TRC1405

Examination of Full-Depth Reclamation Techniques for Shale Areas Across Arkansas

Andrew Braham, Chase Henrichs

Final Report

2015

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Examination of Full-Depth Reclamation Techniques for Shale Areas Across Arkansas		5. Report Date June 2015 6. Performing Organization Code AHTD
7. Author(s) Andrew Braham and Chase Henrichs		8. Performing Organization Report No. TRC 1405
9. Performing Organization Name and Address University of Arkansas 4190 Bell Engineering Center Fayetteville, AR 72701		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Arkansas State Highway and Transportation Department (AHTD) P. O. Box 2261 Little Rock, AR 72203		13. Type of Report and Period Covered Final Report July 2013 – June 2015 14. Sponsoring Agency Code

15. Supplementary Notes

Support by a grant from AHTD

16. Abstract

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. Full Depth Reclamation, FDR, is a potential solution to this problem. This research verified three FDR mix designs (asphalt emulsion, asphalt foam, and Portland cement) on four Arkansas highways, determined which performance tests are suitable to evaluate FDR material, and performed a Life Cycle Cost Analysis on both FDR and traditional maintenance and rehabilitation techniques. 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. The dynamic modulus, Semi-Circular Bend fracture, Unconfined Compressive Strength, and Tube Suction Test were all promising performance tests, while the creep compliance and tests involving moisture conditioning had significant complications. In addition, FDR is very competitive economically to traditional maintenance and rehabilitation techniques. It is recommended that FDR be considered for future pavement rehabilitation in Arkansas.

17. Key Words	18. Distribution Statement
Pavement rehabilitation, Full Depth Reclamation, mix design, performance test, Life Cycle Cost Analysis	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	67	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

1.0 Introduction 05
1.1 The Arkansas Problem 06
1.2 Full Depth Reclamation 06
1.3 Life Cycle Cost Analysis 08
2.0 Research Objectives and Laboratory Plan 10
2.1 Materials 10
2.2 Mix Designs 12
2.3 Optimal Moisture Content (OMC) 14
2.4 Optimal Stabilization Content 16
2.4.1 Optimum Emulsion Content (OEC) and Optimum Foam Content (OFC) 16
2.4.2 Optimum Cement Content (OCC) 17
2.5 Performance Testing 17
2.5.1 Mechanistic Properties 18
2.5.2 Cracking Characteristics 20
2.5.3 Moisture Damage and Strength 21
2.6 Life Cycle Cost Analysis (LCCA) 24
3.0 Mix Design Results 27
3.1 Initial Testing: Atterberg Limits 27
3.2 Optimum Moisture Content (OMC) 27
3.3 Optimal Emulsion Content (OEC) 28
3.4 Optimal Foam Content (OFC) 30
3.5 Optimal Cement Content (OCC) 31
4.0 Performance Testing Results 33
4.1 Dynamic Modulus of Asphalt Emulsion and Asphalt Foam 33
4.2 Creep Compliance of Asphalt Emulsion and Asphalt Foam 35
4.3 Semi-Circular Bend Fracture [SC(B)] 38
4.4 Indirect Tensile Strength 39
4.5 Tube Suction Test (TST) 40
4.6 Unconfined Compressive Strength (UCS) 41
4.7 Evaluator of Rutting and Stripping in Asphalt (ERSA) 41
5.0 Life Cycle Cost Analysis 43
5.1 Step 1 – Establish Alternative Pavement Design Strategies 43
5.2 Step 2 – Determine the Performance Period 43
5.3 Step 3 – Estimate Agency Costs 44
5.4 Step 4 – Estimate User Costs 48
5.5 Step 5 – Develop an Expenditure Stream Diagram 50
5.6 Step 6 – Calculate the Net Present Value 50
6.0 Recommended Equipment Needs 59
7.0 Conclusions 62
8.0 References 63

List of Figures

Figure 1.1 – Pavement Life Span 05
Figure 1.2 – Full Depth Reclamation Overview 07
Figure 2.1 – Highway and Shale Locations 11
Figure 2.2 – Gradations of Four Highways 12
Figure 2.3 – Dynamic Modulus and Creep Compliance Testing Configuration 19
Figure 2.4 – Semi-Circular Bend Test Configuration 20
Figure 2.5 – Cracking from Semi-Circular Bend Test 21
Figure 2.6 – Indirect Tensile Strength Test 22
Figure 2.7 – Tube Suction Test Setup 23
Figure 2.8 – Tube Suction Test 23
Figure 2.9 – Comparing Two Maintenance Options 24
Figure 2.10 – Simplified Example Expenditure Stream 26
Figures 3.1a-d – AR 98, AR 134, AR36, AR5 Optimal Moisture Contents 28
Figures 3.2a-d – AR 98, AR 134, AR36, AR5 Optimal Emulsion Contents 29
Figures 3.3a-d – AR 98, AR 134, AR36, AR5 Optimal Foam Contents 30
Figures 3.4a-d – AR 98, AR 134, AR36, AR5 Optimal Cement Contents 32
Figure 4.1 – Dynamic Modulus Results for Asphalt Emulsion FDR 34
Figure 4.2 – Dynamic Modulus Results for Asphalt Foam FDR 35
Figure 4.3 – Creep Compliance Results for AR 134 (62S:38R) with Asphalt Emulsion 36
Figure 4.4 – Creep Compliance Results for AR 36 (38S:62R) with Asphalt Foam 36
Figure 5.1 – Deterioration Curves for Chips Seal and Two-inch Overlay 44
Figure 5.2 – Expenditure Stream for Chip Seal on Arkansas Highway 98 50
Figure 5.3 – Agency Costs for FDR and Traditional Strategies 53
Figure 5.4 – Agency Costs for FDR with Chip Seal Surface Course 54
Figure 5.5 – Agency Costs for FDR with Two-Inch Overlay Surface Course 54
Figure 5.6a – Agency Costs and User Costs for FDR and Traditional Strategies for AR 98 55
Figure 5.6b – Agency Costs and User Costs for FDR and Traditional Strategies for AR 134 56
Figure 5.6c – Agency Costs and User Costs for FDR and Traditional Strategies for AR 36 56
Figure 5.6d – Agency Costs and User Costs for FDR and Traditional Strategies for AR 5 57
Figure 5.7 – Agency and User Costs for FDR with Chip Seal Surface Course 58
Figure 5.8 – Agency and User Costs for FDR with Two-Inch Overlay Surface Course 58

List of Tables

Table 2.1 – Selected Arkansas Highways 11
Table 2.2 – Material Properties 13
Table 2.3 – Performance Testing Summary 18
Table 3.1 – Optimal Moisture Contents 28
Table 3.2 – Optimal Emulsion Contents 29
Table 3.3 – Optimal Foam Contents 30
Table 3.4 – Optimal Cement Contents 31
Table 4.1 – Summary of Creep Compliance Results (1/kPa) at 100 Seconds 37
Table 4.2 – Summary of Creep Compliance Results (1/kPa) at 1000 Seconds 37
Table 4.3 – Summary of Fracture Energy Results (J/m^2) 38
Table 4.4 – Summary of Indirect Tensile Strength Results (psi) 39
Table 4.5 – Tube Suction Test Rating Structure 40
Table 4.6 – Tube Suction Test Results 40
Table 4.7 – Unconfined Compressive Strength (psi) 41
Table 4.8 – Summary of ERSA testing (mm) 41
Table 5.1 – Cost data from 2014 weighted averages (2014 specifications) 45
Table 5.2a – Necessary thickness of Class 7 aggregate (inches) 46
Table 5.2b – Cost of remove and replace 46
Table 5.3a – AR 98 FDR Costs 47
Table 5.3b – AR 134 FDR Costs 47
Table 5.3c – AR 36 FDR Costs 47
Table 5.3d – AR 5 FDR Costs 48
Table 5.4 – Cost of Autos and Trucks on Four Highways 48
Table 5.5 – Production Rates for Each Strategy 49
Table 5.6 – User Costs for Each Strategy and Highway 49
Table 5.7 – Agency Costs of Traditional Strategies for a 50 year design life ($/lane-mile) 51
Table 5.8 - FDR Agency Costs, HWY 98 (75S:25R), with chip seal ($/lane-mile) 52
Table 5.9 - FDR Agency Costs, HWY 98 (75S:25R), with two inch overlay ($/lane-mile) 52

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 (ASCE, 2013).

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 1.1 highlights the different periods of a typical pavement's life and the need for timely maintenance procedures. As the pavement is still in a new state, the ride quality is performing as expected. 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 structural design period. The goal of resurfacing is to maintain the flexibility and durability of the pavement but it only addresses deterioration due to the environment. Deformation 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 another structural design period. If a pavement is left unmaintained, the rate of deterioration will increase, which is shown by the ride quality on Figure 1.1. 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 (Wirtgen, 2012).

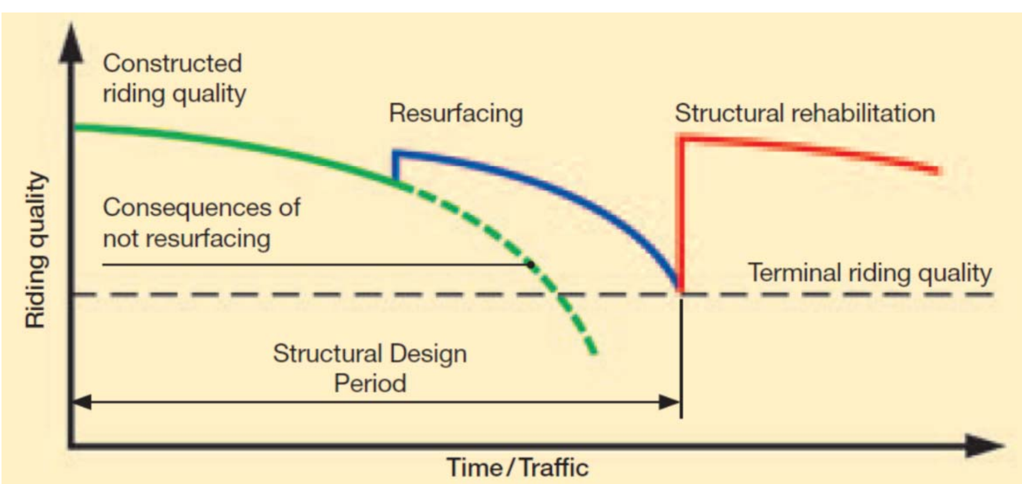

Figure 1.1 - Pavement Life Span (from Wirtgen, 2012)

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 (AHTD, 2015). 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 periods.

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 (ARRA, 2001), as seen in Figure 1.2. 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 (Scullion, 2012). FDR without stabilizers is also possible, but the research suggests that FDR tests sections perform better with stabilization (Jones *et al.*, 2015). 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 (Scullion *et al.*, 2003).

Figure 1.2 – Full Depth Reclamation Overview (from Soils and Recycling Services, 2013)

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 (Kearney and Huffman, 1999). FDR has also been shown to reduce energy consumption by up to 70% compared to the complete removal and reconstruction (Chappat and Bilal, 2003) 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 (Luhr *et al.*, 2008; Kandhal and Mallick, 1997)

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 (Bemanian *et al.*, 2006). 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 (Dai and Thomas, 2011). 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 (Lewis *et al.*, 2006). Several other states have successfully demonstrated FDR, which include Kansas, Louisiana, Maine, Texas, Utah, Wisconsin, Virginia, and Pennsylvania (Morian *et al.*, 2012; Diefenderfer and Apeagyei, 2011).

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.

1.3 Life Cycle Cost Analysis

There has been significant research exploring Life Cycle Cost Analysis, LCCA, exploring pavement design and preservation. These projects tend to fall into two categories: material and design evaluation or variability analysis. A brief overview of these two categories follows. A classic study for material evaluation utilizing LCCA was performed by Hicks and Epps (1999), where they explored the use of asphalt rubber in asphalt pavements. By using three levels of discount rate (2.5, 4.0, and 5.5%), an analysis period of 40 years, three traffic volumes (low, medium, and high), two project lengths (5 and 10 miles) and two production rates (2 and 3 miles), they determined that asphalt rubber is a cost effective alternate in several of the scenarios, but not for all. Meanwhile, Gransberg (2009) examined replacing chip sealing and thin-overlays as preservation tools with shotblasting. He found that shotblasting (on average) was approximately the same cost as chip seals and slurry seals, and approximately half the price of a one-inch overlay and provided similar surface texture benefits, but did not consume and virgin materials. In California, Lee *et al.* (2011) examined a short section of interstate to compare two types of asphalt concrete pavement with Portland cement concrete pavement. Using a sixty year analysis period and a four percent discount rate, the innovative (long-life) asphalt concrete pavement strategy was less expensive (~$39 million) than the standard asphalt concrete (~$53 million) and Portland cement concrete strategy (~$60 million). Lastly, Sakhaeifar *et al.* (2013) compared two sections of nonperpetual pavement and two sections of perpetual pavement on the NCAT test track. Using an analysis period of 55 years and a discount rate of 4%, they found that perpetual pavement design could save upwards to 20% for the cost of the pavement over the life-span.

While there have been several studies evaluating material and design, there have also been studies that examine variability. For example, Whiteley *et al.* (2005) examined how changing the design life influenced the LCCA in an attempt to establish pay factors for performance based specifications. By examining up to 30% difference in in-service performance versus design life, they found that pay bonuses could reach $17,600/km and pay penalties could reach $31,620/km depending on the difference of performance and pavement structure. Harvey *et al.* (2012) built a probabilistic model to evaluate multiple asphalt concrete overlay scenarios versus chip seals, using a discount rate from 0-10%, an analysis period of 5-20 years, traffic loading from 30-2,100 AADTT, and preventative maintenance trigger levels utilizing two levels of alligator cracking. In short, they found that applying preventative maintenance treatments at the right time could save up to 21% over a pavement's life. Pittenger *et al.* (2012) built a stochastic model to evaluate one-inch asphalt concrete overlays versus chip seals, and found that chip seals were more sensitive to service life assumptions versus asphalt concrete, and could be either more or less expensive than asphalt concrete depending on the assumptions used. Similarity, Swei *et al.* (2013) also built a probabilistic model, comparing an asphalt concrete road to a jointed-plain concrete pavement. While local roads tended to be cheaper using asphalt concrete, the concrete pavement was generally cheaper for interstate applications.

For this research, the procedure developed by the Federal Highway Administration (Walls and Smith, 1998) was utilized to compare the LCCA of chip seals, two-inch overlays, mill and fill, complete reconstruction, and three types of Full Depth Reclamation (asphalt emulsion, asphalt foam, and Portland cement) to not only explore the initial costs of these strategies, but to also compare the life-cycle cost.

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:

1. Verify three FDR mix designs using Arkansas materials.
2. Determine which performance tests are suitable to evaluate different FDR mix design technologies and potential predict field performance.
3. Perform a Life Cycle Cost Analysis on traditional AHTD maintenance strategies versus the three FDR technologies.

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 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.

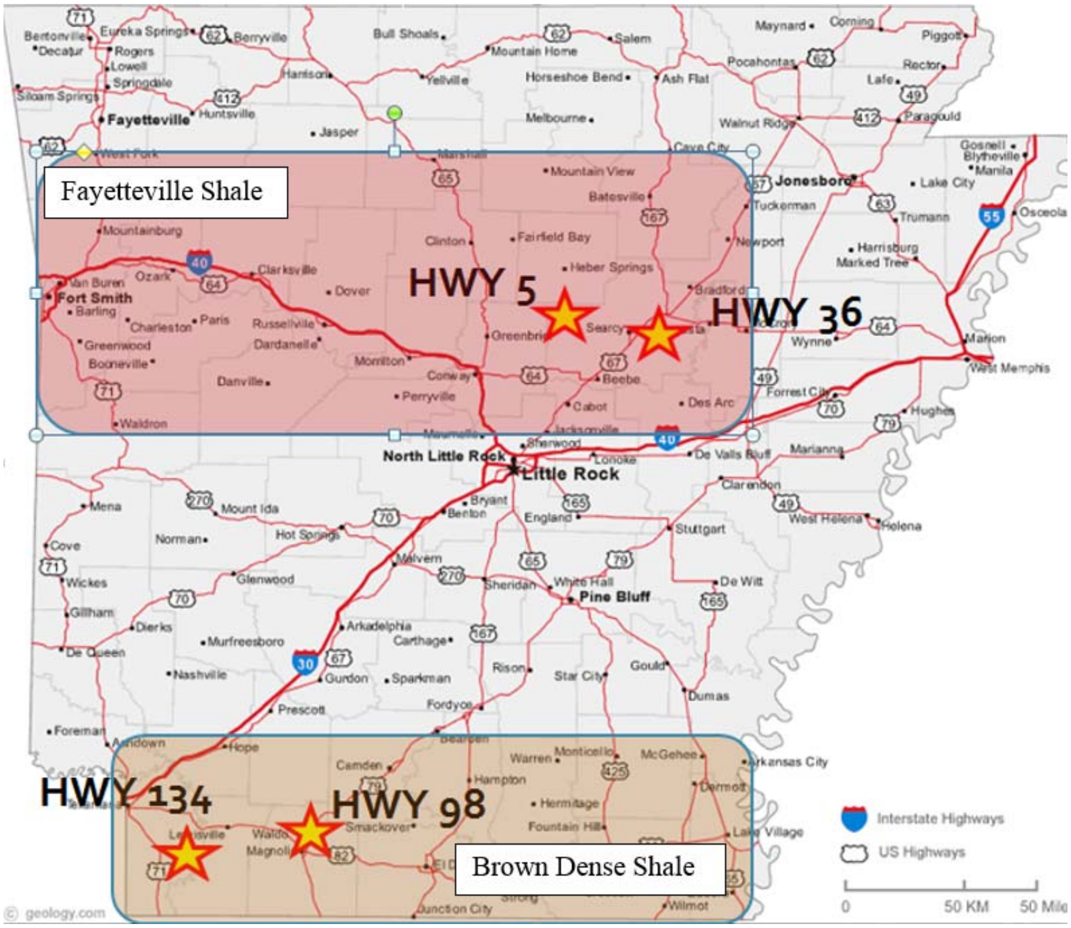

Figure 2.1 – Highway and Shale Locations (geology.com)

Table 2.1 – 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 2.2. The gradations, Figure 2.2, were established using the ideal range given by the Asphalt Academy (2009) 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.

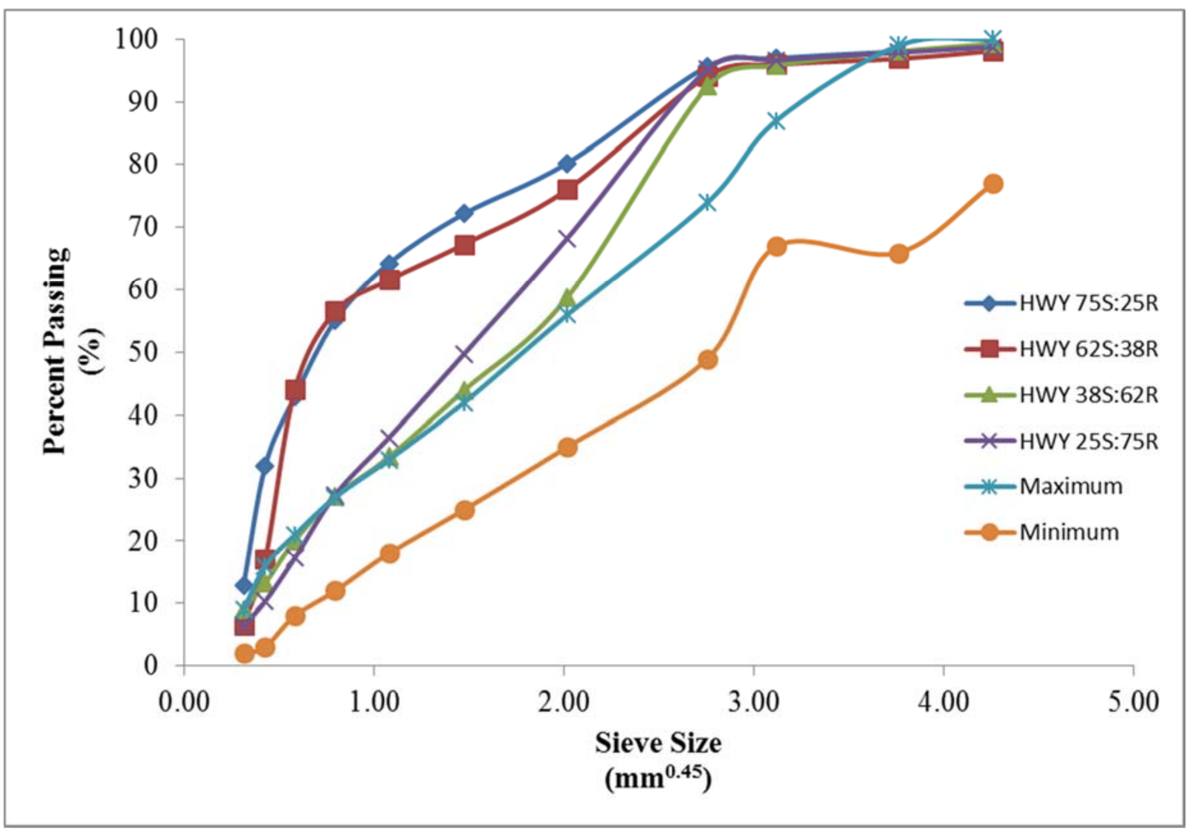

Figure 2.2 – Gradations of Four Highways

Table 2.2 – Material Properties

Highway (S:R)	AR 98 (75:25)	AR 134 (62:38)	AR 36 (38:62)	AR 5 (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 (ASTM D4318), American Association of State Highway and Transportation Officials (AASHTO) soil classification, and sand equivalency (ASTM D2419). 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."

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 (NCDOT, 2012). For the foamed asphalt stabilization, the 2012 Wirtgen mix design was used (Wirtgen, 2012). Finally, for the cement stabilized samples, the Portland Cement Association (PCA) mix design was followed (Luhr *et al.*, 2008). 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 (Thomas and May, 2007). 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 Optimal 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 following ASTM D1557 using the modified Proctor test in a 150 mm mold, Method C. The PCA design called for the OMC determination using the standard Proctor test (ASTM D698). However, it was decided to follow the same procedure, modified Proctor, for all three stabilization technologies for consistency and conservation of materials. 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 Optimal 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 (ASTM D4867). 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 D4867 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 (ASTM C702). 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 (NCDOT, 2012).

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 (ASTM D2041)
- Bulk specific gravity (ASTM D6752)
- Percentage air voids (ASTM D3203)

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 (ASTM D1633). 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 (Yu and Shen, 2012). 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 2.3, can be broken into several categories, which broadly described are:

- Mechanistic properties
- Cracking characteristics
- Moisture damage and strength

Table 2.3 – Performance Testing Summary

Test	**Test Method**	**Asphalt/ 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	Asphalt and cement	Fracture Energy & Cracking Characterization
Indirect Tensile Strength	ASTM D 4867	Asphalt	Strength Moisture Susceptibility
Tube Suction Test	Tex-144-E; Guthrie and Scullion, 2003	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 (AASHTO T342, Underwood *et al.*, 2011). 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 2.3, which has been shown to correlate well with the axial loading of E* tests and conserves material (Kim *et al.*, 2004).

Figure 2.3 – Dynamic Modulus and Creep Compliance Testing Configuration (photo: Henrichs)

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 (AASHTO T322). 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 (FHWA, 2001). It has been found that creep compliance typically increases with an increase in temperature, which shows a greater resistance to thermal cracking (AASHTO TP105). Creep compliance testing was performed on only the asphalt stabilized samples in the same configuration as E*.

2.5.2 Cracking Characteristics

The Semi-Circular Bend test [SC(B)] is a three-point bend test, as seen in Figure 2.4, used to measure low temperature fracture energy of a sample, which is correlated to low temperature cracking resistance (AASHTO TP105). The greater the fracture energy of a specimen, the less susceptible the sample is to thermal cracking (Johnson *et al.*, 2013). 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. Note how the crack generally traveled around large aggregates, so the SC(B) fracture energy can be greatly influenced by the location of larger aggregates. 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 2.4 - Semi-Circular Bend Test Configuration (photo: Henrichs)

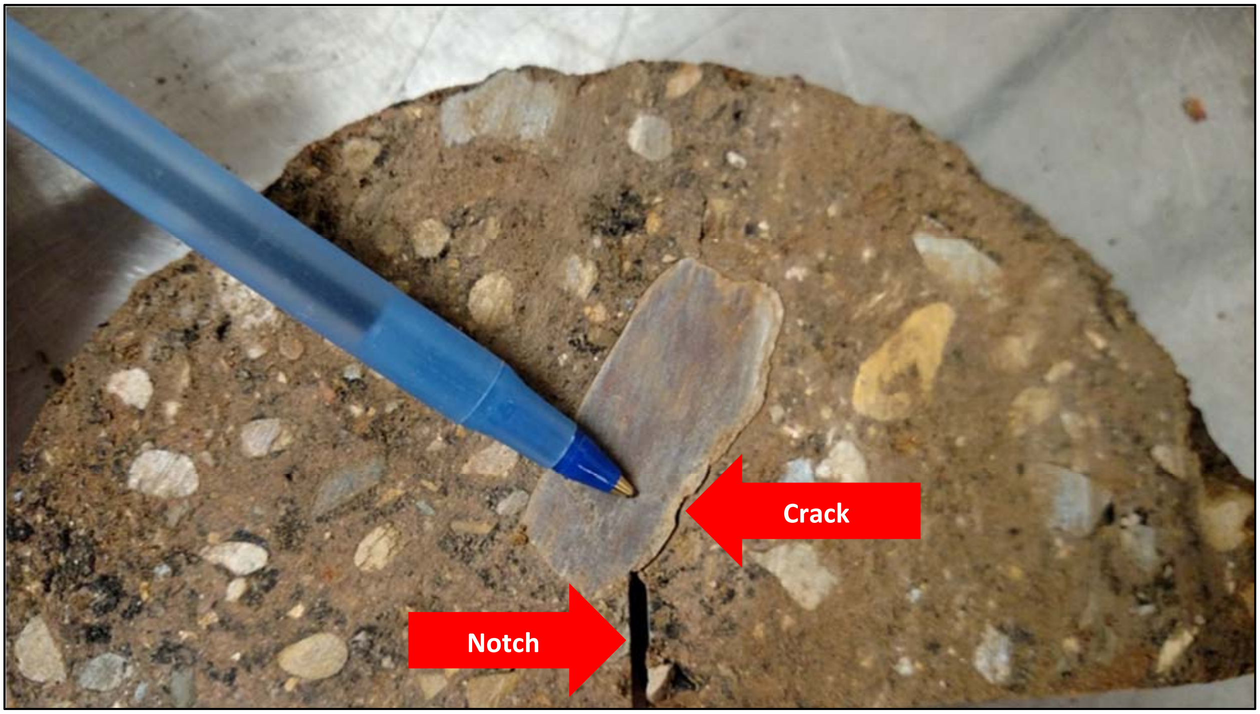

Figure 2.5 – Cracking from Semi-Circular Bend Test (photo: Henrichs)

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 (Kim *et al.*, 2012).

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 2.6, which was used to determine the optimum asphalt stabilization contents, was rerun to verify the tensile strengths.

Figure 2.6 – Indirect Tensile Strength Test (photo: 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 (Guthrie and Scullion, 2003). This test was performed on cement stabilized samples only. Figure 2.7 and Figure 2.8 show the TST samples prior to and during the soak period, respectively.

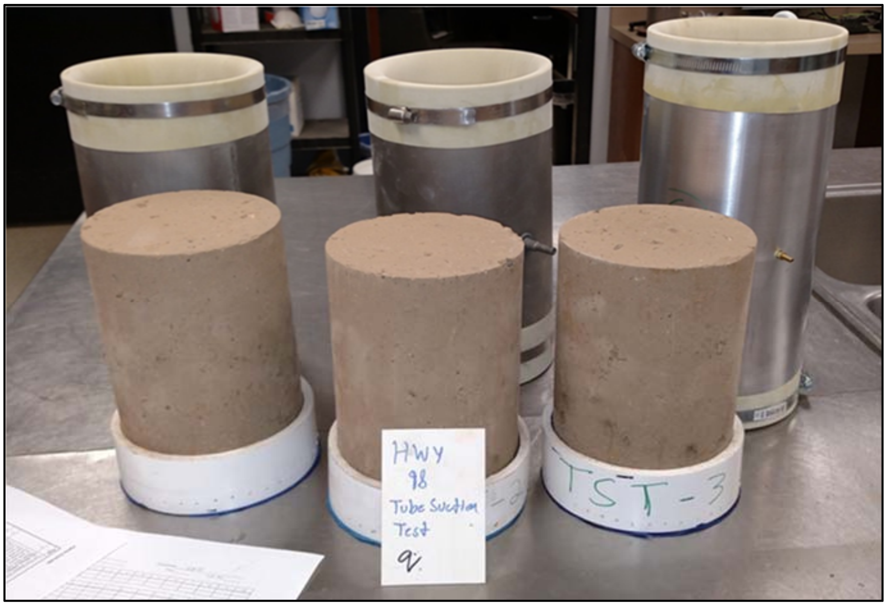

Figure 2.7 – Tube Suction Test Setup (photo: Henrichs)

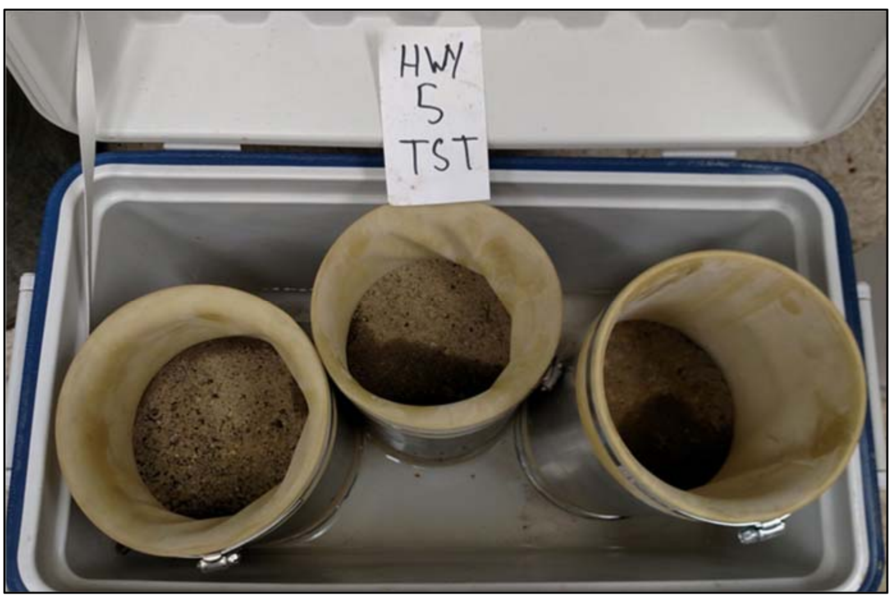

Figure 2.8 – Tube Suction Test (photo: Henrichs)

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.

2.6 Life Cycle Cost Analysis (LCCA)

For this research, the procedure developed by the Federal Highway Administration (Walls and Smith, 1998) was utilized. This procedure has seven steps:

1. Establish alternative pavement design strategies for the analysis period.
2. Determine performance periods and activity timing.
3. Estimate agency costs.
4. Estimate user costs.
5. Develop expenditure stream diagrams.
6. Compute net present value.
7. Analyze results and reevaluate design strategies.

These steps will be analyzed in more detail below.

The first step of a Life Cycle Cost Analysis (LCCA) is to establish alternative pavement design strategies for the analysis period. This research explored chip seal, two-inch overlay, mill and fill, complete reconstruct, and three FDR technologies across the four Arkansas highways. Therefore, a total of seven design strategies were evaluated on four highways, for a total of 28 LCCA analysis. The second step of a LCCA is to determine the performance periods and activity timing. This is a key step to comparing new technologies to existing strategies, as some strategies may be more expensive initially, but the increase in pavement structural performance may provide for a longer and more effective lifespan. Therefore, an attempt to apply realistic projections of future performance will be captured in order to achieve the most beneficial analysis. Figure 2.9 shows a graphical representation of predicting performance periods and activity timing for two different maintenance alternatives. Note how the performance periods are tied to pavement condition. Often, when a pavement condition reaches terminal serviceability, a maintenance or rehabilitation activity is triggered.

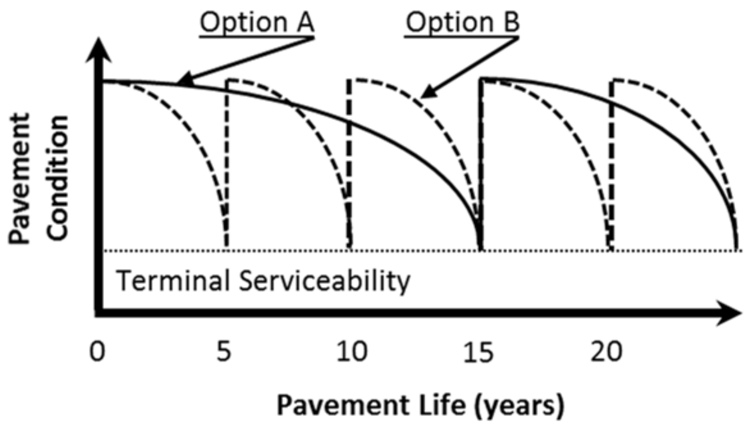

Figure 2.9 – Comparing Two Maintenance Options

The third step of the LCCA analysis is to estimate agency costs. Therefore, it important that accurate and salient dollar amounts will be obtained for the initial production and construction costs. By defining the activity timing in the second step, dollar amounts can be obtained for future costs. This research used 2014 weighted averages from AHTD to define the agency cost. The fourth step takes the costs analysis further by estimating the user costs. While the agency cost is critical to decisions, the cost of users must be accounted for. This research used data from Central Federal Lands Highway Division to estimate production rate, which could be combined with car and truck user costs for delays from AHTD. With these two costs calculated, the fifth step of the LCCA analysis is to develop an expenditure stream diagram. The expenditure stream diagram is simply a graphical representation of initial and future costs. Figure 2.10 is an example expenditure stream diagram, where arrows pointing upward are costs and arrows pointing downward are income. A LCCA assumes that there is residual value at the end of a pavement life that can be applied to the analysis.

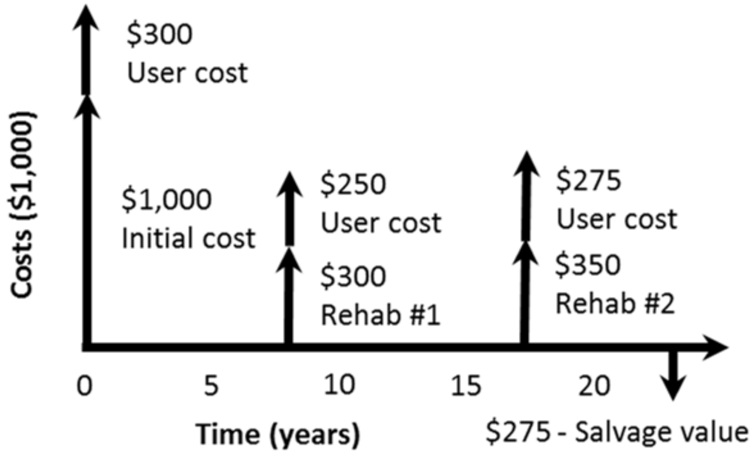

Figure 2.10 – Simplified Example Expenditure Stream (dollar values and activity timings for display only)

Once the present and future costs are calculated, the Net Present Value (NPV) can be calculated, which is the sixth step of an LCCA analysis. This calculation takes all future costs and brings them to a single present cost, allowing for a direct comparison between multiple maintenance and rehabilitation options. This is shown in Equation 1:

$$NPV = Initial\ Cost + \sum_0^{t_n}\left(\frac{Maintenance\ Cost}{(1+r)^{t_n}}\right) + \sum_0^{t_n}\left(\frac{Rehabilitation\ Cost}{(1+r)^{t_n}}\right) - \left(\frac{Salvage\ Cost}{(1+r)^{t_n}}\right) \quad (1)$$

where t is the time period analyzed (years), n is the year of analysis, and r is the discount rate (%). The final step, eight, is an analysis of the results. While there are occasional iterations of the LCCA analysis, this research will focus on the final product of the analysis and not present the iterations. The salvage value was calculated using Equation 2 (NCAT, 2013):

$$Salvage\ Value = CLR \times \frac{Remaining\ Life\ of\ Last\ Resurfacing}{Service\ Life\ of\ Last\ Resurfacing} + CRI \quad (2)$$

where CLR is the cost of the last resurfacing, and CRI is the cost of the lower asphalt layers remaining from the initial construction. This accounts for the in-place value of the pavement structure. Once the NPV was established for the seven different strategies on the four Arkansas highways, the last step in the LCCA analysis, analyzing results and reevaluate design strategies, was performed.

3.0 Mix Design Results

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. All four highways, as outlined in Table 2.1, will be presented.

3.1 Initial Testing: Atterberg Limits

The results from the Atterberg Limits, presented in Table 2.2, 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 (Coduto, 2001). The samples displayed consistent values for the Atterberg Limits tested, including:

- Plastic Limit: 13.5 – 16.7
- Liquid Limit: 20 – 28
- Plasticity Limit: 6 - 12

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 (from 25% to 75% RAP) on performance testing, as it is assumed that the natural subgrade material is relatively equal for all four sections.

3.2 Optimum Moisture Content (OMC)

Using the modified Proctor test in a 150 mm mold, Method C, OMC was determined for the four highway mixtures. Table 3.1 shows the optimal moisture content for each highway, while Figure 3.1a-d shows the curves that determined the optimal moisture content. In general, as the subgrade ratio decreased, the optimal moisture content also decreased. However, at the highest levels of RAP, the optimal moisture content appeared to level out.

Table 3.1 – Optimal Moisture Contents

Highway (S:R)	AR 98 (75:25)	AR 134 (62:38)	AR 36 (38:62)	AR 5 (25:75)
Optimal Moisture Content (%)	7.5	6.0	4.8	5.5

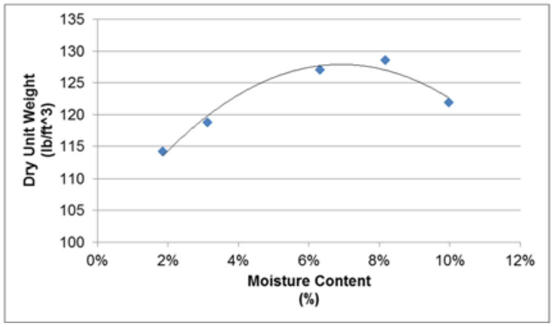

Figure 3.1a – AR98 Optimal Moisture Content

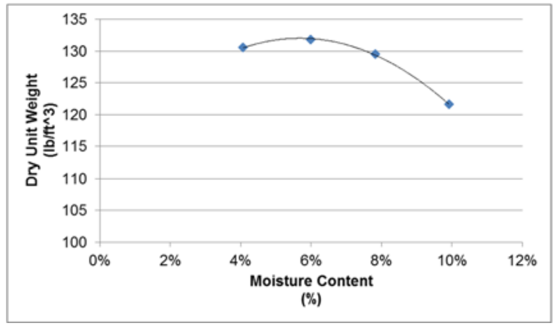

Figure 3.1b – AR134 Optimal Moisture Content

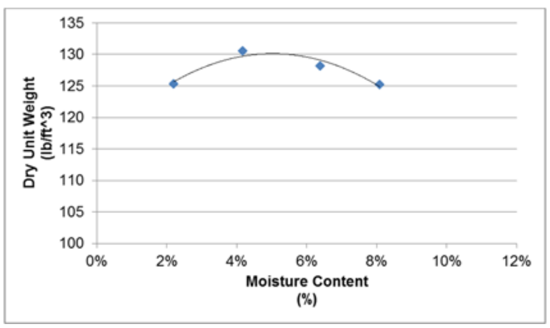

Figure 3.1c – AR36 Optimal Moisture Content

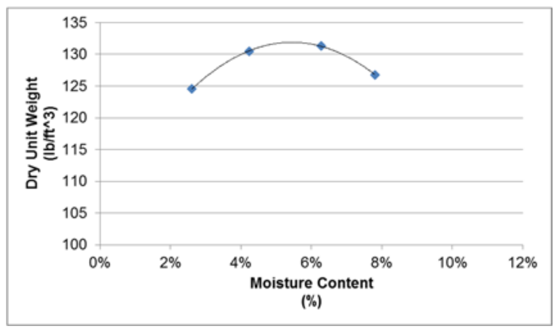

Figure 3.1d – AR5 Optimal Moisture Content

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. Table 3.2 summarizes the optimal emulsion content, while Figures 3.2a-d shows the curves. The highway with the highest subgrade content had the highest asphalt emulsion content, which is intuitive, as there is more surface area to coat. However, as the RAP level increased, the emulsion content leveled out.

Table 3.2 – Optimal Emulsion Contents

Highway (S:R)	AR 98 (75:25)	AR 134 (62:38)	AR 36 (38:62)	AR 5 (25:75)
Optimal Emulsion Content (%)	9.0	5.0	6.0	6.0

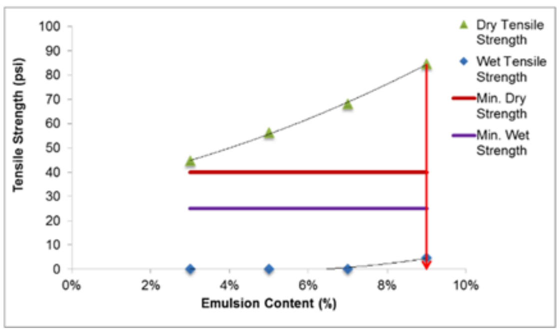

Figure 3.2a – AR98 Optimal Emulsion Content

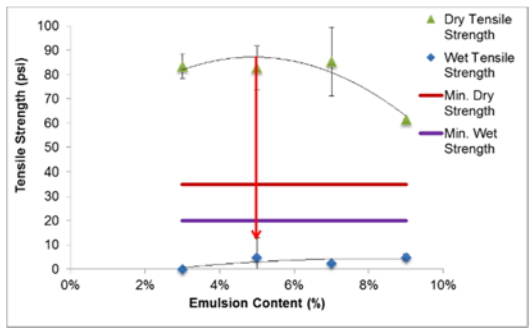

Figure 3.2b – AR134 Optimal Emulsion Content

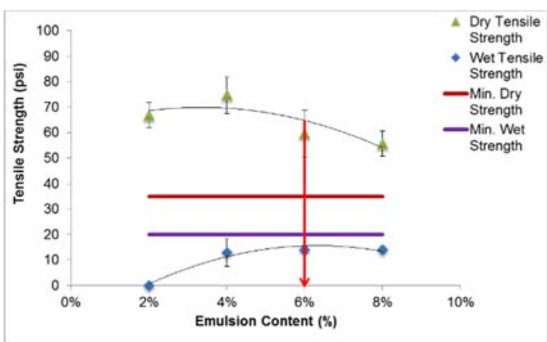

Figure 3.2c – AR36 Optimal Emulsion Content

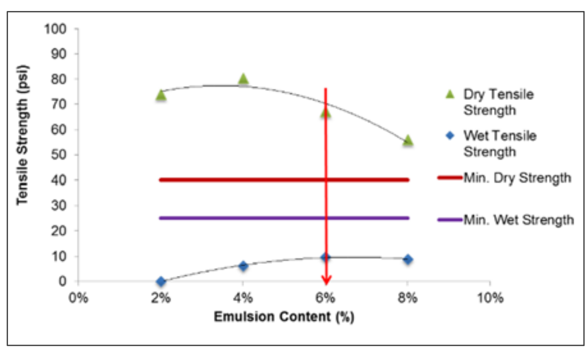

Figure 3.2d – AR5 Optimal Emulsion Content

It should be noted that no wet tensile strength for achieved minimum strength of 20 psi, indicating that the samples were susceptible to moisture damage when saturated. There were 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 was the first of multiple instances where the data indicated 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.

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. Table 3.3 summarizes the optimal foam content, while Figures 3.3a-d shows the curves.

Table 3.3 – Optimal Foam Contents

Highway (S:R)	**AR 98 (75:25)**	**AR 134 (62:38)**	**AR 36 (38:62)**	**AR 5 (25:75)**
Optimal Foam Content (%)	8.0	8.0	8.0	8.0

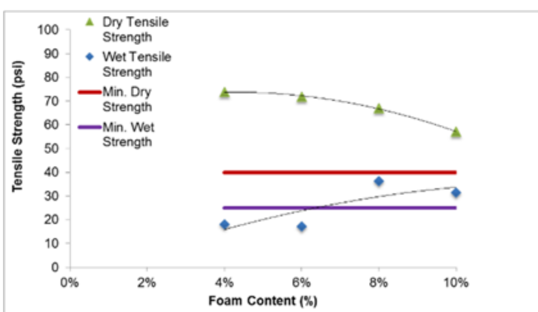

Figure 3.3a – AR98 Optimal Foam Content

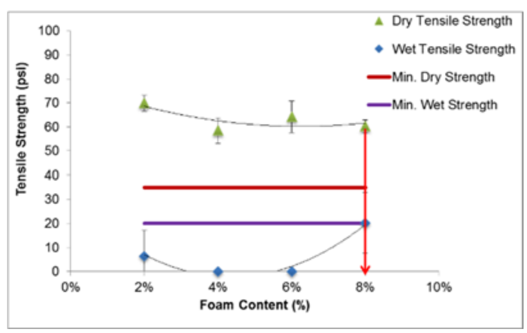

Figure 3.3b – AR134 Optimal Foam Content

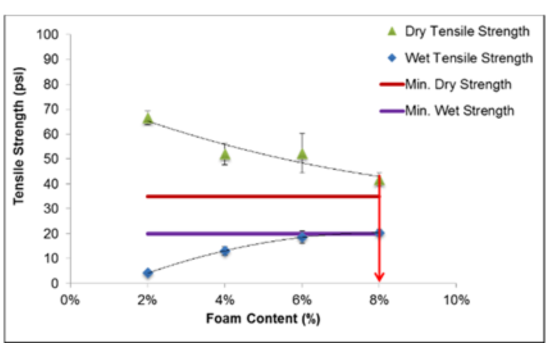

Figure 3.3c – AR36 Optimal Foam Content

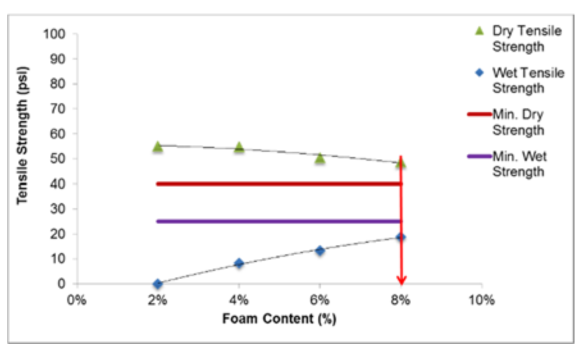

Figure 3.3d – AR5 Optimal Foam Content

Once again, the peak of the wet tensile strength curve was selected as the optimum, which for all 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 not considered since moisture damage of the highways is more critical than dry strength.

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. 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. Table 3.4 summarizes the optimal cement content, while Figures 3.4a-d shows the curves. As the amount of subgrade material decreased, the optimal cement content also decreased.

Table 3.4 – Optimal Cement Contents

Highway (S:R)	**AR 98 (75:25)**	**AR 134 (62:38)**	**AR 36 (38:62)**	**AR 5 (25:75)**
Optimal Cement Content (%)	9.0	5.0	3.0	3.0

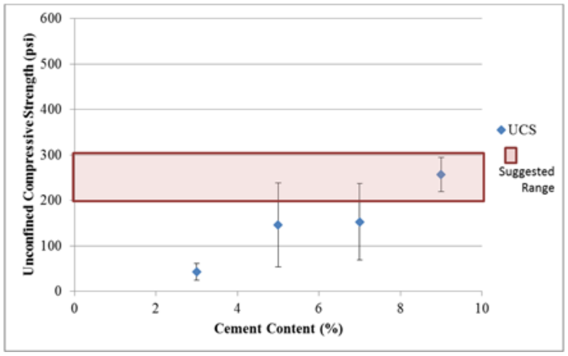

Figure 3.4a – AR98 Optimal Cement Content

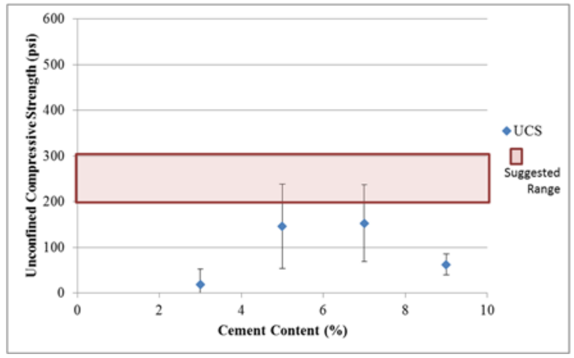

Figure 3.4b – AR134 Optimal Cement Content

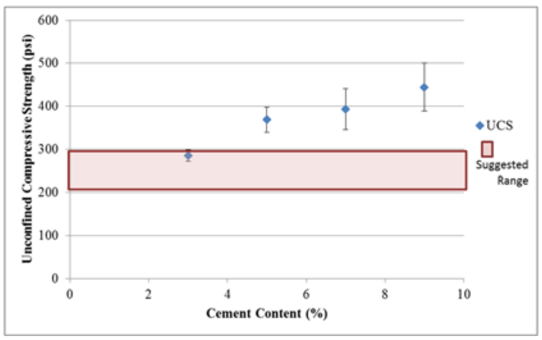

Figure 3.4c – AR36 Optimal Cement Content

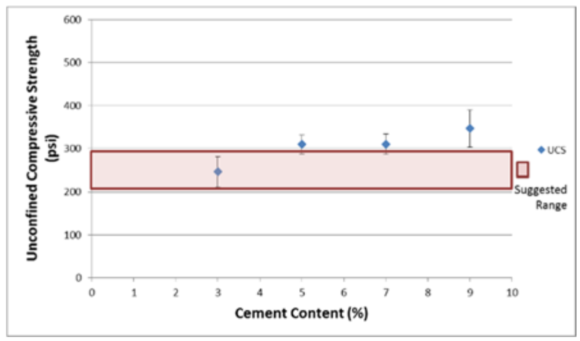

Figure 3.4d – AR5 Optimal Cement Content

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 for this preliminary evaluation of highway material from Arkansas. 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. All of the performance tests were run at optimal binder contents. The performance 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 of Asphalt Emulsion and Asphalt Foam

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. Six frequencies (25, 10, 5, 1.0, 0.5, 0.1 Hz) and five temperature (-10, +4, +21, +37, and +54°C) were examined for each highway, for both asphalt emulsion and asphalt foam stabilization. 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.

The first stabilizing agent explored was asphalt emulsion. Figure 4.1 shows the four dynamic modulus curves constructed from the mixtures at optimal emulsion content. When examining dynamic modulus curves, higher stiffness values at the higher reduced frequencies (simulating higher temperatures and slower traffic loads) indicate a higher susceptibility to rutting, while higher stiffness values at the lower reduced frequencies (simulating lower temperatures and faster traffic loads) indicate a higher susceptibility to cracking. From Figure 4.1, it is interesting to see that AR 134 has the highest stiffness values, indicating a lower probability of rutting but higher probability of cracking. Meanwhile, the other three curves were similar shaped, each indicating about the same susceptibility of rutting and cracking, but all three would be anticipated to have less rutting but more cracking problems.

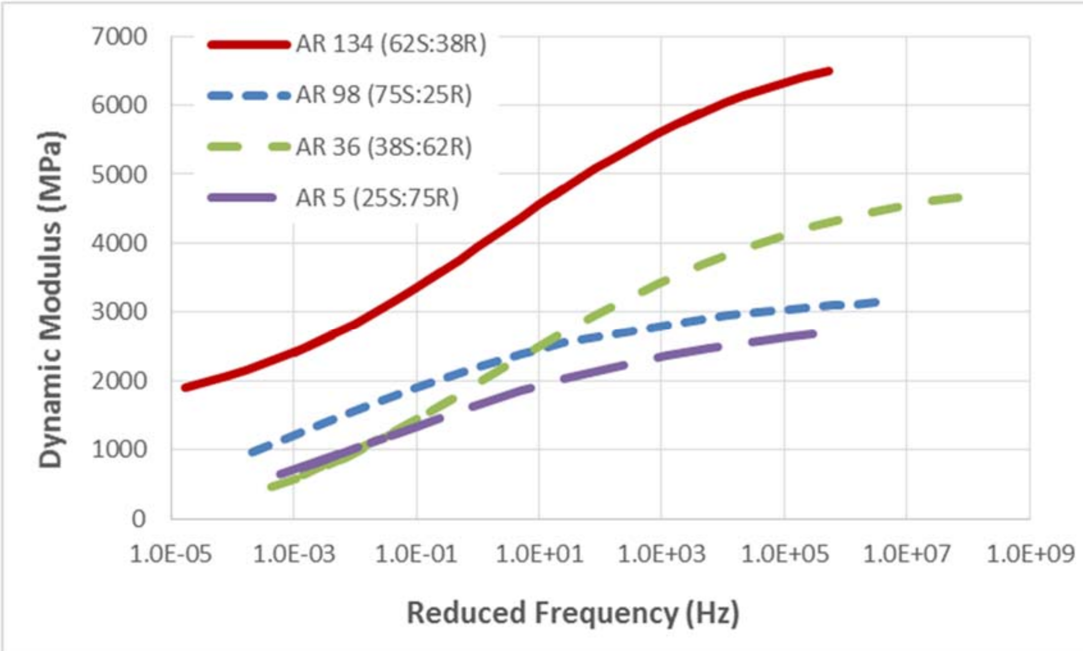

Figure 4.1 – Dynamic Modulus Results for Asphalt Emulsion FDR

The second stabilizing agent explored was asphalt foam. Figure 4.2 shows the four dynamic modulus curves constructed from the mixtures at optimal emulsion content. Here, all four highways showed approximately the same potential susceptibility to rutting and cracking, showing that foam was not as sensitive to the ratio of bound to unbound (RAP to subgrade) material. However, it is worth noting the in general, the dynamic modulus values were less for asphalt foam versus asphalt emulsion at the higher reduced frequencies, indicating that asphalt foam would be more susceptible to rutting than asphalt emulsion. However, the dynamic modulus values at the lower reduced frequencies were approximately the same, indicating that each technology would have similar cracking characteristics. Overall, it appears that dynamic modulus is a good test at characterizing asphalt emulsion and asphalt foam FDR mixtures.

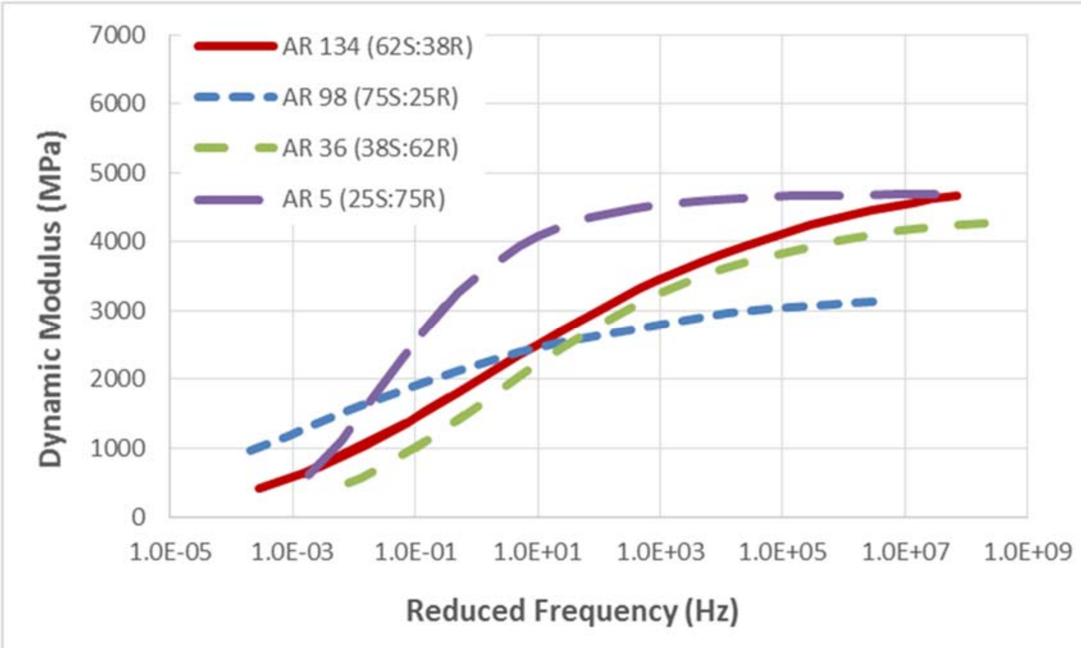

Figure 4.2 – Dynamic Modulus Results for Asphalt Foam FDR

4.2 Creep Compliance of Asphalt Emulsion and Asphalt Foam

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. Typically, creep compliance increases as the temperature increases in HMA mixtures. An example creep compliance curve is shown in Figure 4.3. This shows the creep compliance curves for AR 134 (62S:38R) with asphalt emulsion FDR. Figure 4.3 is a very result that is often seen with HMA mixtures, as the creep (or amount of deflection under a constant load) was increasing as the temperature increased. In addition, the amount of creep was increasing as time was increasing as well. However, these results were not as common with FDR. For example, Figure 4.4 shows data from AR 36 (38S:62R) with asphalt foam FDR, and the relationship expected was inverted, with the lowest temperature exhibiting the greatest creep. These types of unintuitive trends lead to not recommending the creep compliance test for FDR evaluation. Table 4.1 shows the results of all mixtures at 100 seconds, and Table 4.2 shows the results of all mixtures at 1000 seconds.

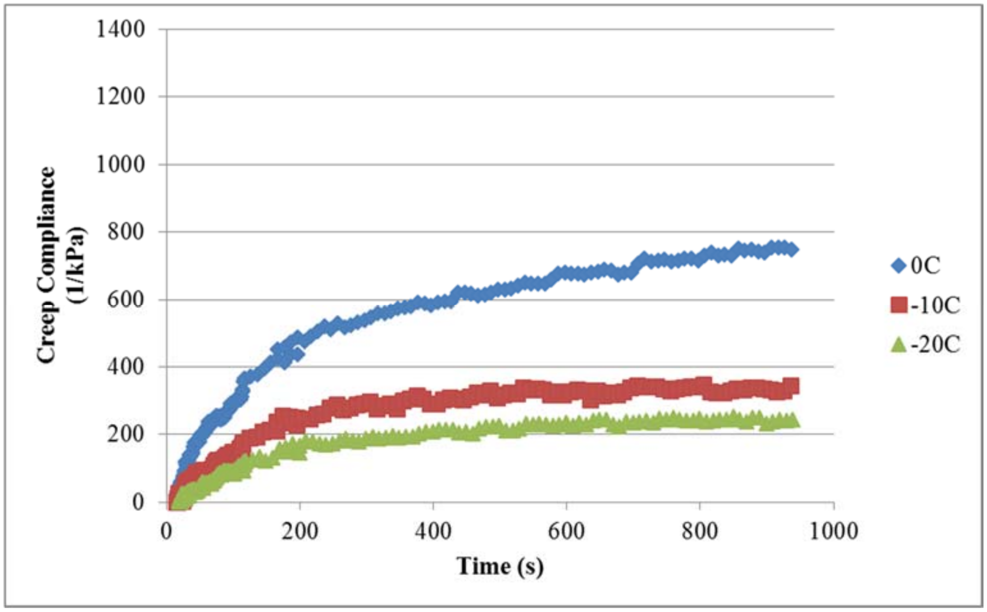

Figure 4.3 – Creep Compliance Results for AR 134 (62S:38R) with Asphalt Emulsion

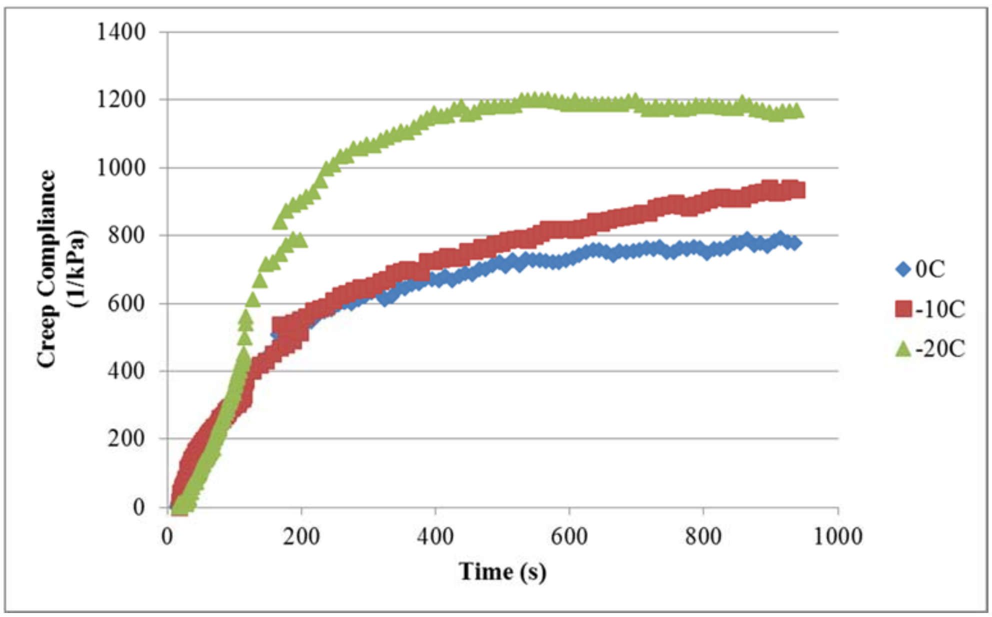

Figure 4.4 – Creep Compliance Results for AR 36 (38S:62R) with Asphalt Foam

Table 4.1 – Summary of Creep Compliance Results (1/kPa) at 100 Seconds

FDR Technique	Temperature (C)	AR 98 (75:25)	AR 134 (62:38)	AR 36 (38:62)	AR 5 (25:75)
Asphalt Emulsion	0	-	390	250	400
	-10	400	350	125	300
	-20	650	40	100	100
Asphalt Foam	0	150	80	300	-
	-10	180	350	300	500
	-20	200	20	400	250

Table 4.2 – Summary of Creep Compliance Results (1/kPa) at 1000 Seconds

FDR Technique	Temperature (C)	AR 98 (75:25)	AR 134 (62:38)	AR 36 (38:62)	AR 5 (25:75)
Asphalt Emulsion	0	-	1050	750	1550
	-10	2000	1025	325	1300
	-20	3700	170	250	440
Asphalt Foam	0	375	225	800	-
	-10	800	1800	925	1750
	-20	690	80	1200	825

Tables 4.1 and 4.2 confirm the findings that creep compliance testing does not produce reasonable results, as there are no trends between temperature and creep compliance, or between percentage of subgrade and creep compliance. The only data that is even remotely reasonable was the AR 5 (25S:75R), which may indicate that a higher level of bound material produced more reasonable results. Overall, however, it is not recommended the creep compliance is used in future testing of FDR.

4.3 Semi-Circular Bend Fracture [SC(B)]

The Semi-Circular Bend [SC(B)] test is a measure of fracture energy used to better understand low temperature cracking. 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 (asphalt emulsion, asphalt foam, and Portland cement) at these temperatures for consistency. Table 4.3 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 per specification (AASHTO TP105).

Table 4.3 – Summary of Fracture Energy Results (J/m^2)

	Temperature (C)	Asphalt Emulsion	Asphalt Foam	Portland Cement
AR 98 (75S:25R)	-12	27.9	40.3	0.0
	-24	34.6	70.1	0.0
AR 134 (62S:38R)	-12	0.0	44.5	0.0
	-24	31.8	53.8	0.0
AR 36 (38S:62R)	-12	79.3	112.8	14.0
	-24	43.4	54.9	0.0
AR 5 (25S:75R)	-12	100.1	149.2	11.7
	-24	46.7	167.3	49.5

In general, as the percentage of bound material increased, the fracture energy increased as well. Surprisingly, however, some mixtures showed higher cracking resistance at lower temperatures, as this trend is usually reversed with HMA mixtures. Finally, it appeared that asphalt emulsion and asphalt foam consistently showed better cracking resistance than Portland cement. This was not a surprise, as cracking can be a significant problem in Portland cement stabilized mixtures. Overall, the SC(B) tests appears to be a valid testing option in determining low temperature or reflective cracking characteristics for FDR.

4.4 Indirect Tensile Strength

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. Table 4.4 shows the results of the testing.

Table 4.4 – Summary of Indirect Tensile Strength Results (psi)

	Condition	**Asphalt Emulsion**	**Asphalt Foam**
AR 98 (75S:25R)	Dry	84.6	67.0
	Wet	6.0	36.3
AR 134 (62S:38R)	Dry	95.6	115.1
	Wet	1.6	18.1
AR 36 (38S:62R)	Dry	94.2	81.0
	Wet	12.6	17.4
AR 5 (25S:75R)	Dry	67.1	48.6
	Wet	9.7	18.7

Once again, all of the moisture conditioned samples did not meet the minimum strength requirements except for AR 98 with foam stabilization. This further proves the need for samples to be kept at optimal moisture content, and not above, when constructed. The dry tensile strengths for all highways well exceeded the minimal requirement which bodes well for areas with proper drainage or that are naturally arid.

4.5 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 Portland cement FDR samples. The tests run for 10 days and the dielectric values are averaged for each TST. Table 4.5 summarizes the rating system used for the TST, as presented by TTI.

Table 4.5 – Tube Suction Test Rating Structure

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

Two characteristics greatly influence the capillary action of a granular base, absorption and interconnected air voids. Table 4.6 summarizes the results of the TST on the Portland cement FDR samples. In general, as the amount of subbase material decreased, the capillary action decreased. This indicated that FDR structures with higher bound material would be less susceptible to water moving up through the pavement structure.

Table 4.6 – Tube Suction Test Results

Highway (S:R)	**AR 98 (75:25)**	**AR 134 (62:38)**	**AR 36 (38:62)**	**AR 5 (25:75)**
10 Day Average Dialetric Value	20.9	15.5	6.8	13.3
Rating	Poor	Marginal	Good	Marginal

4.6 Unconfined Compressive Strength (UCS)

The Unconfined Compressive Strength (UCS) was run again on samples at the optimal Portland cement content. Table 4.7 shows the results. In general, the UCS values were well above the recommended range (300-400 psi), which indicates that while they have enough strength, they may be too brittle for field use. In addition, while the 75% subgrade mixture had a significantly lower compressive strength than the other three mixtures, addition bound material above 38% did not increase the compressive strength.

Table 4.7 – Unconfined Compressive Strength (psi)

Highway (S:R)	**AR 98 (75:25)**	**AR 134 (62:38)**	**AR 36 (38:62)**	**AR 5 (25:75)**
UCS	507	679	694	680

4.7 Evaluator of Rutting and Stripping in Asphalt (ERSA)

The Evaluator of Rutting and Stripping in Asphalt (ERSA) test was run in order to gauge the moisture susceptibility of each of the FDR mixtures. However, since FDR is not a fully bonded material, it was not anticipated that this test would give a strong indication of performance compared to HMA mixtures, however, it could give at least a comparison between FDR technologies. Table 4.8 summarizes the results.

Table 4.8 – Summary of ERSA testing (mm)

Temperature (C)	**Asphalt Emulsion**	**Asphalt Foam**	**Portland Cement**
AR 98 (75S:25R)	25.9	-	23.1
AR 134 (62S:38R)	16.3	-	23.7
AR 36 (38S:62R)	21.7	22.9	21.6
AR 5 (25S:75R)	17.2	25.5	23.7

From Table 4.8, even the best performing FDR mixture performed far worse than the most lenient specification in AHTD's standard specifications for HMA mixtures (8.000mm at 8000 cycles). In addition, there did not appear to be any clear trends between either stabilizing technology or ratio of subgrade to RAP material. Therefore, this test is not recommended for future use in FDR specifications.

5.0 Life Cycle Cost Analysis

5.1 Step 1 – Establish Alternative Pavement Design Strategies

The first step to an LCCA is to establish the alternative pavement design strategies. In Arkansas, there are four traditional pavement maintenance or pavement rehabilitation techniques: place a chip seal, lay a two-inch overlay, mill off two-inches and replace with two-inches of asphalt concrete, or perform a complete removal and replace. While the chip seal is considered a maintenance activity, the overlay, mill and fill, and remove and replace could be considered rehabilitation techniques, as they potentially add structural capacity to the roadway. FDR is also a rehabilitation technique, and three design strategies were explored in this LCCA: asphalt emulsion, asphalt foam, and Portland cement.

5.2 Step 2 – Determine the Performance Period

The second step to an LCCA analysis is to determine the performance period. From AHTD, it is assumed that chip seals last five to seven years, so the life of a chip seal was estimated to be six years. Similarly, from AHTD< it is assumed that an overlay lasts ten to twelve years, so the life of a two-inch overlay was estimated to be eleven years. For all analysis, it was assumed that the underlying pavement structure was structurally sound, and no deterioration occurred during the fifty-year analysis of this project. This is a risky assumption, as, for example, once Portland cement FDR cracks there is little that can be done to remedy the problem other than removal and replacing, but in order to keep the analysis relatively straight forward, all underlying material was assumed to not need replacement, and either the chip seal or two-inch overlay was placed on a consistent basis. Figure 5.1 shows the deterioration curves for both a chip seal program and a two-inch overlay option.

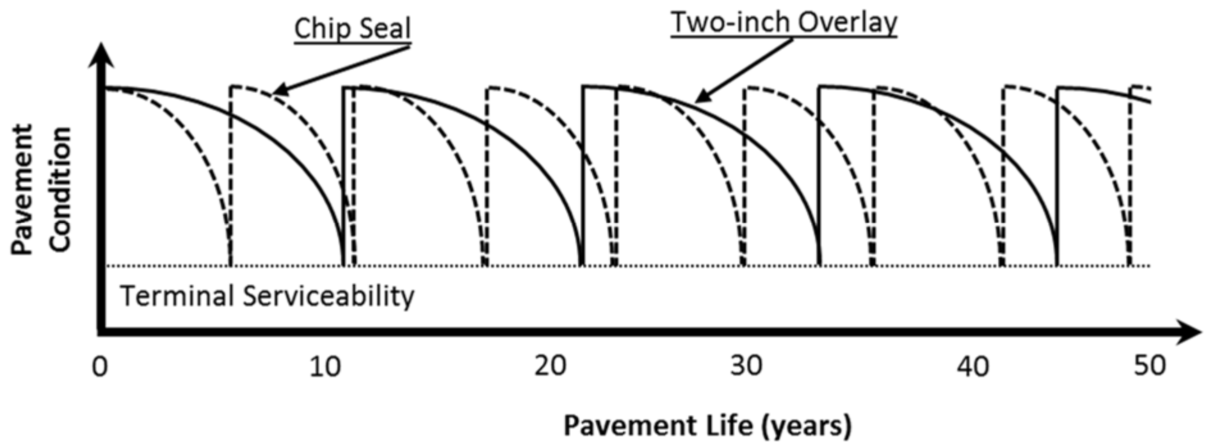

Figure 5.1 – Deterioration Curves for Chips Seal and Two-inch Overlay

5.3 Step 3 – Estimate Agency Costs

The third step to an LCCA analysis is to estimate the agency costs. The primary data source for this project was AHTD. For the initial cost of materials, data from the 2014 weighted averages (using the 2014 specification) were used. In general, the material with the highest quantity shown was utilized, as that would indicate the most stable price. However, in some instances, the average of two materials was used. Table 5.1 summarizes the material costs.

In order to fully compare the four different strategies, a common unit needed to be developed. Therefore, all of the costs in Table 1 were converted to dollars/lane-mile, assuming a twelve foot wide lane and all construction costs are incorporated into the material cost. This conversation was performed for chip seal, two-inch overlay, remove and replace, and FDR.

For the chips seals, chip rates were estimated from Wisconsin Transportation Bulletin No. 10. In this bulletin, the maximum emulsion rate was given as 0.40 gal/ yd^2, while the minimum emulsion rate was 0.25 gal/yd^2. The maximum aggregate rate was 30 lb/y yd^2, while the minimum aggregate rate was 20 lb/ yd^2. By taking the average emulsion and aggregate rate, and averaging the two mineral aggregates in asphalt surface treatment (Mineral Aggr. In A.S.T.), the cost of a chip seal was estimated to be $11,990/lane-mile.

Table 5.1 - Cost data from 2014 weighted averages (2014 specifications) (http://arkansashighways.com/ProgCon/letting/weighted_averages_2014_2014_Specifications.pdf)

Strategy	Specification Number	Material Description	Price
Chip seal	402	Mineral Aggr. In A.S.T. (CL1)*	\$39.63/ton
	402	Mineral Aggr. In A.S.T. (CL2)	\$37.88/ton
	402	POLY.MOD.CAT.EMULS.ASPH(CRS2P)	\$3.75/gal
Two inch overlay	407	AB(PG64-22)ACHM SURF(1/2")	\$357.82/ton
	407	AB(PG70-22)ACHM SURF(1/2")	\$325.82/ton
	407	AB(PG76-22)ACHM SURF(1/2")	\$288.79/ton
	407	MA IN ACHM SURFACE(1/2")	\$72.55/ton
Mill and Fill	412	COLD MILLING ASPHALT PVMT.	\$2.26/yd^2
	407	AB(PG64-22)ACHM SURF(1/2")	\$357.82/ton
	407	AB(PG70-22)ACHM SURF(1/2")	\$325.82/ton
	407	AB(PG76-22)ACHM SURF(1/2")	\$288.79/ton
	407	MA IN ACHM SURFACE(1/2")	\$72.55/ton
Remove and Replace	412	COLD MILLING ASPHALT PVMT.	\$2.26/yd^2
	303	AGGR.BASE COURSE(CLASS 7)	\$19.89/ton
Full-Depth Reclamation	308	PROCESS.CMNT.STAB.CRSHD.STN.BS.	\$8.74/yd^2
	308	CEMENT IN CMNT.STAB.CRSHD.STN.BS.	\$144.21/ton
	401	TACK COAT	\$1.72/gal

*All abbreviations are defined in the following paragraphs

For the two-inch overlay, 5% asphalt binder (thus 95% mineral aggregate in asphalt concrete hot mix surface course (MA ACHM SURF) with ½" nominal maximum aggregate size) was assumed, with a mixture density of 145 lb/ft^3. Assuming the average price of the three asphalt binder (AB), the cost of a two-inch asphalt concrete overlay was estimated to be \$65,175/lane-mile.

For mill and fill, the first step is to remove the existing bound material. It was assumed that this bound material could be milled off in one pass (COLD MILLING ASPHALT PVMT.). After the material was milled, a two-inch overlay was placed using the same numbers as immediately above. The combined cost of milling and placing the overlay was estimated to be \$77,108/lane-mile.

For the remove and replace, it was assumed that all of the existing bound material could be milled off in one pass (COLD MILLING ASPHALT PVMT.). Then, both Class 7 aggregate base course (AGGR.BASE COURSE) was placed, with asphalt concrete on top. Depending on the ratio of thickness of the Class 7 and asphalt concrete, and a varying structural number, the cost of remove and replace varied from a minimum of \$264,106/lane-mile to a maximum of \$501,965/lane-mile. Table 5.2a provides the necessary thickness of Class 7 to achieve the proper structural number, while Table 5.2b summarizes the varying cost based on pavement structure and structural number. In this analysis, using the AHTD Roadway Design Guide, the Class 7 material had a layer coefficient of 0.14 while the asphalt concrete had a layer coefficient of 0.44.

Table 5.2a – Necessary thickness of Class 7 aggregate (inches)

Structural Number	Asphalt Concrete 2" thick	Asphalt Concrete 4" thick	Asphalt Concrete 6" thick
2.0	8.0	2.0	
2.5	12.0	5.5	
3.0	15.5	9.0	3.0
3.5	19.0	12.5	6.5

Table 5.2b – Cost of remove and replace

Structural Number	Asphalt Concrete 2" thick	Asphalt Concrete 4" thick	Asphalt Concrete 6" thick
2.0	\$264,106	\$303,089	
2.5	\$325,017	\$356,387	
3.0	\$378,314	\$409,684	\$448,668
3.5	\$431,611	\$462,981	\$501,965

Finally, for the FDR, the bulk specific gravity utilized for the performance tests for the emulsion and foam were directly measured in the lab, and the bulk specific gravity for the Portland cement was an average of the asphalt emulsion and asphalt foam (this was not measured in the lab). Based on the bulk specific gravity, the density of each highway section was calculated, which allowed for a calculation of the tons/1-inch depth/lane-mile. With the optimal emulsion, foam, and Portland cement content, the price of binder could be calculated, and then the cost of FDR for different depths was calculated. Four depths of FDR were explored, from 8.0" reclaimed depth to 12.0". While there is a significant range of layer coefficients for FDR, from 0.24 – 0.37, the most frequently used layer coefficient is 0.25. Table 5.3a – 5.3d show the cost of FDR for each highway section in dollars/lane-mile at four thicknesses.

Table 5.3a – AR 98 FDR Costs

		Asphalt Emulsion	Asphalt Foam	Portland Cement
	Optimum Content (%)	9.0	8.0	9.0
	Bulk Specific Gravity	1.966	1.981	1.9735
	Density (lb/ft^3)	123	124	123
	ton/inch/lane-mile	324	326	325
FDR Thickness (in)	Binder $/inch/lane-mile	11,364	10,178	4,220
8.0	$/lane-mile	137,059	127,574	79,903
10.0	$/lane-mile	159,787	147,931	88,342
12.0	$/lane-mile	182,515	168,288	96,781
14.0	$/lane-mile	205,243	188,645	105,221

Table 5.3b – AR 134 FDR Costs

		Asphalt Emulsion	Asphalt Foam	Portland Cement
	Optimum Content (%)	5.0	8.0	5.0
	Bulk Specific Gravity	2.097	1.98	2.0385
	Density (lb/ft^3)	131	124	127
	ton/inch/lane-mile	345	326	336
FDR Thickness (in)	Binder $/inch/lane-mile	6,734	10,173	2,421
8.0	$/lane-mile	100,019	127,533	65,518
10.0	$/lane-mile	113,487	147,880	70,361
12.0	$/lane-mile	126,955	168,226	75,204
14.0	$/lane-mile	140,423	188,573	80,047

Table 5.3c – AR 36 FDR Costs

		Asphalt Emulsion	Asphalt Foam	Portland Cement
	Optimum Content (%)	6.0	8.0	3.0
	Bulk Specific Gravity	2.096	2.041	2.0685
	Density (lb/ft^3)	131	127	129
	ton/inch/lane-mile	345	336	341
FDR Thickness (in)	Binder $/inch/lane-mile	8,077	10,487	1,474
8.0	$/lane-mile	110,763	130,041	57,941
10.0	$/lane-mile	126,917	151,014	60,889
12.0	$/lane-mile	143,071	171,987	63,838
14.0	$/lane-mile	159,224	192,961	66,786

Table 5.3d – AR 5 FDR Costs

		Asphalt Emulsion	Asphalt Foam	Portland Cement
	Optimum Content (%)	6.0	8.0	3.0
	Bulk Specific Gravity	2.091	2.054	2.0725
	Density (lb/ft^3)	130	128	129
	ton/inch/lane-mile	344	338	341
FDR Thickness (in)	Binder $/inch/lane-mile	8,058	10,553	1,477
8.0	$/lane-mile	110,609	130,575	57,964
10.0	$/lane-mile	126,724	151,682	60,918
12.0	$/lane-mile	142,839	172,789	63,872
14.0	$/lane-mile	158,955	193,896	66,826

5.4 Step 4 – Estimate User Costs

The forth step to an LCCA analysis is to estimate the user costs. Again, AHTD was contacted in order to establish the necessary information to calculate user costs. The first piece of information collected was the Average Daily Traffic, or ADT. Next, the speed limit and daily percent trucks were collected for each highway. Finally, the cost per hour of delay for both autos ($18/vehicle-hour) and trucks ($24-25/vehicle-hour) were provided. By multiplying the ADT by sixty divided by the speed limit, and then by the percentage of either autos or trucks, the average daily dollar vehicle per lane-mile was calculated. Table 5.4 shows the numbers used in the analysis.

Table 5.4 – Cost of Autos and Trucks on Four Highways

Highway	Average ADT	Average Speed Limit (mph)	Daily Percent Trucks	Average daily $ auto per mile	Average daily $ trucks per mile
98	310	55	5	$5,699	$400
134	396	43	35	$6,413	$4,608
36	3167	55	5	$58,219	$4,341
5	4460	55	9	$78,545	$11,004

Once the cost of vehicles on each highway was established, the time of each activity was estimated. In order to use a consistent source of data, the average production rates from Central Federal Lands Highway Division were utilized (CFLHD, 2009). Several assumptions had to be made for this analysis. First, it was assumed that there were complete lane closures, with no moving work zones. Second, when there were several tasks to be performed on the same section of road (for example, mill and fill requires milling then the placement of a surface course), the slowest process was assumed for the entire process. Then, an additional day was added for each additional process for the slowest process. Again, for mill and fill, it was estimated that the pavement could be milled at 0.56 lane-miles/day. However, after milling, a two-inch overlay is placed. However, for the sake of this estimation, it was assumed that the mill and fill operation would simply take two days to cover the 0.56 lane-miles. Third, FDR layers need time for the water to either evaporate or hydrate. It was assumed that the FDR emulsion takes two days to cure, FDR foam takes one day, and FDR cement takes six days. Using all of these assumptions, Table 5.5 shows the production rates.

Table 5.5 – Production Rates for Each Strategy

	Average Production (lane-miles/day)
Chip Seal	1.42
Two inch overlay	1.18
Mill and fill	0.28
Remove and Replace	0.13
FDR emulsion	0.25
FDR foam	0.38
FDR cement	0.11

The production rates in Table 5.5 were multiplied by the cost of autos on trucks on each highway to obtain to user costs in dollars/lane-mile. This data is summarized in Table 5.6. Note, because the reclamation process takes so much longer than placing a chip seal or a two-inch overlay, the user costs for each FDR technology was the same regardless of the surface placed.

Table 5.6 – User Costs for Each Strategy and Highway

Highway	98	134	36	5
Chip Seal	$4,294	$7,759	$44,042	$63,043
Two inch overlay	$5,189	$9,375	$53,218	$76,177
Mill and fill	$21,471	$38,795	$220,212	$315,213
Remove and Replace	$48,309	$87,288	$495,476	$709,229
FDR emulsion	$24,154	$43,644	$247,738	$354,615
FDR foam	$16,103	$29,096	$165,159	$236,410
FDR cement	$56,360	$101,836	$578,055	$827,434

5.5 Step 5 - Develop an Expenditure Stream Diagram

The fifth step to an LCCA analysis is to develop an expenditure stream diagram. This is simply a graphical representation of the cost of the roadway over time. Figure 5.2 shows the expenditure stream for Arkansas Highway 98 with a chip seal application every six years.

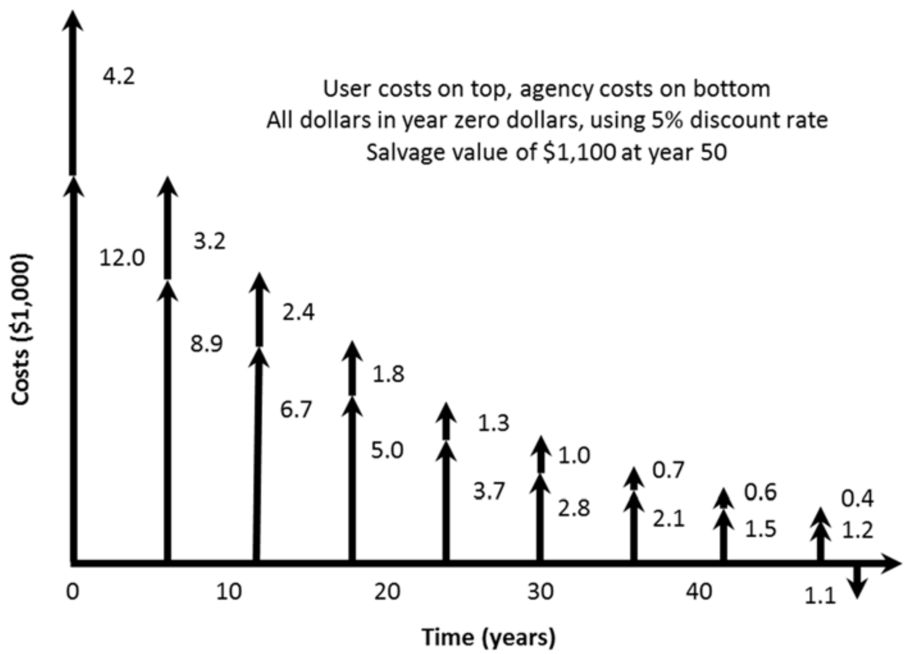

Figure 5.2 – Expenditure Stream for Chip Seal on Arkansas Highway 98

5.6 Step 6 – Calculate the Net Present Value

The sixth step to an LCCA analysis is to calculate the net present value. Table 5.7 shows the traditional maintenance and rehabilitation activities, including the initial price, the price of activities over the period of the roadway, and the maintenance necessary for the fifty year life. Note, Table 5.7 is only the agency costs. Again, it is assumed that the pavement structure is not compromised through the pavement's life, a chip seal is placed every six years, a two-inch overlay is placed every 11 years, and the discount rate is 5.0%. In addition, it is assumed that the reconstruction is maintained by performing a mill and overlay, which is most reasonable based on the quality of the pavement structure placed.

Table 5.7 - Agency Costs of Traditional Strategies for a 50 year design life ($/lane-mile)

	Chip Seal	**Two-inch overlay**	**Mill & overlay**	**Reconstruct (min, SN = 2.0)**	**Reconstruct (max, SN = 3.5)**
Year 0 Initial Price	$11,990	$65,175	$77,108	$264,106	$501,965
Year 6	$8,947				
Year 11		$38,107	$45,083	$45,083	$45,083
Year 12	$6,677				
Year 18	$4,982				
Year 22		$22,280	$26,359	$26,359	$26,359
Year 24	$3,718				
Year 30	$2,774				
Year 33		$13,027	$15,412	$15,412	$15,412
Year 36	$2,070				
Year 42	$1,545				
Year 44		$7,616	$9,011	$9,011	$9,011
Year 48	$1,153				
Year 50 Salvage value	$1,074	$5,985	$7,081	$23,388	$44,130
Net Present Value	$42,783	$140,220	$165,892	$336,583	$553,700

A similar analysis can be completed on the agency costs for the three different FDR technologies, with both a chip seal and a two-inch overlay as the surface course. For demonstration purposes, Table 5.8 and 5.9 show the calculation of the net present value on Arkansas Highway 98, with both a chip seal and an overlay as the surface course.

Table 5.8 - FDR Agency Costs, HWY 98 (75S:25R), with chip seal ($/lane-mile)

	Emulsion FDR		**Foam FDR**		**Cement FDR**	
	(min, SN = 2.0)	(max, SN = 3.5)	(min, SN = 2.0)	(max, SN = 3.5)	(min, SN = 2.0)	(max, SN = 3.5)
Year 0 Initial Price	$149,050	$217,233	$139,565	$200,635	$91,894	$117,211
6	$8,947	$8,947	$8,947	$8,947	$8,947	$8,947
12	$6,677	$6,677	$6,677	$6,677	$6,677	$6,677
18	$4,982	$4,982	$4,982	$4,982	$4,982	$4,982
24	$3,718	$3,718	$3,718	$3,718	$3,718	$3,718
30	$2,774	$2,774	$2,774	$2,774	$2,774	$2,774
36	$2,070	$2,070	$2,070	$2,070	$2,070	$2,070
42	$1,545	$1,545	$1,545	$1,545	$1,545	$1,545
48	$1,153	$1,153	$1,153	$1,153	$1,153	$1,153
Year 50 Salvage value	$13,026	$18,972	$12,199	$17,525	$8,042	$10,250
Net Present Value	$167,890	$230,128	$159,232	$214,977	$115,718	$138,828

Table 5.9 - FDR Agency Costs, HWY 98 (75S:25R), with two inch overlay ($/lane-mile)

	Emulsion FDR		**Foam FDR**		**Cement FDR**	
	(min, SN = 2.0)	(max, SN = 3.5)	(min, SN = 2.0)	(max, SN = 3.5)	(min, SN = 2.0)	(max, SN = 3.5)
Year 0 Initial Price	$162,460	$230,644	$157,125	$218,196	$130,310	$155,627
11	$38,107	$38,107	$38,107	$38,107	$38,107	$38,107
22	$22,280	$22,280	$22,280	$22,280	$22,280	$22,280
33	$13,027	$13,027	$13,027	$13,027	$13,027	$13,027
44	$7,616	$7,616	$7,616	$7,616	$7,616	$7,616
Year 50 Salvage value	$14,469	$20,415	$14,004	$19,329	$11,665	$13,873
Net Present Value	$229,021	$291,259	$224,151	$279,896	$199,675	$222,784

Similar calculations were performed for the other three highways in Arkansas, and the minimum FDR price and maximum FDR price was compared to the traditional methods using only agency costs. A summary of net present values is shown in Figure 5.3.

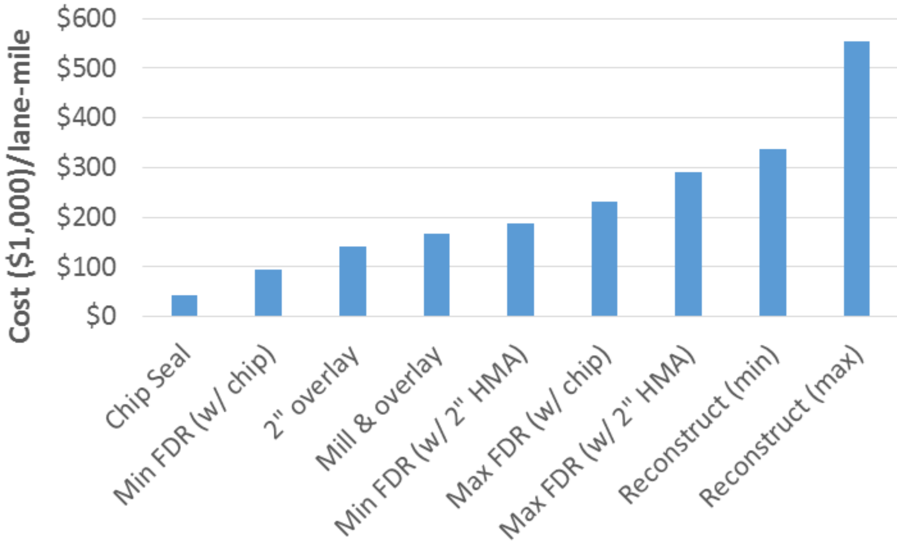

Figure 5.3 – Agency Costs for FDR and Traditional Strategies

In Figure 5.3, it is apparent that FDR is very competitive to traditional strategies used by AHTD. The lowest cost FDR treatment (FDR w/ chip; in this case, FDR with cement stabilization on Arkansas Highway 36 with an SN = 2.0), was quite cheaper than a two-inch overlay. However, even the most expensive FDR treatment (FDR w/ two-inch overlay; in this case, FDR with asphalt emulsion on Arkansas Highway 98 with an SN = 3.5) was less expensive from an agency cost than a full reconstruction with an SN = 2.0, and over half has much as a traditional full reconstruction with an SN of 3.5. In order to obtain a better understanding the agency costs of three FDR technologies, Figures 5.4 and 5.5 compare asphalt emulsion, asphalt foam, and Portland cement across the four highways with a chip seal and two-inch overlay.

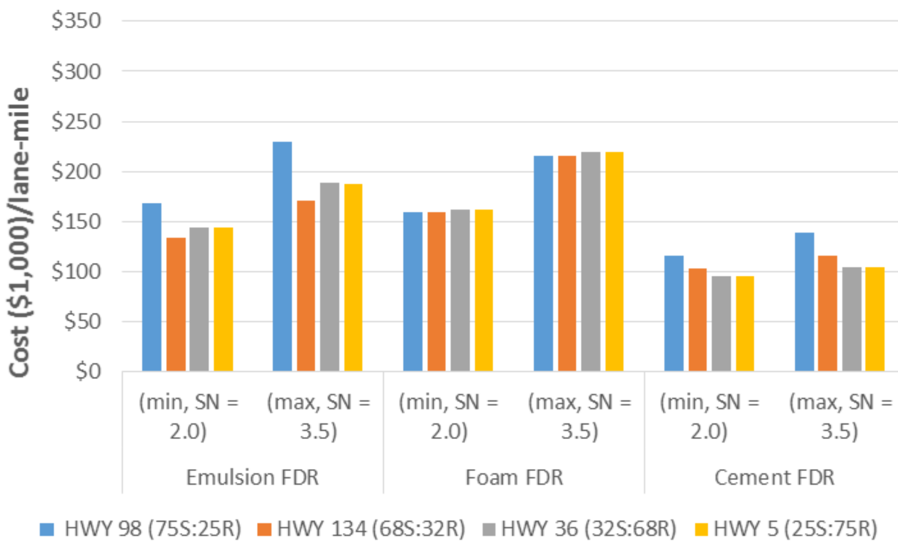

Figure 5.4 – Agency Costs for FDR with Chip Seal Surface Course

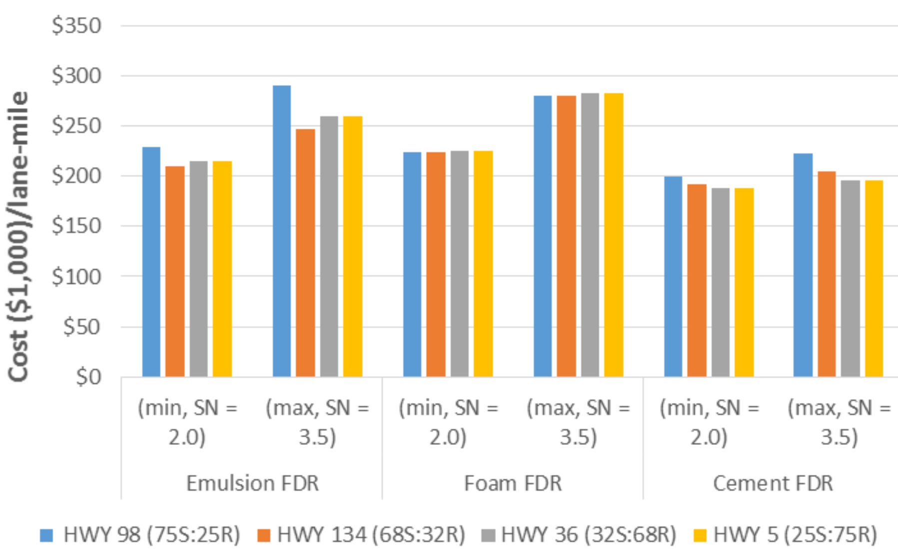

Figure 5.5 – Agency Costs for FDR with Two-Inch Overlay Surface Course

In Figures 5.4 and 5.5, several trends were apparent. First, asphalt foam is not sensitive to the ratio of bound material to in-place subgrade, as the costs does not vary across the four highways. Therefore, asphalt emulsion FDR tends to be a little more expensive with higher levels of subgrade (which is intuitive, as more asphalt emulsion is needed to coat the finer particles), but at lower levels of subgrade material, asphalt emulsion is actually less expensive than asphalt foam. It is also apparent that Portland cement is cheaper than both asphalt emulsion and asphalt foam from an agency perspective, but this brings into consideration the importance of user costs, as Portland cement FDR has a longer curing time. Using the same analysis as directly above for user costs, the net present value of agency costs plus user costs combined can be calculated. These calculations for each highway is shown in Figures 5.6a – 5.6d.

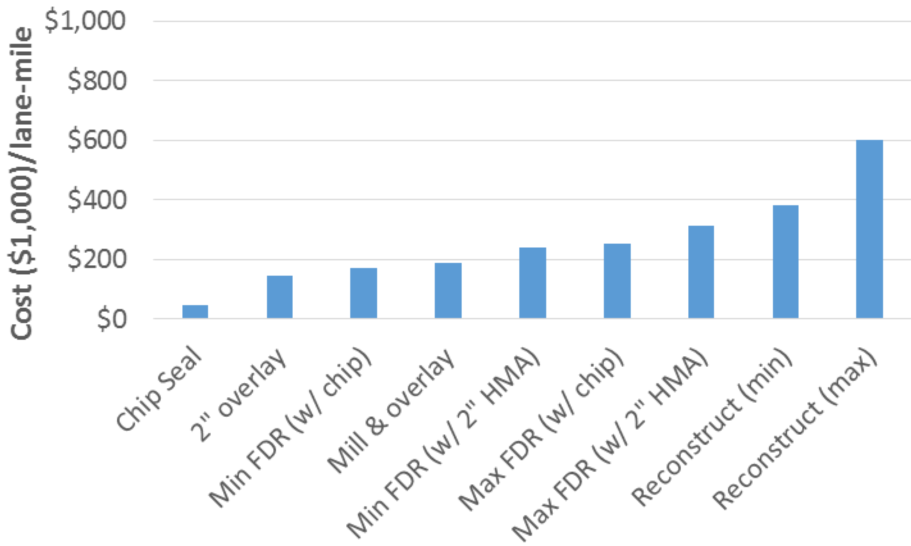

Figure 5.6a – Agency Costs and User Costs for FDR and Traditional Strategies for AR 98

In Figure 5.6a, it is apparent that FDR is very competitive to traditional strategies used by AHTD on Arkansas Highway 98. The lowest cost FDR treatment (FDR w/ chip; in this case, FDR with cement stabilization and an SN = 2.0), was similar in cost to a two-inch overlay looking at both agency and use costs. However, even the most expensive FDR treatment (FDR w/ two-inch overlay; in this case, FDR with asphalt emulsion and an SN = 3.5) was less expensive from an agency cost than a full reconstruction with an SN = 2.0, and over half has much as a traditional full reconstruction with an SN of 3.5.

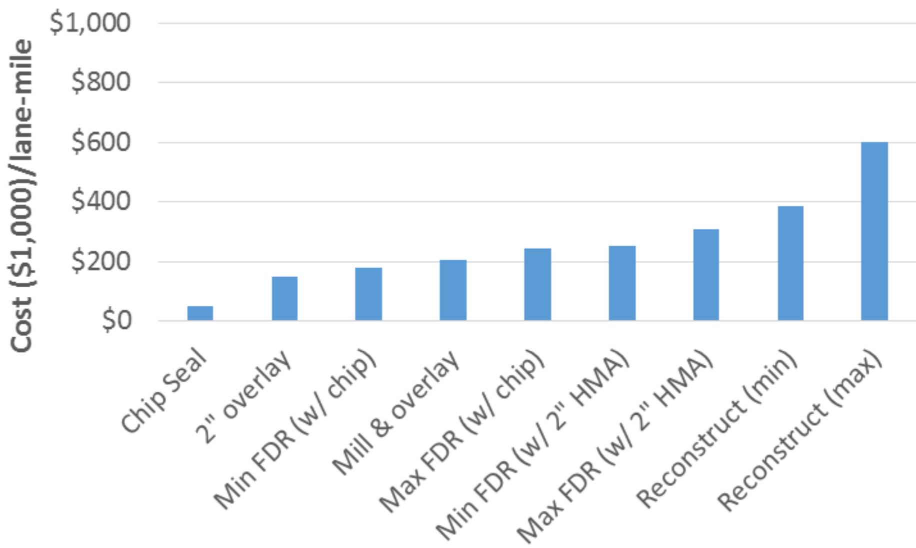

Figure 5.6b – Agency Costs and User Costs for FDR and Traditional Strategies for AR 134

In Figure 5.6b with a similar level of ADT but a much higher percentage of trucks, the lowest cost FDR treatment (FDR w/ chip; in this case, FDR with emulsion stabilization and an SN = 2.0), was quite cheaper than a two-inch overlay. However, even the most expensive FDR treatment (FDR w/ two-inch overlay; in this case, FDR with asphalt cement and an SN = 3.5) was less expensive from an agency cost than a full reconstruction with an SN = 2.0, and half has much as a traditional full reconstruction with an SN of 3.5.

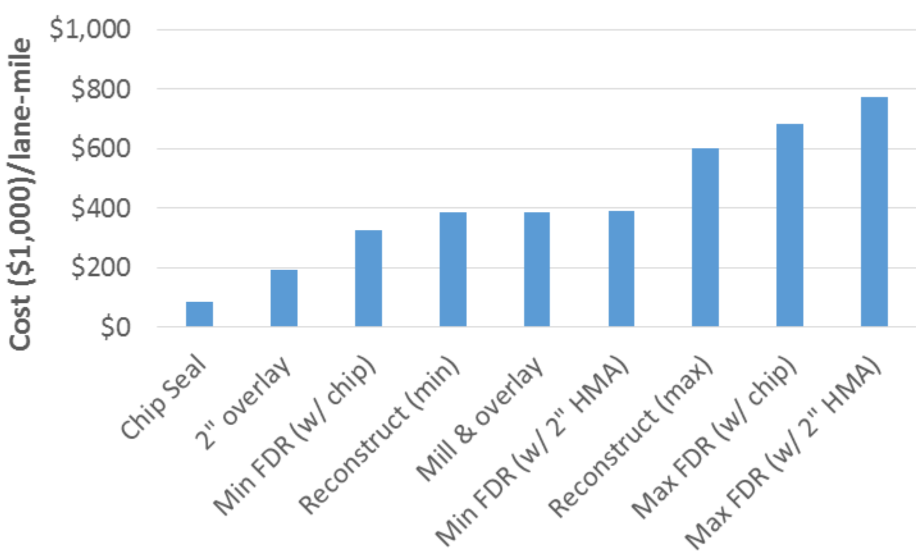

Figure 5.6c – Agency Costs and User Costs for FDR and Traditional Strategies for AR 36

In Figure 5.6c, as traffic increases significantly, the lowest cost FDR treatment (FDR w/ chip; in this case, FDR with foam stabilization and an SN = 2.0), was similar to a reconstruction or mill and overlay when consider both agency and use costs. Now, the most expensive FDR treatment (FDR with both a chip seal and a two-inch overlay; FDR with asphalt cement and an SN = 3.5) were the most expensive option. This clearly shows the importance of incorporating user costs into a LCCA.

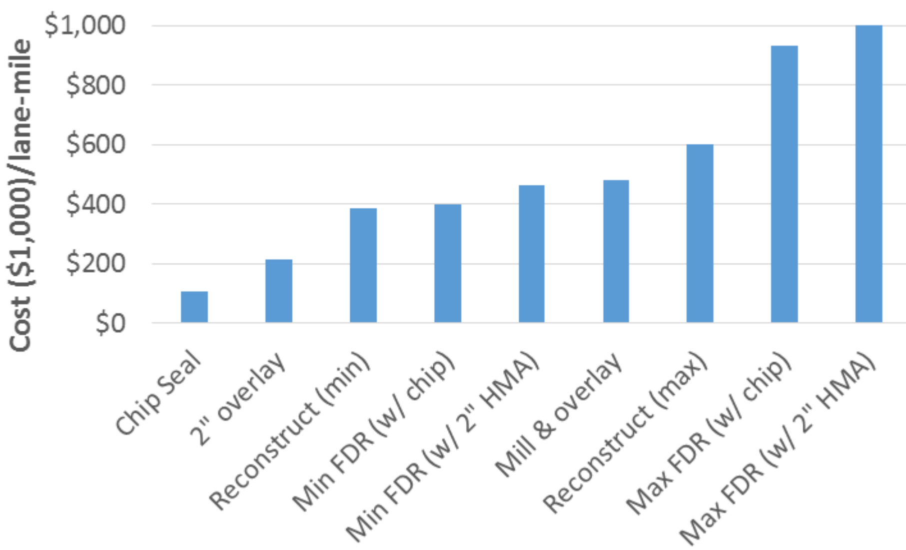

Figure 5.6d – Agency Costs and User Costs for FDR and Traditional Strategies for AR 5

Finally, in Figure 5.6d, there are very similar trends as seen in Figure 5.6c. FDR, in general, becomes less competitive than reconstructions and mill and overlays, on higher traffic sections.

The trends observed in Figure 5.6a – 5.6d are repeated in Figures 5.7 and 5.8, with the price of each agency plus user costs divided into specific technology and pavement structure. It is apparent that the cost of FDR with cement becomes quite a bit more expensive than asphalt emulsion and asphalt foam, as the user costs are quite a bit higher.

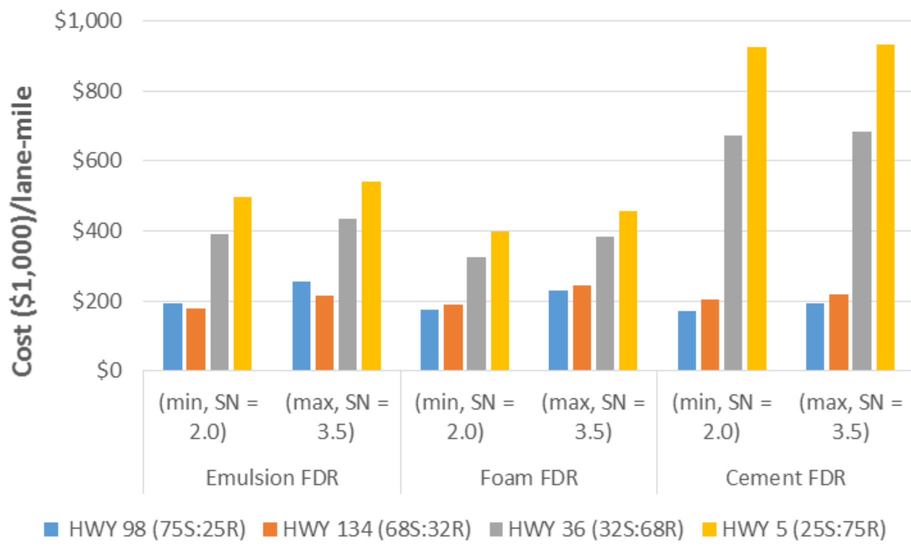

Figure 5.7 – Agency and User Costs for FDR with Chip Seal Surface Course

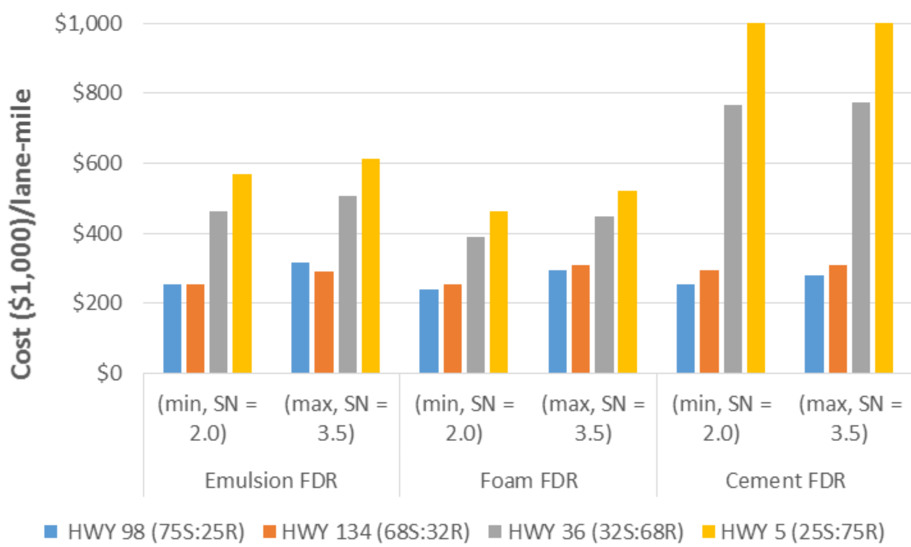

Figure 5.8 – Agency and User Costs for FDR with Two-Inch Overlay Surface Course

6.0 Recommended Equipment Needs

Note: this information is taken in most part from a Federal Highway Administration document titled "Full Depth Reclamation: Construction Methods and Equipment. No date or authors were found for this publication.

In general, there are four different potential procedures for placing Full-Depth Reclamation. Based on which of the four procedures utilized, different processes are necessary in order to complete the process. In short, these can be summarized by:

1. Pulverize bound material and unbound material with multiple and two step sequences
    a. Add and mix stabilizing agent
    b. Fine grade and compact
    c. Prime and place surface course
2. Rip and break up bound material surface
    a. Windrow material
    b. Pulverize bound and unbound material
    c. Add and mix stabilizing agents
    d. Fine grade and compact
    e. Prime and place surface course
3. Pulverize, add and mix stabilizing agent, place on grade with equipment train
    a. Compact
    b. Prime and place surface course
4. Pulverize, add and mix stabilizing agent, place on grade with single machine
    a. Compact
    b. Prime and place surface course

The equipment available for initial ripping or scarifying include a motor grader or a dozer with either front- or rear-mounted ripper teeth. This method is best for thinner bound material sections. After ripping, multiple pieces of equipment are available for size reduction or pulverization. First, rollers can be used for this step, including a sheep foot or grid roller. Second, a motor grader with ripper teeth and a cutter-crusher-compactor in the rear can be utilized. A third option would be a towed or self-propelled hammermill, or an impact breaker or preparator. The fourth and final piece of equipment would be a rotary mixer. These self-propelled, single-pass mixers have either a single or multiple transvers rotary shafts, each containing multiple mixing paddles.

For the two step sequence, the breaking, pulverizing, and sizing operations are combined together using a cold milling machine or a large pulverizing machine. The cold milling machine often includes a rotating drum lined with replaceable, tungsten-carbide-tipped cutting teeth, which grind the existing pavement. These machines have a strong degree of accuracy for cutting depth and can pulverize and size in a single pass, reducing traffic delays. If equipment with a pump and metering system, they can also serve as the mixing unit. A final benefit to the cold milling machine is they often have automatic grade and slope control, which cut down on post-leveling and grading of the reclaimed surface.

Curing or aeration of the mix is required to reduce the water content of the FDR material, which is especially important when using asphalt emulsion or asphalt foam. The material can be placed in a windrow after mixing, and then leveled to the proper slope with a motor grader. The motor grader can continue to aerate the mix by blading the mix back and forth across the roadway. This action helps stabilize the mix to support the weight of the compaction roller. The compaction can be done with a sheep foot, pneumatic-tired, and/or steel wheel roller, depending on the depth and density required of the FDR layer. The factors controlling the number of passes are the properties of the mix, lift thickness, type and weight of roller, and environmental conditions.

Once compaction is achieved, and enough water has evaporated, the surface course can be placed on the FDR layer. While traffic can drive directly on the FDR layer for short periods of time, it needs to be at a reduced speed and only if necessary to prevent excessive raveling. If a chip seal is placed on the FDR layer, extra emulsion will need to be placed as it is often absorbed into the FDR surface (more than a traditional asphalt concrete layer). If an asphalt concrete overlay is placed, a tack coat (with extra applicate rate) should be placed to ensure good bonding and full effectiveness of the pavement structure.

7.0 Conclusions

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.
- The Life Cycle Cost Analysis showed that FDR is very competitive economically to traditional maintenance and rehabilitation techniques.

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.

8.0 References

AASHTO T322, "Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device," American Association of State Highway and Transportation Officials, AASHTO, 2007.

AASHTO T342, "Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures," American Association of State Highway and Transportation Officials, AASHTO, 2011.

AASHTO TP105, "Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semi Circular Bend Geometery (SCB)," AASHTO, 2013

AHTD, "Arkansas State Highway and Transportation Department," 2015. [Accessed online April 2015]. Available: www.arkansashighways.com.

ARRA, "Full Depth Reclamation: A Century of Advancement for the New Millennium," Asphalt Recycling and Reclaiming Association, 2001.

ASCE, "2013 Report Card for America's Infrastructure," American Society of Civil Engineers, 2013.

Asphalt Academy, "Technical Guideline: Bitumen Stabilised Materials," TG 2, Second Edition, South Africa, 2009.

ASTM C702, "Standard Practice For Reducing Samples of Aggregate to Testing Size," ASTM International, 2003.

ASTM D698, "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort," ASTM International, 2012.

ASTM D1557, "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort," ASTM International, 2012.

ASTM D1633, "Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders," ASTM International, 2007.

ASTM D2041, "Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures," ASTM International, 2011.

ASTM D2419, "Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregates," ASTM International, 2009.

ASTM D3203, "Standard Test Method for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures," ASTM International, 2011.

ASTM D4318, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils," ASTM International, 2010.

ASTM D4867, "Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures," ASTM International, 2009.

ASTM D6752, "Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Automatic Vacuum Sealing Method," ASTM International, 2011.

Bemanian, S., Polish, P., Maurer, G. "Cold In-Place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of Practice," Transportation Research Record: Journal of the Transportation Research Board, No. 1949, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 54-71.

Chappat, M., Bilal, J. "Sustainable Development: The Environmental Road of the Future," Colas Group, 2003.

Coduto, D. "Foundation Design: Principles and Practices," 2nd Edition, Pearson Education, 2001.

Dai, S., and Thomas, T. "Response and Performance of Flexible Pavement Test Sections with Stabilized Full Depth Reclamation Base at MnROAD," Proceedings of Transportation Research Board, Washington, D.C., 2011.

Diefenderfer, B., Apeagyei, A. "Analysis of Full-Depth Reclamation Trial Sections in Virginia," Virginia Department of Transportation, FHWA/VCTIR 11-R23, 2011.

FHWA, "Test Method for Determining the Creep Compliance, Resilient Modulus and Strength of Asphalt Materials Using the Indirect Tensile Test Device," Protocol P07, Version 1.1, Federal Highway Administration, US Department of Transportation, 2001.

Geology.com, "Geology.com," [Accessed online April 2015].
Available: http://geology.com/cities-map/arkansas.shtml.

Gransberg, D. "Life-Cycle Cost Analysis of Surface Retexturing with Shotblasting as an Asphalt Pavement Preservation Tool," Transportation Research Record: Journal of the Transportation Research Board, No. 2108, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 46–52.

Guthrie, W., Scullion, T. "Interlaboratory Study the Tube Suction Test," FHWA/TX-03/0-4114-2, Texas Transportation Institute, June, 2003.

Harvey, J., Rezaei, A., Lee, C. "Probabilistic Approach to Life-Cycle Cost Analysis of Preventive Maintenance Strategies on Flexible Pavements," Transportation Research Record: Journal of the Transportation Research Board, No. 2292, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 61–72.

Hicks, R., and Epps, J., “Life Cycle Costs of Asphalt-Rubber Paving Materials,” Rubber Pavements Association, January, 1999.

Johnson, E., Watson, M., Olson, R., Moon, K., Turos, M., Marasteanu, M. "Recycled Asphalt Pavement: Study of High-RAP Asphalt Mixtures on Minnesota County Roads," MN/RC 2013-15, Minnesota Department of Transportation, May 2013.

Jones, D., Wu, R., Louw, S. "Comparison of Full Depth Reclamation with Portland Cement and Full Depth Reclamation with No Stabilizer in an Accelerated Loading Test," Transportation Research Record: Journal of the Transportation Research Board, No. 2462, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 126–135.

Kandhal, P., Mallick, R. "Pavement Recycling Guidelines for State and Local Governments - Participant's Reference Book," Federal Highway Administration, 1997.

Kearney, E., Huffman, J., "Full-Depth Reclamation Process," Transportation Research Record: Journal of the Transportation Research Board, No. 1684, Transportation Research Board of the National Academies, Washington, D.C., 1999, pp. 203-209.

Kim, M., Mohammad, L., Elseifi, M. "Characterization of fracture properties of asphalt mixtures as measured by semicircular bend test and indirect tension test," Transportation Research Record: Journal of the Transportation Research Board, No. 2296, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 115-124.

Kim, Y., Seo, Y., King, M., Momen, M. "Dynamic Modulus Testing of Asphalt Concrete in Indirect Tension Mode," Transportation Research Record: Journal of the Transportation Research Board, No. 1891, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 163-173.

Lee, E., Kim, C., Harvey, J. “Selection of Pavement for Highway Rehabilitation Based on Life-Cycle Cost Analysis,” Transportation Research Record: Journal of the Transportation Research Board, No. 2227, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 23–32.

Lewis, D., Jared, D., Torres, H., Mathews, M. "Georgia's Use of Cement-Stabilized Reclaimed Base in Full-Depth Reclamation," Transportation Research Record: Journal of the Transportation Research Board, No. 1952, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 125-133.

Luhr, D., Adaska, W., Halsted, G. "Guide to Full-Depth Reclamation (FDR) with Cement," Portland Cement Association, Skokie, Illinois, 2008.

Morian, D., Solaimanian, M., Scheetz, B., Jahangirnejad, S. "Developing Standards and Specifications for Full Depth Pavement Reclamation," Pennsylvania Department of Transportation, FHWA-PA-2012-004-090107, 2012.

NCAT. “New Recommendations for Calculating Salvage Value in Life-Cycle Cost Analysis,” Asphalt Technology News, National Center for Asphalt Technology (NCAT), Vol 25, No 2, Fall 2013, pp. 12-13.

NCDOT. “Asphalt Emulsion Full Depth Reclaiming and Stabilization,” North Carolina Department of Transportation, Standard Specifications, Section 612, 2012.

Pittenger, D., Gransberg, D., Zaman, M., Riemer, C. “Stochastic Life-Cycle Cost Analysis for Pavement Preservation Treatments,” Transportation Research Record: Journal of the Transportation Research Board, No. 2292, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 45–51.

Sakhaeifar, M., Brown, E., Tran, N., Dean, J. “Evaluation of Long-Lasting Perpetual Asphalt Pavement with Life-Cycle Cost Analysis,” Transportation Research Record: Journal of the Transportation Research Board, No. 2368, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 3–11.

Scullion, T., Guthrie, S., Sebesta, S. "Field Performance and Design Recommendations for Full Depth Recycling in Texas," Texas Transportation Institute, FHWA/TX-03/4182-1, 2003.

Scullion, T. "Full Depth Reclamation: Workshop Materials," Texas A&M Transportation Institute, College Station, TX, 2012.

Soils & Recycling Services, "Full Depth Reclamation / FDR," [Accessed online September 2013]. Available: http://www.arscompanies.com/fdr.php.

Swei, O., Gregory, J., Kirchain, R. “Probabilistic Characterization of Uncertain Inputs in the Life-Cycle Cost Analysis of Pavements,” Transportation Research Record: Journal of the Transportation Research Board, No. 2366, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 71–77.

Thomas, T., May, R. "Mechanistic-Empirical Design Guide Modeling of Asphalt Emulsion Full Depth Reclamation Mixes," in Proceedings of the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., 2007.

Underwood, S., Ashouri, M., Kim, Y. "Effect of Dynamic Modulus Measurement Protocol on Predicted Pavement Performance," Journal of the Association of Asphalt Paving Technologists, Vol. 80, pp. 65-99, 2011

Walls, J., Smith, M. “Life-Cycle Cost Analysis in Pavement Design — Interim Technical Bulletin,” FHWA-SA-98-0079, Federal Highway Administration (FHWA), September 1998.

Whiteley, L., Tighe, S., Zhang, Z. “Incorporating Variability into Pavement Performance, Life-Cycle Cost Analysis, and Performance-Based Specification Pay Factors,” Transportation Research Record: Journal of the Transportation Research Board, No. 1940, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 13–20.

Wirtgen, "Cold Recycling: Wirtgen Cold Recycling Technology," Wirtgen Group, Windhagen, Germany, 2012.

Yu, H., Shen, S. "An Investigation of Dynamic Modulus and Flow Number Properties of Asphalt Mixtures in Washington State," Transportation Northwest (TransNow), TNW2012-02, Research Project Agreement No. 709867, May, 2012.