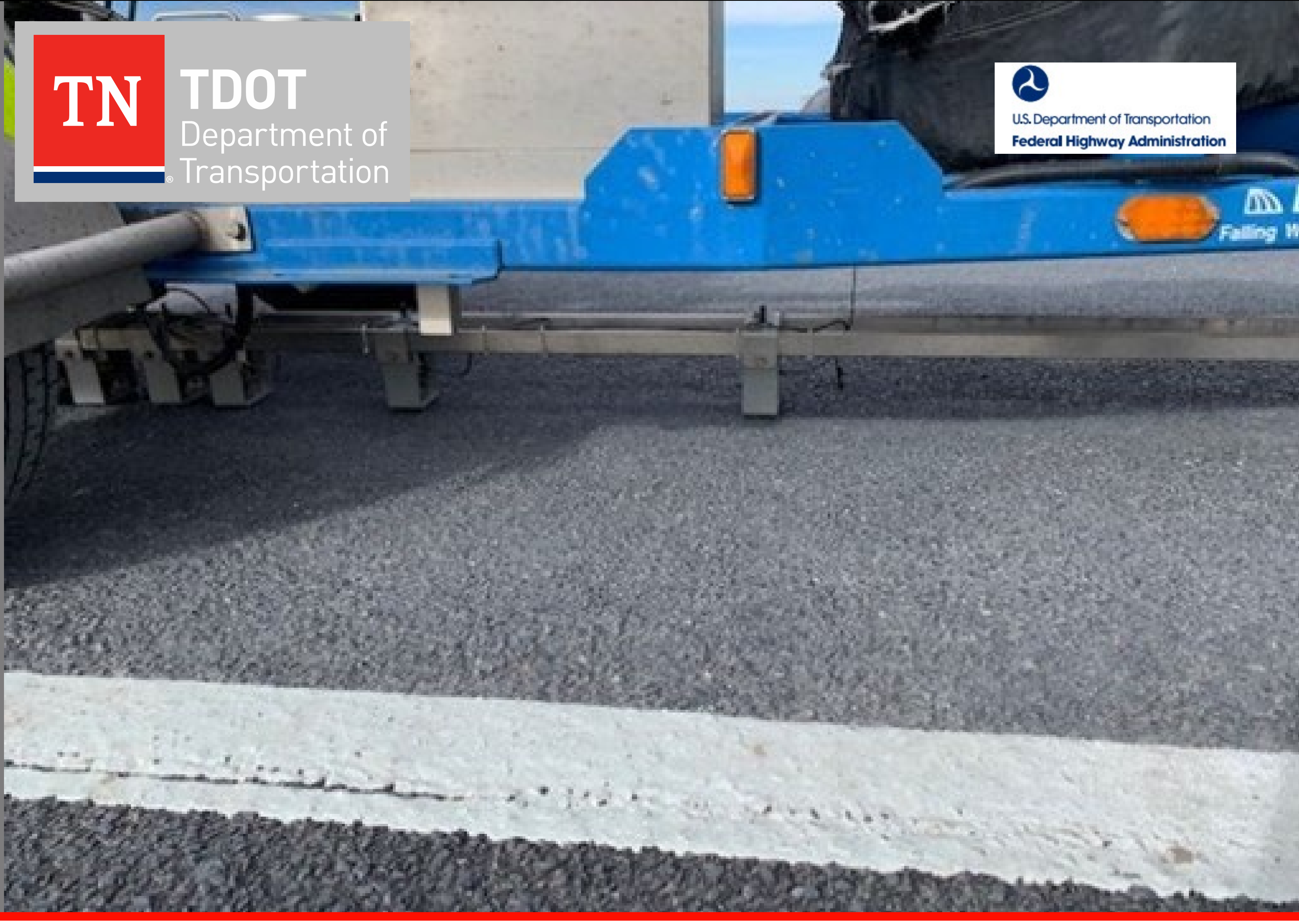

Performance Evaluation of Full Depth Reclaimed (FDR) Pavements in Tennessee

Research Final Report from University of Tennessee at Chattanooga | Joseph Owino (PI), Mbakisya Onyango (Co-PI) Weidong Wu (Co-PI), Ignatius Fomunung (Co-PI), Heather Brown (Co-PI) and Odia Dumbiri (GA), Kelvin Msechu (GA) | March 31, 2022

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DISCLAIMER

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16. Abstract

This research was conducted by the University of Tennessee at Chattanooga (UTC) and Middle Tennessee State University (MTSU) in collaboration with Tennessee Department of Transportation (TDOT) and this report summarizes the research effort accomplished the objectives of TDOT Research solicitation RES2020-11 "Performance Evaluation of Full Depth Reclaimed (FDR) Pavements in Tennessee". To achieve the objective, several activities have been performed: recommend criteria to select appropriate FDR treatment process; develop mix design procedures to determine to determine the stabilization agent content for FDR; study two FDR case studies in Lauderdale County and Weakley County; and develop a selection criterion to identify suitable FDR candidates.

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Executive Summary

This research was conducted by the University of Tennessee at Chattanooga (UTC) and Middle Tennessee State University (MTSU) in collaboration with Tennessee Department of Transportation (TDOT) and this report summarizes the research effort accomplished and the objectives of TDOT Research solicitation RES2020-11 “Performance Evaluation of Full Depth Reclaimed (FDR) Pavements in Tennessee”. To achieve the objectives, several activities have been performed: (1) recommended criteria to select appropriate FDR treatment process; (2) developed mix design procedures to determine the stabilization agent content for FDR; (3) evaluated two FDR case studies in Lauderdale County and Weakley County; and (4) developed a selection criterion to identify suitable FDR candidates.

Full-Depth Reclamation has emerged as a viable pavement rehabilitation technique that is gaining widespread acceptance to restore old and distressed asphalt pavements. This increasing interest is due to several factors: information on the long-term performance of stabilized FDR; improved and reliable equipment; the pavement section returns to service almost immediately; cost savings associated with the technique in comparison to other rehabilitation techniques; and sustainability. In its most basic form, FDR consists of in-situ pulverization of deteriorated pavement and underlying layers, uniform blending of pulverized material, grading, and compaction to produce a homogeneous stabilized base course, usually with addition of materials to improve the quality and capacity of the stabilized base. Some counties in Tennessee have had some experiences with FDR in mostly low volume roads like Weakley County and Rutherford County; other counties are just getting started with FDR while others have no experience at all with FDR.

A comprehensive literature review was conducted to evaluate the current practices of FDR techniques in other states that have used FDR as a technique to rehabilitate distressed pavements. To this end, an online survey was conducted to gather information on best practices of FDR from State DOT’s. The survey was conducted in two phases with questions focusing on experiences with and implementation of FDR. Phase 1 of the survey contains responses from 41 states in the United States, and phase 2 of the survey focused on county engineers in the state of Tennessee.

After compiling the results of the online survey, the study embarked on mix design procedures (including laboratory procedures) for two pavement sections in Tennessee. The sites were State Route (SR) 88 in Lauderdale County and SR 54 in Weakley County. For both pavement sections, mix designs were conducted using Portland cement and asphalt emulsion as stabilizing agent. For SR 88, the decision was made to use Portland cement as the stabilizing agent. SR 88 was bid and rehabilitated in 2021. After construction of SR 88, post-construction assessment was conducted using a falling weight deflectometer test to assess the condition of the new pavement section. SR 54 was bid, but construction has not yet commenced as of now. In addition to compiling mix design procedures, the research team was tasked with developing a robust technique for identifying potential FDR candidates.

Key Findings

The following were the key finding that were observed in this research.

- Portland cement and asphalt emulsion are the two most common stabilizing agents used in FDR in the United States.
- Cement stabilization was less effective in improving the structural capacity of pavement sections with a deep asphalt layer than sections with shallow asphalt layers.
- Cement stabilization was ineffective for materials with 100% RAP content.
- Asphalt emulsion worked well as a stabilizing agent for reclaimed materials of varying RAP contents including 100% RAP content.
- As the RAP content in the reclaimed materials increased, the emulsion content needed for effective stabilization decreased.

Key Recommendations

- Auger sampling can be used for material collection for purposes of mix design preparation. This will result in faster material retrieval and the creation of holes that would cost less to fill.
- A falling weight deflectometer (FWD) serves as an important tool for FDR pavement candidate selection and should be effectively used in addition to core sampling and visual inspection.
- Time should be allowed for possible shrinkage to occur due to curing after construction when using Portland cement as a stabilizing agent before placing a wearing course on the newly constructed pavement. This will reduce the possibility of cracks due to shrinkage reflecting through the wearing course.
- Low cement dosage is recommended to minimize cracks.

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Glossary of Key Terms and Acronyms

FDR	Full Depth Reclamation
FWD	Falling Weight Deflectometer
AASHTO	American Association of State Highway and Transportation Officials
AEFDR	Asphalt Emulsion Full Depth Reclamation
PCFDR	Portland Cement Full Depth Reclamation
AC	Asphalt Concrete
ARRA	Asphalt Recycling and Reclaiming Association
AADTT	Average Annual Daily Truck Traffic
AADT	Average Annual Daily Traffic
HMA	Hot Mixed Asphalt
IRI	International Roughness Index
PCA	Portland Cement Association
MEPDG	Mechanistic Empirical Pavement Design Guide
TDOT	Tennessee Department of Transportation
RAP	Reclaimed Asphalt Pavement
UCS	Unconfined Compressive Strength
SGA	Superpave Gyratory Compactor
OMC	Optimum Moisture Content
SFDR	Stabilized Full Depth Reclamation
NDT	Non-Destructive Test
HIR	Hot in-place Recycling
CIR	Cold in-place Recycling
CKD	Cement Kiln Dust

Chapter 1 Introduction

Full-Depth Reclamation (FDR) is a rehabilitation technique that consists of pulverizing an existing asphalt pavement and its unbound underlying base, subbase and/or subgrade of a failed asphalt pavement. After pulverization, a stabilizing agent (aggregates, asphalt, lime, or Portland cement) is usually added to enhance the structural properties of the materials and the harmful effect of moisture is mitigated. The stabilized material is then compacted, and a new rigid or flexible wearing surface course is finally applied to complete the FDR process [1]. The depth of pulverization can range from 4 to 12in. [2] depending on the thickness of the bound layers.

Selection of stabilizing agents is driven by several factors: price, availability, effectiveness, and policy (certain agents are more effective in certain applications). In general, bituminous stabilizing agents are recommended when pulverizing materials that consist of large particles (from sand to gravel) while cementitious stabilizing agents are recommended for the entire AASHTO Classification System [3]. The use of lime is recommended when the pulverizing materials consist of silt and clay and where the plasticity index is greater than 10 [4]. Several researchers have noticed that after application of some stabilizing agents, reflective cracks developed [5] [6].

Many State DOT's have employed in-place recycling techniques to varying degrees, with reports of tremendous improvements in the structural capacity immediately after construction [7] [8] [9]. Many studies have investigated and developed engineering standards on material characterization and laboratory mix designs and options for selecting appropriate stabilizing agents [10] [11] [12].

1.1 Problem Statement

A detailed research study was conducted to develop guidelines, standards, and specifications for TDOT for the purpose of using Full-Depth Reclamation (FDR) as a viable pavement rehabilitation technique. A wide variety of maintenance and rehabilitation techniques are available and have been used to rehabilitate worn out and distressed pavements. FDR is one of the major rehabilitation techniques available to restore pavements that have deteriorated and distressed to the levels requiring major work.

In its simplest form, FDR consists of in-situ pulverization of existing pavement and underlying layers, uniform blending of pulverized material, grading, and compaction. FDR recycles 100% of the distressed asphalt pavement to form a strong base course with addition of certain materials to improve the quality and capacity of the stabilized base. Three common types of stabilization methods are: (a) mechanical stabilization (addition of aggregates), (b) chemical stabilization (e.g., addition of cement) and (c) bituminous stabilization (e.g., addition of asphalt binder). The type of FDR construction is selected based on the existing pavement condition, locally available materials, and traffic demand. For this research, two specific stabilizing agents, have been studied: Portland cement and emulsified asphalt.

FDR has become an increasingly common technology in recent years to restore the service life of pavement structures requiring deep rehabilitation and to stretch available funding for pavement rehabilitation. Several factors contribute to this interest including improved equipment, stabilization technology, sustainability, and costs relative to more conventional rehabilitation strategies. Despite the increasing use of FDR, questions still linger regarding the behavior of the stabilized materials and their long-term performance under traffic loads.

Many State DOTs have successfully used FDR to mitigate distressed pavements and restored structural integrity. TDOT has conducted a limited number of FDR demonstration projects with varying results, but need to organize and consolidate information about FDR, with the objective of producing an implementable set of guidelines, criteria, and specifications on the FDR related projects.

1.2 Objective of the Research

The objectives of this research project were to:

1. Review and suggest criteria for selecting the appropriate treatment process (mechanical, chemical, or bituminous) of FDR for a given pavement condition.
2. Study the state of FDR in the United States and in the State of Tennessee with the aid of questionnaires.
3. Develop an FDR mix design procedure to determine the stabilization agent content for FDR pavements.
4. Recommend selection criteria for identifying suitable FDR candidate pavements.

1.3 Scope of Work

The scope of this project included:

1. An extensive research review to establish current DOT practices in Full-Depth Reclamation.
2. Developing and deploying a survey to state DOT to establish the current state of practice in FDR.
3. Summarizing the results of the questionnaire.
4. Selecting appropriate additive stabilizing agents (mechanical, chemical, or bituminous) to be further investigated for adoption in TDOT for different types of roadways.
5. Recommending changes, if any, on TDOT construction guidelines and specifications for FDR pavements for the state of Tennessee.
6. Providing and submitting to TDOT a finalized technical report on pavement design guide, FDR mix design and selection criteria for candidate pavement for FDR.

1.4 Organization of Report

Chapter 2 discusses relevant literature review of mix design procedures and construction techniques of FDR projects used by various state DOT’s. This chapter also includes the state of the matter of FDR in the state of Tennessee. Chapter 3 summarizes the results of the survey of State DOTs regarding mix design, construction techniques and problems encountered during and after rehabilitation of the pavement using FDR. Chapter 4 discusses the development of the best practices using two FDR pilot projects in the state of Tennessee. Chapter 5 presents the summary of findings and discussions. Chapter 6 presents conclusions, remarks, and recommendations. Chapter 6 is followed by references and relevant appendices cited throughout the report.

Chapter 2 Literature Review

The strength gained by a newly rehabilitated FDR pavement base depends on different factors including the reclaimed material proportions, the type and nature of the base and subgrade materials, the mix gradation, the environmental condition, and the type of stabilization agent used for the rehabilitation. It is noteworthy that FDR base can be mechanically stabilized without the use of any recycling agents. The resulting base from a mechanically stabilized FDR pavement can be equated to an unbound pavement base, and the process does not necessarily require a mix design as it uses the Reclaimed Asphalt Pavement (RAP) materials and sometimes includes the addition of virgin aggregates to improve material gradation [13]. The compacted mix of crushed RAP with higher load bearing capacity and existing base materials gives a new unbound homogeneous base material capable of resisting more wheel load compared to the existing base layer. Using a chemical or bituminous stabilizing agent improves on this property of the rehabilitated road.

The selection of recycling method is based on many factors including the present condition of the pavement. This also applies to the selection of stabilizing agents for FDR. While rehabilitating deteriorated roads based on present condition yields good improvements on the efficiency and structural capacity of the pavement, future projections of the road condition would be beneficial in the decision-making process for long-term functionality. Maximum utilization of resources for FDR can be achieved by following selection guides or/and laboratory testing protocols to determine suitability of the stabilizing agent on the present condition of the road and the future projection of the road usage [14].

Getting the most benefit from an FDR mix depends a lot on the choice of stabilizing agent used for the project. The stabilization agent affects more than just the structural capacity of the rehabilitated pavement, it affects the mechanical properties, the life expectancy of the pavement and importantly, the cost of rehabilitation.

2.1 Stabilization Using Portland Cement

Advantages of FDR bases stabilized with Portland cement (PCFDR) include its long-term durability and the versatility PCFDR offers on varying load applications and environmental conditions. Lewis et al. demonstrated a cost saving of 42% on a GDOT project using cement stabilization [14].The Portland Cement Association (PCA) estimates agencies that use the FDR process save 30% to 60% in costs over alternative reconstruction methods [15].

Stabilization with Portland cement is usually best suited for all volumes traffic showing severe distress has been caused by heavy traffic and or subgrades with insufficient strength. In addition, severely deteriorated pavements that would require total reconstruction are good candidates for PCFDR. Placement of FDR with cement can be performed in a shorter timeframe saving on labor and road closure costs.

Cement can be placed in dry powder form or in a cement and water slurry. This research study just tested dry powder form however, the placement of slurry can be applied the same as dry powder or injected under the hood of the reclaimer. Slurry can be applied with a concrete ready mixed truck and is not affected by wind during placement. Attention to water content would be similar for both dry powder and slurry to ensure proper compaction and density.

2.2 Stabilization Using Bituminous Agents

2.2.1 Emulsified Asphalt

FDR bases stabilized with asphalt emulsions (AEFDR) demonstrate improved strength and reduced susceptibility to water permeating the void content, more like those of aggregate bases than asphalt concrete [16]. Much like cement-stabilized FDR base, stabilization with emulsified asphalt aims to optimize the moisture content and the asphalt content of the mix. Design guidelines provided by the Asphalt Recycling and Reclaiming Association (ARRA) covers practices adopted for the preparation of emulsified asphalt mix design for FDR [17].

2.2.2 Foamed Asphalt

Foamed asphalt is a thin-film asphalt binder with a high coating capability, which is made by combining cold water with hot asphalt binder. The result of the combination vaporizes the water, and the steam produced is trapped in the asphalt binder creating bubbles of asphalt [18]. Preparing an FDR mix design with foamed asphalt follows eight major steps outlined in a publication for the California Department of Transportation by the University of California [19].

2.3 Other Stabilization Agents

2.3.1 Calcium Chloride Stabilization

The use of calcium chloride as a stabilizer for FDR provides the benefit of a stabilized base that retains maximum density and optimum moisture content for a longer time. Calcium chloride is a hygroscopic deliquescence material with low vapor pressure and high surface tension. Calcium chloride does more than just control moisture in a mix, it also is effective in reducing frost heaving in the mix by depressing the freezing point of capillary water [20].

2.3.2 Lime and Quicklime Stabilization

The benefits of using lime as a stabilization agent as given by the National Lime Association include long-lasting gains in strength, improved resilient modulus, shear strength and stability, reduced plasticity, and moisture holding capacity [22]. Range on lime content used for different construction projects has been dependent on the local conditions, design target and experience. The ARRA recommended that when used as a slurry, lime slurry should contain at least 30% of dry solid content and should conform to the standards established in AASHTO M 216 or ASTM C997 [23].

2.4 Critical Factors Affecting the Performance of FDR

2.4.1 Climatic and Environmental Factors

The impacts of environmental factors on FDR are always present during an FDR project from the time of construction, through the life of the project. During construction, factors like sunshine, wind, rainfall, seasonal water table can alter important parameters in the mix design especially moisture content and mixability. Dry stabilizing media like cement and lime are particularly susceptible to wind impact during construction as the wind can blow the particles away from the target areas during spreading [24].

Table 2.1 Summary Table of Material Type Using Various Stabilizing Agents [15]

Material type including RAP	USCS[2]	AASHTO[3]	Emulsified asphalt SE>30 or PI<6 and P_{200} <20%	Foamed asphalt PI < 10 and P_{200} 5 to 20%	Cement, CKD, or self-cementing class C fly ash PI < 20 SO_4 < 3000 ppm	Lime/LKD PI > 20 and P_{200} > 25% SO_4 <3000 ppm
Well graded gravel	GW	A-1-a	Y	Y	Y	
Poorly graded gravel	GP	A-1-a	Y		Y	
Silty gravel	GM	A-1-b	Y	Y	Y	
Clayey gravel	GC	A-1-b A-12-6	Y	Y	Y	
Well graded sand	SW	A-1-b	Y	Y	Y	
Poorly graded sand	SP	A-3 or A-1-b	Y		Y	
Silty sand	SM	A-2-4 or A-2-5	Y	Y	Y	
Clayey sand	SC	A-2-6 or A-2-7			Y	Y
Silt, silt with sand	ML	A-4 or A-5			Y	
Lean clay	CL	A-6			Y	Y
Organic clay/organic lean clay	OL	A-4				
Elastic silt	MH	A-5 or A-7-5				Y
Fat clay, fat clay with sand	CH	A-7-6				Y

Table 2.1 summarizes the relationship between suggested stabilizing agents and existing material classification. Pavement damage, both in flexible pavement and in rigid pavement, can occur from expansion and contraction of pavement and slab curling (for rigid pavement). Asphalt concrete is very susceptible to heat, and as such, its stiffness increases in cold temperature but reduces as temperature rises, increasing the tendency of rutting. As the temperature increases, so does the viscoelasticity of the asphalt emulsion FDR. At higher temperatures, this could pose a problem in the pavement base especially when the reclaimed material has a high RAP content. Portland cement concrete also has its susceptibility to temperature variations, and this can also be an issue for Portland cement-stabilized FDR. The contractions and expansions from the cement-stabilized base can generate transverse cracking, slab curling in cases of varying rate of expansion, and contraction between top and bottom layers of the rehabilitated base. Unlike many PCC slabs that are built with expansion joints, cement-stabilized FDR is constructed monolithically, and even though the materials are reclaimed and composite with a lower cement

content than PPC slabs, micro expansions from sections of the slab can still cause significant damage in the road [24].

The impact of the freeze-thaw cycle affects both Portland cement and asphalt stabilized bases adversely. Temperatures reduced to freezing point can induce thermal cracking in the pavement although lower temperatures increase the stiffness of an asphalt-stabilized base. The thaw season subjects the layer to settling as the pavement comes under load while the entrapped frozen moisture melts away. The repeated expansion in the freeze season and contraction/settling in the thaw season induces fatigue cracking and rutting, reducing the overall functionality of the pavement [25].

2.4.2 Structural and Material Factors

The strength gained by the newly rehabilitated FDR pavement base depends on different factors including the reclaimed material proportions, the type and nature of the base and subgrade materials, the mix gradation, the environmental condition, and the type of stabilization agent used for the rehabilitation. In its most basic form, an FDR base can be mechanically stabilized (without the use of any recycling agents). The resulting base from a mechanically stabilized FDR pavement can be likened to an unbound pavement base, and the process does not necessarily require a mix design as it uses the RAP materials, and sometimes includes the addition of virgin aggregates, to improve material gradation [26]. The compacted mix of crushed RAP with higher load bearing capacity and existing base materials gives a new unbound homogeneous base material capable of resisting more wheel load compared to the existing base layer. Using chemical or bituminous stabilizing agents improves on this property of the rehabilitated road. Portland cement creates better bonding between the aggregate particles in the rehabilitated base, increasing the rigidity of the base and its resistance to deformation from traffic load. FDR base stabilized with Portland cement exhibits reduced deflection from wheel load due to the rigidity created from the cement component. As it is a property of cement, using too much Portland cement content in the FDR tends to make the FDR base brittle and increases the possibility of cracking. Bituminous stabilization gives FDR a flexible base that binds the reclaimed materials tightly and deflects with the wheel load. The effectiveness of bituminous stabilized base and Portland cement stabilized base varies with the pavement characteristics and material compositions. Fly ash, lime and calcium chloride all improve the FDR base by improving the density, improving the water resistivity of the base.

Also, the avoidance of deleterious materials, especially one containing high clay content in FDR, is essential for the adequate performance. The ARRA and the PCA have published recommendations for material gradation for FDR. The recommendations conclude that materials to be reclaimed for FDR should have a minimum of 20% passing the #200 sieve [26] [27]. This is drawn from the fact that high proportions of fine particles in the reclaimed materials increases the total area needed for bonding between the particles which increases the quantity of stabilizing agents and the overall cost of rehabilitation. Aside the increase in rehabilitation cost, the presence of excessive fine particles has impacts on the overall structural dependability [28], increasing the probability of the particles moving under heavy traffic load leading to the development of pavement rutting.

2.5 Factors in FDR Project Selection

Different State DOTs have different considerations when selecting suitable candidates for FDR, as some pavement distresses can be effectively rehabilitated with other techniques. Identifying the type(s) of distresses and failures associated with the pavement is a first step in selecting pavement candidates for FDR. Pennsylvania Department of Transportation (PennDOT) [29] detailed steps adopted in FDR pavement candidate selection and developed a selection guide (Table 2.2) to aid in determination of the suitability of FDR as rehabilitation technique. As will be discussed in Chapter 3 of this report, different strategies reported by respondents to the survey are utilized for the selection of FDR pavement candidates. These include visual inspection, taking core samples and using machines like the falling weight deflectometer, dynamic cone penetrometer and others for pavement structural and sub-terranean properties. The survey revealed that most popular techniques for most DOT's are taking core samples and visual inspection.

2.5.1 Pavement Distresses and Failure

Visual inspection reveals all pavement distresses visible such as cracking, surface deformation, disintegration, and/or defects. The type of distress observed on the surface and the degree of deterioration gives an idea of where the source of the defect could be located (surface, base, subgrade) [30]. Distresses like potholes, raveling, asphalt bleeding and polishing, which have their sources on the surface, could be rehabilitated with resurfacing and asphalt overlay provided the pavement base layer is unaffected. Cold In-place Recycling (CIR) could be an effective used as a rehabilitation solution for pavement surface defects and surface distresses like alligator cracking and thermal cracking [31]. However, different forms of surface cracking may only be responses of more severe structural failures, and these subterranean causes of distresses are best investigated using equipment, that can analyze the pavement structure below the surface, such as coring, the Falling Weight Deflectometer, the Ground Penetrating Radar, and dynamic cone penetrometer. Coring, one of the most used techniques, provides subterranean information of the structural state of the pavement. Analysis of core samples reveal physical information on the structural composition of the pavement like layer thickness, state of deterioration, and base composition. While CIR provide a good remedial action for some of these surface pavement distresses and failures, it does not provide complete rehabilitation for base distresses and failures which could be responsible for surface cracks like reflective cracking, blocking, fatigue cracking, and other forms of surface deformations like rutting.

Analyses of survey responses (Chapter 3) from DOTs with experience with full depth reclamation (FDR) across the United States shows that FDR provides a good rehabilitation solution to pavement failures that goes beyond the surface, down to the base. Before deciding on the use of FDR for rehabilitation, some DOTs investigate the type(s) of pavement distresses observed, and match them with documented rehabilitation guides, as some level of distresses and failures could be effectively and economically rehabilitated with other techniques. Documents received from the survey respondents show that possible pavement failure for which FDR may be considered as a suitable rehabilitation technique varies amongst States, but mostly includes: (1) Deep rutting, (2) Load associated failures (alligator, wheel path, pavement edge), (3) non-load associated failures (reflection, thermal, block), (4) Maintenance patching, and (5) Weak base or subgrade support, and Poor ride quality.

Table 2.2 FDR Suitability for Pavement Failure Types

Pavement Distress	FDR would be Applicable
Category: Surface Defects	
Raveling	N
Flushing	N
Slipperiness	N
Category: Deformation	
Corrugation	
Ruts-shallow	
Rutting Deep	Y[2,3]
Category: Cracking (Load Associated)	
Alligator	
Longitudinal	Y
Wheel Path	Y
Pavement Edge	
Slippage	
Category: Cracking (Non-Load Associated)	
Block (Shrinkage)	Y
Longitudinal (Joint)	Y
Transverse (Thermal)	Y
Reflection	
Category: Maintenance Patching	
Spray	Y[4]
Skin	Y[4]
Pothole	Y
Deep Asphalt	
Category: Base and Subgrade	
Weak Base or subgrade	Y
Category: Ride Quality/Roughness	
General Unevenness	
Depressions (Settlement)	Y[5]
High Spots (Heaving)	Y[6]

NOTE:

2: The addition of new aggregate may be required for unstable mixes.

3: The chemical stabilization of the subgrade may be required if the soil is soft or wet.

4: In some instances, spray and skin patches may be removed by cold planning prior to these treatments (considered if very asphalt rich, bleeding).

5: Used if depressions are due to a poor subgrade condition.

6: Used if high spots are caused by frost heave or swelling of an expansive subgrade soil.

2.5.2 Traffic Estimate

The traffic volume (current and future estimates) and traffic load serviced by the road needs to be considered in candidate selection. Trucks and large vehicles with large axle wheel loads exert more stress on the pavement than lighter vehicles, just as roads with increasing traffic volumes, higher than what the road was designed for will deteriorate faster. Rehabilitating such deteriorating roads especially those whose base structure is designed for fewer and lighter traffic loads with techniques that targets surface repairs will be costlier in the long run, as more frequent rehabilitations will be required to keep the road in functional condition to service travelers. Pavement failure due to weak base resulting from increased traffic load will need a redesign and reconstruction of the pavement structure instead of surface rehabilitation, and since FDR is a technique that improves pavement base quality, it would be a more ideal rehabilitation technique for such a road. Also, the short opening time for roads rehabilitated with FDR is also beneficial for roads with high traffic.

Lightweight vehicles do not create as much stress as heavy vehicles do, that means the damage to the lower structural layer of the pavement will be more for pavements with more truck proportions, so a good selection consideration for FDR (as it relates with traffic) should consider the axle load. This includes the number of single axle wheel loads, the axle spacing and the number of tires. This provides an estimate of the stresses transferred from the pavement surface through the base to the subgrade, and their possible contribution to the pavement deterioration. The candidate selection consideration should also include the number of repetitions. High traffic volume relates to high repetitions and will result in faster deterioration than roads with lower traffic volumes. Another traffic consideration is the traffic speed. Slow moving vehicles exert more pressure and stress on the pavement than fast moving vehicles.

2.5.3 Pavement Survey and In-Situ Tests

Surveying the pavement helps identify specific pavement characteristics of the road as a whole section or in parts. The information obtained from the survey helps in estimating properties like the layer resilience modulus (M_R), the Pavement Condition Index (PCI), and the pavement Structural Number (SN). Different Departments of Transportation have different preferences in the tools and equipment for determining the layer resilience modulus of the pavement structure. Typical equipment used include the falling weight deflectometer (FWD), dynamic cone penetrometer, and ground penetrating radar [32]. From the survey conducted, the falling weight deflectometer was discovered to be the most used of these types of non-destructive testing methods. The data returned by the falling weight deflectometer are back-calculated to determine the resilience modulus for each of the layers. Several back-calculation tools exist for this purpose, and a few include MODULUS 7.0, EVERCALC, MICHBACK and MODTAG [33]. The data could also be back-calculated manually as was done and is presented in Chapter 3. However, the iterative process could be very tasking especially with a large amount of data.

Based on the type of pavement, the type of distress and failure, the severity of the distress and failure, the PCI is derived as a measure of the pavement performance. The Federal Highway Administration's Distress Identification Manual [34] provides guidance in identifying and measuring pavement distresses and their severity. In general, the overall pavement condition index (OPCI) is made up of different indices which are used to evaluate the pavement condition. Pavement condition distress index ($PCI_{Distress}$) takes account of all observed distresses on the pavement and assigns a threshold value of 60 which indicates the trigger point for pavement repairs; pavement condition roughness index ($PCI_{Roughness}$) measures the ride quality of the pavement and compares it to the international roughness index; pavement condition structural index ($PCI_{Structural}$) compares the structural number of the pavement at the time of assessment to the original pavement structural number at the time of its creation; pavement condition skid index (PCI_{Skid}) is a measure of slipperiness of the pavement surface.

Yang H. Huang defines Structural number as a function of layer thicknesses, layer coefficients and drainage coefficients [35]. The layer coefficient can be estimated from charts or calculated from equations. However, layer coefficient for existing pavement is mostly lower than that of newly designed pavement, and care should be observed when estimating layer coefficient for resilience modulus greater than 450,000 psi due to susceptibility to thermal and fatigue cracking. The drainage coefficients applied to the base and subbase to modify the layer coefficient can be estimated following standard guides that can be found in AASHTO's Guide for Design of Pavement Structures [36]. The thicknesses of the pavement layers can be gotten from core samples or pavement records.

2.5.4 Materials and Environmental Factors

FDR involves reclaiming the pavement materials on the surface, base, and subgrade(optional). The proportions of materials are key factors in preparing the mix design. In some scenarios, extra materials may be needed for the mix, or to correct some material deficiencies, and other times, excess materials on the surface will be milled off. The depths of the pavement layers, therefore, are important factors in selecting suitable candidates. Also, the material composition, particularly the subgrade material composition, is one that affects the design and the cost. From the survey, some respondents reported using supplementary materials like lime to enhance the material properties of the subgrade. Roads with drainage problems will need pre-construction exercises done to improve the drainage condition of the section, and areas with weak subgrade might need complete subgrade removal and replacement with foreign materials before rehabilitation can be done [26].

2.6 FDR Construction Methods

Many of the reclaimers used for FDR are equipped with cutting bits capable of pulverizing pavement materials more than 12 in. deep into the road pavement. They cut and mix all pavement materials within that cutting depth while simultaneously mixing water and the recycling agent into the mix in a single pass. For cement stabilization and other dry recycling agents like lime, a spreader is used to distribute the recycling agent uniformly over the surface of the pavement to be recycled before the reclaimer makes it's pass, mixing all the materials together. For bituminous stabilization, a truck carrying the liquid stabilizing agent rides in front of the reclaimer, feeding it with controlled supply of recycling agent as it cuts and mixes the pavement materials. The recycled materials are then spread and shaped with a motor grader before compaction to design depth or density.

2.7 Current TDOT FDR Publication SP304DR

TDOT currently only has a publication titled "Special Provision for Full Depth Reclamation (FDR) of Flexible Pavement" [37]. The document covers specification on: (1) Materials, (2) Equipment,

(3) Mix Design Submittal Quality Control, (4) Construction Requirements, (5) Acceptance and Verification Testing, and (6) Maintenance.

The potential suggested recommendations to the TDOT's publication SP304FDR are presented in Section 6.2 Recommendations.

2.8 Case Studies of Application of FDR

2.8.1 Cement-Stabilized FDR

Texas DOT (TxDOT) selects the optimum stabilizer content for FDR candidates in accordance with in-house TxDOT guidelines. The TxDOT laboratory test protocols guidelines include gradation, Atterberg limits, optimum moisture content (OMC), unconfined compressive strength (UCS), evaluation of moisture susceptibility and seismic properties. For indirect tensile tests (IDT), TxDOT guidelines, tests samples under wet and dry conditions using the Texas Gyratory Compactor using the traditional TxDOT 6-in. by 8-in. samples. For moisture susceptibility test, TxDOT uses a Texas Transportation Institute (TTI) developed accelerated test procedure called a "dunk test". This is a procedure that submerges the test specimens for four hours at room temperature and then conducts the UCS and IDT tests. Unconfined compression strength (UCS) tests are conducted and values of UCS greater than 175 psi are deemed acceptable. Test results indicate a strong relationship between UCS and IDT. TxDOT currently does not have a criterion for the four-hour dunk test, however a retained strength of 80% of dry strength is acceptable [7].

The Georgia Department of Transportation (GDOT) adopted the standard proctor test (AASHTO 99) in their mix design method. The method requires the determination of the maximum dry density and optimum moisture content before addition of any stabilizing agent. Unconfined compressive strength samples are molded at the optimum moisture content and at varying cement contents. Using 4-in. molds and a standard proctor hammer, samples are compacted into test specimens in three layers with 25 blows per layer. In the 2006 [8] study by GDOT, the compacted samples were sealed in plastic bags and cured for 7 days. Unconfined compression strength (UCS) tests were conducted and values of UCS greater than 450 psi were deemed acceptable.

PennDOT adopted the ASTM D1633 Method for their UCS sample test preparation. As in the GDOT adoption, samples are cured for 7 days after mixing and compaction. However, unlike with the GDOT, job acceptance is based on pavement thickness. For pavements that are to be overlaid by an overlay greater than 3 in., the method requires that the design mix's average UCS must be between 200 and 500 psi. For overlays less than 3 in., a mix design is acceptable if an average UCS between 300 and 500 psi is achieved [9].

The New York DOT (NYSDOT) cement-stabilized FDR design method is very similar to the Pennsylvania method. The only difference is the job formula acceptance criteria. The NYSDOT requires the average UCS to be greater than 350 psi and less than 800 psi [10].

2.8.2 Asphalt-Stabilized FDR

The Colorado Department of Transportation (CDOT) adopted the proctor and the modified proctor test (AASHTO T 180 Method D) to select the optimum emulsion content for FDR projects. For the purpose of selecting optimum emulsion content, CDOT required that samples to be prepared that meet certain gradation requirements with specified moisture content. CDOT evaluated five criteria: (1) Short-term strength test - modified cohesiometer, (2) Indirect Tensile Stress (ITS), (3) Conditioned ITS, (4) resilient modulus and (5) thermal cracking. Table 2.3 depicts the optimum binder content job acceptance criteria for CDOT [11].

Table 2.3 Performance Test Criteria for Selecting Optimum Binder Content for CDOT [38]

Test Method	Sample Curing Condition	Criteria	
		For mixtures containing <8% passing #200 sieve	For mixtures containing >8% passing #200 sieve
Short-term strength test, 1 hour – modified cohesiometer, AASHTO T246 (Part 13), g/5mm of wITSh	60 minutes at 25°C	>175	>150
Indirect Tensile Strength (ITS), ASTM D4867, Part 8.11.1, 25°C, psi	72 hours at 40°C	>40	>35
Conditioned ITS, ASTM D4867, psi		>25	>20
Resilient modulus, ASTM D4123, 25°C, 1000psi		>150	>120
Thermal cracking (ITS), AASHTO T322		<-20°C	<-20°C

The Illinois Department of Transportation (IDOT) uses the Superpave Gyratory Compactor (SGC) mix design method. Samples are prepared at OMC in accordance with the modified proctor test (ASTM D1557 Method C). Test specimens are compacted with a SGC machine using 30 gyrations with 600 kPa compaction pressure and tested for short-term strength (STS) (ASTM D1560) and ITS (ASTM D4867). Unlike CDOT, IDOT only used three criteria for job acceptance: (1) short-term strength test (2) ITS, and (3) Conditioned ITS. Table 2.4 depicts the optimum binder content job acceptance criteria for IDOT [12].

PennDOT used two different asphalt stabilizing agents for design of FDR materials – asphalt emulsion and foamed asphalt. As such, PennDOT developed two different guidelines for asphalt emulsion and foamed asphalt but used SGC (600 kPa and 30 gyrations) test samples for both stabilizing agents. Test specimens are cured at 40°C for 30 minutes after mixing and at room temperature for 48 hours after compaction. For test samples using foamed asphalt standard (AASHTO) or modified (AASHTO 180) determination of the OMC is carried out. The test samples are then prepared at 85% of the OMC, cured at 40°C for 30 minutes after mixing and compacted into 4-inch or 6-inch molds. In the absence of a reasonable calculation of OMC, values of between 2% and 3% is recommended for samples of FDR using asphalt emulsion. ITS values greater than 50 psi and ITS ratios of 0.7 is considered a job acceptance and the asphalt (emulsion or foamed) content of the sample that has the highest ITS value is selected as the design asphalt content [5].

South Carolina DOT (SCDOT) prepares their test samples based on the classification of the recycled materials and OMC. SCDOT uses the AASHTO T 180 standards to determine the optimum moisture content of the samples. For aggregates with a sand equivalent greater than 30, SGC samples are prepared at 45% to 65% of OMC and 60% to 75% of OMC for aggregates with sand equivalences less than 30. If no peak dry density value can be determined, SCDOT recommends using a moisture content of 3% for preparation of the SGC samples. SGC is used to compact test samples at 600 kPa and 30 gyrations at room temperature. Four different tests were performed on the compacted test specimens: ITS (under dry and moisture conditioned cases), Gyratory Quotient, stability, and flow characteristics. For the stability test, the test is performed in accordance with AASHTO T 245 for both initial cure (cure in forced draft oven for 48 hours at 140^{o}F then cooled at room temperature for 24 hours) and final cure (cure at room temperature for 24 hours). The flow test was performed also in accordance with the AASHTO T 245 guidelines only for the final cure condition (cure in forced draft oven for 48 hours at 140^{o}F then cooled at room temperature for 24 hours). For the ITS, job acceptance criteria were for dry conditions ≥ 45 psi and for moisture conditions ≥ 25 psi. For Gyratory Quotient test values of between 150 to 500 ksi is considered acceptable. For stability, acceptance is a value of ≥ 3,000 lb for final cure (as described above), and a value ≥ 1500 lb for initial cure (as described above). Flow of 0.1 to 0.25 in. is deemed acceptable. All four criteria must be achieved for job acceptance [6].

Table 2.4 Performance Test Criteria for Selecting Optimum Binder Content for IDOT [39]

Property	Criteria	
	For mixtures containing <8% passing #200 sieve	For mixtures containing >8% passing #200 sieve
Short-term strength test, ASTM D1560	>175	>150
Indirect Tensile Strength (ITS), ASTM D4867, psi	>40	>35
Conditioned ITS, ASTM D4867, psi	>25	>20

Chapter 3 State-of-the-Practice Survey

3.1 Survey of Design and Construction Best Practices of State DOT's

A comprehensive online survey was conducted to establish the state of the discipline and best practices of FDR in the United States. In phase 1, a total of 361 online surveys were sent to pavement engineers, materials engineers, and construction engineers in the different state department of transportation and transportation agencies around the country. Of the questionnaires sent, there were 75 respondents from 41 states, with respondents from 4 states reporting no experience with FDR. Phase 1 of the survey questions contained 19 questions and the responses are summarized in section 3.2 Survey Results.

The second phase of the survey which was completed and deployed after the assessment of the first phase, focuses on the local road agencies, including counties and cities in Tennessee. Its design is like that of phase one, but more localized to the county and city level.

3.2 Survey Results

3.2.1 Phase 1

Figure 3.1 shows a color-coded map of the United States with the states' responses from the online survey. States marked in blue represent are those state's where no response was received, yellow indicates states whose respondent(s) have no experience with FDR. All regions in white represent states with respondents have experience with full depth reclamation. A summary of the answers from states is provided in the rest of this section.

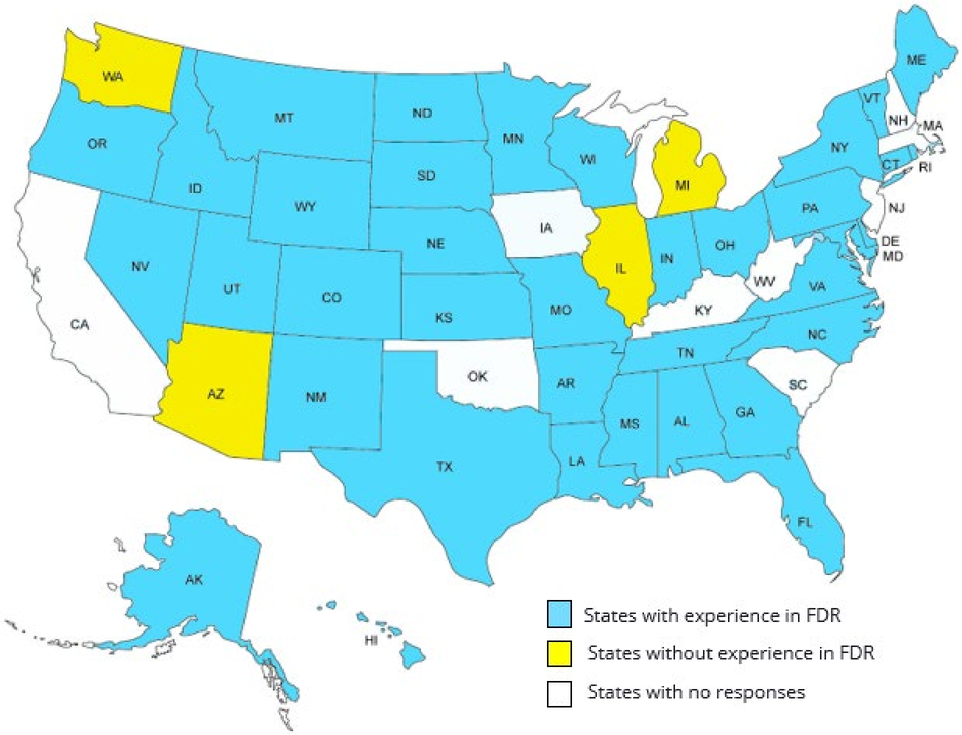


Figure 3-1 Survey Response Map

Question 1: What type of full depth reclamation (FDR) experience has your state DOT/county had?

Full-depth reclamation (FDR) can be achieved with or without the addition of a stabilizing agent. 75 responses from 41 states, 13 respondents reported having no experience with FDR. Amongst those with FDR experience, 58 respondents (93.5%) have utilized one form of stabilizing agent or another in their FDR project(s) such as Portland cement, asphalt emulsion, foamed asphalt, lime, and calcium chloride. Respondents from the state of Tennessee and surrounding states of Missouri, Alabama, Georgia, North Carolina, Virginia, and Arkansas all report utilizing one stabilization medium or another for their FDR projects. While almost all states who responded have experiences using one stabilizing agent or another or multiple experiences with different agents as well as mechanical stabilization, only Connecticut and Wisconsin had respondents reporting mechanical stabilization without stabilizing agents in their FDR experience.

Question 2: Of the FDR experiences in (1), what stabilization agent(s) did you use?

The choice of stabilization agent used for FDR as gathered from the survey varied irrespective of the region. The more defining factor, however, is the experience in its application as states who are relatively new in the use of full-depth reclamation as a tool for road rehabilitation have tried fewer stabilization agents. Respondents mostly have utilized Portland cement in their projects, after which were asphalt emulsion or foamed asphalt. Overall. Other stabilization agents, as reported by respondents, which have been used for full-depth reclamation included, but was not limited to, lime, foamed asphalt, and fly ash – see Figure 3.2.

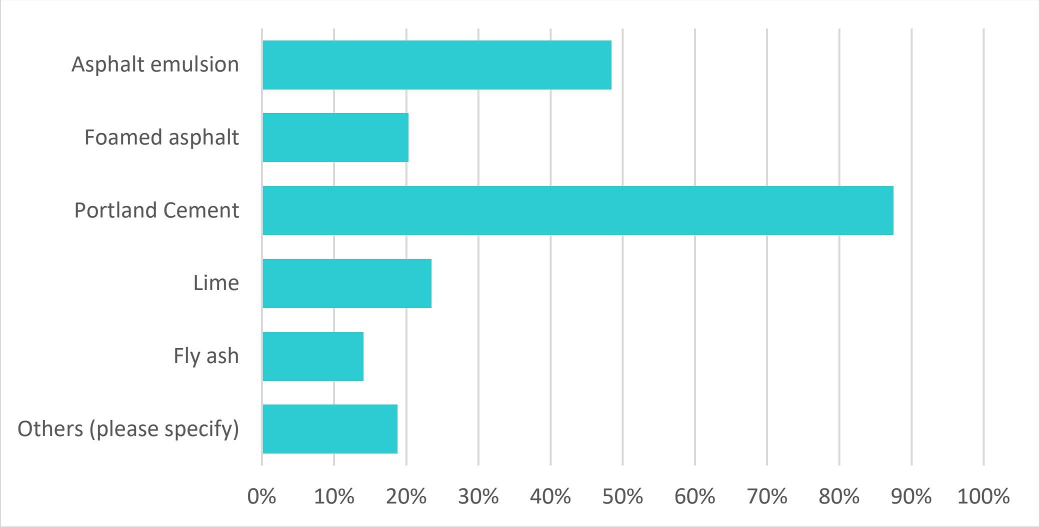


Figure 3-2 Stabilizing Agents used for FDR

Question 3: Of the stabilizers, which one do you prefer and why?

A greater percentage of respondents who answered this question responded with Portland cement as their preferred stabilizing agent. While some only have experience using Portland cement as the stabilizer for FDR, others prefer it because of the adaptable nature of Portland cement for all soil types within their states and the ease and straight-forward nature of its use during construction. Respondents from the states around Tennessee also chose Portland cement for their preference.

Question 4: Do you have a specific mix design method(s) your state DOT/county uses for FDR?

Since the introduction of FDR as a rehabilitation solution for road pavements, different states' departments of transportation have developed design standards for FDR. This question was asked such that the team could understand which states have developed specific mix designs for FDR, and to help understand the contents, considerations, and requirements by different states. Among the 64 respondents to this question, 37 respondents from 25 states confirmed that their states have specific mix design they use for FDR. Figure 3.3 shows a geographic representation of respondents from 13 different states who sent us copies of their State DOT/county design mix guide for FDR.

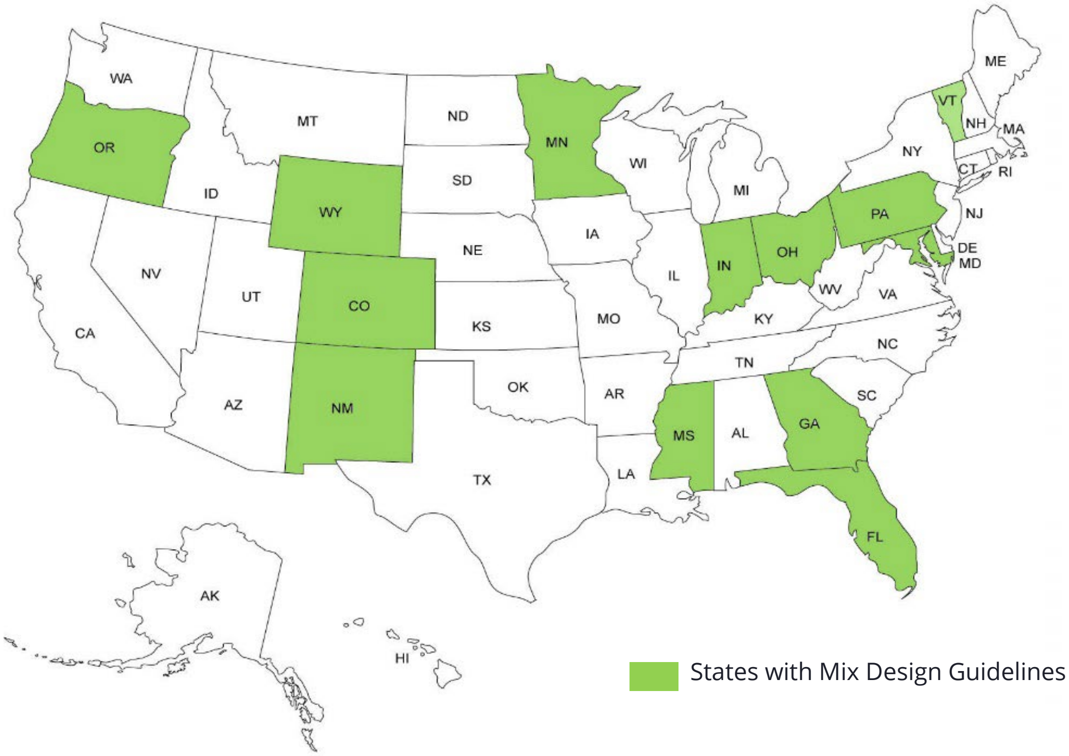


Figure 3-3 Geograhical Representation of State DOTs with Mix Design Guidelines

Question 5: Generally, what proportion of subgrade is in your FDR mix?

Since utilization of the section subgrade for FDR is optional, the responses received varied from zero percent (0%) to maximum provided in the survey (50%). It can be safely assumed that the use of subgrade in the FDR mix design is subject to various factors such as soil type, particle size distribution, design strength requirement, cost effectiveness, etc.

Question 6: Does your state DOT/county have a specification for FDR?

Over 80% of respondents to this question reported having specifications required for the approval of FDR projects and the team was able to get some of these specifications from some of the states.

Question 7: Has your state DOT/county tried supplementary materials such as fly ash?

Since FDR is a process that rehabilitates pavement failure down to the base, it is common to encounter subgrade properties and terrains that are akin to specific portions of the pavement and will require extra preparations and rectifications before the effective rehabilitation can commence. Such conditions sometimes require the use of supplementary materials and compound. Many of the respondents replied that they have not used any supplementary materials, while some of those who did share their experience with us.

Two respondents from Missouri said that they used fly ash in FDR, but they encountered negative issues due to inconsistency of the product, and a respondent from South Dakota reported an unsuccessful utilization. Most of the respondents who used supplementary materials had acceptable results in the different conditions in where they were used, like using fly ash as a substitute for cement where there is a shortage or drying out saturated existing grades adjacent to irrigation fields, setting the materials, and others.

Question 8: What type of pavement have you used FDR to treat?

The use of FDR as seen from the survey cuts across different types of pavements. The highest application was found to be highways, followed by local roads. Parking lots and airports have the least application of FDR. Figure 3.4 gives a description of FDR usage for different pavement types.

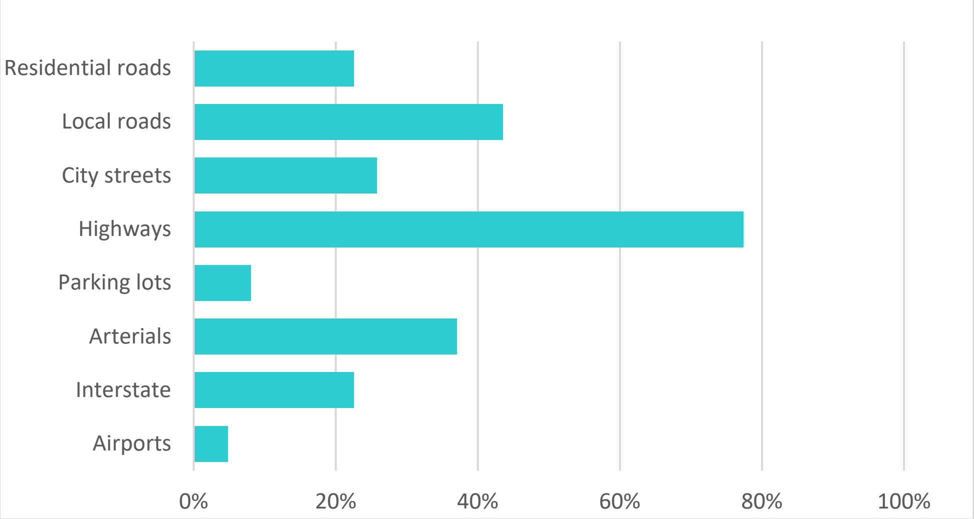


Figure 3-4 Pavements Treated with FDR

Question 9: Does your agency have guidelines for when FDR is appropriate?

Thirty-seven of sixty-four responding to this question indicated that they have guidelines for when FDR is appropriate for use as a rehabilitation technique.

Question 10: During the field investigations for candidate selection, which of the following techniques do you employ?

Various techniques have been employed in the selection of suitable candidates for FDR. These techniques help assess the state of deterioration and pavement condition of the proposed road. Popular techniques used in the selection process include visual inspection, core sampling and analysis, use of a falling weight deflectometer, use of a dynamic cone penetrometer, the list goes on. Question 10 provided a view of the techniques mostly used in the field by engineers and State DOTs.

As depicted in Figure 3.5, the most utilized technique in selecting suitable candidates is to take core samples. This helps in assessing the subterranean damage done to the pavement along with revealing vital information about the structural composition of the pavement. Visual inspection comes next, as it is important in revealing the surface conditions of the pavement (both cause and effect). Almost 50% of respondents use Falling Weight Deflectometer testing in addition to other techniques in selecting their candidates while others use other techniques like the pit test in their selection process.

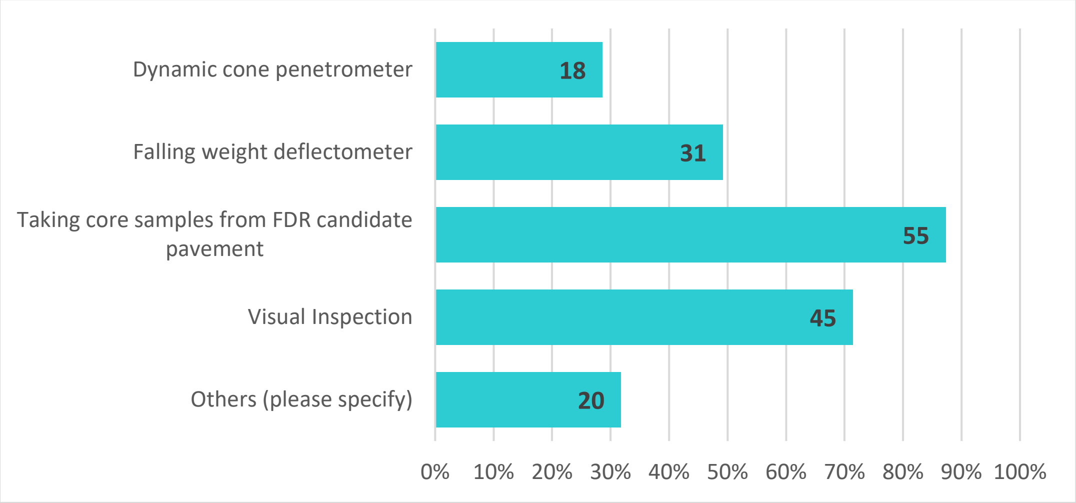


Figure 3-5 Techniques for Candidate Selection

Question 11: Do you take samples or cores of the pavement after a field investigation?

This question builds on the previous one, and it showed that most engineers and State DOTs take core samples from the candidate pavement after investigation.

Question 12: Do you follow an Inspector's Checklist or other documentation for acceptance before and during projects?

While different State DOTs have different requirements listed in their checklists to ensure that the project conforms to standard, 36 respondents reported that, they do not follow an inspection checklist before and during the projects. Twenty-five of the 61 respondents reported following an inspector's checklist for project acceptance.

Question 13: What are some of the frequently encountered problems during construction?

Frequent problems encountered during construction as derived from the survey ranked "improper moisture control" as the most prevalent. Figure 3.6 shows how the common problems measured up to one another, with some recurring mentions listed under "others". Among those not listed in Figure 3.6 include weather conditions (temperature, humidity, wind, rain); failure to meet gradation requirements; cement content control when applied dry; incomplete mixing of stabilizer into pulverized materials; large boulders in the subgrade; change in the thickness of the HMA being recycled; and proper recycling depth.

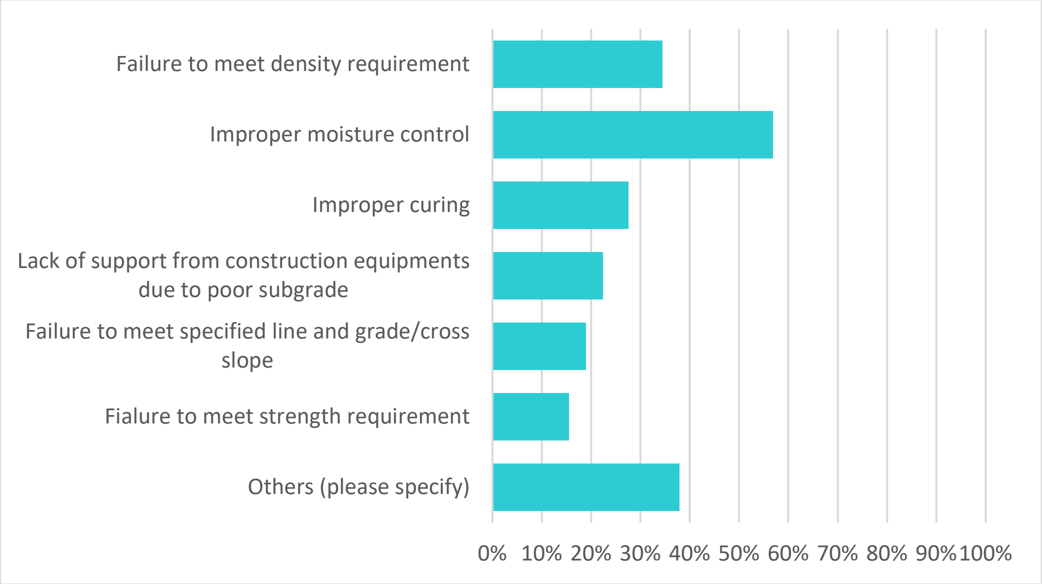


Figure 3-6 Common Problems Encountered During Construction

Question 14: Do you have information regarding long-term performance of FDR/SFDR projects in your state/county?

Most of the respondents do not have information regarding long-term performance of FDR/SFDR.

Question 15: If you answered yes in (14), when were the projects constructed and what are the conditions of the pavements currently?

Of the 75 respondents to the survey, 15 of them have information of pavements constructed using FDR that are over 10 years old while some of the pavements are within 5 to 10 years old.

Question 16: Have you performed an economic assessment when selecting FDR/SFDR that includes both the initial costs and future maintenance/rehabilitation costs?

Majority of respondents replied “NO” when asked if they have performed economic assessment for the FDR projects. A few said that they have performed assessments on proposed and future cost of maintenance and rehabilitation.

Question 17: Would you recommend FDR/SFDR and under what conditions?

Three respondents (2 from Delaware and 1 from Hawaii) answered that they would not recommend FDR while all remaining respondents from the 60 who answered this question recommended FDR with conditions for which their recommendations are based. Some conditions given for the recommendation of FDR are: (1) For treating and repairing roads to full depth in a cost-effective manner, typically for pavements with inadequate structure and high stresses, (2) For its “green” benefits of recycling roadway materials and the economic savings by not wasting used materials and saving on virgin materials for projects that would typically not be reconstructed, (3) For restoring a road in poor condition, (4) If you have a severely fatigued or old HMA pavement with minimal or no base course, the FDR can be used to create a platform for new pavement construction, (5) At the time of the 2nd or 3rd overlay where more strength is need than CIR can provide, (6) For pavements that are very thick and have contaminated or no base course remaining. Pavements beyond being treated by CIR, (7) For any condition where reconstruction is considered, (8) Would not recommend chemically stabilized FDR for road sections shorter than 1 mile. It is not cost effective in such a situation, (9) For any road with base failure, high level of distress, and full depth cracking, (10) Valid treatment on small arterials or county roads in rural areas preferably with less than 4in. of asphalt, (11) When building strength and getting rid of cracks is wanted. If no extra strength is needed, then CIR or overlay, (12) Under all conditions. FDR is a very good low-cost way to get consistent supports that lasts under pavements, (13) A go-to rehab method that is cost effective, (14) If a good gradation can be achieved with the existing pavement and base/subbase materials and where frost and drainage issues are not a concern, (15) HMA with alligator cracking and when a rise in profile is allowable, (16) Less than 300 trucks/day, at least 3in. of AC over top and subgrade, not saturated, and (17) When you have sufficient depth of asphalt to mix with soil, plenty of right-of-way, and a project scope that is focused on pavement reconstruction.

Question 18: What issues have you seen occur during the life of an FDR project?

This question gave us an insight to some on-site issues as well as some futuristic issues to be aware of in the life span of an FDR project. Abridged below are some of the answers provide by respondents for this question: (1) Shrinkage cracking and public perception, (2) Presence of large rocks and hand-placed stone bases that made it non-practical to use FDR. Other issues have been too much cement in the mix which led to cracking of the base, also we have had environmental concerns with cement dust, (3) Edge line cracking and moisture damage leading to rutting in the FDR layer, (4) Reflective cracking, (5) Once built, they are generally good. Biggest issue is going too deep into the base. Sometimes the base is contaminated by subgrade, or the reclaimer goes through the base, (6) Early in the life of the FDR, the pavement can shove and tear while it is still tender. Moisture problems have occurred because the FDR does not drain in certain circumstances, (7) Proper site investigation (that is, subgrade soil profile) is key during project development, and can often identify potential subgrade issues before the project starts, (8) Environmental issues: avoid temperatures below 5 degrees Celsius during construction and curing. Also, wind is dangerous for cement or lime stabilization as is spreads it outside the target areas. Also, maintaining the moisture content from factors like rain and rapid drying, (9) Edge support can occur on narrow segments, surface slippage can occur if not fog sealed, (10) Relief cracking through the surface commonly with cement FDR, (11) High volatile clays have led to premature cracking of some previous FDR in some areas, (12) Variability in road structure and materials, (13) Cement SFDR got too hard/stiff, then cracked and reflected through the asphalt in a very short time frame, (14) Lack of repair to severe drainage issues; use of too much cement and lack of design work causes block cracking. The belief that harder is always better, (15) We once had a foamed asphalt FDR project that had localized “boils” that damaged top lift of pavement. It was attributed to accumulated road salt in the base course that was incorporated into FDR, (16) Cracking and smoothness issues; early FDR projects only had a single lift placed over the FDR as wearing course. These projects showed early cracking in the HMA but after investigation, it was suspected that the cracks were top-down because the base was still intact. All FDR after that time have used two lifts of HMA and have alleviated these issues, (17) Bad candidate, isolated subgrade failures, and cross slopes, (18) Some of the lower volume roads had thin asphalt thicknesses, (19) Lack of subsequent preventive maintenance treatment such as chip seal, (20) Presence of underground utilities, and (21) Roughness during the first winter on some projects. They were a lot smoother just after construction.

Question 19: Have you ever had to rehabilitate an FDR pavement during its lifetime and if what did it entail?

Rehabilitating an FDR pavement is possible, and State DOTs reported the following could be done: (1) Mill and overlay or overlay with HMA, (2) You can regrind an FDR years after an initial FDR, (3) Most of the time we overlay the existing surface. Some of the older FDR have been re-pulverized and re-stabilized, (4) Reclaiming with a different stabilizer, (5) Had to crack seal reflective cracking in cement stabilized FDR, (6) Typical crack filing/sealing operations are done if cracking occurs in the asphalt to try to mitigate the issue. If located in the subgrade, corrective measures are done to the subgrade itself, (7) Just fixed spots that had severe drainage problems to begin with and living with block cracking issues, and (8) Another FDR with thicker HMA overlay was done to handle increased truck volumes.

3.2.2 Phase 2

Phase 2 of the online survey which focused on the use of FDR as a rehabilitation method in Tennessee was developed and deployed. The survey which has some similarities to the previous online survey (phase 1) was sent to the various county engineers in Tennessee, and the responses provided the research team with valuable insight on the state of FDR in the state at the county level. Ninety-four (94) online surveys were sent to county engineers during phase 2. Nineteen (19) responses were received from different counties across the state of Tennessee.

Figure 3.7 shows a color-coded map of the state of Tennessee showing the 4 TDOT regions. The shaded areas represent counties that responded to the online survey. The questionnaire shows that there is at least one county in each region with experience in FDR. A summary of the answers from these counties is provided in the rest of this section.

Figure 3-7 Common Problems Encountered During Construction

Question 1: Have you used Full Depth Reclamation (FDR) for road rehabilitation within your county? (If you answered No, please respond to question #14 and #15 and submit the survey)

The response to this question can be taken as an adaptation for evaluating and estimating the popularity of FDR as a pavement rehabilitation tool in Tennessee. As shown in Figure 3.8 of the 19 respondents, less than one-third (1/3) reported using FDR in one or more projects. Even though a greater number of respondents have not used FDR in pavement rehabilitation, the responses indicate that the technique is not new to all who answered. In addition, we can deduce that full-depth reclamation has been used in all regions except for Region one where only two responses were from Blount County and Washington County. From the survey, counties with respondents who have experience with FDR includes Hamilton County and Coffee County in region 2; Rutherford County in region three; and Henry County, Weakley County and Lake County in region 4.

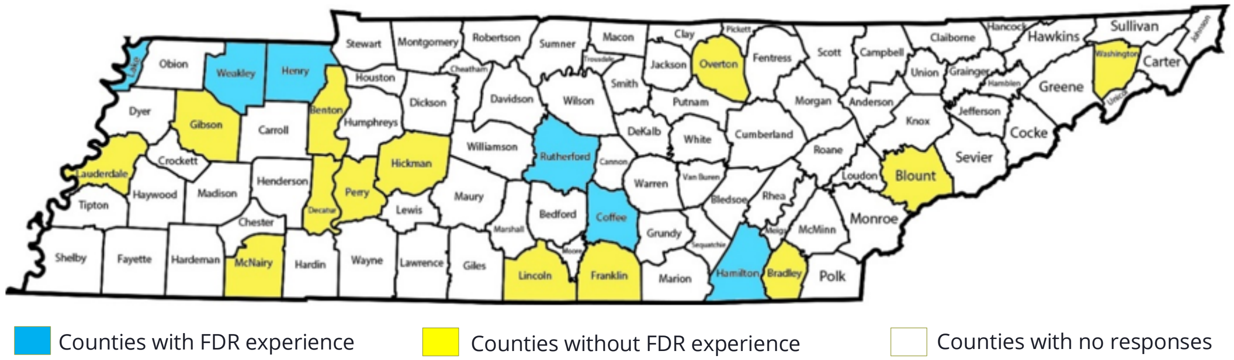


Figure 3-8 FDR Response Map within the State of Tennessee

Question 2: What stabilization method did you use?

Fifty percent (50%) of respondents to this question, including all respondents from regions two and three, reported experience on FDR using a stabilizing agent. Respondents from region 4 (Weakley County and Lake County) reported the use of both mechanical stabilization for FDR and a stabilizing agent. Some respondents indicated that they do not have any experience in FDR but have heard of it but responded to this question as well. Three respondents reported the use of mechanical stabilization, while one reported the use of SFDR. From this question, a conclusion could be drawn that the low utilization of FDR for pavement rehabilitation across the state is not a factor of unawareness in the part of county engineers, rather from a combination of factors like time, acceptance, recommendation, and so on.

Question 3: What stabilization method do you prefer and why?

Portland cement was the preferred stabilization agent among respondents. Preferences for some other respondents were limited to the single method of stabilization they are experienced in as well as the stabilizing agent used. Highlighted limitations include mechanical stabilization in Gibson County, use of Rs2 emulsion in Overton County and Portland cement in Weakley County.

Question 4: Did you use a specific mix design method for the project?

All respondents with experience in FDR reported that they had specific mix designs which were used in project(s) in their respectively counties.

Question 5: Does your county have any specification and guideline for FDR?

While nearly all respondents indicated absence of FDR specifications and guidelines at the county level, respondent from Weakley County reported otherwise. Responses to this question, when cross-examined with responses to similar questions from phase 1 of the online survey, will help the research team understand the development of state guidelines and specifications on FDR that will help promote the practice and utilization of FDR in pavement rehabilitation.

Question 6: What percentage of the pavement materials did you use in the FDR mix? Respond with 0-100% for each layer. Choose one or more.

The responses received from experienced respondents showed that all layers of the selected pavement structure were pulverized and used for FDR projects. The major difference however is the portion of subgrade materials added to the mix. Responses from Lake and Rutherford County indicated 100% subgrade inclusion. This could be interpreted as the inclusion of a substantial portion of subgrade materials in their design, and the reason could be attributed to several conditions, such as thin asphalt pavement structure, target thickness of the FDR structure, or good quality subgrade materials. Hamilton, Coffee, and Weakley County included subgrade materials in their designs within the ranges of 10% to 25%. It is known that FDR is a process which uses existing pavement materials that makes up the pavement structure. However, the proportion of subgrade materials is dependent on several factors which include pavement thickness, subgrade composition, target mix design, and others.

Question 7: Has your county used any supplementary materials such as fly ash in your rehabilitation process?

Supplementary materials such as fly ash are sometimes required in an FDR process to condition the soil, as substitutes for stabilizing agents, to facilitate drying processes and to address drainage problems. However, reports from respondents showed that aside from the regular chemical stabilizing agents such as Portland cement, Tennessee counties have not used any supplementary material yet in their FDR projects.

Question 8: If your answer in (Q7) above is "YES" please indicate the supplementary material, and how it performed.

This question builds on question 7. As there were no reports on the use of any supplementary material, information on this question is unavailable.

Question 9: What type of pavement have you used FDR to treat? Choose all that apply.

This question presents the options of different pavement categories to the respondents including residential roads, interstate, highways, airports. This distribution covers all types of roads in the states maintained by the state and county officials at the different county levels. Most of the applications of FDR within Tennessee have been on local roads as reported on the survey. This is seen in the three regions where respondents have experience in FDR. Other pavement types include residential roads, highways, and arterials. Figure 3.9 shows the pavement type distribution according to the responses received.

Question 10: During the field investigations for pavement selection, which of the following techniques do you employ? Choose all that apply.

Several techniques are used in pavement selection. From phase one of the survey, it was discovered that the most used technique for pavement selection across the United States was by taking core samples, followed by visual inspection, and falling weight deflectometer testing. At the county level in Tennessee, responses to this same question reported the use of two techniques from a list of techniques, with the first and most used being “visual inspection”, then “taking core samples”. Figure 3.10 shows the responses provided to this question.

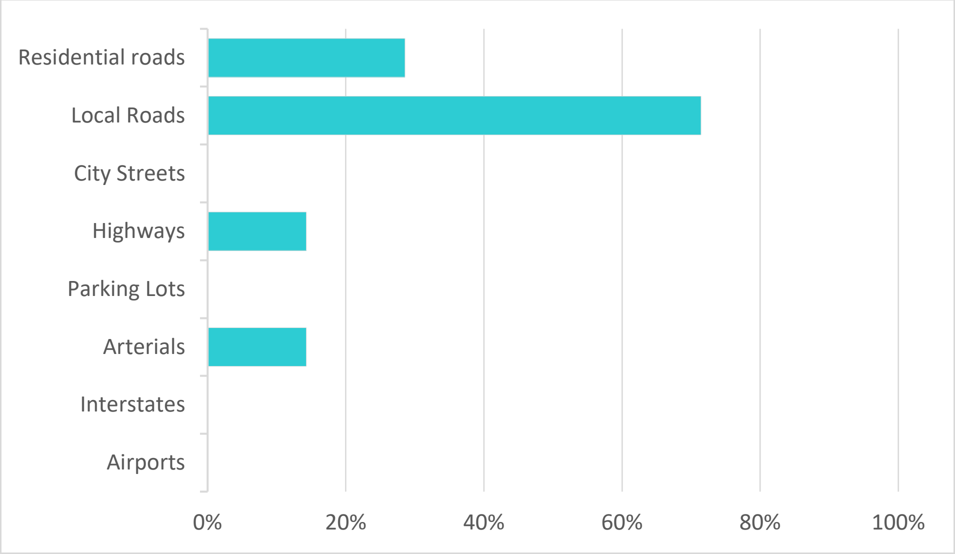


Figure 3-9 Pavement Types Treated with FDR

Question 11: What are some of the frequently encountered problems during FDR construction?

The survey only reported a few problems encountered by the county engineers during FDR construction. Among such problems include Improper moisture control, traffic control and sanitation problems, which had dust and concrete splatter getting on vehicles.

Question 12: What pavement failure type(s) was the FDR rehabilitation meant to fix, and what is the current condition of the road?

Question 12 was asked in a bid to know the pavement failures that were rehabilitated using Full Depth Reclamation and the current performance of Full Depth Reclamation as a rehabilitation technique. Table 3.1 show the survey responses.

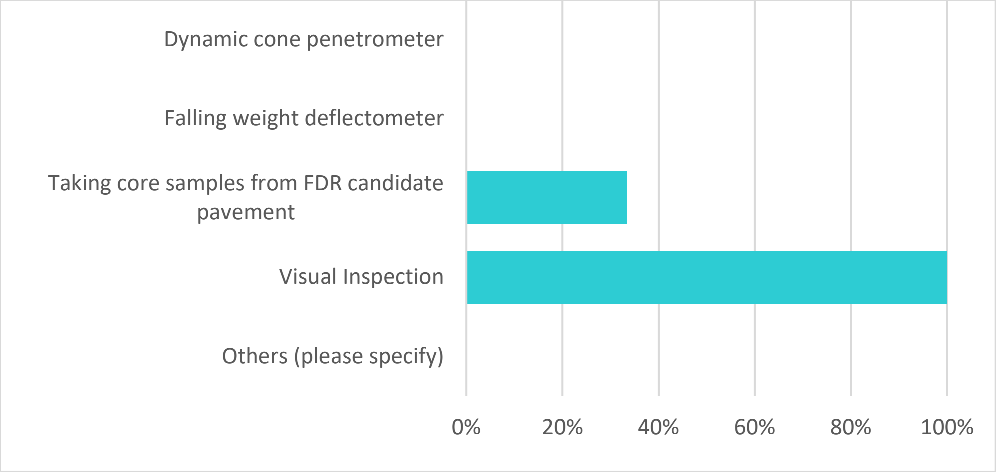


Figure 3-10 Techniques for Pavement Selection

Table 3.1 FDR Treated Pavement and Current Conditions

County	Failure Type	Current Condition
Lake County	Base failure	Good condition
Henry County	Subsurface failure	Good condition
Rutherford County	Load bearing capacity	Excellent condition
Weakly County	Poor base condition	Ongoing project
Hamilton County	Total subbase failure	Good condition
Coffee County	Alligator cracking and subgrade damage	"After four years of increased traffic, road still shows no sign of failure"

Question 13: Do you have information on cost savings gained from the use of FDR from your county?

The cost factor is a very important part of any project. None of the respondents to this question had information on cost savings gained from the use of FDR.

Question 14: What is the most common pavement failure noticed in your county?

The responses from fifteen counties to this question are listed in Table 3.2.

Question 15: What other rehabilitation techniques has your county used?

There are other rehabilitation techniques used for pavement depending on the type of failure and degree of deterioration. Listed below are some of the rehabilitation techniques used by counties that responded: (1) Asphalt resurfacing, chip sealing, and micro seal. Used for pavement with general deterioration, (2) Dig and fill: used for places with subgrade failure, (3) Cold in-place recycling for alligator cracking and potholes, (4) Scrub deal and fog seal for cracking due to age, (5) Filling soft spots with rocks, (6) Total reconstruction, isolating critical sections for repairs, (7) Undercut with graded solid rock and wick drains for entrapped water, (8) Reconstruction, and (9) Removal and replacement where there are subgrade failures.

Question 16: Would you recommend Full Depth Reclamation and under what conditions?

All respondents with experience in FDR reported that they would recommend it as a rehabilitation technique, and some of the conditions given are listed below: (1) It is an excellent way to treat a road with thin base or alligator cracking or subgrade failure working its way to the surface, (2) if you have sub-base or subgrade failure with a quarter-of-a-mile needing repair, (3) When there are predominating base issues, (4) For conditions too severe for other methods, and (5) When greater load bearing capacity is required.

Table 3.2 Responses on Common Pavement Failures

County	Pavement
Overton County	Cracks, potholes, and heavy truck wear
Lake County	Base
Franklin County	General deterioration
Rutherford County	Subgrade failure
Weakley County	Alligator cracking, potholed, etc.
Bradley County	Soft spots usually due to underground springs
Benton County	Mostly cracking due to age
Hickman County	Soft spots
Hamilton County	Pumping of the subbase
Lincoln County	Poor subgrade
Perry County	Failure caused by weight on trucks.
Gibson County	Subbase failure from heavy loads.
Coffee County	Random potholes, and shoulders breaking off.
Lauderdale County	Alligator cracking and rutting
Blount County	Subgrade failure resulting in separation of Asphalt layers and degradation.

Chapter 4 Field Investigation and Laboratory Testing

This research studied the suitability of PCFDR and AEFDR on reclaimed pavement materials from two identified FDR candidates and was instrumental in understanding the performance of stabilizing agents on reclaimed materials of different compositions and proportions. The FDR candidates used for this research are located along SR 88 in Lauderdale County and along SR 54 in Weakley County.

4.1 State Hwy SR 88 – Lauderdale County, Tennessee

SR 88 is approximately a 44.78 miles state route that runs west-to-east through Lauderdale and Crockett Counties, north of Memphis. The section has a combined annual average daily traffic (AADT) of approximately 159 (or 4%) trucks [39]. The original pavement consisted of 3 ¾ to 11 in of HMA. The base layer was estimated to have 10 in. of granular aggregate materials with some sections having crushed rocks and some sections having crushed lime stones aggregates. From the site investigation, numerous pavement distresses like longitudinal and fatigue cracking, edge cracking, and rutting were identified. The core samples taken from the pavement at the time of investigation revealed multiple layers of asphalt overlay at different sections of the road with some layers being completely de-bonded. Images of the core samples and the analyses are presented in Appendix C. The section chosen for FDR is 9.5 miles long on route SR-88 extending from Dee Webb Road to Porter's Gap Road in Lauderdale County - from coordinates 35.8981468,-89.6286038 to 35.9032222,-89.5339325.

4.1.1 Preconstruction Pavement Condition and Evaluation

Before the sampling for the FDR work began, the research team spray painted FWD testing location points every ½ mile on the SR 88 project. Cores were extracted, and core analyses are presented in the Appendix C. Buckets and shovels were used to collect various samples from different depths to get a representative sample that included a portion of the soil (see Figure 4.1). A single set of laboratory evaluations for FDR mix design requires a large amount of material for completion. The research team hauled approximately 250 lb of materials per sampling station in 5-gallon buckets for laboratory analysis. MTSU coordinated the standard proctor testing and compressive strength testing at the MTSU laboratory with cement as the FDR stabilizer, while UTC conducted laboratory experiments for emulsified asphalt as an FDR stabilizer.

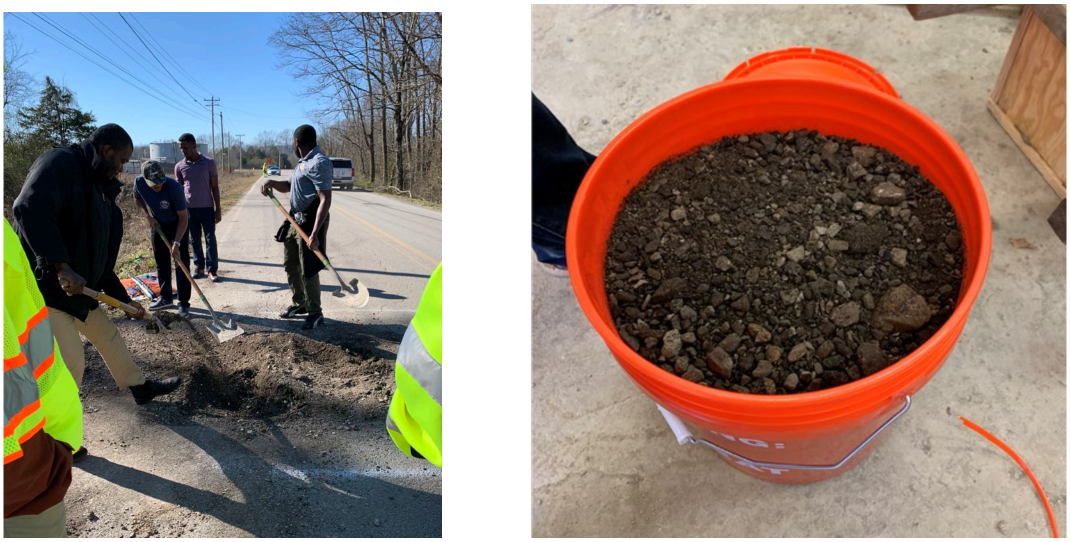
A Dynatest falling weight deflectometer (FWD) was used in carrying out deflection measurements. The equipment has seven sensors at radial distances of 0, 12, 18, 24, 36, 48 and 60 in. from the center of the load plate located at the wheel path. Testing was conducted at a load level of 9,000 lb. This process was repeated for all 15 stations along the road section and for each section, 4 drops were taken. From each station, coring was done to assess the asphalt thickness and properties. The deflection data from all stations, the station temperature readings (air, surface, and pavement) and the pavement layer properties (surface, base, and subgrade), were fed into a back-calculation algorithm. Data from each station starting with mile marker 0 were analyzed individually with the pavement structural information most relative to the core samples drilled from the stations. Two drops were used as warm up drops which help the base plate sit properly on the surface. Between the third and fourth drop, the drop closest to 9000 lb was selected for analysis. Poisson's ratio of 0.35 was adopted for surface and base materials, and 0.4 was adopted for subgrade materials. The subgrade was largely comprised of clayey materials with a liquid limit of less than 50%, and a uniform base depth of 10 in. was assumed for all stations throughout the road section.

The raw pre-construction FWD test data collected from SR 88 Lauderdale County is presented in Table C 1, and Table C2 presents the back-calculated results obtained from the back-calculation tool (MODULUS 7.0). The relationship between the surface layer coefficient (a_1) and the surface layer resilient modulus (E_1) is depicted in Equation 4.1 while the relationship between the base layer coefficient (a_2) and the base layer resilient modulus (E_2) is depicted in Equation 4.2 [39].

$$\boldsymbol{a_1 = 0.4 * log\left(\frac{E_1}{435\ ksi}\right) + 0.44} \qquad \text{Equation 4.1}$$

$$\boldsymbol{a_2 = 0.249(logE_2) - 0.977} \qquad \text{Equation 4.2}$$

Since the layer coefficient for an existing pavement is considered lower than for a new pavement, the additional parameter (0.44) in Equation 1 is replaced with 0.34. A publication by the Federal Highway Authority suggests the possibility of an existing granular base having a layer coefficient of zero (0), and as such, stations with a low base layer modulus yielding a negative layer coefficient from Equation 4.2 were assigned a zero value. Table 4.1 presents the pre-construction summary statistics for the road, D_1 is the thickness of the surface layer, E_{sg} is the subgrade resilient modulus, and SN is the pavement structural number.



(a) Reclaiming Pavement Materials (b) Reclaimed Pavement Materials

Figure 4-1 SR-88 Pavement Material Collection

Table 4.1 Pre-Construction Summary Statics

	E_1 (psi)	a_1	D_1 (in)	E_2 (psi)	a_2	E_{sg} (psi)	SN
Average	1,283,007	0.47	7.08	25,860	0.087	9,013	4.13
Std Dev (sample)	1,127,259	0.14	2.37	25,447	0.096	2,300	2.05
Median	749,900	0.43	7.00	15,500	0.066	8,400	3.85
Lowest	327,000	0.29	3.75	5,000	0.00	5,900	2.12
Highest	3,807,100	0.72	11.25	75,600	0.24	13,700	9.83

4.1.2 Material Gradation and Testing

To provide adequate structural support for the rehabilitated pavement, gradation of the pulverized base and sometimes the subgrade must meet specific gradation requirements. On-site, reclaimed materials for full depth reclamation are required to have 100% materials passing the 3-inch sieve, and a maximum of 20% passing the #200 sieve (P200) [40] [15]. To maintain a proper relationship between laboratory sample size and maximum aggregate size, laboratory tests are conducted with materials passing the 1.5-inch sieve with 0% retention [41]. Materials that fail to meet the #200 restriction (usually clay or silt), are either excluded from the mix, have a different mix design method is adopted, or add virgin/foreign aggregates to the mix such that the resulting gradation meets the requirements. For the stabilizing agents, emulsified asphalt used should meet the requirement of 62% weight of residue by evaporation (typical) and must comply with the requirements for the PG binder specified [42], and type 1 Portland cement or cement kiln dust (CKD) can be used for PCFDR [15].

Pavement materials collected from the Lauderdale County Road were separated into 3 batches, batch 1-3-5, batch 7-9-11 and batch 13-15, according to the stations they were collected and based on the properties of the pavement structure which included the thicknesses of the asphalt layers and the base material composition. This was done to have different mix designs that caters to the specific pavement section structure. The laboratory procedures involved several steps however, the main purpose of the laboratory tests was to determine the optimum binder contents and optimum water content for the pulverized material for the FDR base capable of supporting the traffic load. Appendix A presents the mix design procedures for the PCFDR and AEFDR.

To begin the laboratory procedures, the asphalt binder content in the RAP materials for each batch were determined with a binder ignition furnace [41]. A wash sieve analysis was then carried out on the residue to determine the particle sizes of the aggregates in the RAP materials [43]. A wash sieve analysis was also performed on base materials of batches 1-3-5 and 7-9-11 as well as on the subgrade materials from station 7 of batch 7-9-11 separately to determine their particle size distribution and to ensure that it met the gradation requirements. The results obtained showed that the base materials met the requirement of 100% materials passing the 1.5-inch sieve and a maximum of 20% passing the #200 sieve while the subgrade material from station 7 failed to meet this requirement with 70% of its content passing the #200. Consequently, the subgrade materials were excluded from the mixes for the design. A wash sieve analysis was not performed on the base materials of batch 13-15 as the materials were already mixed with RAP materials.

Sieve analyses results from batch 1-3-5 for base materials and RAP aggregate materials are presented in Appendix B in Table B 1 and Table B 2 respectively. The results show 100% of the materials passing through the 1.5-in sieve and less than 20% materials passing the #200 sieve. This conforms with the gradation requirement for the design mix.

Results of sieve analyses performed on materials from batch 7-9-11 are shown in Appendix B in Table B 3, Table B 4 and Table B 5. Table B 3 shows results of the particle size distribution of the subgrade materials. The results from Table B 3 show that the subgrade materials fail to meet the requirements as more than 70% of its materials passes the #200 sieve. Adding materials that fail to meet the requirement in the mix design will result in an uneconomical mix design and should be avoided. Table B 4 and Table B 5 presents sieve analyses results for base materials and RAP materials of Batch 7-9-11 meeting the gradation requirements.

Samples of mixed materials from the batches (base and RAP materials) were placed in the binder ignition furnace to extract the asphalt binder. After extraction, the percentages of RAP materials present in each batch was determined, sieve analysis was also performed on the materials of the batches (base materials and RAP). Table B 6 depicts the results of the asphalt binder contents by dry mass of RAP, design mixes for the different batches, and the RAP content by mass in the mixes for the different batches and Table B 7, Table B 8 and Table B 9 show result of the particle size distribution of the mixed materials for all batches. The mixed materials comprise of base and RAP materials.

4.1.3 Mix Design for Portland Cement

Specimens were prepared in accordance with ASTM standards (see Figure 4.2) to select the optimum stabilizer content for FDR base-course mix design by using 6-inch by 8-inch specimens. The laboratory testing protocol includes the determination of gradation, Atterberg limits, optimum moisture content, unconfined compressive strength, and evaluation of the moisture susceptibility. Determining the maximum dry density at the optimum moisture content was conducted as recommended in ATSM standards. A generic example of dry density/moisture content plot is shown in Figure 4.3.

For purposes of evaluating a suitable mix design, the road section was divided into sections for testing based on initial look at some of the cores and their layers and soil conditions. A range of 4.00%, 6.00%, 8.00% cement was tested for potential mix designs. A rock correction factor was taken into consideration based on the material sampled from the site. Anything over 5.00% over the ¾-inch sieve was corrected in the standard proctor values. 27 mixes were used to make compressive strength specimens which were cast for 3-day and 7-day strengths. A summary of the experimental results is presented in Table 4.2; the moisture density curve is presented in Figure 4.3.

(a) Blending of samples (b) Rock correction from sample (c) Weighed samples with cement

(d) Mixing of sample (e) Curing compressive samples (f) Tested compressive samples

Figure 4-2 Sample testing at MTSU Laboratory

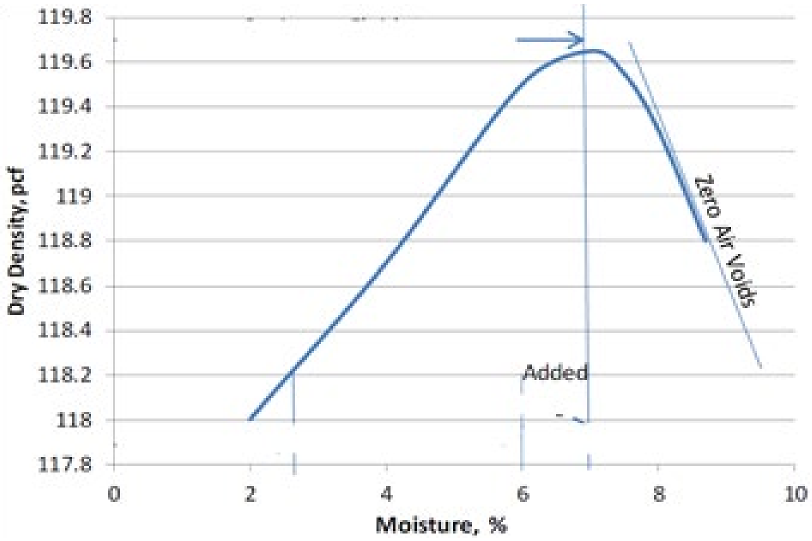


Figure 4-3 Typical Dry Density vs Moisture %

Table 4.2 Summary of Results for SR 88–Lauderdale County

Mix ID	Average Density (pcf)	% Moisture	3 Day Strength (avg)	7 Day Strength (avg)
4.00% 1-3-5	136.00	6.6	247	298.5
4.00% 7-9-11	138.10	7.8	276	272
4.00% 13-15	134.62	6.3	228	330.5
6.00% 1-3-5	140.59	7.7	493	605
6.00% 7-9-11	138.90	10.4	376	424.5
6.00% 13-15	134.62	6.1	378	532.5
8.00% 1-3-5	140.63	7.8	592	754
8.00% 7-9-11	136.89	10.6	400	426.5
8.00% 13-15	140.63	8.6	692	740.5
0% 1-3-5*	128.00	N/A	N/A	N/A
0% 7-9-11*	125.8	N/A	N/A	N/A
0% 13-15*	124.4	N/A	N/A	N/A

4.1.4 Mix Design for Emulsified Asphalt

With the determination of the reclaimed material properties and following the provisions for AEFDR mix design in Appendix A2, laboratory experimentation on the reclaimed materials was advanced with the determination of the optimum moisture content. The materials are dried (0.00% moisture content), and the water content needed for the optimization is a combination of the water content present in the emulsion and added water. The emulsion used for the tests was grade PG58-28 with an asphalt residue content of 2/3 by emulsion mass. A constant emulsion content of 3.00% dry mass of mixed aggregate materials (the emulsion had a 2.00% mass of asphalt residual and a 1.00% mass of water present in the constant emulsion content) was used for the optimization of the water content. The added water percentages established for the tests was set at 2.00%, by mass of dry mixed materials, to 6.00% with a 1.00% increment for every target water content. Two 6-inch test samples were made for each of the target water content percentages.

Four water content values (3.00%, 4.00%, 5.00% and 7.00%) were selected for the water optimization of batches 1-3-5 and 7-9-11, while five water content values (3.00%, 4.00%, 5.00%, 6.00% and 7.00%) were used for the optimization of batch 13-15. This required to the preparation of 8 test samples for batches 1-3-5 and 7-9-11, and 10 test samples for batch 13-15 (2 samples for each selected water content). The results of the test are presented in Table B 10, Table B 11 and Table B 12 and the water optimizations curves are presented in Figure B 1, Figure B 2 and

Figure B 3. The optimum water content corresponds to the water content value giving the maximum bulk density. Table 4.3 presents a summary of the optimum water content for all batches.

Table 4.3 Optimum Water Contents for all Batches

Batches	Optimum Water Content
1-3-5	5.60%
7-9-11	5.45%
13-15	5.70%

After the determination of the optimum water content for each batch, 16 test samples were prepares for determining the optimum emulsion content, 8 samples for dry Marshall test and 8 samples for wet Marshall test. The target emulsion contents for all batches were set at 2.00%, 3.00%, 4.00% and 5.00%, and 4 test samples were prepared for each emulsion content. The required water mass at the target emulsion content for the batches was then calculated by subtracting the mass of water present in the emulsion from the optimum mass of water required to prepare 4000 g (dry reclaimed material) samples. Table 4.4 summarizes the water masses present in the different emulsion content, and the required water mass for the optimization.

Table 4.4 Water Content by Mass for Asphalt Optimization

Batch	Asphalt Emulsion Content	Optimum Water Mass (g)	Emulsion Water Mass (g)	Added Water Mass (g)
1-3-5 sample mass (4000 g)	2.00%	224	26.67	197.33
	3.00%	224	40.00	184.00
	4.00%	224	53.33	170.67
	5.00%	224	66.67	157.33
7-9-11 sample mass (4000 g)	2.00%	218	26.67	181.33
	3.00%	218	40.00	178.00
	4.00%	218	53.33	147.67
	5.00%	218	66.67	151.33
13-15 sample mass (4000 g)	2.00%	228	26.67	201.33
	3.00%	228	40.00	188.00
	4.00%	228	53.33	174.67
	5.00%	228	66.67	161.33

In a similar manner to the water optimization process, the bulk density of the samples at different emulsion contents and optimum water contents were calculated, and the results are presented in Table B 13 to Table B 15. Figure B 4 to Figure B 6 are plots of bulk density against emulsion content for batches 1-3-5, 7-9-11 and 13-15, respectively.

As reported in the first phase of the online survey, failure to meet density requirement is a common problem during FDR construction, so comparison between sample bulk density results for the asphalt optimization and the bulk density from the optimum water content is crucial in ensuring that the prepared samples are within the range of the optimum water content. The results from the bulk density tests showed that the test samples for batch 1-3-5 and batch 13-15 had peak bulk densities at 3.00% emulsion content and 3.60% emulsion content, respectively, which fall closely within range of the bulk densities for the optimum water contents for those batches, while batch 7-9-11 had peak bulk density at 3.80% emulsion content which fell short compared to the bulk density at optimum moisture content (OMC) for the batch. Table 4.5 shows a comparison between the bulk density from the optimum water content and the peak bulk density for the asphalt optimization samples.

Table 4.5 Bulk Density for all Batches

Batch	Bulk Density at OMC (lb./ft^3)	Peak Bulk Density for Asphalt Optimization (lb./ft^3)
1-3-5	133.70	133.53
7-9-11	135.55	133.97
13-15	131.72	132.00

The determination of optimum asphalt content in AEFDR design, which determines the reliability of the design in terms of load resistance and moisture susceptibility, is conducted using the Marshall stability test. For this test, four samples at the emulsion contents used for bulk density tests were prepared. Also, new emulsion contents were set for the batches: 3.50% emulsion content for batch 1-3-5 and batch 13-15 and 3.10% emulsion content for batch 7-9-11. These emulsion contents were set for the purpose of determining the peak stability strength, and 3.10% emulsion content for batch 7-9-11 was set to determine and track the change in sample stability strength resulting from a small increase in emulsified asphalt content. Following the steps listed in Appendix A2, dry Marshall stability and wet Marshall stability tests were then carried out on two samples each for every emulsion content of each batch. Table B 16 to Table B 18 show the results from the tests for each batch, and Figure B 7 to Figure B 9 show the plot of stability strength against emulsion content for each batch.

Marshall stability tests showed that while the samples had high stability in dry conditions, the samples showed rapid gain in wet stability with increase in asphalt content until a peak stability is reached. The trend continues as the samples rapidly lose stability strength with continued increase in asphalt content. Results of the wet Marshall stability test from Table B 17 shows the increased rate of gain of stability strength with the increase in emulsion content for the samples where a rather slight increase of 0.10% emulsion content from 3.00% emulsion content resulted in a significant rise in stability strength. And Table B 16 and Table B 18 show the resulting change in stability strength made by a 0.50% emulsion content difference. The significance of this relates to the sensitivity of AEFDR strength to asphalt content and the importance of maintaining optimum asphalt content during FDR construction with emulsified asphalt. Table 4.6 summarizes the results of the Marshall stability tests and peak retained stability for the batches, and Table

4.7 shows the emulsion content corresponding to peak stability and the Optimum asphalt content (residual).

Table 4.6 Summary of Asphalt Emulsion Optimization

Batch	Dry Marshall (lbf)	Wet Marshall (lbf)	Retained Stability (%)
1-3-5	12261.95	8012.55	65.34
7-9-11	12104.6	7200	59.48
13-15	12150.2	8796.95	72.40

Table 4.7 Summary of Optimum Asphalt Content

Batch	Optimum Emulsion Content (%)	Optimum Asphalt Content (%)
1-3-5	3.50	2.33
7-9-11	3.30	2.20
13-15	3.50	2.33

Acceptance criteria for asphalt emulsion optimization is based on minimum required strength and retained stability. The minimum strength requirement for test samples for emulsion optimization is 1625 lbf [44], and the result of the tests performed indicated that all samples for the different batches exceeded this minimum requirement with peak stability strengths at 3.50% emulsion content for batches 1-3-5 and 13-15, and peak stability strength at 3.30% emulsion content for batch 7-9-11. The average acceptable retained stability of 60% was surpassed by batches 1-3-5 and 13-15, while retained stability result of batch 7-9-11 at 3.30% emulsion content just fell short of the acceptable average.

4.1.5 Post Construction SR 88 – FWD Testing

On January 14, 2021, part of the research team met up with TDOT Headquarters' FWD trailer for post-construction testing of the FDR pavement with a double chip seal treatment. The trailer tested all the previous spots from where core samples were taken. There were a few locations that never would produce an FWD test reading, so at the end of testing, we had 10 locations out of the original 15 with FWD test data. Figure 4.4 presents images of the post construction falling weight deflectometer test being conducted on SR 88 in Lauderdale County. Post construction FWD testing data collected were back calculated and analyzed, and the results were compared to the pre-construction FWD testing data. The back calculated post construction resilient modulus results are presented in Table C3, and Table 4.8 present the summary statistics. From the tables, E_1 represents the FDR resilient modulus, a_1 represent the FDR layer coefficient, D_1 represents the FDR layer thickness, E_{sg} represents the subgrade resilient modulus and SN represents the structural number.

Figure 4-4 FWD Testing on SR-88 after FDR and Double Chip Seal Treatment

Table 4.8 Post Construction Summary Statistics

	E_1 (psi)	a_1	D_1 (in)	E_{sg} (psi)	SN
Average	1,579,300	0.51	12	8,009	6.11
Std Dev (sample)	891,313	0.09	0	2,572	1.10
Median	1,187,500	0.48	12	7,485	5.72
Lowest	774,000	0.41	12	5,304	4.96
Highest	3,200,000	0.66	12	1,3118	7.96

Table 4.9 shows the stations with comparable results, the total depth of surface and base layers (10 in. base thickness was assumed for all pavement sections), the FDR thickness, and compares the pre-construction structural numbers to the post construction structural numbers for the different sections, while Figure 4.5 gives a pictorial representation of how the structural numbers for the different stations compare.

Table 4.9 Comparison of Pre-Construction and Post Construction SN

Station	Mile Marker	Surface and Base Thickness (in)	FDR Thickness (in)	Pre-FDR Structural Number	Post-FDR Structural Number
Station 1	0	13.75	12	1.79	7.96
Station 2	0.5	14.5	12	3.04	7.5
Station 3	1.1	14	12	4.57	7.43
Station 4	1.5	14.5	12	3.18	6.02
Station 5	2.1	20.5	12	3.5	5.37
Station 7	3.1	16.5	12	4.55	5.23
Station 9	3.9	18.75	12	2.26	5.83
Station 10	4.6	21.25	12	9.67	5.2
Station 11	5.1	18.25	12	5.92	5.6
Station 14	6.6	17	12	1.72	4.96

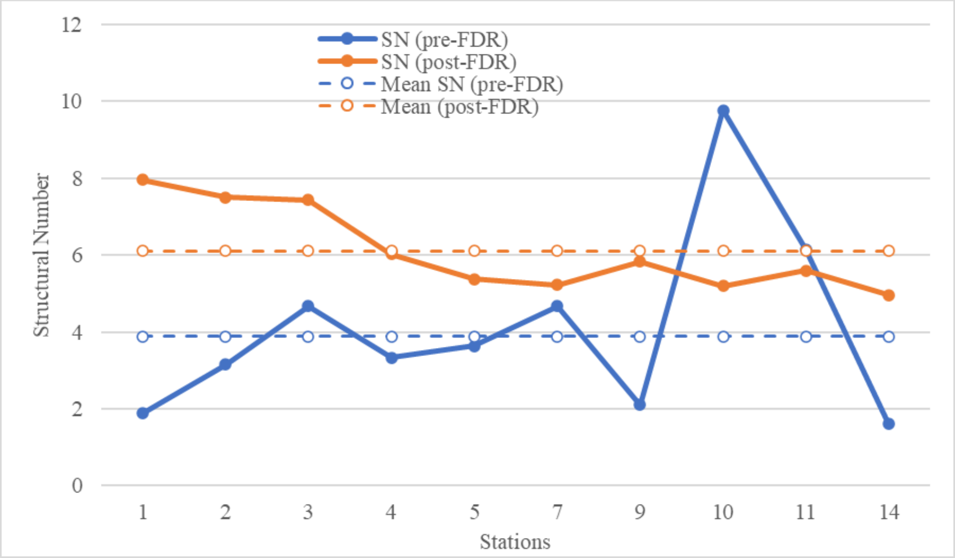


Figure 4-5 Pre-Construction and Post Construction Chart

4.2 State Hwy SR 54 – Weakley County, Tennessee

SR 54 is a rural highway that runs West-to-East from the cities of Covington to Alamo, cutting through Gibson, Weakley, and Henry Counties. Various portions of the road experience traffic volume ranging from a combined annual average daily traffic (AADT) of approximately 2000 (with 5% trucks) to 3500 [39]. Core samples from the original pavement revealed a 13- to 15-inch, heavily deteriorated HMA layer comprised of a mix of Bituminous Macadam and Surface Asphalt. The section considered for rehabilitation is about 4.2 miles long on route SR 54, and from the site investigation, the pavement showed numerous structural distresses and failures.

4.2.1 Material Gradation and Testing

For Hwy SR 54, the sample materials collected were completely made up of RAP materials without any base materials in them; neither was there a separate collection of reclaimed base materials. The reason for this was the depth of the asphalt layer, which was too deep for any base material reclamation. Materials on site were required to meet the same requirements stated previously in section 4.1.2. The materials were expected to have 100% of the largest particles passing the 3-inch sieve and a maximum of 20% passing the #200 sieve (P200). In the lab, the materials are required to have 100% passing the 1-5-inch sieve and a maximum of 20% passing the #200 sieve. Wet sieve analyses were performed on the reclaimed materials, as well as the material residue from asphalt extraction. The results obtained were satisfactory, indicating that the reclaimed materials met the requirements for full depth reclamation with Portland cement and asphalt emulsion stabilization. The results from the sieve analysis for the RAP materials are presented in Table B 19, and the gradation curve is presented in

Figure 4.6. Table B 20 and Figure 4.6 show the result and gradation curve for the material residue after the asphalt content extraction.

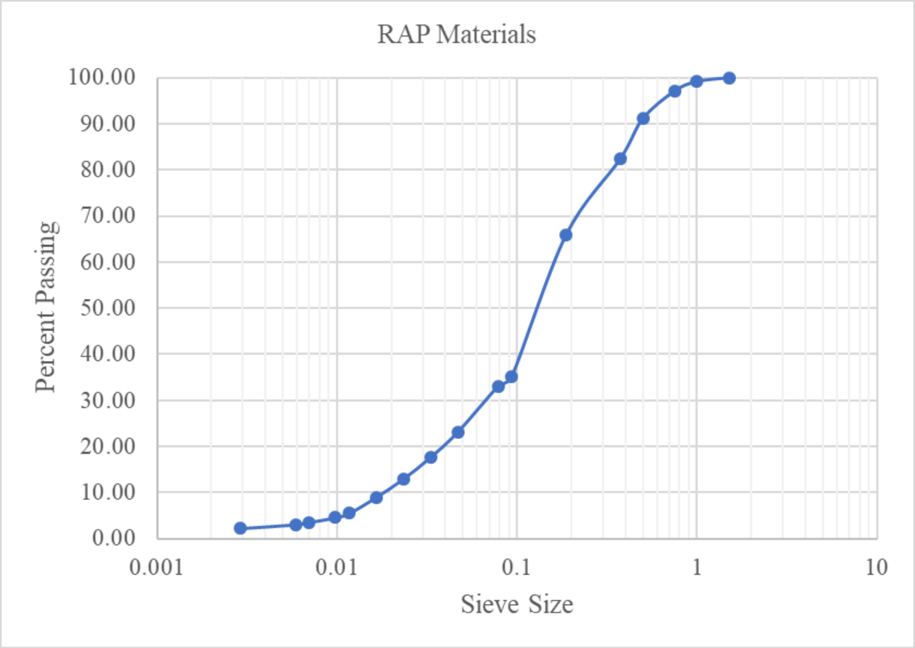


Figure 4-6 Particle Gradation for RAP Materials

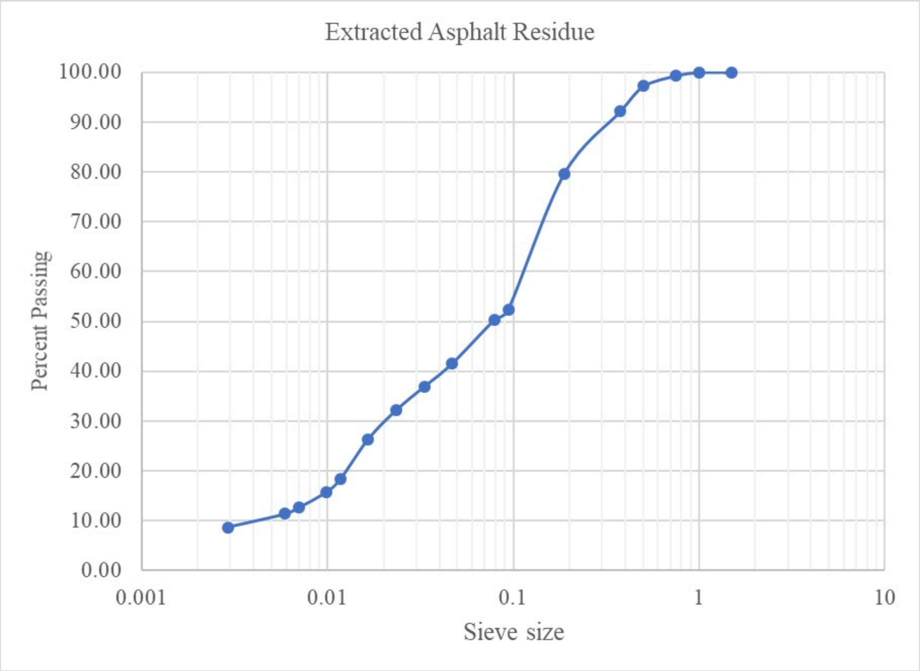


Figure 4-7 Particle Gradation for Material Residue from Asphalt Extraction

4.2.2 Mix Design for Portland Cement

The FDR mix design process for cement includes sampling the existing roadway to determine thickness of asphalt, aggregate base, and subbase as well as classifying the materials that will be incorporated. The sampled material is tested to determine an appropriate cement content, optimum moisture content and maximum density. Figure 4.8 shows the general steps for determining a mix design [15].

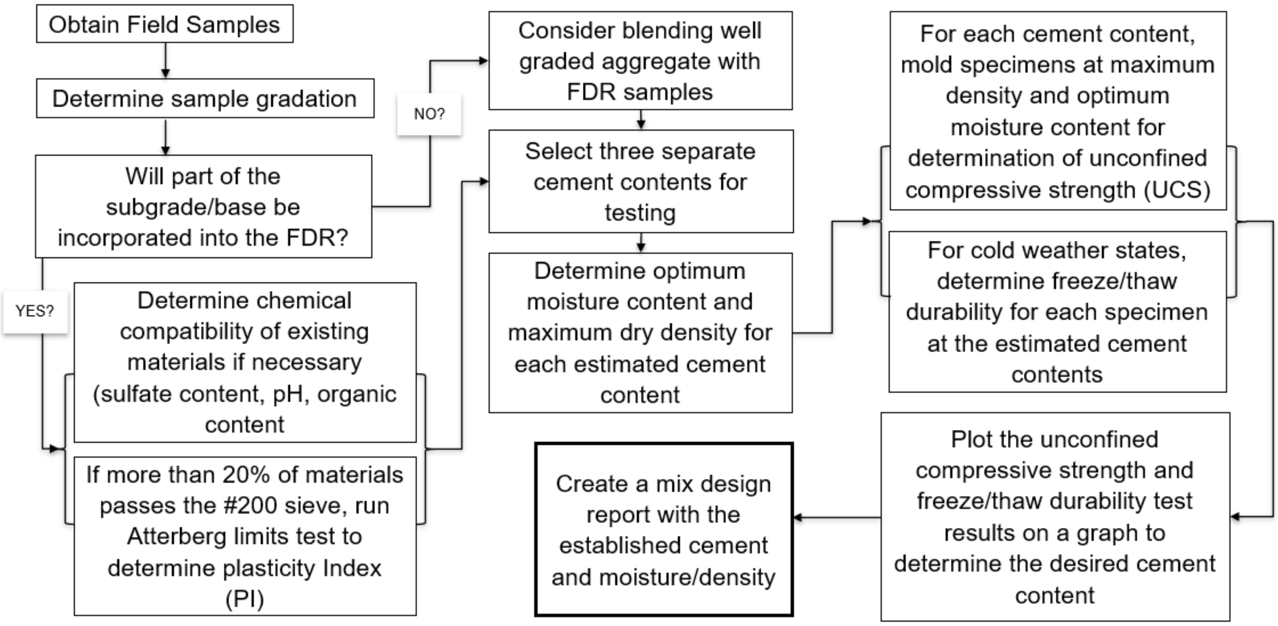


Figure 4-8 General Steps for Determining Portland Cement Mix Design for FDR layer [15]

4.2.3 Mix Design for Emulsified Asphalt

Asphalt emulsion stabilization processes were conducted in three major phases: AEFDR preliminary tests and characterization; water optimization; and asphalt emulsion optimization. The results were compared to the results of the Portland cement stabilization conducted at MTSU for the same batch of reclaimed pavement materials to ensure consistency of material properties and characteristics. Figure 4.9 presents general steps for emulsified asphalt mix design preparation.

The materials which were reclaimed from State Route 54 were mostly comprised of reclaimed asphalt pavement (RAP) materials with little to no base and subgrade materials, and this was largely due to the thick asphalt surface in the pavement structure. Tests using Portland cement as a stabilization agent were first conducted on samples of the reclaimed materials, and what was left of the materials were taken to UTC for the emulsified asphalt mix design. Details of the preliminary tests and characterization like gradation, moisture content and asphalt content are presented in section 4.2.2. Due to limited reclaimed materials for the asphalt emulsion stabilization tests, tests samples which were prepared and used for the water optimization phase were broken down (pulverized) and reintegrated into the batch materials. Thus, the difference in total asphalt content and the changes resulting from this reintroduction were noted and recorded.

The result of the emulsified asphalt stabilization showed excellent Marshall stability and retained stability. Higher stability values were obtained from lower emulsion contents with the lowest emulsion content used for the experiment having the highest result. Due to this, an optimum emulsified asphalt content was not determined for the mix design, and it implies that only a low amount of stabilizing agent is required for rehabilitating a road section of similar properties when using asphalt emulsion as the stabilizing agent.

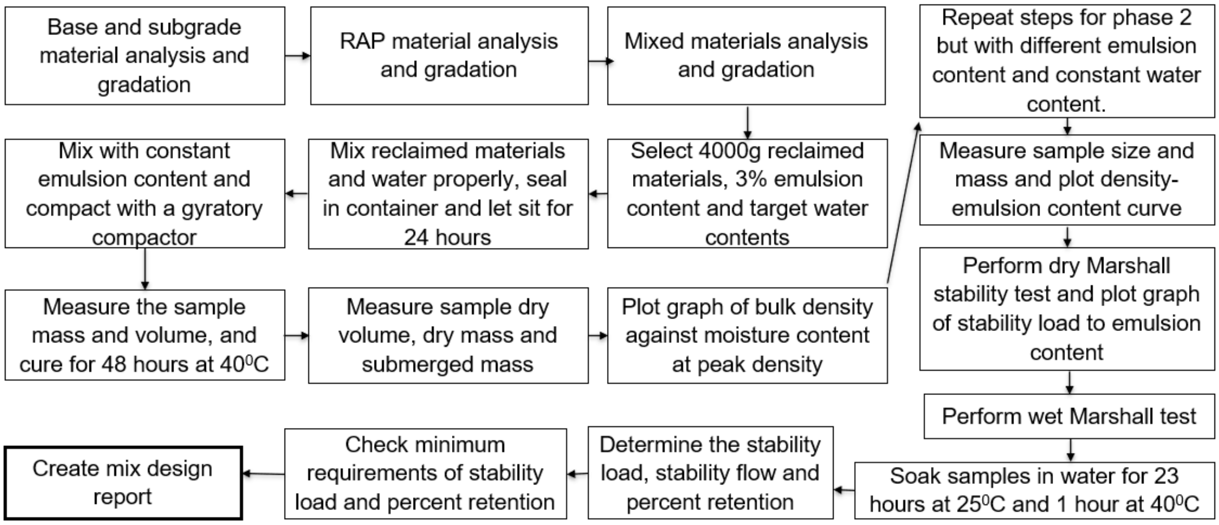


Figure 4-9 General Steps for Determining Emulsified Asphalt Mix Design for FDR layer

4.2.3.1 Water Optimization

The preliminary test result placed the in-situ moisture content of the reclaimed materials at 3.70% of the material mass. This in-situ moisture content was used as the starting point for the moisture contents for the water optimization phase. Increments in moisture content were set at 1.50% of sample mass, and four target moisture contents were established (3.70%, 5.20%, 6.70% and 8.20%). Two test samples were prepared for each moisture content, for a total of 8 test samples for the determination of the optimum moisture content for the mix. A standard asphalt emulsion content of 3.00% by dry material weight was used for the water optimization phase. At 3.70% and 5.20% moisture contents, the mixed materials did not show any strange compaction properties when compacted except for some light and considerably insignificant quantities of water sticking to the super gyratory compactor mold cover after extraction of the compacted samples. However, at 6.70% moisture content, sludges of water, emulsified asphalt and fine reclaimed materials started forming on the surfaces of the samples and the mold cover when the samples were extracted. The sludges formed on the samples at this moisture content mostly stayed on the surface where they were formed (the samples surface and the mold) without dripping. Sludge formed on samples prepared with 8.20% moisture content collected and formed pools on the surfaces of the sample and the mold cover.

As presented in the step for AEFDR stabilization in Appendix A2 the samples were cured for 48 hours, and the bulk densities of the samples at the different moisture contents were determined. A graph of bulk density against moisture content was plotted, and the maximum bulk density (and corresponding moisture content) was identified as the optimum moisture content for the samples. Table 4.10 gives the sample properties for the water optimization and Figure 4.10 presents a graph of bulk density against moisture content. The graph in Figure 4.10, shows that the optimum moisture content which yields the most bulk density of 2.065 g/cm^3 is at 6.90%.

Table 4.10 Optimum Asphalt Content

Moisture Percentage	Sample Number	Dry Mass (g)	Saturated Mass (g)	Submerged Mass (g)	Density (g/cm^3)
3.70% moisture	1	4081.3	4173.1	2140.1	2.007
	2	4079.5	4170.9	2138.9	2.008
	average	4080.4	4172	2139.5	2.008
5.20% moisture	1	4140	4150.5	2120	2.039
	2	4144.4	4172.8	2138	2.037
	average	4142.2	4161.65	2129	2.038
6.70% moisture	1	4136.4	4148.5	2137.5	2.057
	2	4146.7	4139.1	2138	2.072
	average	4141.55	4143.8	2137.75	2.0645
8.20% moisture	1	4123.3	4150.1	2113.5	2.025
	2	4137.2	4153.9	2133.5	2.048
	average	4130.25	4152	2123.5	2.036

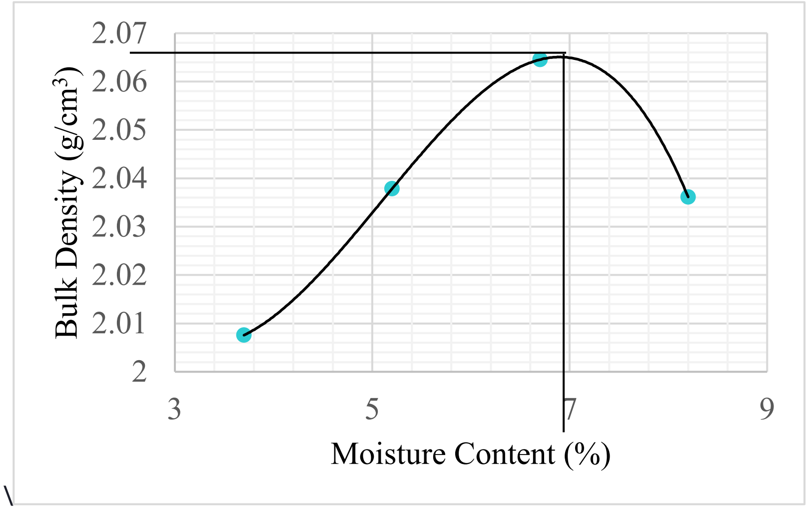


Figure 4-10 Bulk Density Vs. Moisture Content

4.2.3.2 Emulsion Optimization

With the optimum moisture content successfully determined, optimization for the emulsified asphalt content was started. Due to materials shortage, the research team reached a decision to utilize materials from the samples used for the water optimization. A fixed emulsified asphalt content of 3.00% of dry materials mass having 2/3 parts asphalt content was used in preparing each sample at each moisture content. The samples were crushed, dried out to remove all moisture, and weighed. Enough of the reclaimed materials was collected to prepare 16 test samples (8 samples tested for dry Marshall and 8 samples for wet Marshall). The measured reclaimed pavement material was mixed with the materials from the crushed samples, and the mixed properties were determined. The mixed materials had an increase in the asphalt content of 0.94% of dry material mass and total moisture content of 1.15% of dry material mass.

Four different emulsified asphalt contents from 2.00% through 5.00% with a 1.00% increase were selected, and the required moisture content for each of the emulsion contents was calculated. Two pairs of samples were prepared for the Marshall stability test and retained stability test for each of the emulsion contents, and the samples were tested. The results obtained from the emulsion optimization phase are presented in Table 4.11.

From Table 4.11, it can be deduced that the retained stability of the samples decreases as the asphalt content increases, and all emulsion contents met the requirement for the minimum acceptable strength value of 1625 lbf [44]. The nature of the stability curve from the selected emulsion contents in Figure 4.11 did not show an optimum emulsion content. The stability is highest at the lowest emulsion content, and the curve generated from the result turned to not a specific breaking point as indicated in Figure 4.11.

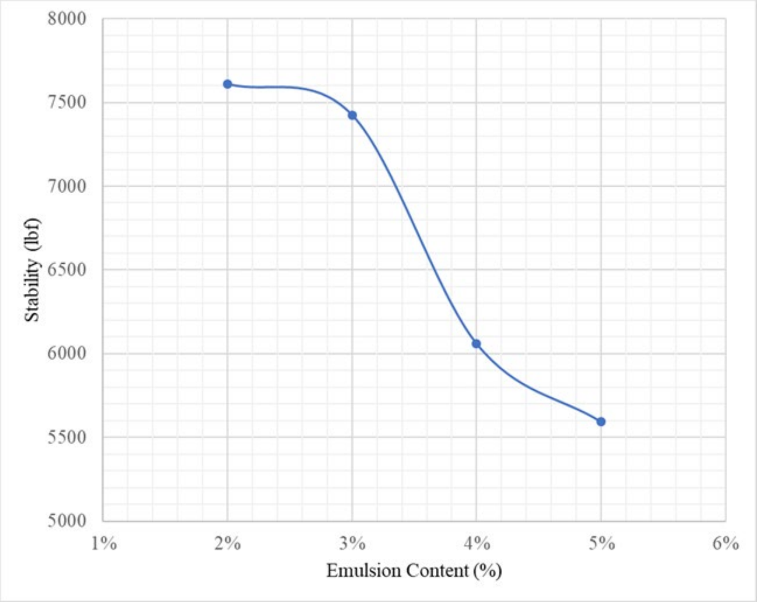


Figure 4-11 Stability Curve

The effectiveness of the stabilization agent is dependent on several factors, and the amount of RAP materials is one such factor. Where the result for PCFDR mix design was unsuccessful, AEFDR proved effective at low asphalt content. One major underlying factor differentiating the results from State Route 54 in Weakley County and State Route 88 in Lauderdale County is the proportion of RAP in the reclaimed materials. Analysis of post FDR construction data for State Route 88 showed that sections of the rehabilitated road, which had more RAP materials during rehabilitation, had a less resilient modulus. Information from some of the respondents to the FDR survey where Portland cement was identified as the most utilized stabilization agent recommended that FDR be used for roads with asphalt surface no more than 4 in. thick (5).

While Portland cement stabilization worked effectively for the road section of State Route 88 with an acceptable mix of RAP materials, base materials, and subgrade materials, the same could not be said for the materials from County Road 54. The experiment conducted on materials from this road had the cement content increased from 4.00% to 14.00% and still could not break the moisture/density curve. The possible reasons behind this occurrence were that there was possibly too much asphalt content and not enough base/subgrade materials. The experiment for the emulsified asphalt optimization was set at an initial emulsion content of 2.00%. With the emulsified asphalt having two-thirds parts asphalt content, the total asphalt content (including what was added from the samples used for water optimization) at each emulsion content level was determined as 2.27%, 2.94%, 3.61% and 4.27%. At 2.27% asphalt content, which is equivalent to 3.41% emulsified asphalt content, the materials had acceptable stability and retained stability. Lower levels of asphalt content were not used in this experiment, and due to this lack of information, the research team could not ascertain direct stability results for the materials at lower emulsified asphalt content.

Table 4.1 Marshall Stability and Retained Stability Results

Samples		Dry Marshall Test		Wet Marshall Test		Stability
Emulsion Content	Sample Number	Stability (lbf)	Flow (in.)	Stability (lbf)	Flow (in.)	Retained Stability (%)
2.00%	1	10531	0.025	7320	0.142	0.66592
	2	12322	0.032	7898	0.147	
	Average	11427	0.0285	7609.45	0.1445	
3.00%	1	12119	0.037	6802	0.145	0.62472
	2	11642	0.034	8042	0.145	
	Average	11881.2	0.0355	7422.5	0.145	
4.00%	1	NA	NA	5650	0.15	0.50733
	2	11939	0.051	6463	0.16	
	Average	11939.1	0.051	6057.1	0.155	
5.00%	1	12628.6	0.069	5486.1	0.153	0.44807
	2	12331.3	0.073	5697.7	0.155	
	Average	12480	0.071	5591.9	0.154	

Chapter 5 Results and Discussion

5.1 Project Selection

Selecting pavement candidates for FDR began with assessing the physical characteristics of the road, which is easily done by visual inspection. Visible pavement distresses can easily be identified, classified, and quantified, and pavements with moderate to severe deterioration were considered for FDR. The distresses and failures and their degree of deterioration can then be assessed and used in developing a PCI for the candidate pavement. Resurfacing, mill and fill, overlay, and CIR and HIR are sufficient for treating mild to moderately deteriorated pavements with structurally sound base structures. While FDR has the added benefit of restoring all distressed pavements to good structural and functional conditions, severe surface deterioration should be considered as an indicator of a more critical rehabilitation approach such as what FDR offers.

In situations (especially for mild deteriorations) where the choice is to be made between FDR or another rehabilitation solution like CIR and HIR, visual inspection should be augmented with other assessment techniques like core sampling and NDTs like falling weight deflectometer testing. Core samples will reveal the health condition of the pavement structure, especially the HMA layer while NDTs will provide valuable information of the entire pavement structure including the base and the subgrade layers. The data can then be analyzed, and the structural number or layer stiffnesses calculated from the NDT can be checked to see if the pavement deterioration has exceeded the agency’s trigger point.

When considering the urgency of undertaking an FDR project between the identified FDR candidates, the traffic estimate and axle load of the FDR candidates need to be considered. Traffic volume and axle load can be tied to the economic importance of a particular road and as such can be used in organizing candidate pavements in order of priority.

Finally, material availability and proximity, pavement structural composition, environmental suitability, and economic association to the different FDR candidates needs to be considered for an optimized candidate selection process. Statistical tools like the Excel Solver tool or more advanced tools can be used to reach conclusions among potential FDR candidates.

5.2 Online Survey

The goal of the survey was to establish an understanding of the state of FDR in the United States and in the state of Tennessee. On the national level, while the reports and research findings have shown that FDR is indeed an effective rehabilitation technique, experience in the area is still in its early stages.

Findings from the survey reveal that of the different stabilizing agents, Portland cement has been the preferred agent of choice for stabilizing FDR before emulsified asphalt.

While there is no official unified guide for preparing a mix design for FDR from the transportation governing body, state agencies have taken to developing their mix design guides for FDR and those state agencies that are yet to develop design guides employ the services of third parties for the provision of mix designs for their FDR projects. It is also up to the individual agencies to provide guidelines for when the use of FDR is appropriate, and most States agencies have specifications for FDR projects.

During construction as reported in 3.2.1 Phase 1 of the survey, it is not certain what ideal or preferred proportion of subgrade materials should be included in FDR projects as the reports ranged from 0% to 50% of subgrade materials across the United States. Aside from the major stabilizing agents used for the projects, most respondents rarely utilize supplementary materials in their FDR projects. Roads that are mostly rehabilitated with FDR are highways, local roads and major and minor arterials and the most adopted methods for determining candidate selection for FDR are core sampling and visual inspection and more than half of respondents also use falling weight deflectometer testing. The most common problem reported during the construction of an FDR project from the survey was improper moisture control, and several other identified problems had to do with density requirements, curing, strength requirements and specification requirements.

Regarding long term performance, a larger percentage of respondents replied that they did not have long-term performance information on FDR since a large portion of the projects were no more than 10 years in age. For issues seen during the life of an FDR project, respondents mentioned issues associated with the construction process like going too deep into the pavement layers, issues associated with the environmental factors like the presence of large rocks, improper drainage, wind and curing, and issues associated with stabilizing agents like shrinkage cracks and relief cracks.

It is accepted that FDR is a cost-effective method of rehabilitation and pavement maintenance; however, most of the respondents replied that they haven't performed an economic assessment on their projects. Almost all respondents indicated that they would recommend the use of FDR for pavement rehabilitation for various reasons, including the correction of most pavement distresses and failures, and as a good means of cost management while specifying conditions on asphalt layer thicknesses, traffic load and environmental conditions for their recommendations.

On the state level (Tennessee), experience in FDR coming from six counties revealed that all had experience in FDR using a stabilizing agent, and the preferred choice of stabilizing agent for FDR from the counties was Portland cement. The county engineers all reported to have used a mix design method for their projects, but no specification or guidelines were reported except for Weakley County.

The pulverization in the county level FDR projects all used the full depth of the pavements with varying proportions of subgrade inclusion, and none of the respondents reported the use of supplementary materials like fly ash. Most FDR projects were performed on local roads and residential roads. FDR has also been used for highways and arterials.

Taking cores and visual inspection were the most sort after means of candidate selection for the counties, and moisture control, traffic and sanitation were the problems mostly encountered during construction. The failure types that were targeted with FDR for the counties included all failures associated with the base layer of the pavement and fatigue cracking, and all respondents reported that they would recommend FDR for pavement treatment.

Outside the findings from the online survey, discussions on FDR stabilizing agents and their applicability with Ariel Soriano from the City of Chattanooga shed light on alternative materials that could improve cost efficiency of the process while delivering satisfactory results for the intended purpose. The discussion was centered on the utilization of Cement Kiln Dust (CKD) which is a by-product of cement production as a stabilizing agent. The properties of CKD as a modifier for soils with high plasticity, and its relatively cheap acquisition could be taken advantage of in situations where traditional stabilizing agents like Portland cement and emulsified asphalt are insufficient for effective and economic FDR stabilization.

5.3 Stabilizing Agents

The effectiveness of the FDR stabilization agent is dependent on several factors including pavement structural composition, material composition, environmental and climatic factors. For each of these factors and/or a combination of multiple factors, different stabilizing agents would be required for optimal functionality of an FDR project. From the research on the Portland cement and emulsified asphalt as stabilizing agents for FDR, the results and summaries in the ensuing sub-sections are generated.

5.3.1 Portland Cement

Cement is a type of chemical stabilization that is achieved by mixing pulverized asphalt pavement and subsurface materials with a chemical stabilizing agent. Common chemical stabilization materials are Portland cement, lime, fly ash, lime kiln dust, calcium, or magnesium chloride. Cement stabilization is an engineered alternative to realize cost savings through reduction of hauling and less labor for removing and replacing existing material. All the alternatives gain this advantage. This research focused on the performance of the mixtures knowing that TDOT had early indication that this method would save agency funding. Cement stabilization can achieve high early strengths and this research wanted to understand more about strength development with different percentage additions. In addition to early performance, durability is very important for FDR roads and while this study did not have the opportunity to monitor for long term durability, the literature suggests that you will see better moisture resistance and freeze/thaw resistance. Lastly, cement stabilization works with a wide variety of existing materials and can accommodate higher plasticity soils. We captured the PI of the soils to be able to monitor performance on a variety of subsurface conditions.

Analyses of postconstruction data suggests that the differences in resilient modulus in different sections of the road are subject to factors which mainly comprised of reclaimed material proportions since no effort was taken to mill off excess asphalt surface materials before rehabilitation to ensure consistent RAP proportions in the reclaimed mix. From the information provided in section 4.1.5, lower post construction structural numbers are associated with sections of the road with thicker asphalt layers, and though not researched upon, it is believed that base material compositions also have some contributions to the post construction results. Identifying the extent and range to which these factors affect the post-construction resilient modulus and overall pavement performance would require further studies.

5.3.2 Emulsified Asphalt

Sieve analyses results for the base materials, RAP materials and composite materials for all batches for SR 88, compared with the reclaimed asphalt pavement and underlying materials requirements from the Asphalt Reclaiming and Recycling Association is provided in Table 5.1. The results show all materials for the mix designs meeting the requirements except the subgrade materials for SR 88 batch 7-9-11, which were eventually excluded from the mix.

Asphalt binder content in the RAP materials and composite materials were determined separately using the procedure outlined in Appendix A2. The results were used to determine the proportion of RAP materials in the reclaimed mix which, in turn, is taken as the reclaimed material composition for the mix design. This composition will be used to determine the depth in the pavement to which the reclaimer will retrieve materials during the FDR construction. The reclaimed material proportions during construction will have to be maintained as much as possible as the same proportion of RAP content in the mix as indicated in the design. This implies that on some portion of the roadway, it might be needed to mill off some asphalt surface materials to stick to the designed RAP content. Table 5.2 shows the report of binder content in the RAP materials, reclaimed materials, and the RAP content in the reclaimed materials for the batches.

The summary of the optimizations (water and emulsified asphalt) for all the batches are presented in Table 5.3. The summary compares the results to minimum Marshall stability recommendation by ARRA [44] and the stability retention to the common acceptable average of 60% [45]

Table 5.1 Material Gradation Summary

	Sieve Sizes	3-in (75mm)	2-in (50mm)	#200 (0.075mm)
Materials by Batch	Requirements	100%	95 – 100%	2 – 20%
Batch 1-3-5 Materials	Subgrade	X	X	X
	Base	100%	100%	0.6%
	RAP	100%	100%	4.8%
	Composite	100%	100%	4.11%
Batch 7-9-11 Materials	Subgrade	100%	100%	71.6%
	Base	100%	100%	15.4%
	RAP	100%	100%	8.1%
	Composite	100%	100%	11%
Batch 13-15 Materials	Subgrade	X	X	X
	Base	X	X	X
	RAP	X	X	X
	Composite	100%	100%	6.5%
SR 54 Materials	Subgrade	X	X	X
	Base	X	X	X
	RAP	100%	100%	2.24%
	Composite	X	X	X

The optimum moisture content reported in the mix design considers the in-situ moisture present in the reclaimed materials, water present in the asphalt emulsion, and extra water used during the pulverization process as well as the general construction process. Using the sample maximum bulk density in its determination, the optimum moisture content will provide maximum compaction during construction while preventing slurry formation. The optimum emulsion content reported in the mix gave the maximum stability under load and retained stability when subjected to saturated moisture conditions. A lower optimum moisture content was determined for batch 7-9-11. Though the OMC was lower, it produced a mix with the highest bulk densities. While the RAP materials of batch 7-9-11 had the highest binder content, the optimum emulsion content for the mix design turned out to be the lowest emulsion content of the three batches. The Marshall stability load for the batch samples greatly exceeded the minimum requirement, but the retained stability for this batch fell just below the requirement of 60% retention of dry stability strength. Mix design for batch 13-15 gave the highest optimum moisture content amongst all batches for SR 88 and an optimum asphalt content same as the mix design for batch 1-3-5. The Stability strength of the mix design samples was as promising of the other mix designs with values going well above the minimum requirement. The retained stability for this batch, however, was the most promising of all the batches as test samples retained percentages of their stability that were much higher than the specification when submerged in water over a period.

Table 5.2 Binder Content and RAP Content

Batches	1-3-5	7-9-11	13-15	SR 54
Binder Content in RAP	4.52%	4.92%	4.52%	7.56%
Binder Content in reclaimed materials	3.63%	3.35%	3.42%	7.56%
RAP Content in reclaimed materials	80%	68%	76%	100%

Table 5.3 Optimization Summaries

Water Optimization	Batch 1-3-5	Batch 7-9-11	Batch 13-15	SR 54	Specification Requirement
OMC	5.60%	5.45%	5.7%	6.9%	NA
Bulk Density	133.70 lb./ft^3	135.55 lb./ft^3	131.72 lb./ft^3	128.91 lb./ft^3	NA
Emulsion Optimization	Batch 1-3-5	Batch 7-9-11	Batch 13-15	SR 54	Specification Requirement
Emulsion Content	3.50 %	3.30%	3.50%	3.03%	NA
Bulk Density	133.53 lb./ft^3	133.97 lb./ft^3	132.00 lb./ft^3	122.69 lb./ft^3	NA
Dry Marshall Stability	12262 lbf	12104.6 lbf	12150.2 lbf	11427 lbf	NA
Dry Marshall Flow	0.017 in	0.016 in	0.017 in	0.029 in	NA
Wet Marshall Stability	8013 lbf	7200 lbf	8796.95 lbf	7609.45 lbf	1625 lbf (minimum)
Wet Marshall Flow	0.053 in	0.051 in	0.074 in	0.145 in	NA
Retained Stability	65.34 %	59.48 %	72.40 %	66.59%	60%

Chapter 6 Conclusion and Recommendations

6.1 Conclusions

FDR is accepted as a suitable rehabilitation solution for most pavement distresses. It is considered by many state agencies as an ideal solution for the improvement of pavement structural capacity and widening of the pavement shoulders. At present, it is up to the different state transportation agencies to provide mix design guides for FDR projects in the states as well as candidate selection guides and construction specifications. Potential FDR candidates could be any type of pavement, but the most common pavements rehabilitated with FDR are highways, local roads, and arterials. As a very cost-effective alternative to reconstruction, the cost effectiveness of FDR can be tied to the stabilizing agent used for the construction of the projects. For instance, where Portland cement is used to stabilize an FDR base, an asphalt layer is typically placed over the FDR as a wearing course to protect the base from moisture intrusion and improve the ride quality, and this contributes to the cost of construction. Candidate selection for both the national and state level of the survey revealed visual inspection and core sampling to be the most adopted means of FDR candidate selection.

The selection of candidate pavements for FDR should start with the identification and classification of visible distresses on the pavements. The identified distresses would then be used in the development of a pavement condition index for the candidates where all candidates falling below the trigger point for the agency would be considered as potential FDR candidates. Pavement core sample analyses and NDT equipment like the falling weight deflectometer and ground penetrating radar should then be used in assessing the condition of the pavement layers. Pavements with poor base layers incapable of supporting the pavement design loads should be considered as acceptable FDR candidates. Amongst acceptable FDR candidates, pavements with more economic relevance based on traffic conditions should be given priority, and statistical analyses tools like Excel Solver and other preferred tools should be utilized in reaching an optimized choice between acceptable candidates based on the cost estimate of stabilization and rehabilitation, the proximity of the candidates to materials, and other quantifiable factors.

A proper material gradation is vital to the performance of FDR projects. These materials are required to have restrictions on the amount passing the #200 sieve, and the sizes of the coarse aggregates in the mix. Too much fine materials in the mix will result in an increase in the amount of recycling agent for the stabilization, and deleterious materials are preferably removed so as not to compromise the properties of the mix design. Reclaimed materials with high RAP contents are better stabilized with emulsified asphalt, and materials with 100% RAP contents are unsuitable for cement stabilization and would require lower amount of emulsified asphalt for optimum stabilization. Cement stabilization works best when there is significant inclusion of granular materials from the base and subgrade (optional) layers provided they are of acceptable properties. In certain conditions, it would be required to mill off some portions of the asphalt layer to allow for an inclusive proportion of the other pavement materials. However, the cost, effort and implications of such procedures should be compared to the merits and demerits of other stabilizing agents, and their suitability.

6.2 Recommendations

TDOT's specification for FDR projects (SP304FDR) appears to be well established with no need for major specification alterations. However, having analyzed the findings from the research, and from the discussions and the interactions with industry professionals, the research team strongly recommends that some provisions be made to the specification to improve on the existing provisions which would help save costs and improve the performance of the FDR projects.

In the Materials section, TDOT would benefit from the inclusion of Cement Kiln Dust (CKD) as possible material for FDR stabilization. CKD as a waste product from the production of cement, has been used in stabilizing and improving the properties of soil with high plasticity. Proper integration of this material in FDR as a stabilizing agent or a supplementary agent would save TDOT significantly in construction cost.

Under the Mix Design Submittal and Quality Control sections, the research team recommends that different mix designs be adopted for sections of the FDR pavement with largely different structural properties. Information from the postconstruction analyses for SR-88 suggests that the difference in resilient modulus in different sections of the road resulted from using the same FDR mix design on a road with largely different reclaimed materials proportions, owing to differences in pavement structural layer thicknesses. The benefits from different mix design for pavement sections with largely different characteristics are better consistency with the post construction pavement properties and close adherence to the FDR mix design.

It is also recommended that appropriate time be given before the installation of an asphalt surface course for cement stabilized FDR base. This draws from the factor that cement curing is usually accomplished by shrinkage and possible development of cracks. Other bituminous preservative methods like chip seal could be used immediately after construction to protect the base form moisture loss until a permanent wearing course is installed.

After construction, for roads with high traffic volume, where redirection of the entire vehicular traffic is impossible, restrictions should be placed on the class of vehicle driving on the newly constructed road according to the engineer's advice until the pavement is sufficiently cured (typically 7 Days). This would protect the new pavement base from damage and defects in its early curing stage.

The teams also recommends that to battle the challenge of environmental pollution of cement particles by wind dispersion reported by respondents to the survey, the Department should set plans for the development of provisions for the use cement slurry to combat such challenges when spreading cement and other dry media for FDR projects.

TDOT's specification has no provisions for emulsified asphalt as a stabilizing agent for FDR. The development and inclusion of emulsified asphalt specifications on mix design, material quantity and properties and construction procedures to TDOT's FDR specifications will provide valuable alternative for project success. The research team observed that savings can be derived from the use of emulsified asphalt on pavement candidate with certain properties, like thick asphalt layers as is detailed in section 4.2.3 of the report where low amount of emulsified asphalt is required for effective stabilization of FDR candidate pavement with thick asphalt layers and no base and subgrade material inclusion in the reclaimed mix.

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Appendix A. Mix Design

A1: Portland Cement Mix Design (PCFDR)

The design of Portland cement stabilized FDR focuses on optimizing the cement content and the water content for the materials. The Portland Cement Association's guide to full-depth reclamation with cement specified recommended tests to conduct for the preparation of a cement stabilized FDR mix design. The steps include:

1. Determination of the sample gradation following AASHTO T11 and T27 or ASTM C117 and C136 standards. The gradation plays an important role in ensure a strong bond between the particles and keeping cost in check as too many fines will require more cement content for the mix. Hence the minimum percentages of 100% passing the 3-in sieve, 55% of materials passing the No 4 sieve and a maximum of 20% passing the #200 sieve are required.
2. Atterberg Limits Test using AASHTO T 90 or ASTM D4318. This test is recommended when the materials passing the #200 sieve is at least 20% of the total combined materials. It determines the liquid limit, plastic limit and plasticity index of the portion of the materials passing the #200 sieve and this provides information on the bonding characteristics of the aggregates, and aid in the classification of the soil materials.
3. Chemical compatibility. The test associated with this include sulfate content, pH value of the existing materials and the organic material content in the reclaimed materials. Reeder e al suggested that these tests can be minimized on the basis of familiarity with the soil and materials composition of the road, and experience in the use of FDR to rehabilitation.

With the completion of the tests to classify and characterized the materials for the mix, a cement arbitrary cement content is established and varied (preferably by 2 – 3% intervals) to establish other cement contents for testing and determining the optimum content. following AASHTO T 134 or ASTM D558 for the determination of compaction density, the maximum dry density (MDD) and the optimum moisture content (OMC) are calculated. To achieve this, material mixtures are compacted at different moisture contents and a cement content that is midrange of all cement contents considered for the test, and their dry densities are calculated. The results of the dry densities are plotted against the water content, and the moisture content where the curve breaks (maximum dry density) is marked as the OMC. The cement content and water content are determined using equations A.1 and A.2 respectively.

$$\boldsymbol{Cement\ content}(\%) = \frac{\boldsymbol{weight\ of\ cement}}{\boldsymbol{dry\ weight\ of\ reclaimed\ materials}} * \mathbf{100} \qquad \text{Equation A.1}$$

$$\boldsymbol{water\ content}(\%) = \frac{\boldsymbol{weight\ of\ water}}{\boldsymbol{dry\ weigth\ of\ reclaimed\ materials}} * \mathbf{100} \qquad \text{Equation A.2}$$

Maintaining the optimum moisture content values, specimens should be prepared at the different established cement contents and tested for their unconfined compressive strength (UCS) following the standards of ASTM D1633. The graph of UCS against cement content is then used to select the required cement content for the desired compressive strength of the mix according to the agencies' specification.

A2: Emulsified Asphalt Mix Design (AEFDR)

The FDR mix design involves three phases:

Phase 1: Determination of the percent passing sieve #200

1. Dry samples obtained from the site for 24 hours.
2. Determine the percent passing #200 (P200) sieve for each of the dry materials collected.
3. Determine the binder content of the Reclaimed asphalt pavement (RAP) materials.
4. Mix the RAP, base and or subgrade samples at required ratios.
5. Determine the percent passing #200 sieve from the above mix (requirement: P200 < 20%).
6. Determine the binder content of the mix.

Phase 2: Optimum moisture content determination

1. Using a riffle splitter and a weighing scale, obtain 4000g of the dry sample mix in different containers (3 samples per % moisture content value).
2. For optimum moisture determination using asphalt emulsion, the amount of asphalt emulsion is selected as a percentage by mass of the dry sample and kept constant through the process (example 3%). Since the asphalt emulsion contains part residuals and part water, the water part is to be considered in optimum moisture content determination.
3. For each of the 4000g samples, add water to attain the preferred moisture content (e.g. 4%, 5% and 6% by weight of dry sample) while keeping into consideration the additional water from the emulsion to be used as decided in step 2 above. Note three (3) samples are to be prepared for each moisture content value.
4. Mix each of the 4000g samples in a mixer with the moisture content required till the mix becomes homogeneous.
5. Contain each of the mixed samples in sealed containers and let them soak for 24 hours.
6. After 24 hours, add the predetermined asphalt emulsion content by percent mass of the dry sample (examples 3% of dry mass of mix) as decided in step 2 to each of the soaked samples.
7. Using an asphalt mixer, mix each of the samples with the asphalt emulsion till a homogenous mix is obtained.
8. Let the mixture sit for 30 minutes, then compact each of the samples for 30 gyrations using a Gyratory compactor.
9. Extrude the sample from the Gyratory compactor and measure the wet mass and thickness of the sample (Thickness is obtained as the average thickness of three or more measurements on the sample). Calculate the sample wet density from the measured parameters.
10. Place the compacted samples in the oven at 40^{o} C for 48 hours
11. After 48 hours, remove the compacted samples and when cool measure the dry masses and thicknesses of the samples. Calculate the Dry density of the samples from the measured parameters.
12. Calculate the bulk density of the samples. Bulk density is calculated as saturated mass (measured at SSD condition) divided by the sample volume. (6)

13. Plot a graph of bulk density versus moisture content. The optimum moisture content can be obtained as the moisture content giving the maximum bulk density from the plotted curve.

Phase 3: Optimum emulsion content determination

1. Optimum emulsion content determination initial procedures are much like those of the optimum moisture content determination (Step 1 to 12), whereby for emulsion optimization the moisture content is kept constant while the emulsion contents are varied. The moisture content used here corresponds to the optimum moisture content. Also, for emulsion content optimization it is advised to use six (6) samples per asphalt content.
2. Plot a graph of bulk density versus emulsion contents.
3. Perform Marshal stability tests on the samples. Marshall stability tests include dry and wet tests. From the six (6) samples for each emulsion content; three (3) are used for dry Marshall stability and the other three (3) for wet Marshall stability test.
4. Dry Marshall stability test
    i. Place the sample on the load frame and perform the Marshall test.
    ii. Record the maximum stability strength of each test sample at different emulsion contents
    iii. Plot a graph of Stability versus emulsion content. The optimum emulsion content can be obtained as the emulsion content at which maximum stability is observed on the plotted curve.
    iv. The dry Marshall test is targeted at a minimum strength value of 1625 lbf for 6inch samples
5. Wet Marshall stability test
    i. Soak the samples in the water bath at 25^{o} C for 23 hours then at 40^{o} C for an hour.
    ii. Place the sample on the load frame and perform the Marshall test.
    iii. Record the maximum stability strength of each test sample at different emulsion contents.
    iv. Plot a graph of Stability versus emulsion content. The optimum emulsion content can be obtained as the emulsion content at which maximum stability is observed on the plotted curve.
    v. Determine the ratio of the maximum wet Marshall Stability to the Maximum dry Marshall stability values to see if it meets the percent requirement set by the required agency. An average of 60% retained stability is usually accepted for emulsion FDR.

Appendix B. Laboratory Results: Tables and Graphs

Table B 1 Batch 1-3-5 Base Materials Particle Size Distribution

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.000
1	1	185.6	185.6	96.239
0.75	0.75	304.2	489.8	90.074
0.5	0.5	486.2	976	80.222
0.375	0.375	233.8	1209.8	75.484
4	0.187	577.7	1787.5	63.777
8	0.0937	468.2	2255.7	54.289
10	0.0787	139.6	2395.3	51.460
16	0.0469	425	2820.3	42.848
20	0.0331	648.4	3468.7	29.708
30	0.0234	472.5	3941.2	20.133
40	0.0165	557.8	4499	8.829
50	0.0117	172.2	4671.2	5.340
60	0.0098	41.5	4712.7	4.499
80	0.007	56.1	4768.8	3.362
100	0.0059	53.5	4822.3	2.278
200	0.0029	81.4	4903.7	0.628
pan	0	31	4934.7	0.000

Table B 2 Batch 1-3-5 RAP Aggregate Materials Particle Size Distribution

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.000
1	1	0	0	100.000
0.75	0.75	0	0	100.000
0.5	0.5	126.4	126.4	92.735
0.375	0.375	312.8	439.2	74.755
4	0.187	385.7	824.9	52.585
8	0.0937	175.9	1000.8	42.474
10	0.0787	34.2	1035	40.508
16	0.0469	79.6	1114.6	35.933
20	0.0331	55.75	1170.35	32.728
30	0.0234	63.12	1233.47	29.100
40	0.0165	89.18	1322.65	23.974
50	0.0117	141.55	1464.2	15.838
60	0.0098	60.55	1524.75	12.357
80	0.007	70.36	1595.11	8.313
100	0.0059	26.39	1621.5	6.796
200	0.0029	34.72	1656.22	4.800
pan	0	83.51	1739.73	0.000

Table B 3 Batch 7-9-11 Subgrade Materials Particle Size Distribution

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0.0	100.000
1	1	0	0.0	100.000
0.75	0.75	37.9	37.9	98.685
0.5	0.5	84.2	122.1	95.764
0.375	0.375	49.4	171.5	94.050
4	0.187	100.8	272.3	90.553
8	0.0937	99.3	371.6	87.108
10	0.0787	17.9	389.5	86.487
16	0.0469	41.8	431.3	85.037
20	0.0331	30.1	461.4	83.993
30	0.0234	40.4	501.8	82.591
40	0.0165	47.7	549.5	80.936
50	0.0117	40.5	590.0	79.531
60	0.0098	25.9	615.9	78.632
80	0.007	21.5	637.4	77.886
100	0.0059	18.2	655.6	77.255
200	0.0029	161.7	817.3	71.645
pan	0	2065.1	2882.4	0.000

Table B 4 Batch 7-9-11 Base Materials Particle Size Distribution

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.000
1	1	0	0	100.000
0.75	0.75	8.9	8.9	99.703
0.5	0.5	309	317.9	89.403
0.375	0.375	186.2	504.1	83.196
4	0.187	420.6	924.7	69.176
8	0.0937	462.5	1387.2	53.758
10	0.0787	104.9	1492.1	50.262
16	0.0469	252.1	1744.2	41.858
20	0.0331	150.8	1895	36.831
30	0.0234	138	2033	32.231
40	0.0165	133.2	2166.2	27.791
50	0.0117	120	2286.2	23.791
60	0.0098	43.6	2329.8	22.337
80	0.007	66.5	2396.3	20.121
100	0.0059	48.4	2444.7	18.507
200	0.0029	91.5	2536.2	15.457
pan	0	463.7	2999.9	0.000

Table B 5 Batch 7-9-11 RAP Materials Particle Size Distribution**.**

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.000
1	1	0	0	100.000
0.75	0.75	0	0	100.000
0.5	0.5	62.5	62.5	96.795
0.375	0.375	140.8	203.3	89.575
4	0.187	360.8	564.1	71.073
8	0.0937	266.5	830.6	57.407
10	0.0787	61	891.6	54.279
16	0.0469	142.1	1033.7	46.992
20	0.0331	100.2	1133.9	41.854
30	0.0234	113.6	1247.5	36.029
40	0.0165	134.6	1382.1	29.127
50	0.0117	163.1	1545.2	20.763
60	0.0098	87	1632.2	16.302
80	0.007	55.3	1687.5	13.466
100	0.0059	30.1	1717.6	11.922
200	0.0029	75.4	1793	8.056
pan	0	157.1	1950.1	0.000

Table B 6 Binder content and RAP content.

Batches	Binder content in RAP	Binder content in mix	RAP content in mix
batch 1-3-5	4.52%	3.63%	75%
batch 7-9-11	4.92%	3.35%	78%
batch 13-15	4.52%	3.42%	76%

Table B 7 Batch 1-3-5 mixed materials particle size distribution.

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.00
1	1	0	0	100.00
0.75	0.75	9	9	99.70
0.5	0.5	255.3	264.3	91.20
0.375	0.375	371.6	635.9	78.84
4	0.187	781.5	1417.4	52.83
8	0.0937	442.5	1859.9	38.11
10	0.0787	85.5	1945.4	35.26
16	0.0469	186.2	2131.6	29.06
20	0.0331	128.5	2260.1	24.79
30	0.0234	130.2	2390.3	20.46
40	0.0165	146.9	2537.2	15.57
50	0.0117	158.1	2695.3	10.31
60	0.0098	54.3	2749.6	8.50
80	0.007	62.2	2811.8	6.43
100	0.0059	34.4	2846.2	5.28
200	0.0029	35.4	2881.6	4.11
pan	0	123.4	3005	0.00

Table B 8 Batch 7-9-11 mixed materials particle size distribution.

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.00
1	1	0	0	100.00
0.75	0.75	0	0	100.00
0.5	0.5	331.3	331.3	89.15
0.375	0.375	402.7	734	75.96
4	0.187	775.7	1509.7	50.55
8	0.0937	462.2	1971.9	35.41
10	0.0787	92.7	2064.6	32.37
16	0.0469	178.4	2243	26.53
20	0.0331	104.3	2347.3	23.11
30	0.0234	97.5	2444.8	19.92
40	0.0165	86.6	2531.4	17.08
50	0.0117	66.5	2597.9	14.91
60	0.0098	22.6	2620.5	14.17
80	0.007	31.8	2652.3	13.12
100	0.0059	19	2671.3	12.50
200	0.0029	46.1	2717.4	10.99
pan	0	335.6	3053	0.00

Table B 9 Batch 13-15 mixed materials particle size distribution

Sieve no	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.00
1	1	0	0	100.00
0.75	0.75	0	0	100.00
0.5	0.5	168.8	168.8	88.67
0.375	0.375	132.9	301.7	79.76
4	0.187	323	624.7	58.09
8	0.0937	242.3	867	41.83
10	0.0787	49.4	916.4	38.52
16	0.0469	111.8	1028.2	31.02
20	0.0331	68.9	1097.1	26.39
30	0.0234	75.4	1172.5	21.34
40	0.0165	74.4	1246.9	16.34
50	0.0117	58.3	1305.2	12.43
60	0.0098	23.2	1328.4	10.88
80	0.007	28.8	1357.2	8.94
100	0.0059	15.5	1372.7	7.90
200	0.0029	20	1392.7	6.56
Pan	0	97.8	1490.5	0.00

Table B 10 Water Optimization for Batch 1-3-5

Water Content	Sample Number	Wet Density (lb./ft^3)	Dry Density (lb./ft^3)	Bulk Density (lb./ft^3)
3% water	1-3-5/301	134.400	131.418	132.440
	1-3-5/302	133.620	130.364	131.418
	average	134.009	130.889	131.928
4% water	1-3-5/401	135.429	131.844	132.758
	1-3-5/402	136.188	131.976	132.840
	average	135.808	131.910	132.799
5% water	1-3-5/501	138.819	133.360	133.988
	1-3-5/502	137.976	132.356	133.129
	average	138.397	132.857	133.557
7% water	1-3-5/701	139.731	132.270	132.796
	1-3-5/702	139.435	131.451	131.872
	average	139.583	131.859	132.332

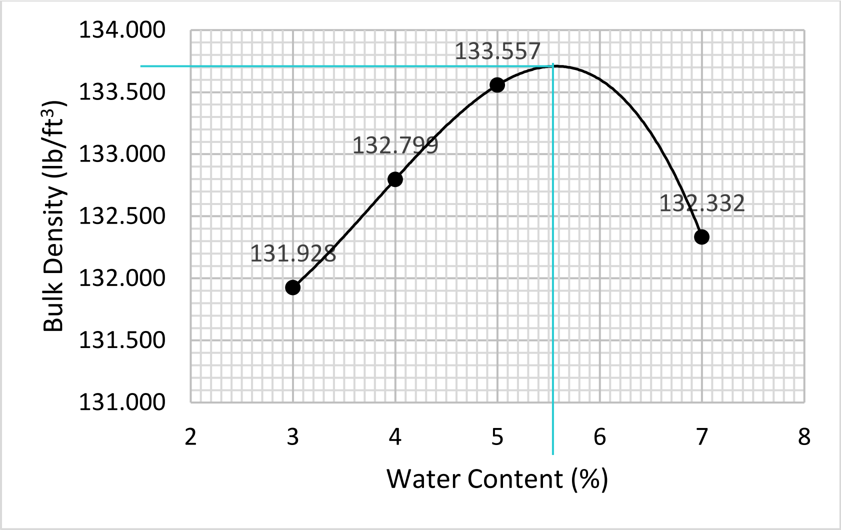

Figure B 1 Water Optimization for Batch 1-3-5

Table B 11 Water Optimization for Batch 7-9-11

Water Content	Sample Number	Wet Density (lb./ft^3)	Dry Density (lb./ft^3)	Bulk Density (lb./ft^3)
3% water	7-9-11/301	133.770	130.669	132.315
	7-9-11/302	133.165	130.046	132.038
	Average	133.467	130.357	132.176
4% water	7-9-11/401	137.216	132.936	134.325
	7-9-11/402	137.518	132.781	133.981
	average	137.367	132.859	134.153
5% water	7-9-11/501	140.735	134.931	135.593
	7-9-11/502	140.149	134.531	135.213
	average	140.441	134.731	135.402
7% water	7-9-11/701	140.019	132.505	132.796
	7-9-11/702	140.579	133.204	133.639
	average	140.298	132.853	133.216

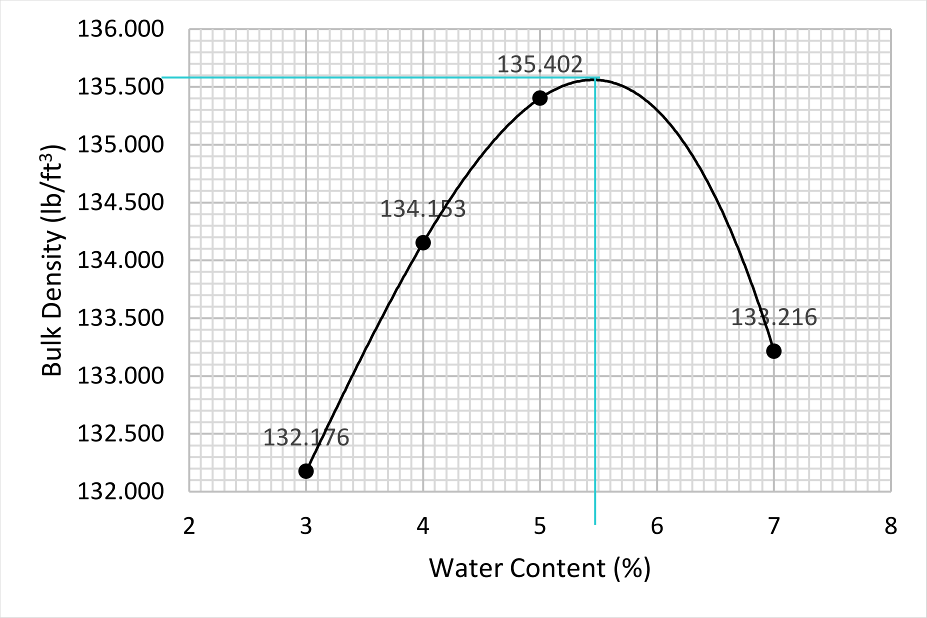

Figure B 2 Water Optimization for Batch 7-9-11

Table B 12 Water Optimization for Batch 13-15

Water Content	Sample Number	Wet Density (lb./ft^3)	Dry Density (lb./ft^3)	Bulk Density (lb./ft^3)
3% water	13-15/301	131.647	128.356	129.377
	13-15/302	132.321	129.135	129.932
	average	131.983	128.744	129.654
4% water	13-15/401	134.382	130.163	130.872
	13-15/402	134.271	130.079	130.953
	average	134.327	130.121	130.913
5% water	13-15/501	136.785	131.164	131.758
	13-15/502	136.421	130.591	131.419
	average	136.603	130.877	131.588
6% water	13-15/601	137.647	130.858	131.275
	13-15/602	138.447	131.706	132.083
	average	138.046	131.281	131.678
7% water	13-15/701	138.784	130.662	131.028
	13-15/702	138.687	130.899	131.271
	average	138.736	130.781	131.150

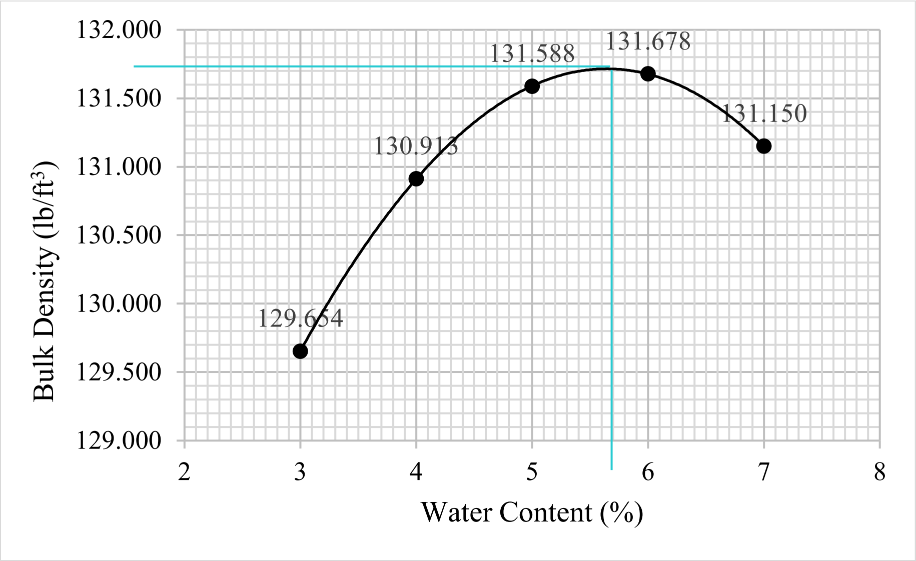

Figure B 3 Water Optimization for Batch 13-15

Table B 13 Asphalt Emulsion Density for Batch 1-3-5

Emulsion Content	Sample Number	Wet Density (lb./ft^3)	Dry Density (lb./ft^3)	Bulk Density (lb./ft^3)
2% water	1-3-5/201	138.213	132.673	133.320
	1-3-5/202	137.425	131.671	132.460
	average	137.818	132.170	132.889
3% water	1-3-5/301	139.132	133.373	133.793
	1-3-5/302	138.356	132.681	133.252
	average	138.743	133.027	133.522
4% water	1-3-5/401	138.936	133.243	133.530
	1-3-5/402	137.667	132.282	132.811
	average	138.298	132.761	133.169
5% water	1-3-5/501	138.201	132.430	132.887
	1-3-5/502	138.161	132.543	133.057
	average	138.181	132.487	132.972

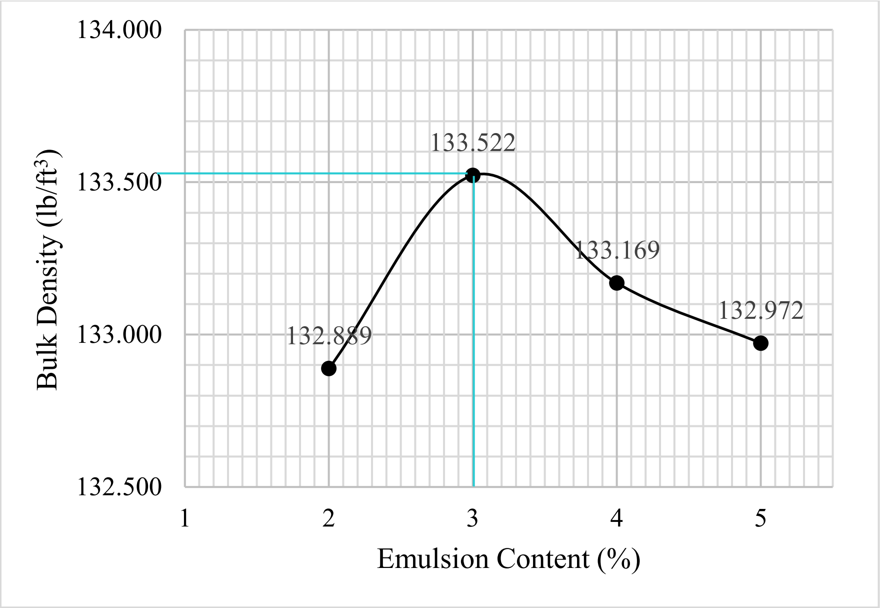

Figure B 4 Bulk Density for Batch 1-3-5

Table B 14 Asphalt Emulsion Density for Batch 7-9-11

Emulsion Content	Sample Number	Wet Density (lb./ft^3)	Dry Density (lb./ft^3)	Bulk Density (lb./ft^3)
2% water	7-9-11/201	138.849	132.909	133.681
	7-9-11/202	138.857	132.936	133.594
	average	138.853	132.923	133.637
3% water	7-9-11/301	138.896	132.899	133.686
	7-9-11/302	139.168	133.231	133.781
	average	139.031	133.064	133.733
4% water	7-9-11/401	139.555	133.486	133.974
	7-9-11/402	139.485	133.459	133.867
	average	139.520	133.472	133.921
5% water	7-9-11/501	138.831	132.984	133.477
	7-9-11/502	137.155	131.491	132.215
	average	137.987	132.233	132.842

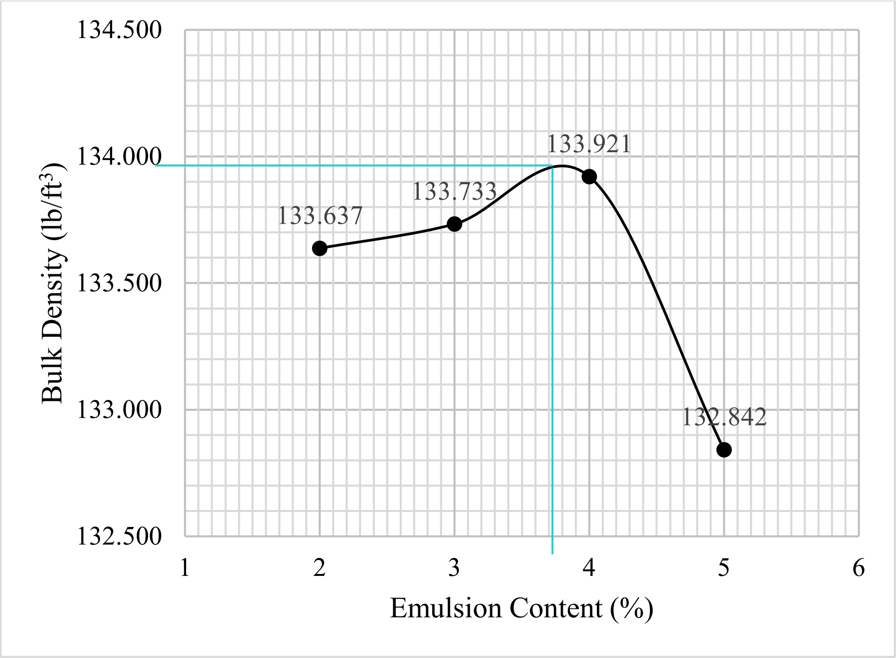

Figure B 5 Bulk Density for Batch 7-9-11

Table B 15 Asphalt Emulsion Density for Batch 13-15

Emulsion Content	Sample Number	Wet Density (lb./ft^3)	Dry Density (lb./ft^3)	Bulk Density (lb./ft^3)
2% water	13-15/201	137.944	131.477	131.846
	13-15/202	135.899	129.542	130.005
	average	136.913	130.503	130.919
3% water	13-15/301	137.570	131.216	131.515
	13-15/302	137.910	131.662	132.035
	average	137.740	131.439	131.775
4% water	13-15/401	138.008	131.577	132.046
	13-15/402	137.922	131.535	131.828
	average	137.965	131.556	131.937
5% water	13-15/501	136.273	130.116	130.713
	13-15/502	136.334	130.189	130.597
	average	136.303	130.153	130.655

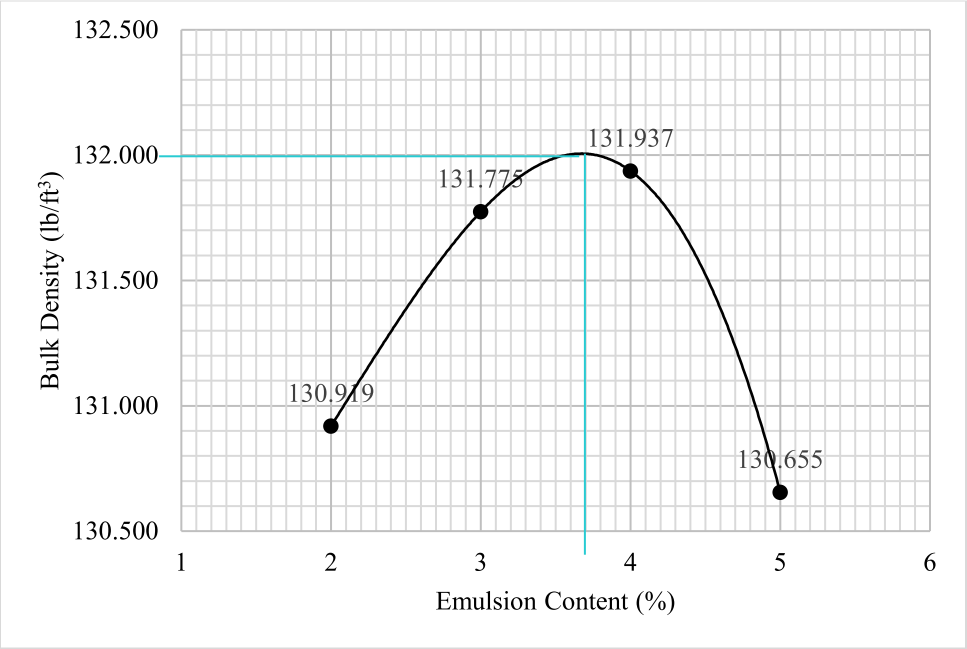

Figure B 6 Bulk Density for Batch 13-15

Table B 16 Marshall Stability Test for Batch 1-3-5

Batch 1-3-5		Dry Marshall		Wet Marshall		Retained stability (%)
Emulsion Content	Sample Number	Stability (lbf)	Flow (in.)	Stability (lbf)	Flow (in.)	
2%	1-3-5/201	12847.5	0.027	5236.2	0.043	42.76
	1-3-5/202	12781.8	0.027	5723.3	0.049	
	Average	12814.65	0.027	5479.75	0.046	
3%	1-3-5/301	12538.3	0.017	5538.1	0.053	43.32
	1-3-5/302	12172.6	0.014	5167.0	0.051	
	Average	12355.45	0.0155	5352.55	0.052	
3.50%	1-3-5/351	11337.1	0.014	8296.2	0.055	65.34
	1-3-5/352	13186.8	0.019	7728.9	0.051	
	Average	12261.95	0.0165	8012.55	0.053	
4%	1-3-5/401	11865.2	0.015	6539.6	0.07	49.15
	1-3-5/402	12050.3	0.018	5215.3	0.068	
	Average	11957.75	0.0165	5877.45	0.069	
5%	1-3-5/503	12657.8	0.018	4760.0	0.075	38.59
	1-3-5/502	12962.4	0.021	5125.9	0.08	
	Average	12810.1	0.0195	4942.95	0.0775	

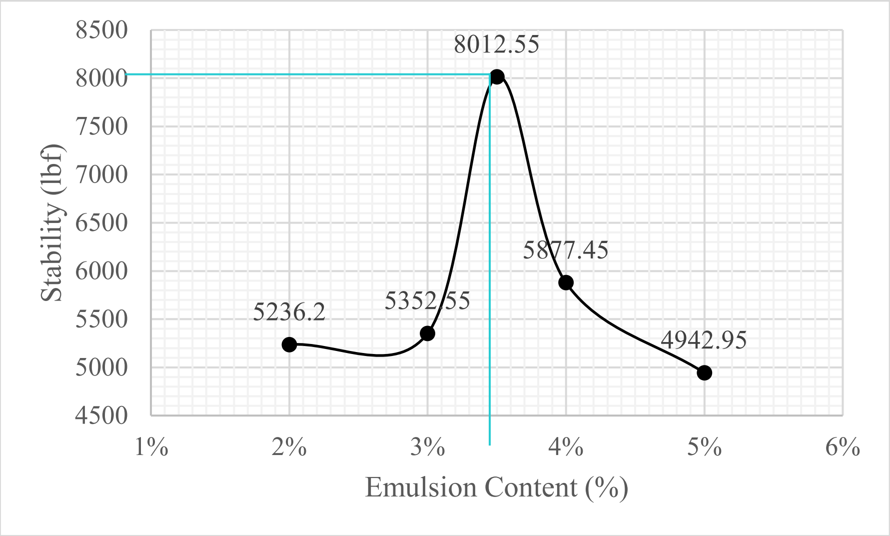

Figure B 7 Stability Flow for Batch 1-3-5

Table B 17 Marshall Stability Test for Batch 7-9-11

Batch 7-9-11		Dry Marshall		Wet Marshall		Retained stability (%)
Emulsion Content	Sample Number	Stability (lbf)	Flow (in.)	Stability (lbf)	Flow (in.)	
2%	7-9-11/201	12126	0.017	3128	0.048	29.17
	7-9-11/202	12230.9	0.012	3978	0.043	
	Average	12178.45	0.0145	3553	0.0455	
3%	7-9-11/301	12133.3	0.016	5462	0.053	53.46
	7-9-11/302	12170.7	0.013	7532	0.055	
	Average	12152	0.0145	6497	0.054	
3.10%	7-9-11/311	11815.9	0.014	7303	0.052	58.36
	7-9-11/312	12393.3	0.017	6825.1	0.049	
	Average	12104.6	0.0155	7064.05	0.0505	
4%	7-9-11/401	12055.8	0.017	5550.9	0.05	53.59
	7-9-11/402	11484.9	0.015	7061.3	0.054	
	Average	11770.35	0.016	6306.1	0.052	
5%	7-9-11/501	11769.4	0.016	7046.7	0.06	55.70
	7-9-11/502	11185.7	0.015	5738.8	0.063	
	Average	11477.55	0.0155	6392.75	0.0615	

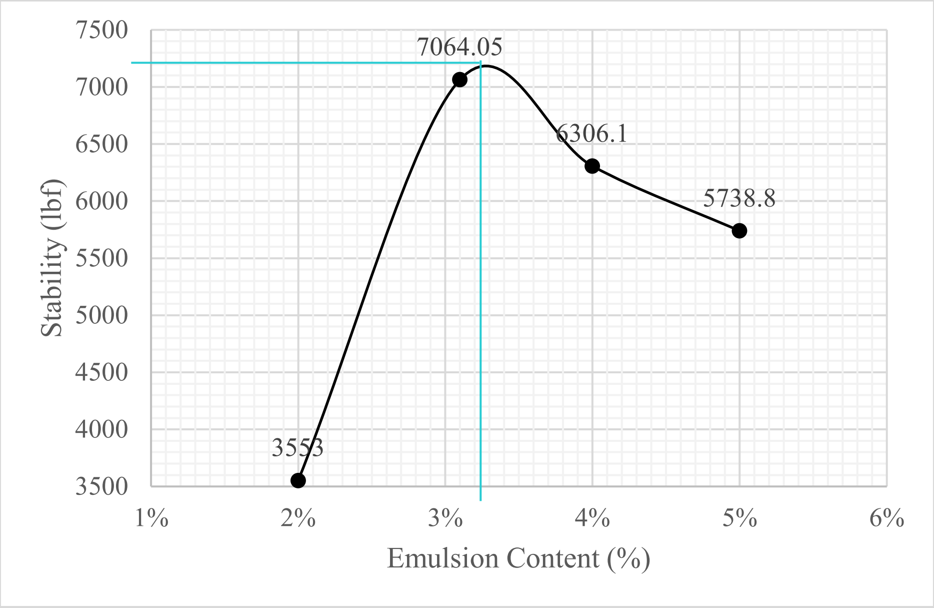

Figure B 8 Stability Flow for Batch 7-9-11

Table B 18 Marshall Stability Test for Batch 13-15

Batch 13-15		Dry Marshall		Wet Marshall		Retained stability (%)
Emulsion Content	Sample Number	Stability (lbf)	Flow (in.)	Stability (lbf)	Flow (in.)	
2%	13-15/201	11066.2	0.022	8116.6	0.049	67.31
	13-15/202	11275.8	0.02	6921.7	0.052	
	Average	11171	0.021	7519.15	0.0505	
3%	13-15/301	11412.8	0.026	7889.5	0.054	71.59
	13-15/302			8452.2	0.056	
	Average	11412.8	0.026	8170.85	0.055	
3.50%	13-15/351	11744.8	0.015	8800.6	0.086	72.40
	13-15/352	12555.6	0.018	8793.3	0.062	
	Average	12150.2	0.0165	8796.95	0.074	
4%	13-15/401	11254.1	0.031	7691.5	0.063	72.72
	13-15/402			8677.5	0.061	
	Average	11254.1	0.031	8184.5	0.062	
5%	13-15/501	10836.4	0.032	6555.1	0.072	68.15
	13-15/502	11703.8	0.035	8806.1	0.145	
	Average	11270.1	0.0335	7680.6	0.1085	

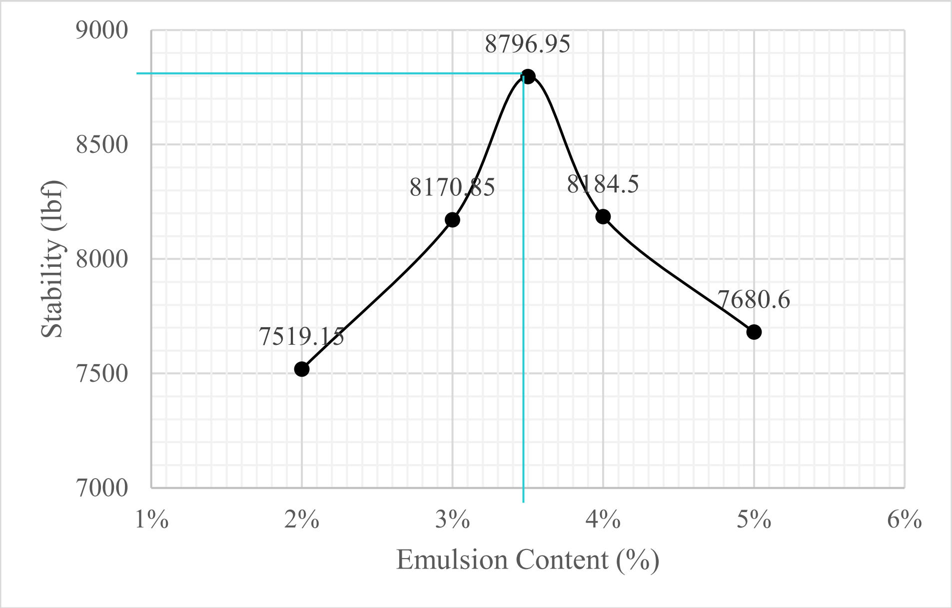

Figure B 9 Stability Flow for Batch 13-15

Table B 19 Particle Size Distribution for RAP Materials

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.00
1	1	16.4	16.4	99.15
0.75	0.75	39.7	56.1	97.09
0.5	0.5	115.7	171.8	91.10
0.375	0.375	167.5	339.3	82.42
4	0.187	320	659.3	65.83
8	0.0937	590.4	1249.7	35.23
10	0.0787	40.8	1290.5	33.12
16	0.0469	192.8	1483.3	23.13
20	0.0331	105.8	1589.1	17.64
30	0.0234	91	1680.1	12.93
40	0.0165	77.1	1757.2	8.93
50	0.0117	66.4	1823.6	5.49
60	0.0098	17.5	1841.1	4.58
80	0.007	19.9	1861	3.55
100	0.0059	9	1870	3.08
200	0.0029	16.2	1886.2	2.24
pan		43.3	1929.5	0.00

Table B 20 Particle Size Distribution for Material Residue from Asphalt Extraction

Sieve No.	Sieve Size (in.)	Retained (g)	Cumulative Retained (g)	% Passing
1.5	1.5	0	0	100.00
1	1	0	0	100.00
0.75	0.75	11	11	99.33
0.5	0.5	34.6	45.6	97.21
0.375	0.375	82.8	128.4	92.16
4	0.187	205.7	334.1	79.59
8	0.0937	445	779.1	52.41
10	0.0787	34.4	813.5	50.31
16	0.0469	142.1	955.6	41.62
20	0.0331	77.1	1032.7	36.92
30	0.0234	76.6	1109.3	32.24
40	0.0165	96	1205.3	26.37
50	0.0117	131.5	1336.8	18.34
60	0.0098	42.6	1379.4	15.74
80	0.007	50.7	1430.1	12.64
100	0.0059	20.4	1450.5	11.39
200	0.0029	43.5	1494	8.74
Pan		143	1637	0.00

Appendix C. Core Sample Analyses

Table C 1 Pre-Construction FWD Data

Station #	Drop ID	Stress lb./in^2	Drop Force (lb.)	0 (in) d_1 (mils)	12 (in) d_2 (mils)	18 (in) d_3 (mils)	24 (in) d_4 (mils)	36 (in) d_5 (mils)	48 (in) d_6 (mils)	60 (in) d_7 (mils)
1	4	82.1	8989	25.64	21.48	18.17	14.16	11.29	6.82	3.66
2	4	82.6	9053	21.44	21.04	12.72	10.33	8.65	6.06	3.63
3	4	82.5	9032	13.16	10.61	9.03	7.25	6.04	4.13	2.44
4	3	82.1	8997	19.10	14.96	12.24	9.53	7.82	4.78	2.40
5	4	81.8	8957	12.83	11.41	9.93	8.31	7.31	5.13	2.72
6	3	82.0	8981	30.23	23.93	19.82	15.28	12.17	7.54	3.83
7	4	81.60	8937	10.28	9.09	8.03	6.81	5.76	4.05	2.25
8	4	82.10	8989	18.68	17.05	15.61	13.40	11.83	8.39	4.14
9	4	81.10	8889	25.91	22.33	19.68	16.37	13.71	9.24	4.46
10	4	82.50	9037	7.02	6.78	6.67	6.31	5.98	5.04	3.15
11	4	82.60	9048	13.03	11.32	10.39	9.30	8.21	6.35	3.49
12	4	82.50	9040	11.57	9.92	8.74	7.68	6.86	5.26	3.11
13	4	82.00	8981	24.59	19.10	16.07	12.81	10.36	6.56	3.48
14	4	81.90	8968	29.07	24.23	20.51	15.51	12.46	7.58	3.60
15	3	82.30	9016	19.61	15.08	13.17	10.77	9.14	6.21	3.44

Table C 2 Back-Calculated Pre-Construction Results

Station #	E_1 (psi)	a_1	D_1 (in)	E_2 (psi)	a_2	m_2	D_2 (in)	E_{sg} (psi)	SN
1	2,708,200	0.65	3.75	5,000	0.00	1	10	8,000	2.47
2	901,700	0.46	4.5	22,800	0.11	1	10	9,000	3.18
3	2,447,700	0.63	4	60,700	0.21	1	10	12,700	4.70
4	1,313,400	0.53	4.5	20,400	0.10	1	10	10,500	3.35
5	634,700	0.40	10.5	5,000	0.00	1	10	11,800	4.26
6	566,000	0.38	5.5	8,100	0.00	1	10	6,800	2.12
7	2,980,800	0.67	6	15,500	0.07	1	10	13,700	4.71
8	749,900	0.43	9	5,000	0.00	1	10	6,600	3.91
9	368,500	0.31	8.75	5,000	0.00	1	10	5,900	2.72
10	3,807,100	0.71	11.25	43,000	0.18	1	10	8,200	9.83
11	951,100	0.47	8.25	68,500	0.23	1	10	8,200	6.20
12	707,100	0.42	8.75	75,600	0.24	1	10	10,000	6.09
13	327,000	0.28	8	6,500	0.00	1	10	8,400	2.32
14	380,900	0.31	7	5,000	0.00	1	10	7,000	2.22
15	401,000	0.32	6.5	41,800	0.17	1	10	8,400	3.85

Table C 3 Back-Calculated Post Construction Results

Station #	E_1 (psi)	a_1	D_1 (in)	E_{sg} (psi)	SN
1	3,200,000	0.66	12	10,419	7.96
2	2,675,000	0.62	12	9,390	7.5
3	2,600,000	0.62	12	13,118	7.43
4	1,385,000	0.50	12	8,448	6.02
5	982,000	0.45	12	5,304	5.37
7	910,000	0.44	12	9,295	5.23
9	1,260,000	0.49	12	6,420	5.83
10	892,000	0.43	12	5,816	5.2
11	1,115,000	0.47	12	5,360	5.6
14	774,000	0.41	12	6,522	4.96

CORE DRILL REPORT

Date Drilled 1/28/2020
WEATHER
LOCATION State Route 88
PERSONAL UTC Research, MTSU Research, HQ M&T, SE cement assoc. District 49 ops, region 4 pavement engineer

Reference #
Project #
Contract #
County Lauderdale
Engineer
Region 4
Sheet 1 of 1

LANE	WIDTH	LOG MILE	CORE STATION	CORE NUMBER	DISTANCE FROM		REMARKS
					EDGE LINE	CENTER LINE	
		0	0	1			3 ¾” solid asphalt core, 1 ½” D mix, 2” A mix, ½” down on a gravel base
		0.5	0.5	2			4 ½” solid asphalt core, 2” CW, 2 1/2” of A mix, on a gravel base
		1.1	1.1	3			4” solid asphalt core, 1 3/8” CW, 2 5/8” BM2 on a gravel base
		1.5	1.5	4			4 1/2” solid asphalt core, 1 ½” CW, 3” BM2 on a gravel base
		2.1	2.1	5			10 1/2” solid asphalt core, 1 ¼” CW, 2 ¼” BM, 2 1/4 2 layers of D mix (1 ¼” and 1), 1 ¼” CW, 1” D, 1 ½ A mix on a gravel base
		2.6	2.6	6			5 1/2” solid asphalt core, 2 ¼” D mix, 3 ¼” BM2 limestone base
		3.1	3.1	7			6” solid asphalt core, 1” CW, 1 ¼” D mix, ¼” CS, 3 ½” A mix limestone base
		3.5	3.5	8			Hole depth 9”, 1 1/4” D mix, ¼” CS, 3 ½” A mix, 1 ¼ D stripped, 1 ¼” D mix, 1 ½” BM2 on a gravel base
		3.9	3.9	9			8 ¾” solid asphalt core,
		4.6	4.6	10			11 1/4” solid asphalt core, 1” CW, 1 ¼” D, 2 ¾” multi-layer D, 6 ¼” multi-layer A on gravel base
		5.1	5.1	11			8 ¼” solid asphalt core 1 1/2” CW, 3” multi-layer D, 2 1/2” multi-layer CW, 1 ¼” remains of BM on gravel base
		6.6	6.6	13			7” solid asphalt core, 1 ¼” D mix, 6 ¾” of stripped D and CW, on remains of A mix on gravel base
		9.1	9.1	15			6 1/2” solid asphalt core, 1 1/2” D, 2 ¾” BM with remains of A mix, 1 ¼” D with remains of CW and BM mixes on gravel base

Core # 1 was drilled at 0-mile marker and corresponds to Sample #1

Figure C 1 Core#3 (4”) was drilled at 1.1 mile and corresponds to Sample # 2

Figure C 2 Core#4 (4 ½”)

Figure C 3 Core#5 (10 ½”) was drilled at 2.1 mile and corresponds to Sample # 3

Figure C 4 Core#6 (5 ½”)

Figure C 5 Core#7 (6”) was drilled at 3.1 mile and corresponds to sample # 4

Figure C 6 Core#8 (6 ¼”) Hole depth 9”-lost 2 ¾”

Figure C 7 Core #9 (8 3/4") was drilled at 4.0 mile and corresponds to sample # 5

Figure C 8 Core#10 (11 ¼")

Figure C 9 Core #11 (8 ¼") was drilled at 5.1 mile and corresponds to sample # 6

Core #12 bit bent-core destroyed, hole depth 8 ¾".
Sample # 7 was taken at 6.1 mile no core was drilled at that location.

Figure C 10 Core #13 (7")

Figure C 11 Core #15 (6 ½")