compliance Results

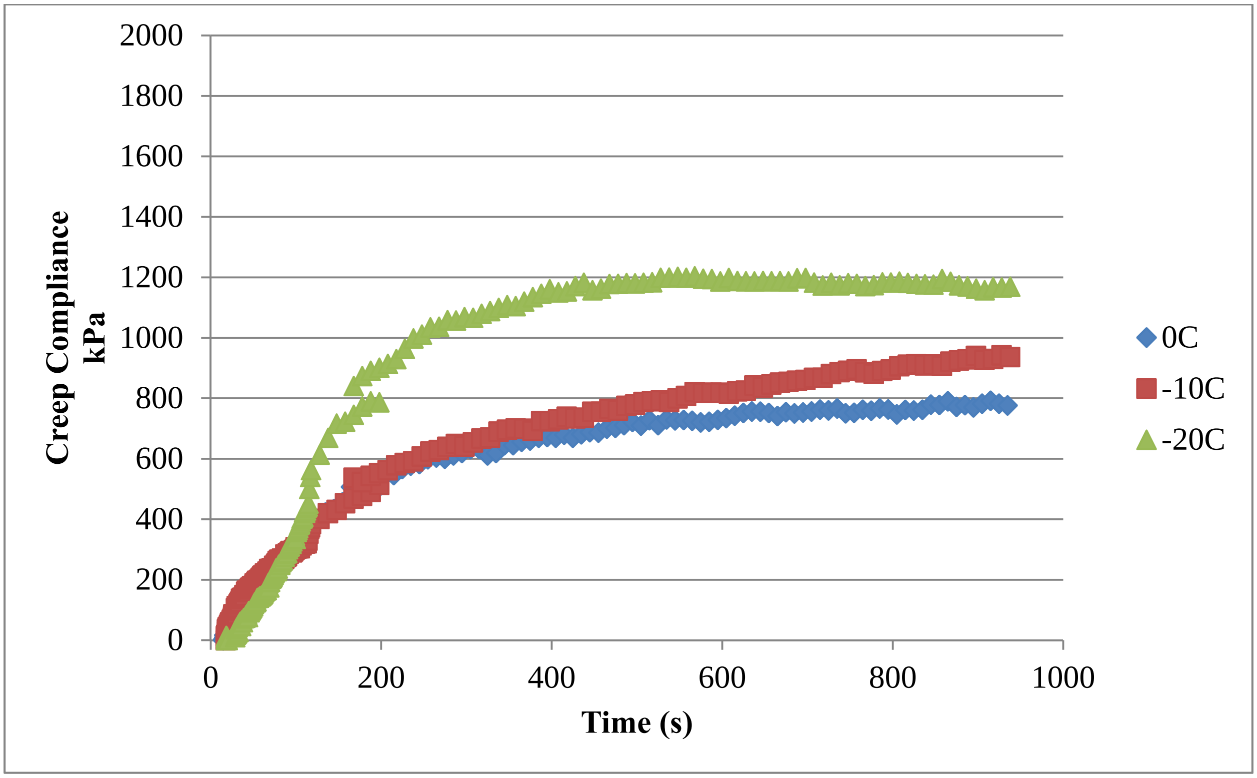

Figure 4.3.3 – HWY 38S:62R Performance Foam Content Creep Compliance Results

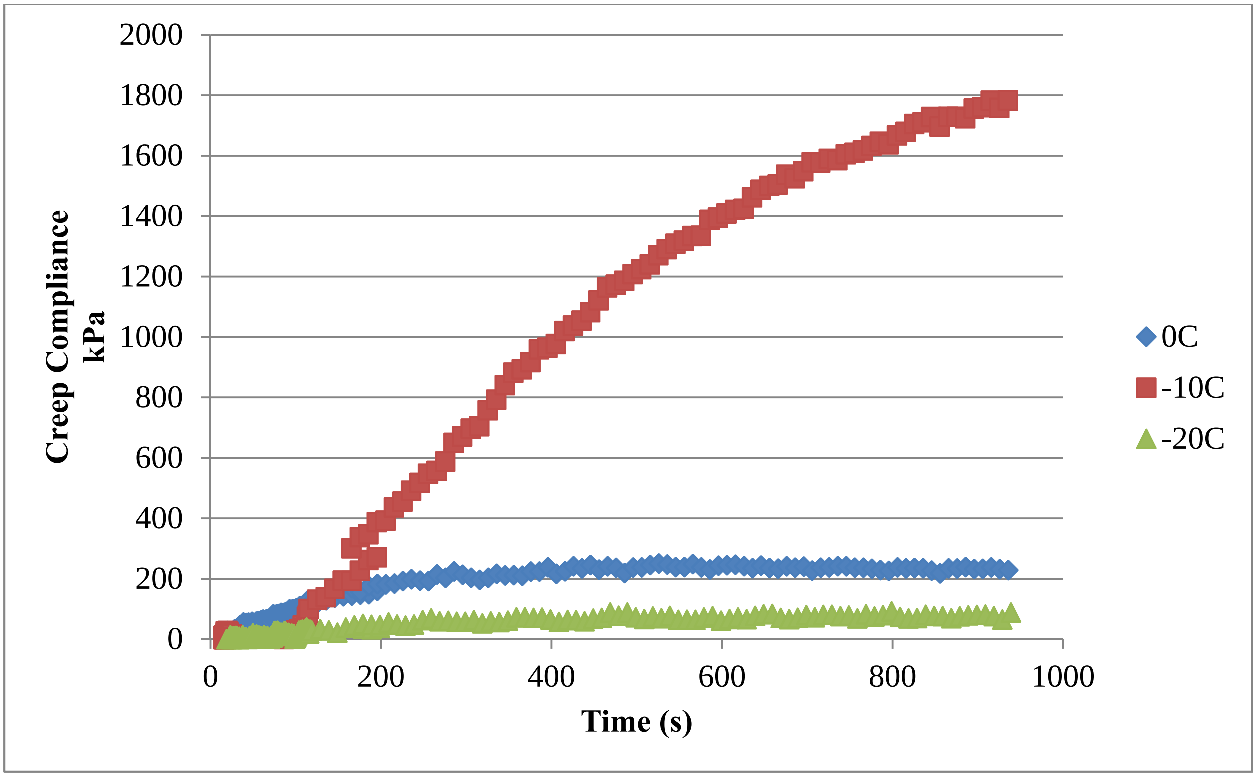

Figure 4.3.4 – HWY 62S:38R Performance Foam Content Creep Compliance Results

In general, the emulsion stabilized samples performed as expected, with the exception being HWY 38S:62R -10°C test, Figure 4.3.1, in that the creep compliance increased with temperature increase. The foam stabilized samples do not show any clear trends, Figures 4.3.3 and 4.3.4, but this may be attributed to the action of asphalt foam. Asphalt foam stabilization acts in a "tack-weld" fashion, whereas asphalt emulsion has a coating effect and distributed bonding, which may have caused highly variable areas within the sample, including gauge point locations. This may have caused the data to be variable in small samples, but as a complete stabilized base course, the effect is not noticed.

When comparing the creep compliance to the dynamic modulus results, there was no noticeable tendency for the data to agree for each highway and stabilization method. It was the hope that the creep data would reinforce the E*, or vice versa, but no such trend is shown. As such, creep compliance may not be a viable option for testing FDR materials to determine low temperature cracking characteristics.

4.4 Semi-Circular Bend Test [SC(B)]

The Semi-Circular Bend [SC(B)] test is a measure of fracture energy used to better understand low temperature cracking [38]. Tests were performed on 25mm thick semi-circular shaped disks with a 15 mm deep notch. The temperatures selected were based off the asphalt binder used, which is -2°C and +10°C of the low temperature of binder. Since PG64-22 binder was used in the asphalt foaming process, the temperatures were set to -24°C and -12°C. The SC(B) test was performed on all stabilization techniques at these temperatures for consistency. Table 4.4.1 has a summary of the average fracture energy from three specimens. Fracture energy was calculated as the energy under the load displacement line starting at a load of 300 N and ending when the load fell below 500 N. If the sample did not reach a peak load of 500 N, the fracture energy was recorded as 0 J/m^2.

Table 4.4.1 – Semi-Circular Bend Fracture Energy Results

Fracture Energy (J/m^2)	**HWY 38S:62R**		**HWY 62S:38R**	
Temperature (°C)	**-12**	**-24**	**-12**	**-24**
Performance Emulsion Content	79.3	43.4	0	31.8
Performance Foam Content	112.8	54.9	44.5	53.8
Performance Cement Content	14.0	0	0	0

The SC(B) tests results shed light on several characteristics of the FDR mixes. Similarly to the dynamic modulus results, the impact of RAP content is noticed. HWY 38S:62R displays higher fracture energy than HWY 62S:38R for all tested scenarios that were able to record the fracture energy, implying the RAP content is directly responsible for the greater fracture energy of HWY 38S:62R. Results from SC(B) testing also indicate that foam stabilization provides greater thermal cracking resistance, as the fracture energies for the foam stabilized samples are greater than their emulsion and cement stabilized counterparts. The SC(B) tests appears to be a valid testing option in determining low temperature cracking characteristics for asphalt stabilized FDR applications, but other options should be explored for cement FDR applications.

4.5 Indirect Tensile Strength (ITS)

Using the same criteria from the NCDOT mix design that was used in determining OEC and OFC, the ITS test was performed on the performance samples. The minimum dry strength was still kept at 35 psi while the minimal wet strength was 20 psi [22]. Once again, the moisture conditioned samples did not meet the minimum strength requirements. This further proves the need for samples to be kept at optimal moisture content, and not above, when constructed. The dry tensile strengths for both highways well exceeded the minimal requirement which bodes well for areas with proper drainage or that are naturally arid. Dry samples from HWY 62S:38R performed minimally better than HWY 38S:62R with emulsion stabilization, but did so more easily with foam stabilization. Although this test was in tension, it does reflect similar findings that the dynamic modulus showed with HWY 62S:38R being slightly stiffer, acting as a granular base material.

Table 4.5.1 – Indirect Tensile Strength Performance Results

	HWY 38S:62R		**HWY 62S:38R**		**Minimum Tensile Strength Requirements (psi)**
	Emulsion	**Foam**	**Emulsion**	**Foam**	
Dry Tensile Strength (psi)	94.2	81.0	95.6	115.1	35
Wet Tensile Strength (psi)	12.6	17.4	1.6	18.1	20
Dry Strength Coefficient of Variance (%)	3.52	13.7	0.26	2.43	N/A
Wet Strength Coefficient of Variance (%)	10.7	9.17	57.7	26.0	
Post Moisture Condition Saturation (%)	71	62	N/A	105	

From Table 4.5.1 which displays the final ITS results and the variation within a sample set, HWY 62S:38R shows very little variance between dry samples, as determined by the coefficient of variance (COV), yet the most between wet. ITS testing of performance samples provides a greater understanding of the detrimental effects of moisture on FDR samples and the variability within sample sets when saturated, and should be considered for future testing in Arkansas for anticipated FDR field performance.

4.6 Tube Suction Test (TST)

The tube suction test (TST) was developed to help quantify the capillary action of granular bases and was performed on the performance cement content (PCC) samples. The tests run for 10 days and the dielectric values are averaged for each TST. Table 4.6.1 summarizes the rating system used for the TST, as presented by TTI. Two characteristics greatly influence the capillary action of a granular base, absorption and interconnected air voids. The absorption, which was presented in Table 2.1.2, was similar for both highways, as HWY 38S:62R had 3.6% and HWY 62S:38R had 3.42%. The absorption of the materials may have influenced the rate of the capillary action, as reflected by the increase in dielectric values. The interconnected air voids may stem from the using the SGC. Air voids are likely different at the bottom than the top of a compacted sample, which means if samples were flipped at any point, the capillary action may have been influenced.

Table 4.6.1 – Tube Suction Test Rating Structure

Final 10 Day Average Dielectric Value	
<10	Good
10-16	Marginal
>16	Poor

The results from all three HWY 38S:62R PCC TST replicates, Figure 4.6.1, rank below a dielectric value of 10, which falls into the "Good" category. The average 10 day value for all three samples for HWY 38S:62R PCC was 6.8. This highway also had the most variance between the average 10 dielectric values with a COV of 33% and the lowest slope between day 0 and day 1. The increased RAP content likely reduced the capillary action of the samples, as the RAP was mostly non-absorbent.

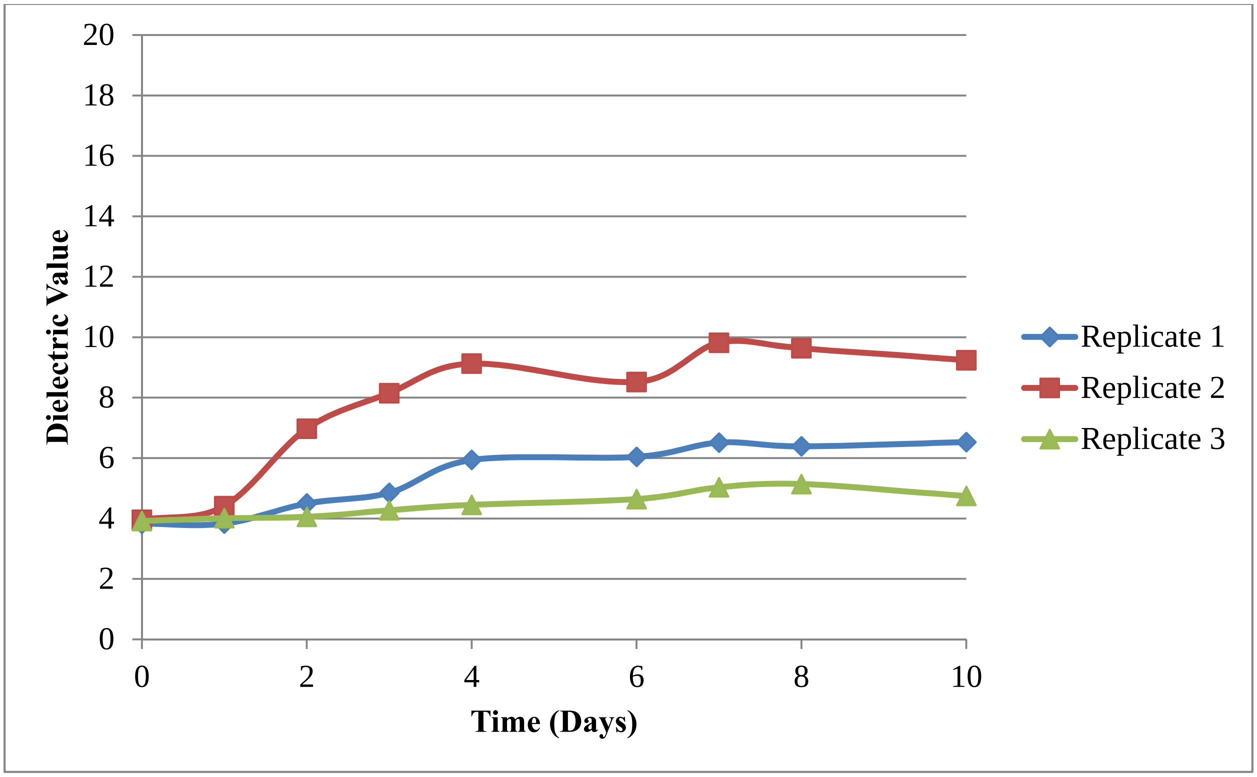

Figure 4.6.1 – HWY 38S:62R Performance Cement Content Tube Suction Test Results

HWY 62S:38R, Figure 4.6.2, showed a high capillary action in the first day, as the day 0 dielectric values are much lower than the day 1 readings. The higher capillary action is likely attributed to the increased subgrade content in HWY 62S:38R. The samples quickly levels off and stays around its final average dielectric value of 15.5 for the majority of the testing period with a low COV of 3.4%. The final average ranking for HWY 62S:38R falls on the border of

"Marginal" and "Poor."

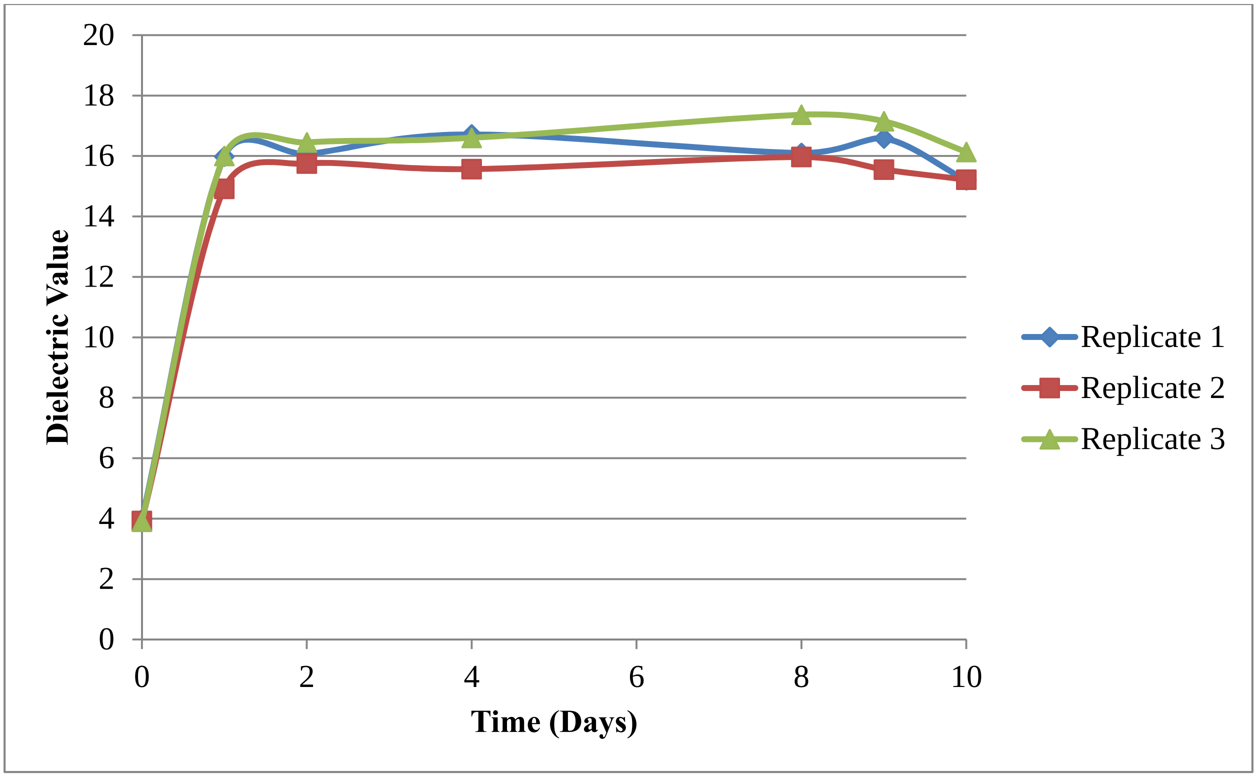

Figure 4.6.2 – HWY 62S:38R Performance Cement Content Tube Suction Test Results

4.7 Performance Testing Discussion

The performance tests completed gave insight into their potential use to characterize materials for future FDR applications in Arkansas. The first two performance tests, dynamic modulus and creep compliance, are HMA tests, which appeared to influence the results for creep compliance. Dynamic modulus was determined as a feasible test to further understand rutting potential for a FDR mixture and the impact of increased RAP content decreasing modulus values. Creep compliance did not reinforce the findings from dynamic modulus testing, with no noticeable trends, and was determined not to be suitable for low temperature cracking characteristics of FDR mixtures. This is thought to be from forcing a HMA test upon a composite, cold recycled material. The semi-circular bend showed promise for asphalt stabilized FDR samples as a low temperature cracking characteristic test, although a substitute should be explored for cement FDR samples. Indirect tensile strength testing provided more insight about variability within sample sets and the effect of moisture upon tensile strength. Finally, the tube suction test allows for capillary action to be quantified and can help predict performance of samples when introduced to moisture and is recommended for use by AHTD.

5.0 Conclusions and Recommendations

Full depth reclamation recycles the entire flexible pavement structure creating a stronger, stabilized base course. FDR aims to succeed where the conventional pavement maintenance and rehabilitation methods, such as crack sealing or overlaying, have failed by addressing the distresses below the surface course in the pavement structure. Many of the stresses can be attributed to loading, which requires a structural rehabilitation, such as FDR, to offer a lasting solution. Loading failures have accelerated in Arkansas in the Fayetteville Shale and Brown Dense Shale areas due to heavy loads of the logging and natural gas fracking industry. This accelerated deterioration of Arkansas highways is forcing AHTD to investigate into cheaper, lasting solutions for rehabilitating many of its state highways.

FDR has shown to be successful in several states with several benefits. With estimated savings of up to 50% and energy reduction of up to 70% of complete removal and reconstruction, FDR is an attractive solution for premature pavement failure rehabilitation for AHTD. Using common laboratory tests that AHTD uses to characterize materials in order to predict field performance for common distresses, three mix designs and the laboratory tests were evaluated for potential use in Arkansas.

- The NCDOT emulsion, Wirtgen foam, or PCA cement mix designs are all potential options for FDR applications in Arkansas, as each provided samples capable of conducting performance tests.
- Moisture saturation of ITS samples should be further explored, as FDR samples tend to disintegrate during this process.
- Dynamic modulus testing of asphalt stabilized samples provided good agreeableness between predicted and measured E* values which indicates the dynamic modulus tests is worthwhile option for characterizing rutting potential with FDR materials.
- Dynamic modulus indicated that the RAP proportion influenced the modulus. Increasing the RAP proportion, and subsequently decreasing the subgrade proportion, caused modulus values to decrease. HWY 62S:38R performed more like a non-plastic, granular base than did HWY 38S:62R, recording higher modulus values.
- Emulsion stabilization provided higher dynamic modulus values while testing, which indicates the emulsion stabilization action creates a stiffer sample than does foam.
- Creep compliance results exhibited no global trends and did not reinforce dynamic modulus findings, and therefore may not be a suitable test for characterizing low temperature cracking in FDR applications.
- Semi-circular bend testing suggests RAP content influences fracture energy results. The increased RAP content of HWY 38S:62R resulted in higher fracture energy than HWY 62S:38Rfor all stabilization methods and temperatures tested.
- Semi-circular bend testing indicated asphalt foam stabilization provides more resistance to low temperature fracture than does asphalt emulsion or cement FDR stabilization.
- The semi-circular bend test appears to be an option for FDR cracking testing when

asphalt stabilization is utilized, but other options should be explored for cement stabilization.

- Indirect tensile strength testing further highlights the variability and moisture susceptibility of FDR samples.
- Tube suction testing assists in the prediction of moisture susceptibility of a granular base course by quantifying the capillary action.

To fully understand the potential of FDR in Arkansas, FDR will have to be further explored. Laboratory testing of field materials that fall into the suggested Asphalt Academy ranges to determine the effect of gradation on FDR test results. The use of active fillers in asphalt emulsion and asphalt foam FDR stabilization samples should also be investigated. Fatigue testing, such as the semi-circular bend test at intermediate temperatures, should be explored to better understand the performance of FDR. The Hamburg wheel tracking test, or equivalent, should be used to better understand rutting behavior and compared to dynamic modulus results. Finally, field trials should begin to relate findings from the lab to actual field performance of FDR in Arkansas, which can be accomplished through falling weight deflectometer and similar field tests.

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