EVALUATING THE MECHANICAL PROPERTIES AND LONG-TERM PERFORMANCE OF STABILIZED FULL-DEPTH RECLAMATION BASE MATERIALS

Eugene Annan Amarh

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Civil Engineering

Gerardo W. Flintsch, Chair

Linbing Wang

Samer Katicha

May 2, 2017

Blacksburg, Virginia

Keywords: Recycled base, Full-Depth Reclamation, Time-Dependent Response, Elastic Modulus, Critical Condition Index

EVALUATING THE MECHANICAL PROPERTIES AND LONG-TERM PERFORMANCE OF STABILIZED FULL-DEPTH RECLAMATION BASE MATERIALS

Eugene Annan Amarh

ACADEMIC ABSTRACT

State highway agencies are searching for more cost-effective methods of rehabilitating roads. One sustainable solution is full-depth reclamation (FDR), a pavement rehabilitation technique that involves pulverizing and reusing materials from existing distressed pavements in place. There is, however, limited information on the long-term properties of these recycled materials. One important property, the elastic modulus, indicates the structural capacity of pavement materials and is highly recommended for design purposes by the Mechanistic Empirical Pavements Design Guide (MEPDG). The elastic modulus directly impacts selection of the overall pavement thickness, and an accurate estimation of the modulus is therefore key to a cost-effective pavement design. This thesis researched the modulus trends and functional properties of three in-service pavements rehabilitated with the FDR technique during the 2008 Virginia Department of Transportation (VDOT) construction season. Foamed asphalt (2.7% with 1% cement), asphalt emulsion (3.5%), and Portland cement (5%) were used as stabilizing agents for the FDR layers. Several deflection tests and distress surveys were conducted for the pavement sections before and after construction. An automated road analyzer (ARAN) was used to collect distress data over a period of 7 years. Deterioration models were developed to predict the durability of differently stabilized FDR pavements and compared to reference sections rehabilitated with traditional asphalt concrete (AC) overlays. The results of the moduli measured for the recycled base materials varied significantly over time. These changes were attributed to curing after construction, seasonal effects, and subgrade moisture. The structural capacity of the pavements improved irrespective of the stabilizing agent used. Rutting was higher for the foamed asphalt and emulsion sections. The International Roughness Index (IRI) was better for the cement stabilized sections compared asphalt stabilized sections. The Critical Condition Index (CCI) was similar for all treatments at the end of the evaluation period. The durability of the sections was comparable, with the cement stabilized FDR sections slightly outperforming the asphalt stabilized sections.

EVALUATING THE MECHANICAL PROPERTIES AND LONG-TERM PERFORMANCE OF STABILIZED FULL-DEPTH RECLAMATION BASE MATERIALS

Eugene Annan Amarh

GENERAL AUDIENCE ABSTRACT

Replacing all roads in bad condition with new reconstruction or with traditional rehabilitation alternatives such as the mill and overlay will cost state highway agencies (SHAs) huge sums of funds. State departments of transportation are therefore seeking cost-effective ways to rehabilitate roads under their jurisdiction. An innovative technique being used by several SHAs today is full depth reclamation (FDR) which involves breaking down an existing roadway and immediately reusing the materials to construct a strengthened base layer for a new road. Despite the increasing use of FDR in recent years, several questions remain unanswered regarding the behavior of the strengthened base materials and their performance in the long-term under traffic loads. The elastic modulus is one material property that indicates the strength or structural capacity of pavement materials and usually impacts the selection of the overall thickness of the roadway. This thesis researched the modulus trends and functional properties of three in-service roadways rehabilitated with the FDR technique in 2008 by the Virginia Department of Transportation. Foamed asphalt (2.7% with 1% cement), asphalt emulsion (3.5%), and Portland cement (5%) were used to strengthen the FDR base layers. Several deflection tests and distress surveys were conducted for the pavement sections before and after construction. The moduli measured for the recycled base materials varied significantly over time. These changes were attributed to curing after construction, seasonal effects, and subgrade moisture. Long term performance monitoring of the projects showed that rutting was higher for the foamed asphalt and emulsion sections. The International Roughness Index (IRI), which gives an indication of the overall ride quality i.e. how smooth the pavement surface is, was better for the cement stabilized FDR sections compared to the asphalt stabilized counterparts. The structural capacity of the pavements improved irrespective of the stabilizing treatment used. The Critical Condition Index (CCI) was similar for all treatments at the end of the evaluation period. The durability of the sections was comparable, with the cement stabilized sections projected to last slightly longer than asphalt sections.

ACKNOWLEDGEMENTS

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

Approximately 20% of America's highways are in poor condition with close to 32% of the nation's urban roads in worse shape, compared to urban roads according to the American Society of Civil Engineers (*1*). The cost to road users travelling on these roads in the amount of time spent in traffic and vehicle mile traveled due to road closures or diversions for new constructions and vehicle repair costs is estimated at 112 billion dollars in 2014 (*1*). With over 2.5 million center-line miles of flexible pavements in the United States (*2*), it will cost significant investments in State Highway Agency (SHA) funds to replace these roads with entirely new pavements or if additional lanes were to be added. Uncaptured emissions and fumes from the production and transportation of virgin materials to and from the site for a new construction is threatening to human life and the environment, even though the extent and severity of the impacts are still debated (*3*). One of the solutions to mitigate or address these concerns is pavement recycling.

The concept of pavement recycling is gaining increasing acceptance as a method of restoring the service life of pavements in the United States. In particular, in-place pavement recycling techniques can be grouped into 3 broad categories; Cold Recycling (CR), Hot Recycling (HR) and Full Depth Reclamation (FDR). Cold recycling can be further categorized as Cold In-place Recycling (CIR) and Cold Central Plant Recycling (CCPR). The main advantages of the CR and FDR techniques over HR are the reduction in costs, emissions and energy achieved through eliminating the need to heat the pavement and reclaimed materials during the milling and remixing stages. Apart from cost and availability of construction equipment, the selection of the recycling technique for a rehabilitation project mainly depends on the type and severity of the pavement deterioration (*4*).

Together, these techniques address almost every aspect of asphalt pavement deterioration. In addition to providing a more environmentally friendly method of rehabilitation, asphalt pavement recycling offers significant economical savings both in reduced cost of construction and in reduced road user delays (*5*). The Virginia Department of Transportation (VDOT) employed the CIR, CCPR and FDR techniques to address the deterioration on a section of Interstate 81 in 2011 and has since reported tremendous improvements in the structural capacity during the first year after construction (*5*).

While CR techniques may differ in the detailed processes involved and equipment used, they serve a common purpose i.e. reusing the existing pavement materials to provide a form of base material layer with adequate strength on which a hot mix asphalt (HMA) overlay, hydraulic concrete overlay, chip seal other surface treatments may be placed. Adequate strength of this base layer is usually achieved through stabilization using either mechanical, bituminous, cementitious stabilization or a combination of these techniques. Among the cold-recycling techniques briefly mentioned, FDR permits extending the recycling process deeper into the pavement to eliminate distresses within the pavement layers.

Full Depth Reclamation (FDR) is a rehabilitation technique whereby a failed asphalt pavement and a predetermined portion of the underlying layers (may include the subgrade) are pulverized and blended together, and often stabilized with an additive such as foamed asphalt,

asphalt emulsion, lime, fly ash or Portland cement to form a homogeneous stabilized base. The stabilized base may be surfaced with an HMA overlay or hydraulic concrete (*6*) and other treatments such as chip seals to complete the process. In spite of the research progress made in the studying FDR bases with different stabilizing agents, the long-term in-situ properties and related performance of these mixtures are not fully documented. The mechanical properties documented in existing literature mainly support empirical design and most of these have been obtained from laboratory or accelerated pavement tests using heavy vehicle simulators (HVS). The Mechanistic-Empirical Design Guide (MEPDG) for instance, provides little guidance for CIR and FDR products (*5*). Also, there is limited information on the assessment of the economic and environmental implications of these mixtures in FDR applications.

Over the past decade, research on FDR has been mainly focused on developing appropriate engineering standards of practice with emphasis on material characterization and mix designs performed in the laboratory (*7*). Mallick et al. (*8)* studied the design procedures of new mixes using different options for stabilizers. Syed et al. (*9*) assessed durability and moisture sensitivity in FDR mixtures using contemporary test procedures such as the tube suction test following a series of durability investigations carried out by Somer (*10*). Several studies (*11; 12*) have been carried with the objective of resolving the problem of reflective cracking in cement stabilized layers leading to the development of the concept of micro-cracking. Wen et al. (*13)* evaluated the contribution of fly ash to the structural performance of FDR pavements in Wisconsin. These research projects, among others, indicate the growing interest in recycled pavement materials.

1.1 Problem statement

State Highway Agencies are interested in knowing the long-term performance of recycled pavement materials. The VDOT is investigating the long-term structural adequacy and environment benefits of different FDR base mixtures. Despite several studies undertaken by researchers and State Highway Agencies in pavement recycling, the engineering properties of these recycled base materials obtained for pavements in service and their long-term performance are rarely documented. There is limited information on their properties to support mechanistic-empirical design and s side-by-side comparison of the long-term performance between different treatment options for FDR applications has been seldom performed.

1.2 Objective

The main objective of this research is to assess the in-situ performance of the different FDR base mixtures over a period of time in service. To meet this broader objective, the research was broken down into the following specific objectives: (1) evaluating the elastic layer modulus (stiffness) of the FDR base mixtures as an initial strength measure and its behavior with respect to time, seasonal effects, and temperature; (2) to evaluate the structural and functional performance (International Roughness Index (IRI), Permanent Deformation (Rut), Cracking (fatigue and transverse) of pavements rehabilitated with the FDR technique using three different stabilizers and develop performance models.

1.3 Methodology

To accomplish the project goals, a series of tasks were conducted as outline below.

1. Conducted a literature review on (1) pavement recycling with specific emphasis on FDR and the different stabilization techniques available. (2) Laboratory and field evaluation of material properties for FDR mixtures, (3) Existing methods of evaluating the structural capacity of FDR applications.

2. Estimated the in-situ layer modulus for the FDR layers. Through a case study conducted on trials sections from the VDOT FDR demonstration projects, thickness of the in-service pavement obtained from Ground Penetrating Radar (GPR) test and deflection data from Falling Weight Deflectometer (FWD) tests was used. A model of the pavement structure, together with the uploaded FWD data files were then used in performing backcalculations to estimate the moduli for the pavement layers. ELMOD6 from Dynatest was used for the backcalculations, with the results validated with other backcalculation software (Evercalc, BAKFAA or CalBack).

3. Evaluated the Structural and Functional Performance. The pavement condition data was extracted from the VDOT Pavement Management System (PMS). The data will be used to plot distress curves for the trial sections from the FDR demonstration project. The mechanical behavior of the pavement will then be analyzed in relation to the moduli trends

obtain from task 2 over a period of two years. The study of the performance curves was extended to a period of seven years in an attempt to develop deterioration models for FDR pavements.

1.4 Significance

There are over 2.5 million center lines miles of roadway currently in service in the United States with close to 32% in poor to mediocre condition. With road maintenance budgets shrinking, it has become imperative that SHAs find a more effective method of rehabilitating roads in order save costs. Reusing materials from existing pavements combined with a technique that performs the rehabilitation in-place is a sustainable approach to solving this problem. However, there is limited information on the long-term properties of these reused materials. For instance, the elastic modulus is an important property which gives an indication of the structural capacity of pavement materials and is needed for mechanistic-empirical design. It directly impacts selection of the overall pavement thickness and an accurate estimation of the modulus is therefore key to a cost effective pavement design. When underestimated, there is a risk of designing an overlay which may be more substantial than required. There is risk of premature failure as a result of an insufficient overlay design when the modulus is overestimated for the recycled base materials. This research investigated the long-term properties and contributed to the existing body of knowledge relating to rehabilitation designs for recycled materials. It will also aid pavement engineers in the selection of more economic stabilizing agents with less environmental burdens for FDR applications.

1.5 Thesis Outline

This thesis is presented using the manuscript format with the following chapters:

Chapter 1 is an introduction comprising:
- Condition of roads in the United States and the need for pavement recycling as a more sustainable choice for rehabilitation
- Full Depth Reclamation as a pavement recycling technique

Chapter 2 is a literature review illustrating the developments in Full Depth Reclamation relating to existing research and findings on the different FDR stabilizers regarding structural properties, performance and LCAs to support the significance of this research.

Chapter 3 is a paper to discussing the characterization of the structural properties (layer moduli from backcalculations) of FDR stabilized base materials using *materials and data* from the VDOT FDR demonstration projects.

Chapter 4 is a paper to discussing the performance in the long-term of the FDR projects with the various stabilizers with data from the VDOT PMS.

Chapter 5 summarizes the findings from this research and provides conclusions on the results from this study.

2. LITERATURE REVIEW – DEVELOPMENTS IN FULL DEPTH RECLAMATION APPLICATIONS

2.1 Pavement Deterioration

A typical pavement deterioration curve (Figure 1) describes a series of maintenance activities carried out at different periods throughout the lifecycle of the pavement. A newly constructed pavement has excellent ride quality and carries traffic with very limited damage to its structure. Subject to the adverse conditions of climate and increasing traffic loads over time, the pavement begins to deteriorate. Research has shown that the deterioration will follow a predicted pattern and several models have been developed to predict the rate of deterioration. At the initial stages after construction, preventive maintenance programs in the form routine resurfacing are performed to preserve the pavement or slow down deterioration especially from the effects of climate and essentially maintain the ride quality of the pavement. Deterioration accelerates quickly with age and increasing traffic. The cost of rehabilitation increases if these remediation measures are not taken at the appropriate times, leading to a situation where costly reconstruction is the only option. Budgetary constraints of the Agencies responsible for maintenance usually determines the appropriate time intervals for remedial action (*14*).
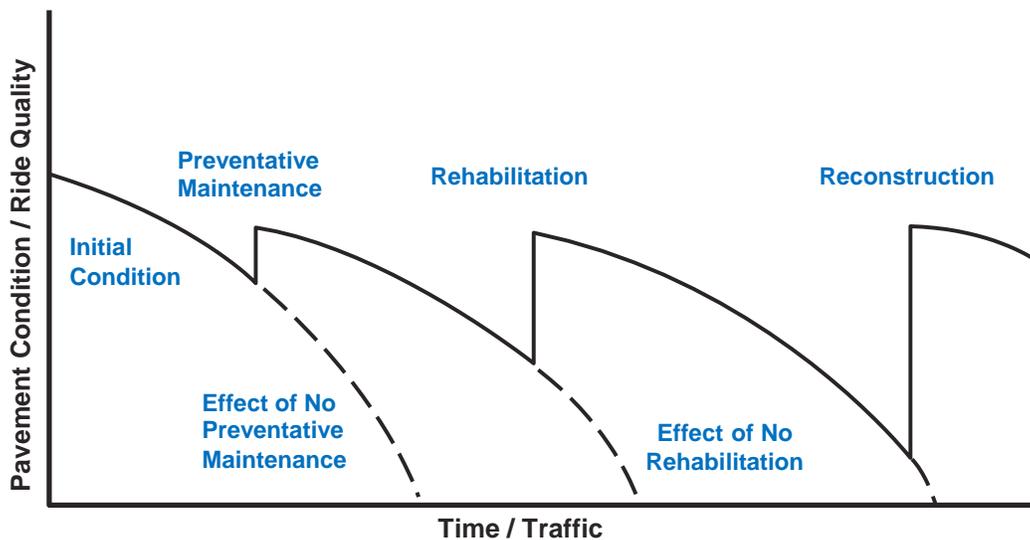
FIGURE 1: Typical Pavement Deterioration Curve (*15*)

Distresses resulting from repeated traffic use and aging of the pavement materials will require some form of structural rehabilitation to address deterioration deep inside the pavement layers. A wide variety of maintenance and rehabilitation methods including traditional milling and repaving techniques have been used to cost effectively rehabilitate such distressed pavements. However, more innovative techniques such as in-place recycling are serving as alternatives for most SHAs to restore the structural capacity and extend the service life of pavements. Full Depth Reclamation is one of the in-place recycling techniques suited for these type of distresses since the technique is

capable of pulverizing the distressed pavement layers to depths up to 12 inches depending on the thickness of the bound layers of the existing pavement (*15*).

2.2 Application of Full Depth Reclamation

Most FDR applications have been limited to low-medium traffic volume roads, such as primary and secondary network routes and rural roads but the technique has been successfully applied also to interstate highways and other heavy-duty pavements (*16; 17*). Currently, FDR has been used by many State Highway Agencies in the US and other countries (*8; 13; 18-30*). Also, Mohammad et al. (*28)* reported the recycling of composite pavements (a jointed concrete pavement with an HMA overlay) with an FDR application using foamed asphalt as a stabilizer showed excellent results in terms of the structural capacity of the pavement. Many US DOTs (California, Georgia, Illinois, Louisiana, Maine, Maryland, Minnesota, Nevada, Texas, Utah, and Virginia) and Countries (Canada, Chile, Spain, Italy, South Africa, Australia, New Zealand, and China) have used FDR to:

- Strengthen the base underlying pavement layers (base and subgrade)
- Improve moisture resistance to the base
- Remediate distresses such as rut and permanent deformation, transverse, alligator and wheel path cracks
- adjust cross-slopes and/or profile grades or widen existing pavements

2.3 Benefits of Full Depth Reclamation for Pavement Rehabilitation

Evident benefits of FDR have been reported in several studies (*4; 31-33*). FDR eliminates the potential of reflective cracking and improves the bearing capacity by removing deep pavement cracks, making way for reduction in future maintenance costs. FDR rehabilitated pavements have shown significant improvement in the load carrying capacity and resistance to permanent deformation over time according to Diefenderfer and Apeagyei (*16)*. A pavement condition index (PCI), which combines components of ride condition and pavement structural performance, was better for FDR applications than for traditional HMA overlays (*24; 34*). Also, a strengthened base layer implies less expensive HMA overly could be needed. The FDR process minimizes hauling distances and speeds up the construction period by reducing the some construction phases (*35*).

2.4 Overview of Stabilizers

The pulverized materials could be used as a base course after grading and compaction without any additives (*36; 37*). In most cases, however, many different types of additives have been used to improve strength of the pulverized base. The process of improving the mechanical or physical properties (strength, durability and reduce susceptibility to moisture) is known as *stabilization.* Stabilization maybe mechanical (without additives), bituminous, cementitious, or a combination of the aforementioned. Several studies have evaluated the properties of FDR pavements with different stabilizing techniques. A brief discussion of key research and findings, and an overview of the stabilization processes is presented below.

2.4.1   Cementitious Stabilization

Portland cement reacts with moisture in the soil, causing the bonding of the soil particles. In practice, the addition of water during mixing initiates a cementitious hydration reaction and provides early strength gain. Lewis et al. (*25)* reported early shrinkage and reflective cracking failures in FDR applications due to high cement contents. Several FDR projects with CSB layers have exhibited transverse and fatigue cracks after 10-15 years in service (*18*). Portland is recommended for use with material having a plasticity index (PI) less than 20. Miller et al. (*6*) investigated the strength and durability of Cement stabilized base (CSB) materials through extensive laboratory tests (particle-size distribution, moisture-density relationships, UCS values and moisture susceptibility classifications) in New England. The results showed significant increments in the strength and stiffness of the CSB materials in the first three to five days compared to sections without cement. The study also investigated the effects of early trafficking on the structural properties (stiffness) of CSB materials and developed specifications for use in FDR applications. The sections subjected to early trafficking showed significant reductions in stiffness compared to sections without traffic. A similar study carried out by Jones, Wu and Louw (*38)*, compared Portland cement stabilized FDR bases with untreated ones in an accelerated loading test. The results showed the cement treated section outperformed the untreated section for performance indicators measured.

Lime is an alternative to Portland cement recommended for use with highly plastic soils (PI greater than 20). Two common variants used in soil stabilization include quicklime and hydrated lime. Lime reacts with aluminates and silicates in clay minerals to form calcium silicate hydrates with high strength (*39*). These are the principal source of strength gain in cementitious reactions. Georgia Department of Transportation was the first to develop specifications for the use of hydrated lime in FDR for non-state routes and reported continuous improvements in structural strength of the base after a one year evaluation period (*39*). In FDR mixes, the shear strength of the recycled base is increased by a rise in compressive strength, reduction in the plasticity and moisture susceptibility and decreasing permanent deformation when Portland cement or lime is used (*25; 39*). **Class C fly ash**, produced by burning lignite or sub-bituminous coal is characterized by a calcium oxide (CaO) content between 8% and 30% (*40*), can be used as a substitute for Portland cement. The higher calcium content makes Class C fly ash a cementitious pozzolan that requires on water to hydrate and harden (*41*). It improves the engineering properties (UCS and resilient modulus) of the FDR mix in the early stages with Benson et al. (*42)* reporting improvement in UCS after 5 freeze-thaw cycles in these mixes.

2.4.2   Bituminous Stabilization

Kroge et al. (*43*) reported a structurally upgraded base layer using **asphalt emulsion** as a stabilizing agent for an FDR project in Fairburn, Georgia using the modulus, structural number and layer coefficients as indicators. Bitumen droplets are held in water-or vice versa- by an emulsifying agent which controls the charge of the emulsion. The emulsions can be cationic slow setting, high float medium setting, anionic or engineered emulsions. According to Quick and Guthrie (*44*), the bitumen emulsion contents may range from 25% to 60% water, 40 to 45% bitumen with penetration grades (PG) of 50 to 100, and 0.1% to 2.5% emulsifier. Engineered emulsion have been extensively studied. This type of emulsion is manufactured with the objective

of acquiring selective properties to suit a given project; including mixing and coating properties, curing times, resistance to moisture (*44*). Mixing asphalt emulsion with aggregates is done at ambient temperatures ranging from 10 to 40 °C (*45*). During mixing, the charged asphalt droplets are attracted to the aggregate particles with opposite polarity. Due to the charge concentration and surface area of smaller particle sizes, faster bonding occurs with the charged emulsion. When the emulsion is pumped and injected in the pulverized base materials, the emulsion breaks (the separation of bitumen-water phase through flocculation and subsequent coalescence of bitumen droplets) to form films of bitumen on the material particles. Premature breaking is avoided by heating the undiluted bitumen emulsion at temperatures between 50 and 60 °C during pumping and injection. After compaction, more moisture is lost during curing when the moisture evaporates. The remaining asphalt binder then retains the adhesion, durability and resistance as the original asphalt binder. The selection of appropriate emulsion is influenced by the type of aggregate as a chemical attraction is needed between bitumen and aggregate for the stability and cohesion of the mix (Wirtgen, 2004). Quick and Guthrie (*44*) investigated the early age structural properties of FDR base mixes stabilized with asphalt emulsion. It was reported that the strength gain of the mixes after 3 months was up to 80%. Field measured stiffness was low for the first 2 weeks but increased dramatically by the 4th month and decreased considerably after a year of construction. Shuler (*46*) recently published best practices for full depth reclamation using asphalt emulsion.

The use of **foamed asphalt** as a stabilization agent for FDR mixes have been extensively studied. Kim and Lee (*7*) reviewed numerous publications from 1976 to 2003 on the development of foamed asphalt mix design for FDR use; a new mix design procedure was finally validated for Iowa DOT by Kim, Lee and Heitzman (*47*). Lane and Kazmierowski (*24*) reported the performance of FDR foamed asphalt project in comparison to other control FDR sections without foamed asphalt stabilization on the Trans-Canada Highway in Canada. The performance (pavement distress and roughness) was monitored annually over a period of 10 years. The results showed superior performance for the foamed asphalt sections compared to the ministry's average reconstruction projects and the control sections. Cold water is injected into hot bitumen with PG between 60 and 200 at temperatures ranging from 160 °C to 180 °C to produce foamed asphalt. This phenomenon causes spontaneous foaming of the asphalt. When the cold water comes into contact with the hot bitumen, the physical properties such as viscosity are temporarily altered and explosively transformed in vapor trapped in thousands of bitumen bubbles (*14*). Foamed bitumen is produced at a mixing chamber and incorporated into the aggregate while in an unstable (bubble collapse under a minute) foamed state. The bitumen bubbles burst during mixing to produce tiny splinters which disperse throughout the aggregate by adhering to finer particles to form a mastic. On compaction, the bitumen particles in the mastic adhere to the larger aggregate particles resulting in localized non-continuous bond.

2.5 Long-term Performance Studies

Even though several agencies and state DOTs have used the FDR technique to rehabilitated distressed roads in the past three decades, only a few have documented the long-term performance of these projects. With growing interest in the use or implementation of mechanistic-empirical design, data is needed to develop performance models to be included in the mechanistic empirical

rehabilitation design methods. Several studies have reported the performance of various FDR projects using different indicators. Lane and Kazmierowski (*24*) studied FDR projects stabilized with foamed asphalt using three different mix designs and compared the projects with a control FDR section without foamed asphalt stabilization. The authors reported a 10-year roughness data, and pavement distress data (summarized into a PCI) showing significant difference between the test sections and the control section. The foamed asphalt test sections delivered superior results over the control section. Jones et al. (*38*) compared the performance of a Portland cement stabilized section with an unstabilized FDR section in an accelerated loading test facility. The authors reported the Portland cement sections outperforming the unstabilized sections most notably on the rutting performance. After approximately 490,000 equivalent single axle loads (ESALs), the unstabilized sections had reached a terminal rut depth of 0.5 in. compared to the cement section that recorded a rut depth of only 0.12 in. after 43.3 million ESALs. There were no visible cracks on either of the projects at the end of the test period.

Romanoschi et al. (*29*) conducted similar accelerated pavement tests on foamed asphalt stabilized bases and reported the rutting performance compared to a conventional pavement with a granular base material. The authors reported that a 1 in. foamed asphalt–stabilized FDR base material is equivalent to 1.0 in. of conventional Kansas AB-3 granular base on the basis of the permanent deformation and rut depth measurements obtained at the end of the tests. Miller et al. (*6*) compared the performance of two FDR projects (a section with cement stabilization and the other without any stabilization) and a conventional (box-cut) reconstruction after five years in service. The authors reported no rutting in any of the projects after five years. However, some cracking was reported in all three test sections stemming from thermal cracking. Lewis et al. (*25*) reported the performance of cement stabilized FDR constructed as a pilot project in Georgia. The authors took rut measurements and carried out visual inspections after nine months in service. Out of a total of 152 rutting measurements taken, 10 showed a 0.062 in. deformation with 4 of these readings reported caused by the asphalt spreader at the time of paving. The authors also observed signs of cracking in isolated areas which were assumed to be shrinkage cracks as a result of excessive cement content in the base material.

While several state DOTs and other agencies have studied the FDR performance, there has not been consistency in the stabilizers used, and the parameters or performance measures studied. A side-by-side comparison or evaluation of the performance of the different stabilizers have been seldom reported. Most of the studies did not monitor the performance on a yearly basis. Accelerated pavement testing have been used in some of the cases but further validation with field performance is needed.

2.6 Factors Critical to Performance of FDR Applications

2.6.1 Moisture Susceptibility

Of particular concern for FDR and other cold recycled mixes is the susceptibility to the adverse effects of moisture as a result of higher in place air voids compared to HMA. Moisture can penetrate the FDR layer and subsequently break down and weaken the mixture structure. Wirtgen (*14*) and Saleh (*30)* noted about 3 to 5 times higher in-place air voids for FDR materials after compaction. As reported in Chen et al. (*48)* in their study of the US82 FDR project in Texas, the

presence high moisture content caused severe failures (rutting, longitudinal and alligator cracking) in the FDR layer. This was mainly attributed to the poor strength of the foamed asphalt stabilized layer caused by a high moisture content in the underlying plastic subgrade soil coupled with excessive fine gradation and inconsistent construction procedure. As a result, movement of moisture from the subgrade into the FDR base layer caused the breakdown of the base layer from the bottom leading to subsequent failure as the pavement was unable to support the loads from traffic after 1 year in service.

2.6.2 Curing

The process whereby a material develops strength and stiffness over a period of time (*49*). Curing is essential for maximum strength gain and it is crucial factor occurring in all FDR mixtures. For FDR using foamed asphalt with Portland cement, Jones et al. (*50)* reported that the curing process is related to evaporation of water at the mastic aggregate interface. The study noted that curing in FDR using foamed asphalt with Portland cement is similar to curing in regular cementitious mixtures. For asphalt emulsions, curing occurs when asphalt breaks from solution and bonds to the coarse aggregates. Kroge, McGlumphy and Besseche (*43*) stated that a cured FDR layer is indicated by a moisture content of 3% or less. Many modified curing procedures have been used to evaluate the structural properties of FDR mixtures for laboratory testing, (*6; 8; 17; 22; 26; 32; 49-52*).

2.6.3 Other Factors

Other factors that have been reported in literature related to the FDR process are early failures stemming from shrinkage and reflective cracking, as a result of high cement contents (*25*), rutting caused by structural deficiencies or weak subgrade (*43*), and raveling due to early stages weakness of the mixtures in particularly wet conditions and without the use of active fillers (*24*). Bemanian, Polish and Maurer (*18)* noted that several cement-stabilized FDR project sections are showing transverse or fatigue cracking after 10-15 years of service. The thickness of the existing pavement layers must be accurately estimated in order to ensure greater uniformity of the new pulverized layer. An accurately estimated HMA layer thickness is critical to mix design as it impacts the amount of bitumen additives to be injected during pulverization. Bleeding defects seen in most bitumen stabilized FDR applications are commonly associated with this problem, leading to too much asphalt in the finished FDR product. Also, if excess water was added during the mixing process, some sections treated with asphalt emulsion took several days to cure, as emulsion required longer time than usual to break due to the high in-situ moisture (*27*).

2.7 Methods of Evaluating Structural Capacity

Despite several SHAs adopting FDR, there is no widely accepted approach used to describe the structural capacity of FDR materials for design purposes. With the majority of highway agencies still using empirical-based pavement design methodologies (*53*), much of the work related to quantifying the structural capacity of FDR has been performed with respect to determining an appropriate layer coefficient of the material (*13; 18; 21; 29; 51; 54*). The mechanistic-empirical design guide recommends the use of the elastic modulus of materials for design purposes. Only a few publications have evaluated the structural capacity using the elastic moduli for the FDR layer. Quick and Guthrie (*44)* documented the average emulsion treated base (ETB) moduli measured

with the FWD as 26.0, 286.4, and 89.6 ksi during the first 2 weeks, at 4 months, and at 1 year, respectively.

2.8 Environmental Evaluation

As global warming and depletion of the ozone layer become more of a national concern, materials manufacturers are seeking ways to market their products as environmentally friendly or "green." A preferred and equitable procedure to compare competing materials such as Portland cement and Asphalt concrete pavements is to perform a life cycle assessment. A life cycle assessment (LCA, also known as life-cycle analysis, eco-balance, and cradle-to-grave analysis) is a technique to assess environmental impacts associated with all stages of a product or process from cradle to grave. The goal of LCA is to compare the full range of environmental effects assignable to products and services in order to improve design process, support policy determination and provide a sound basis for informed decisions. Three LCA models; process-based LCA model, Economical Input Output (ECOIO)-based LCA model, and hybrid LCA model, are widely used among many disciplines and companies. LCA involving the comparison of Portland cement and asphalt concrete pavements from traditional construction methods are common and have been extensively studied (*55-58*). LCAs involving traditional construction methods and pavement recycling have also been studied (*59; 60*).

Pavement LCAs are generally categorized according to the different activities that occur during their life. Five distinct life-cycle phases: materials, construction, use, maintenance and rehabilitation (M&R), and end-of-life (EOL) and ideally, any LCA should examine each phase of the product life cycle in detail. Given time, data, and knowledge constraints, this is very difficult for most products, including pavements.

REFERENCES

1. American Association of Civil Engineers (ASCE), *2017. Report Card for America's Infrastructure*. American Society of Civil Engineers, 2017.
2. FHWA. Highway Statistics 2000 Table HM-51, Federal Highway Administration 2000.
3. Calkins, M. *Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials*. John Wiley & Sons, 2008.
4. Stroup-Gardiner, M. *Recycling and reclamation of asphalt pavements using in-place methods*. 2011.
5. Diefenderfer, B. K., and A. M. Overton. Research Pays Off: Pavement Recycling: An Effective Reuse of Resources. *TR News*, No. 299, 2015.
6. Miller, H. J., W. S. Guthrie, R. A. Crane, and B. Smith. Evaluation of cement-stabilized full-depth-recycled base materials for frost and early traffic conditions. 2006.
7. Kim, Y., and H. D. Lee. Development of mix design procedure for cold in-place recycling with foamed asphalt. *Journal of Materials in Civil Engineering,* Vol. 18, No. 1, 2006, pp. 116-124.

8.   Mallick, R., M. Teto, P. Kandhal, E. Ray Brown, R. Bradbury, and E. Kearney. Laboratory study of full-depth reclamation mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1813, 2002, pp. 103-110.

9.   Syed, I., T. Scullion, and J. P. Harris. Durability of Recycled and Stabilized Pavement Materials.In *Recent Advances in the Characterization of Transportation Geo-Materials*, ASCE, 1999. pp. 25-36.

10.   Sommer, H. Strength and Durability Requirements for Cement-Stabilised Materials.In *International Symposium on Subgrade Stabilisation and In Situ Pavement Recycling Using Cement, 1st, 2001, Salamanca, Spain*, 2001.

11.   Litzka, J., and W. Haslehner. Cold In-place Recycling on Low-Volume Roads in Austria.In *Transportation Research Board Conference Proceedings*, 1995.

12.   Scullion, T. Field investigation: Pre-cracking of Soil-cement bases to reduce reflection cracking.In *TRB 81st Annual Meeting. Washington, DC: Transportation Research Board*, 2002. pp. 1-10.

13.   Wen, H., M. Tharaniyil, B. Ramme, and S. Krebs. Field Performance Evaluation of Class C Fly Ash In Full-Depth Reclamation: Case History Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1869, 2004, pp. 41-46.

14.   Wirtgen, F. Cold Recycling Manual. *Windhagen, Alemania*, 2012.

15.   Asphalt Recycling and Reclamation Association (ARRA). Basic Asphalt Recycling Manual. *Annapolis, Maryland*, 2001.

16.   Diefenderfer, B. K., and A. K. Apeagyei. I-81 In-Place Pavement Recycling Project.In, 2014.

17.   Loizos, A., and V. Papavasiliou. Evaluation of foamed asphalt cold in-place pavement recycling using nondestructive techniques. *Journal of Transportation Engineering,* Vol. 132, No. 12, 2006, pp. 970-978.

18.   Bemanian, S., P. Polish, and G. Maurer. Cold in-place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1949, 2006, pp. 54-71.

19.   Berthelot, C., B. Marjerison, G. Houston, J. McCaig, S. Warrener, and R. Gorlick. Mechanistic comparison of cement-and bituminous-stabilized granular base systems. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2026, 2007, pp. 70-80.

20.   Diefenderfer, B., and A. Apeagyei. Time-dependent structural response of full-depth reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2253, 2011, pp. 3-9.

21.   Diefenderfer, B. K., and A. K. Apeagyei. Analysis of full-depth reclamation trial sections in Virginia.In, 2011.

22.   Guthrie, W., A. Brown, and D. Eggett. Cement stabilization of aggregate base material blended with reclaimed asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2026, 2007, pp. 47-53.

23.   Hilbrich, S. L., and T. Scullion. Evaluation of Laboratory Mix Design and Field Performance of Asphalt Emulsion and Cement Stabilized Full-Depth Reclamation Project in Texas.In *Transportation Research Board 87th Annual Meeting*, 2008.

24. Lane, B., and T. Kazmierowski. Ten-Year Performance of Full-Depth Reclamation with Expanded Asphalt Stabilization on Trans-Canada Highway, Ontario, Canada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2306, 2012, pp. 45-51.

25. Lewis, D., D. Jared, H. Torres, and M. Mathews. Georgia's use of cement-stabilized reclaimed base in full-depth reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1952, 2006, pp. 125-133.

26. Mallick, R., D. Bonner, R. Bradbury, J. Andrews, P. Kandhal, and E. Kearney. Evaluation of performance of full-depth reclamation mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1809, 2002, pp. 199-208.

27. Maurer, G., S. Bemanian, and P. Polish. Alternative strategies for rehabilitation of low-volume roads in Nevada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1989, 2007, pp. 309-320.

28. Mohammad, L., M. Y. Abu-Farsakh, Z. Wu, and C. Abadie. Louisiana experience with foamed recycled asphalt pavement base materials. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1832, 2003, pp. 17-24.

29. Romanoschi, S., M. Hossain, A. Gisi, and M. Heitzman. Accelerated Pavement Testing Evaluation of the Structural Contribution of Full-Depth Reclamation Material Stabilized with Foamed Asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1896, 2004, pp. 199-207.

30. Saleh, M. Effect of Aggregate Gradation, Mineral Fillers, Bitumen Grade, and Source on Mechanical Properties Of Foamed Bitumen-Stabilized Mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1952, 2006, pp. 90-100.

31. Bocci, M., A. Grilli, F. Cardone, and G. Ferrotti. Full-depth reclamation for the rehabilitation of local roads: a case study. *International Journal of Pavement Engineering,* Vol. 15, No. 3, 2014, pp. 191-201.

32. Nataatmadja, A. Some characteristics of foamed bitumen mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1767, 2001, pp. 120-125.

33. Thenoux, G., Á. González, and R. Dowling. Energy Consumption Comparison for Different Asphalt Pavements Rehabilitation Techniques Used In Chile. *Resources, Conservation and Recycling,* Vol. 49, No. 4, 2007, pp. 325-339.

34. Alkins, A., B. Lane, and T. Kazmierowski. Sustainable pavements: environmental, economic, and social benefits of in situ pavement recycling. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2084, 2008, pp. 100-103.

35. Bocci, M., F. Canestrari, A. Grilli, E. Pasquini, and D. Lioi. Recycling techniques and environmental issues relating to the widening of an high traffic volume Italian motorway. *International Journal of Pavement Research and Technology,* Vol. 3, No. 4, 2010, p. 171.

36. Kearney, E., and J. Huffman. Full-depth reclamation process. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1684, 1999, pp. 203-209.

37. Wilson, J. R., D. Fischer, and K. Martens. *Pulverize, Mill & Relay Asphaltic Pavement & Base Course*. Wisconsin Department of Transportation, Division of Transportation Infrastructure Development, Bureau of Highway Construction, Pavements Section, Technology Advancement Unit, 1999.

38. Jones, D., R. Wu, and S. Louw. Comparison of Full-Depth Reclamation with Portland Cement and Full-Depth Reclamation with No Stabilizer in Accelerated Loading Test. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2524, 2015, pp. 133-142.

39. Smith, C., D. Lewis, J. Turner, and D. Jared. Georgia's Use of Lime in Full-Depth Reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2059, 2008, pp. 89-94.

40. Federal Highway Administration (FHWA), Transportation Applications of Recycled Concrete Aggregate. *FHWA state of the Practice National Review*, 2004.

41. King, B. *Making better concrete: guidelines to using fly ash for higher quality, eco-friendly structures*. Green Building Press, 2005.

42. Benson, C., T. Edil, P. Bloom, A. Ebrahimi, B. Kootstra, and L. Li. Use of fly ash for reconstruction of bituminous roads. 2009.

43. Kroge, M., K. McGlumphy, and T. Besseche. Full-Depth Reclamation with Engineered Emulsion in Fairburn, Georgia. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2095, 2009, pp. 136-143.

44. Quick, T., and W. Guthrie. Early-Age Structural Properties of Base Material Treated with Asphalt Emulsion. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2253, 2011, pp. 40-50.

45. [44] Collings, D., and K. Jenkins. The long-term behaviour of bitumen stabilised materials (BSMs).In *Conference on Asphalt Pavements for Southern Africa [CAPSA11], 10th, 2011, KwaZulu-Natal, South Africa*, 2011.

46. Shuler, S. Best Practices for Full-Depth Reclamation Using Asphalt Emulsions.In, 2015.

47. Kim, Y., H. D. Lee, and M. Heitzman. Validation of new mix design procedure for cold in-place recycling with foamed asphalt. *Journal of Materials in Civil Engineering,* Vol. 19, No. 11, 2007, pp. 1000-1010.

48. Chen, D.-H., J. Bilyeu, T. Scullion, S. Nazarian, and C.-T. Chiu. Failure investigation of a foamed-asphalt highway project. *Journal of infrastructure systems,* Vol. 12, No. 1, 2006, pp. 33-40.

49. Fu, P., D. Jones, J. T. Harvey, and F. A. Halles. Investigation of the curing mechanism of foamed asphalt mixes based on micromechanics principles. *Journal of Materials in Civil Engineering,* Vol. 22, No. 1, 2009, pp. 29-38.

50. Jones, D., P. Fu, J. T. Harvey, and F. Halles. Full-depth pavement reclamation with foamed asphalt: Final report. *Institute of Transportation Studies*, 2008.

51. Marquis, B., D. Peabody, and R. Malick. Using Foamed Asphalt as a Stabilizing Agent in Full Depth Reclamation of Route 8 in Belgrade, Maine. *Recycled Materials Resource Center, Maine Department of Transportation and Worcester Polytechnic Institute (October)*, 2002.

52. Thompson, M. R., L. Garcia, and S. H. Carpenter. Cold In-Place Recycling and Full Depth Recycling with Asphalt Products (CIR&FDRwAP).In, Illinois Center for Transportation (ICT), 2009.

53. ARA Inc., E. C. D. Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures. *NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, DC.*, 2004.

54. Dai, S., E. Skok, T. Westover, J. Labuz, and E. Lukanen. Pavement Rehabilitation Selection. 2008.
55. Athena, I. A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. *Cement Association of Ottawa: Ottawa, ON, Canada*, 2006.
56. Häkkinen, T., and K. Mäkelä. Environmental adaption of concrete: Environmental impact of concrete and asphalt pavements. *Vtt tiedotteita*, 1996.
57. Horvath, A., and C. Hendrickson. Comparison of environmental implications of asphalt and steel-reinforced concrete pavements. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1626, 1998, pp. 105-113.
58. Stripple, H. Life cycle assessment of road. *A pilot study for inventory analysis. 2nd revised Edition. Report from the IVL Swedish Environmental Research Institute,* Vol. 96, 2001.
59. Santos, J., J. Bryce, G. Flintsch, A. Ferreira, and B. Diefenderfer. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering,* Vol. 11, No. 9, 2015, pp. 1199-1217.
60. Chiu, C.-T., T.-H. Hsu, and W.-F. Yang. Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resources, Conservation and Recycling,* Vol. 52, No. 3, 2008, pp. 545-556.

3. NON-DESTRUCTIVE IN SITU CHARACTERIZATION OF ELASTIC MODULI OF FULL-DEPTH RECLAMATION BASE MIXTURES[1]

Eugene A. Amarh
Graduate Research Assistant, Center for Sustainable Transportation Infrastructure
Virginia Tech Transportation Institute
3500 Transportation Research Drive, Blacksburg, VA 24061
Tel: 540-998-9802; Email: amarheu2@vt.edu

Wilmar Fernandez-Gómez, Ph.D.
Postdoctoral Research Associate, Center for Sustainable Transportation Infrastructure
Virginia Tech Transportation Institute
Associate Professor, Universidad Distrital Francisco José de Caldas.
Tel: 540-577-4593 Email: wfernandez@udistrital.edu.co

Gerardo W. Flintsch, Ph.D., P.E.
Director, Center for Sustainable Transportation Infrastructure
Virginia Tech Transportation Institute
Professor, Department of Civil & Environmental Engineering, Virginia Tech
Tel: 540-231-9748 / 231-1569; Email: flintsch@vt.edu

Brian K. Diefenderfer, Ph.D., P. E.
Associate Principal Research Scientist, Virginia Transportation Research Council
530 Edgemont Rd, Charlottesville, VA 22903
Tel: 434-293-1944; Fax: 434-293-1990; Email: Brian.Diefenderfer@VDOT.Virginia.gov

Benjamin F. Bowers, Ph.D., P. E.
Research Scientist, Virginia Transportation Research Council
530 Edgemont Rd, Charlottesville, VA 22903
Tel: 434-293-1423; Fax: 434-293-1990; Email: Ben.Bowers@VDOT.Virginia.gov

Word count: 5961 words text + 6 tables/figures x 250 words (each) = 7461 words

Submission Date: August 1, 2016

3.1 ABSTRACT

State highway agencies are searching for more cost-effective methods of rehabilitating roads. One sustainable solution is full-depth reclamation (FDR), which is a pavement rehabilitation technique that involves pulverizing and reusing materials from existing distressed pavements in place. However, there is limited information on the long-term properties of these recycled materials. One important property, the elastic modulus, indicates the structural capacity of pavement materials and is highly recommended for design purposes by the Mechanistic Empirical Pavements Design Guide (MEPDG). The elastic modulus directly impacts selection of the overall pavement thickness, and an accurate estimation of the modulus is therefore key to a cost-effective pavement design. This research investigated the elastic modulus trends of three in-service pavements rehabilitated with the FDR technique during the 2008 Virginia Department of Transportation (VDOT) construction season. Foamed asphalt (2.7% with 1% cement), asphalt emulsion (3.5%), and Portland cement (5%) were used as stabilizing agents for the FDR layers. The results of the moduli measured for the recycled base materials varied significantly over time. These changes were attributed to curing after construction, seasonal effects, and subgrade moisture. The structural capacity of the pavements improved irrespective of the stabilizing agent used.

Keywords: recycled base, full-depth reclamation, time-dependent response, Critical Condition Index

3.2 INTRODUCTION

The FHWA (*1*) estimates the total length of flexible pavements in the United States at approximately 2.5 million centerline miles. A 2013 ASCE report on the nation's infrastructure suggests that 32% of those roads are in poor to mediocre condition (*2*). Given the high costs and environmental impacts of repairs at such a scale, traditional methods to rehabilitate or reconstruct these roads are not feasible or sustainable. Pavement recycling offers an innovative option that is gaining increasing acceptance among state departments of transportation (DOTs) as a method of restoring the service life of pavements with medium to high traffic.

Pavement recycling is often performed in place, reusing materials from the existing pavement to form a base layer usually requiring an asphalt concrete overlay. Pavement recycling offers many advantages over traditional rehabilitation methods, such as lower construction costs and a smaller environmental footprint (*3*) from reducing the use of virgin materials and eliminating the need to haul materials to landfill sites. Pavement recycling may be performed as hot-in-place, cold recycling or full depth reclamation (FDR). Cold recycling is usually carried out as cold in-place recycling (CIR) or cold central-plant recycling (CCPR) depending on the severity of the pavement distresses among other reasons.

FDR is better suited for deteriorated pavements with distresses penetrating deep into the unbound layers. FDR involves pulverizing the existing pavement materials usually up to a depth of 12 in., remixing, and finally compacting the mixture to form a uniform base. The pulverized base mixture is strengthened through the addition of stabilizers (such as foamed asphalt or asphalt emulsion, Portland cement, lime, or fly ash) prior to compaction during the FDR process. Many state DOTs have used FDR to successfully restore the structural capacity of pavements (*4-18*). For example, in 2011 the Virginia DOT (VDOT) used all three cold recycling techniques together in a strategically layered configuration to rehabilitate sections of Interstate-81 (*19*).

Studies of the structural properties of FDR materials have focused on the structural number and layer coefficients (*4, 7, 16, 18, 20, 21*) as most agencies continue to rely on empirical methods for new pavement and rehabilitation design. There is, however, a paradigm shift in the design of pavements as more state DOTs implement or plan to implement practices from AASHTO's Mechanistic-Empirical Pavement Design Guide (MEPDG) (*22*). The MEPDG recommends the use of the elastic modulus for characterizing the structural properties of materials for design purposes. Yet, only a few studies have investigated the elastic modulus of FDR base mixtures, and these have been limited to laboratory evaluations or accelerated pavement tests using heavy vehicle simulators (HVSs). The long-term, in situ properties and related performance of FDR mixtures have not received much attention, and several questions remain unanswered regarding the behavior of FDR mixtures over time. The objective of this research was therefore to evaluate changes in the elastic modulus over time and its sensitivity to temperature and seasonal effects for three road rehabilitation projects in Virginia constructed in 2008.

3.3 METHODOLOGY

3.3.1 Overview

To assess the feasibility of implementing the FDR technique in future road maintenance projects under the climatic conditions in the state of Virginia, three trial sections were constructed in 2008 using FDR with different stabilizing agents and were monitored over a 2-year period. The trial sections were located on State Routes (SRs) 40, 13, and 6 in Franklin, Powhatan, and Goochland Counties, respectively. Foamed asphalt (with 1% cement) and asphalt emulsion were used as stabilizing agents for two adjacent sections in the SR 40 project, while Portland cement was used in sections along SR 13 and SR 6. The construction and reclamation processes were similar and have been documented by Diefenderfer and Apeagyei (*7*), together with a comprehensive description of the project sites. The authors assessed the performance of the projects at early ages. In the three projects, the existing pavement was pulverized to a predetermined depth, followed by the injection and mixing of the stabilizers, and subsequently compacted to contract specifications. A motor grader, a pad foot, and steel-wheeled and rubber-tired rollers were used for the construction. Table 1 summarizes the projects.

TABLE 1 Summary of VDOT's FDR Demonstration Project

	SR 40	SR 40	SR 13	SR 6
County	Franklin	Franklin	Powhatan	Goochland
Relative Milepost	21.70 – 21.97	21.97 – 22.24	16.25 – 19.93	67.48 – 71.11
Stabilizing Agent	Foamed Asphalt	Asphalt Emulsion	Portland Cement	Portland Cement
Stabilizing Agent Content	2.7%	3.5%	5.0%	5.0%
Chemical Additive	1% cement	na	na	na
AADT[a] (% Trucks)	4,400 (4%)	4,400 (4%)	2,300 (5%)	3,900 (7%)
Approx. Project Length (Lane-Miles)	0.5	0.5	7.4	7.3
CCI[b]: Before Intervention	41/100	41/100	58/100	47/100
CCI: 1 Year after Intervention	99/100	99/100	100/100	98/100
AC[c] Overlay Thickness (in.)	2.4	2.4	3.6	3.6
FDR Base Thickness (in.)	9.4	9.8	9.2	9.1
Reclamation Dates	May 13–15, 2008	May 19–22, 2008	June 18–July 21, 2008	July 21–August 7, 2008
Time from Reclamation to AC Overlay	3 weeks	3 weeks	1 week	1 week

[a]Annual Average Daily Traffic [b]Critical Condition Index [c]Asphalt Concrete na = not applicable

3.3.2 Site Descriptions

SR 40, Franklin County

SR 40 lies approximately 35 mi south of Roanoke, running east-west through south-central Virginia. The trial section was originally a 10-ft wide pavement composed of a 6- to 10-in. unbound granular (crushed aggregate and uncrushed gravel) base overlaid with 5- to 6-in. of HMA and surface treatments. Structural distresses such as longitudinal cracking and fatigue cracking within the wheel paths were prevalent in the original pavement. Multiple thin layers with complete debonding were evident in cores collected during site investigations prior to reclamation.

SR 13, Powhatan County

Located approximately 25 mi west of Richmond, SR 13 (Old Buckingham Road) runs east-west in Powhatan County. The trial section was originally composed of a 4.5- to 6-in. HMA overlying an aggregate base. Minor fatigue cracks and widespread longitudinal cracking were evident in the wheel paths of the original pavement. Cores taken during site investigations prior to reclamation revealed debonded and stripped layers.

SR 6, Goochland County

SR 6 (known for most of its length as River Road) is an east-west road located about 25 mi west of Richmond. The test section was originally composed of approximately 9 in. of HMA over an aggregate base. The pavement exhibited similar distresses to SR 13. Cores extracted during the pre-reclamation site investigation revealed stripping and layer debonding.

3.3.3 Assessment of FDR Layer Elastic Modulus

Diefenderfer and Apeagyei (*6, 7*) conducted a series of laboratory and field evaluations to assess the mechanical properties and structural capacity of the in-service FDR projects with field cores and two non-destructive techniques at early ages. As VDOT and many other state DOTs use empirical methods for pavement design, the authors conducted the structural evaluation in accordance with the 1993 AASHTO *Guide for Design of Pavement Structures (23),* placing emphasis on investigating the structural number of the pavement and estimating layer coefficients for the FDR base layer through the AASHTO design equations. In this current research, however, emphasis was placed on evaluating the elastic modulus of individual layers as a mechanical property supported by the MEPDG.

Data Collection

Ground penetration radar (GPR) was used to estimate the layer thicknesses of the three FDR projects after construction. GPR has been used in several other projects to ensure that specifications for thickness and material uniformity were met during construction. The results from the GPR testing were used in the deflection data analysis for subsequent evaluation of the structural capacity of the reclaimed sections.

A Dynatest Model 8000 falling weight deflectometer (FWD) was used in carrying out deflection measurements in both directions along the reclaimed pavements for all test sites. The equipment had nine sensors at radial distances of 0, 8, 12, 18, 24, 36, 48, 60, and 72 in. from the

center of a load plate located in the wheelpath. At SR 40, testing was conducted at 100-ft intervals and at four load levels (6,000, 9,000, 12,000, and 16,000 lbf). The SR 13 and SR 6 sites were tested at 250-ft. intervals with three load levels (6,000, 9,000, and 12,000 lbf).

Analysis of Deflection Data
The collected deflection data were analyzed in accordance with the backcalculation methodology and procedures outlined in Von Quintus, Rao, and Irwin (*24*), together with ASTM D5858, *Standard Guide for Calculating In Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory,* and *Guidance Notes on the Backcalculation of Layer Moduli and Estimation of Residual Life Using Falling Weight Deflectometer Test Data* (*25*). The analysis was performed using Dynatest ELMOD (Evaluation of Layer Modulus and Overlay Design) software, version 6. ELMOD provides two methods to backcalculate the elastic modulus, radius of curvature and deflection basin fit. These approximate methods are based on the Boussinesq equations and Odermark's method of equivalent thickness. The difference between the methods is that the deflection basin fit method runs additional iterations until the calculated deflections match the measured deflections to within the defined tolerance.

The pavement structure was modeled in ELMOD as a three-layered structure: a top HMA layer, an intermediate FDR base layer, and a subgrade layer at the bottom. The deflection data obtained from each FWD test were examined to ensure that data points with large fluctuations or inconsistencies such as non-decreasing deflections were removed prior to the backcalculation. The accumulated differences of the center deflections were used to divide the length of the test run into homogeneous sections in ELMOD. The accumulated difference (A.d.) at the ith station was defined as follows:

$$A.d. = \sum \delta_i - i\mu$$

where

$\sum \delta_i$ = sum of deflections from the 1st station to the ith station inclusively;

i = number of stations from δ_1 to δ_i inclusively;

μ = mean deflection of the test run.

A section was considered homogeneous when the cumulative differences continued in the same upward or downward trend. A significant change in trend marked a change in section. Figure 2 shows the output of the deflection data consistency checks and the resulting sectioning of SR 40.
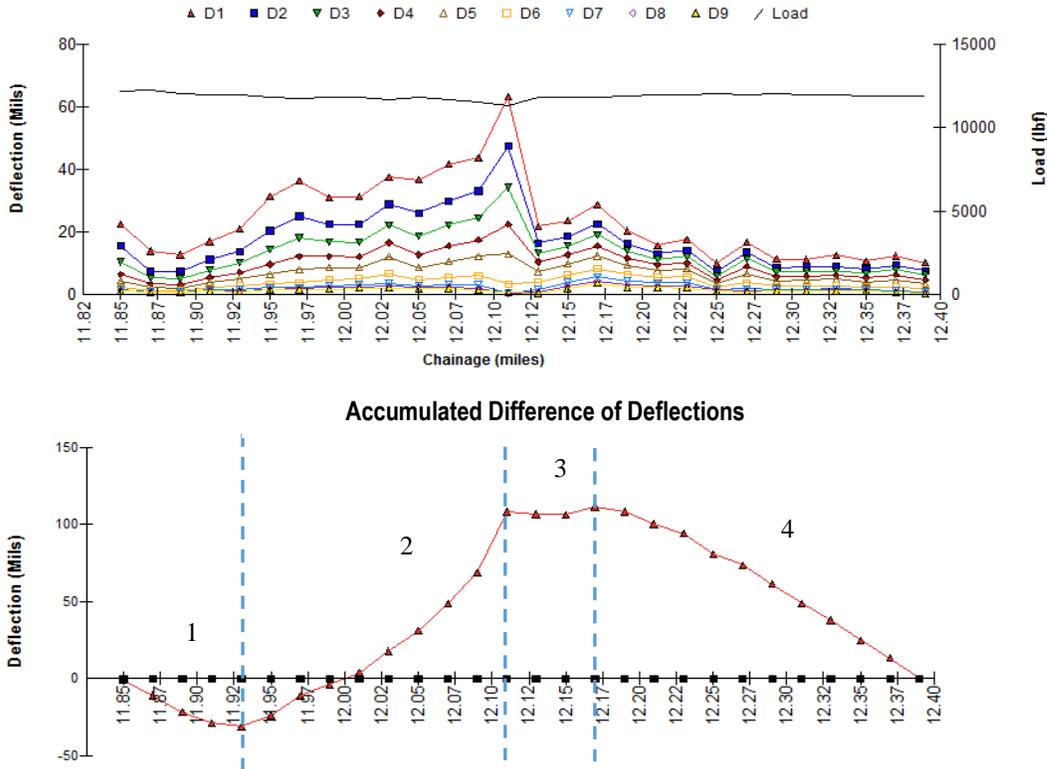
FIGURE 2: Deflection data checks and sectioning of SR 40.

The thickness of each layer in a homogeneous section was then input into ELMOD from the results of the GPR testing. The Poisson ratios selected for the pavement layers were within the range of typical values recommended in ASTM D5858 and other literature. A value of 0.35 was used for the HMA layer and subgrade. Values of 0.35 and 0.26 were used for the bitumen-stabilized and cement-stabilized bases respectively (*26, 27*).

ELMOD carries out the backcalculation using the following procedure (*25, 28*):

1. The program uses the Boussinesq equations to calculate the surface modulus from the surface deflections. The surface modulus, i.e., the weighted mean modulus of a semi-infinite space, at a certain distance r gives a rough estimate of the modulus at the same equivalent depth $z = r$. Under the condition that the subgrade behaves as a linear elastic semi-infinite space, the surface modulus should be the same at varying distances. Based on this, the subgrade modulus is estimated using the outer deflections as these are almost entirely controlled by the subgrade.

2. The accuracy of results from the backcalculations is usually impacted by the presence of a stiff layer and subgrade moisture. The presence of a stiff layer at some depth beneath the subgrade is checked by evaluating the change in modulus with varying distances from the center of the load plate by calculating the surface modulus, E_0:

$$E_0(0) = \frac{2 \cdot a \cdot \sigma_0 \cdot \left(1 - \mu^2\right)}{d_0(0)} \qquad (1)$$

22

$$E_0(r) = \frac{a \cdot \sigma_0 \cdot (1 - \mu^2)}{r \cdot d_0(r)}, \qquad (r > 2a) \tag{2}$$

where

$E_0(r)$ = surface modulus at distance r;
μ = Poisson's ratio of the subgrade;
σ_0 = uniform stress on the plate;
a = load plate radius;
r = distance from the center load;
$d_0(r)$ = surface deflection at distance r.

3. If a stiff layer is not found, a check is performed for non-linearity due to high moisture content resulting from the presence of a ground water or a wet layer. The coefficients C and n are obtained from the following equation:

$$E_0 = C \cdot \left(\frac{\sigma_1}{\sigma} \right)^n \tag{3}$$

where

E_0 = surface modulus;
σ_1 = major principal stress;
σ = reference stress (usually 160 MPa);
C = constant;
n = negative constant.

C decreases linearly with the increase in moisture content, and n usually measures the non-linearity; the subgrade is linear elastic when n is zero, with the non-linearity becoming more evident as n decreases.

4. Using the deflection basin fit method, the moduli of the HMA layer and FDR base are then determined through a series of iterations using the center deflection and the curvature or shape of the basin under the load plate.

5. The subgrade modulus is then adjusted according to the estimated stress level under the load center. The outer deflections are checked and additional iterations are carried out if necessary.

6. The calculated deflection profile and measured deflection profile are then matched with the percentage difference (root mean square [RMS]) between the calculated and measured values reported. The iterations are performed with the objective of minimizing the RMS as the convergence criteria.

A total of 26 FWD files with 36 stations were analyzed for SR 40, 26 FWD files with 38 stations for SR 13, and 37 FWD files with 21 stations for SR 6. A total of 16,205 deflection basins were analyzed for this study.

Evaluating Long-Term Performance

23

Deterioration models were developed and analyzed to assess the long-term performance of the projects. The critical condition index (CCI), along with the pavement age were obtained from the VDOT Pavement Management System (PMS). VDOT currently uses the generalized form:

$$CCI = 100 - \exp\left(a + b \times c^{\log\left(\frac{1}{Age}\right)}\right) \qquad (4)$$

where

CCI = Critical Condition Index (100 when pavement age is zero)
a, b, c = model coefficient
Age = age of pavement after treatment was last applied

The model was calibrated with the CCI and age data for the sections to obtain numerical values for the coefficients a, b, and c. The values of a, b, and c for primary roads managed by VDOT are 15.32, 15.38 and 1.11. These were used as initial values for the FDR sections in the calibration process.

3.4 RESULTS

3.4.1 Deflection Data Analysis

As described earlier, FWD testing was undertaken for all three recycling projects approximately 3 weeks after reclamation at varying intervals for 28 months. The deflection data files (the same as used by Diefenderfer and Apeagyei (*5, 6*) for the projects were analyzed as a three-layered structure using ELMOD6. Acceptable results were defined as an RMS less than or equal to 3%, with the range of backcalculated *E*-values for each layer falling within an acceptable range for each layer type and category based on the default range of values included in the MEPDG (*23*).

3.4.2 Elastic Modulus Trends

SR 40

Strength of the Base Layer Figure 3a shows the results of the average moduli for the FDR base layer. The moduli for the foamed asphalt section, in both directions, were in the approximate range of 133 to 638 ksi (920 to 4,400 MPa). The moduli for the asphalt emulsion sections were lower and within the approximate range of 36 to 485 ksi (250 to 3,350 MPa). Quick and Guthrie (*29*) reported low moduli results for deflection tests undertaken in the month of June 2010 (89.6 ksi) as observed for this study.

For both FDR treatment types, there was a general increase in the moduli up to the sixth month after reclamation. Strong seasonal variations were evident in both sections, with the foamed asphalt and asphalt emulsion sections attaining the highest and lowest moduli in the winter and summer seasons.
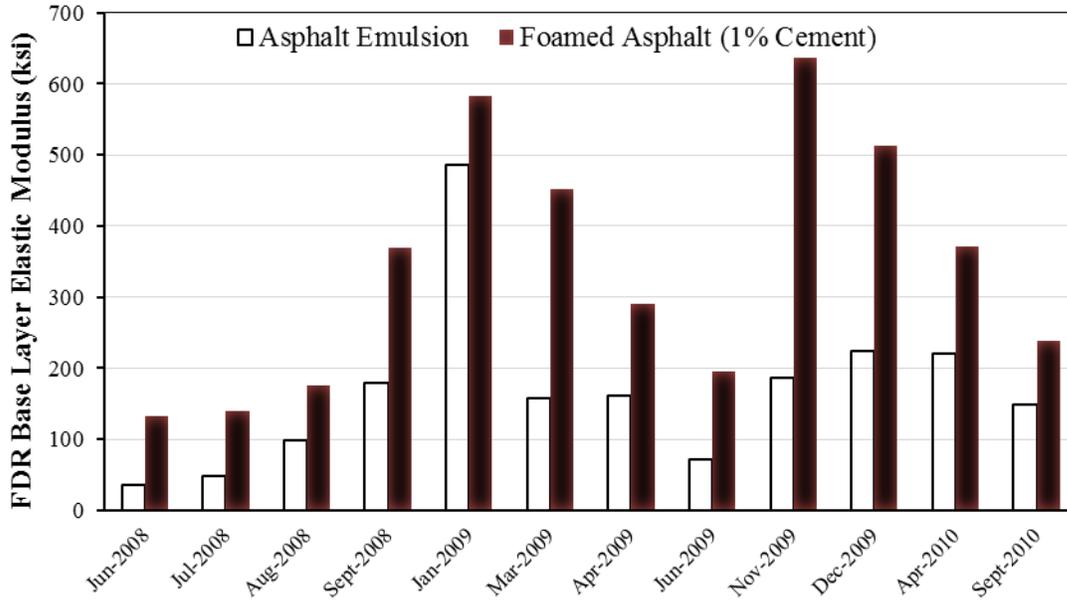
(a)
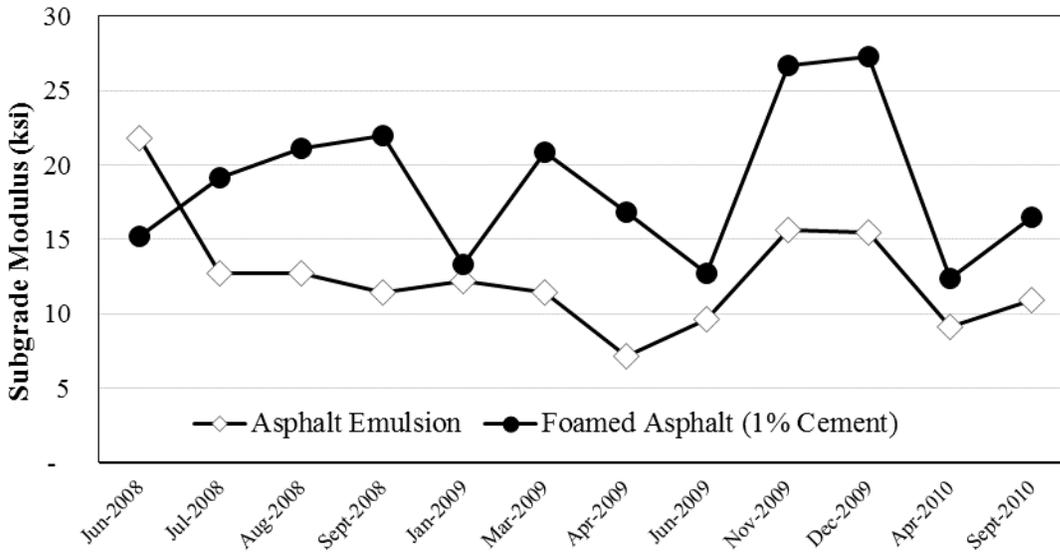
(b)

FIGURE 3: Comparison of backcalculated moduli for SR 40 project: (a) bitumen-stabilized layer and (b) subgrade.

Subgrade Strength and Support The purpose of the FDR base layer is to protect the subgrade from damage. It is therefore key to report how well each of the treatments served this purpose. Figure 3b shows the results of the subgrade moduli for the bitumen-stabilized sections. The moduli were higher for the foamed asphalt sections, with a range of 12 to 28 ksi (85 and 190 MPa). The range of the moduli for the asphalt emulsion sections was between 8 and 16 ksi (50 to 110 MPa). There was no evidence of bedrock in these sections. The trends were impacted by seasonal variations. For both sections, the highest subgrade modulus was in the winter season, which may

25

be representative of the frozen conditions underneath the pavement structure. The lowest moduli for both projects were in the spring, which represents the end of freeze-thaw cycles. However, lower results were reported for the emulsion asphalt sections than the foamed asphalt sections during the same period, an indication of higher susceptibility to moisture effects. This observation is confirmed by the subgrade non-linearity constants, C (moisture content) and n (measure of non-linearity), obtained from the backcalculation. C values of 11.3 ksi and 16.7 ksi for the asphalt emulsion and foamed asphalt, respectively, indicate a higher moisture content in the asphalt emulsion section. The addition of 1% cement in the foamed asphalt base mixture as a chemical additive may have contributed to the reduced impact of moisture on those sections. Generally, the area around the site tended to drain towards the eastern end of the emulsion section with the roadway rising to either side of the section. It is also possible that the increased moduli of the overlaying layers may have contributed to the increased moduli for the foamed sections as a result of the backcalculation process.

SR 13 and SR 6

Strength of the Base Layer Figure 4a shows the average moduli reported from the SR 13 and SR 6 FDR projects stabilized with Portland cement. The moduli for the SR 13 project were higher, within the range of 550 to 1,045 ksi (3,800 and 7,200 MPa), than the moduli for SR 6, which ranged from 377 to 776 ksi (2,600 to 5,350 MPa). The impact of seasonal variations was not evident in either of the projects even though the modulus fluctuated with time over the analysis period. Additional results from the deflection data analysis revealed very non-linear conditions in the pavement structure for the SR 6 project, indicating high moisture content in the subgrade for the majority of the sections analyzed. The section also had a higher annual average daily traffic (AADT) than the SR 13 section. These two factors may have contributed to the low stiffness results compared with SR 13 and requires further investigation. The source of the high moisture content was not investigated in this study.
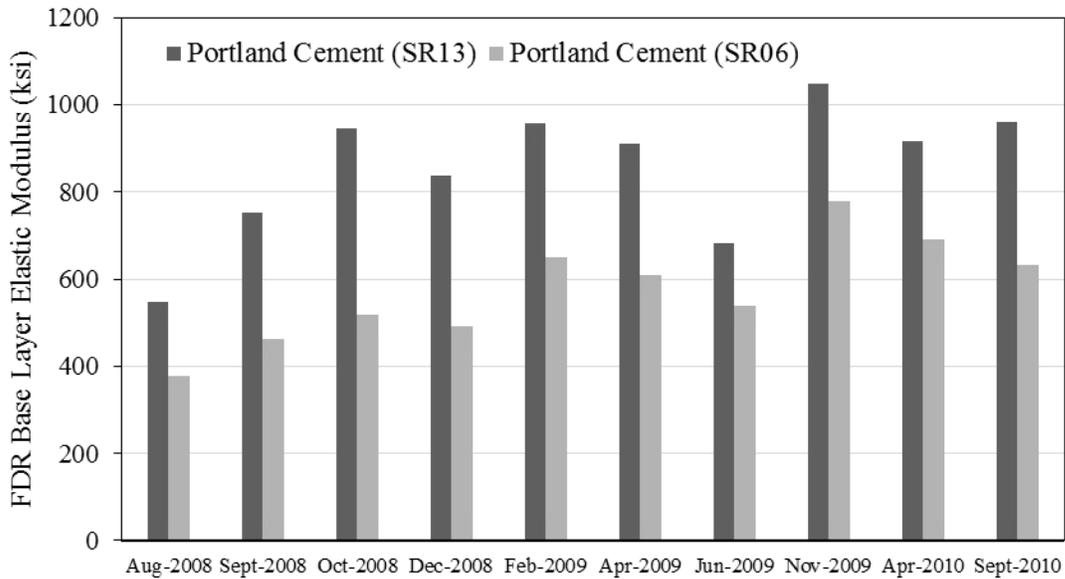
(a)
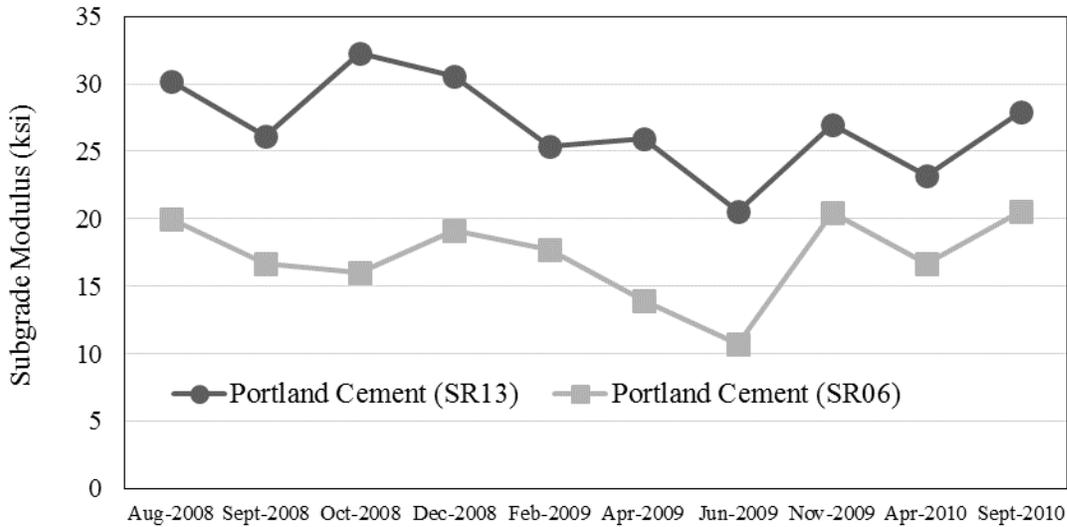
(b)

FIGURE 4: Comparison of backcalculated moduli for SR 13 and SR 6 projects: (a) cement-stabilized FDR layer and (b) subgrade.

Subgrade Strength/Support Figure 4b shows the results of the moduli of the subgrade for the Portland-cement stabilized projects. The backcalculated moduli were generally higher in the SR 13 project, ranging from 17 to 35 ksi (120 to 240 MPa), than the results for the SR 6 project, which were in the range of 10 to 20 ksi (70 to 140 MPa).

The results were similar to the subgrade resilient modulus values obtained by Diefenderfer and Apeagyei (*7*). The impact of a seasonal trend was not significant, and the moduli remained almost stable over the period analyzed for both projects. The difference in the stiffness results for the two projects may be explained by the moisture contents in the subgrade. The SR 6 project showed

27

higher moisture content during the non-linearity check from the backcalculations. Average *C* values of 26.9 ksi and 14.2 ksi were obtained for SR 13 and SR 6 respectively.

3.4.3 Temperature Sensitivity

SR 40
Asphalt materials are sensitive to changes in temperature. Figure 5a shows the variations in moduli of the FDR base layer with changes in temperature for the SR 40 project. The temperature used in the analysis was the pavement mid-depth temperature calculated from the BELLS3 equation using the average of the previous day high and low temperature. The moduli for both sections generally decreased with increasing temperature (change in stiffness over time considered). The variation, however, is greater for the emulsion asphalt section compared with the foamed asphalt sections. This may be a result of the 1% cement addition to the foamed asphalt sections as the cement reduces the viscoelastic properties. If this relationship is true, then the time of the day at which field evaluations are undertaken must be taken into account as this will impact the results obtained for both the AC overlay and FDR base layers.
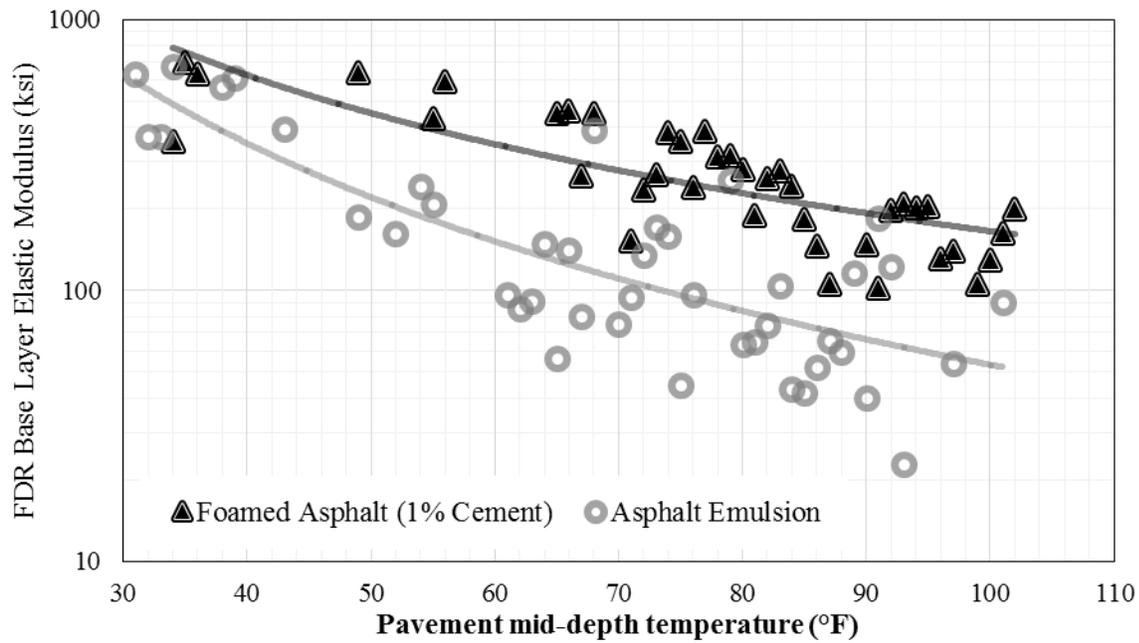
(a)
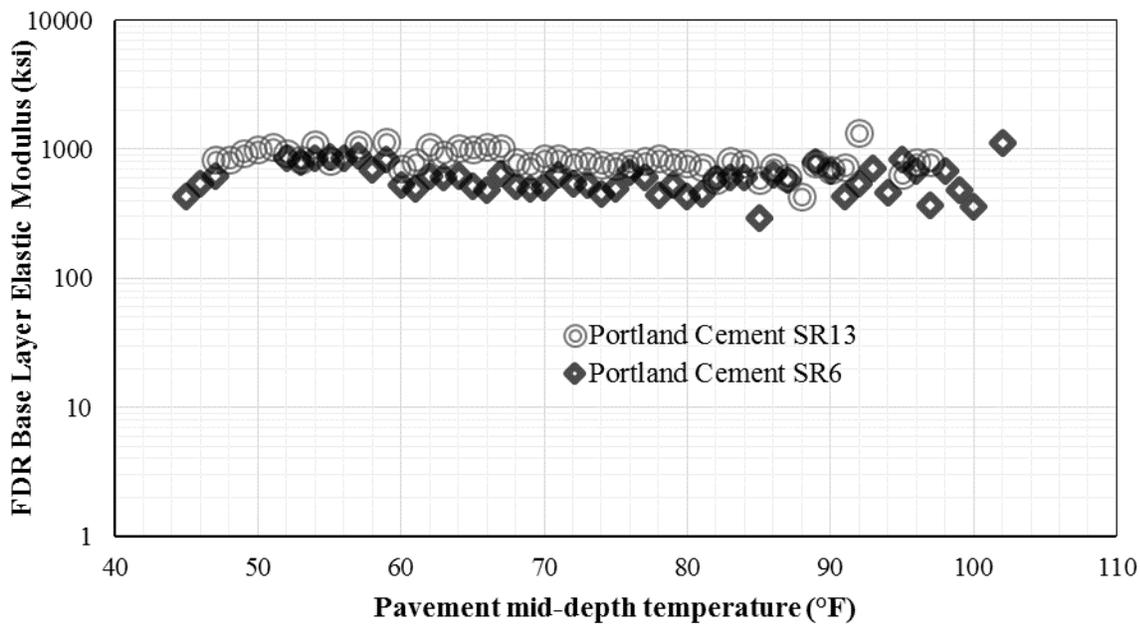
(b)

FIGURE 5: **Variation of elastic modulus with temperature for (a) bitumen-stabilized FDR base layers and (b) cement-stabilized FDR base layers.**

SR 13 and SR 6

The relationship between the backcalculated moduli and temperature is shown in Figure 5b for the Portland cement-stabilized projects. As expected, the effect of temperature on the modulus results does not seem to be significant as the modulus does not change with variation in temperature for both projects. This result confirms that the addition of cement as the stabilizing agent not only

improves the strength of the base layer but also reduces the effect of temperature on the stiffness of the materials.

3.4.4 Time-Dependent Variations

SR 40
Figure 6a shows the variation in the average eastbound and westbound moduli for the SR 40 projects over time. For both the foamed asphalt and asphalt emulsion sections, the moduli increased significantly over the first 2-year period following construction. The FDR process incorporating foamed asphalt with 1% cement resulted in a stiffer base mixture than reclamation with asphalt emulsion stabilization. For both sections, a sharp increase in the moduli was evident in the first 4 months after reclamation before leveling out around a long-term average of 174 and 420 ksi (1,200 and 2,900 MPa) for asphalt emulsion and foamed asphalt, respectively, in the last 18 months. Within the first 4 months, the foamed asphalt section achieved a stiffness of 362 ksi (2,500 MPa) close to its long-term average, from an initial stiffness of 110 ksi (758 MPa). Within the same period, the emulsion asphalt section achieved a stiffness of 115 ksi (790 MPa) close to its long-term average, from an initial stiffness of 24 ksi (165 MPa). This confirms the slower curing time for emulsion asphalt widely reported in the literature (*29-30*). The authors believe the addition of cement may have contributed significantly to the curing time and overall higher stiffness of the foamed asphalt section.

A logarithmic trend line was added to predict the variation of stiffness of the FDR base materials during the curing process. Due to the temperature sensitivity of the bitumen-treated bases observed from the modulus-temperature analysis, two data points representing the highest (June 2009) and lowest (January 2009) temperatures of the year were eliminated from analysis to reduce the effect of temperature on the model.
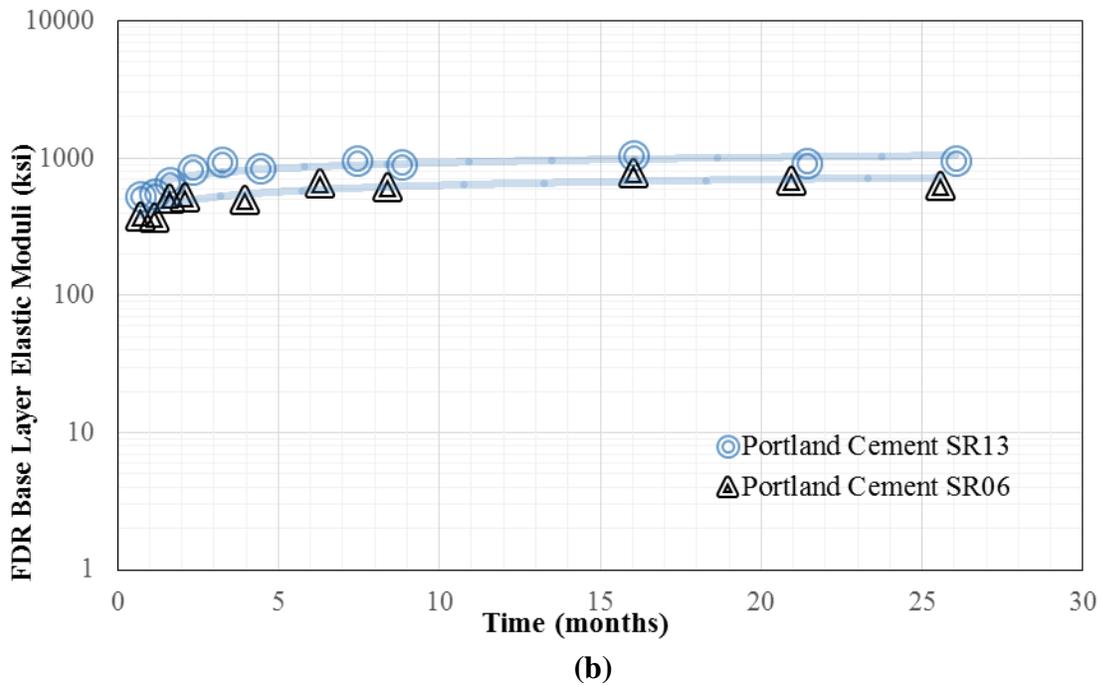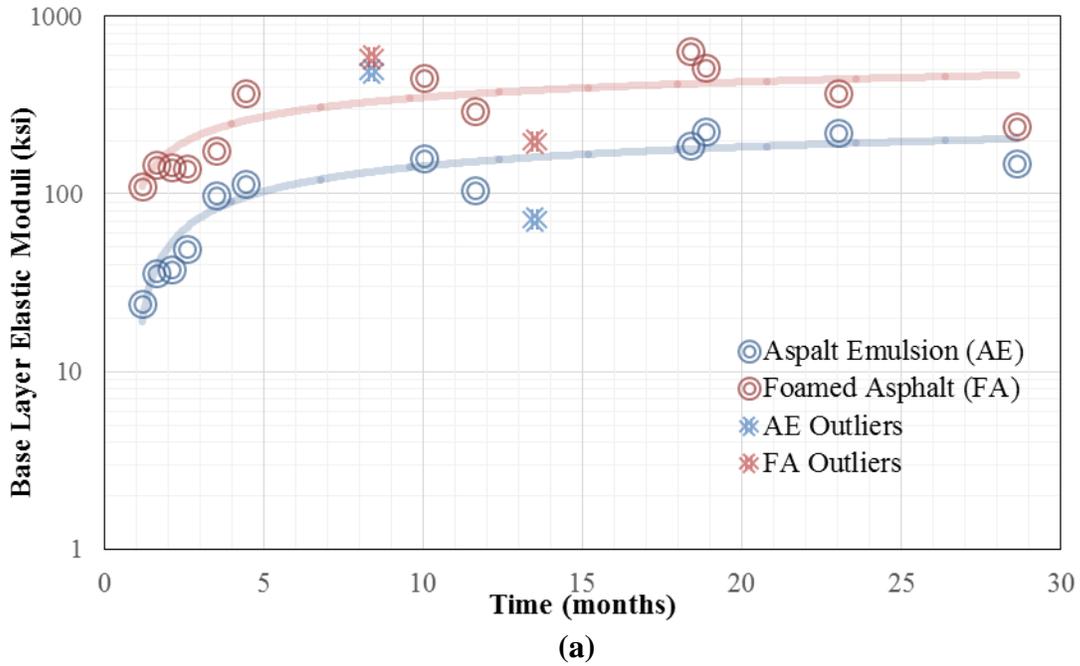
**FIGURE 6: Evolution of backcalculated elastic modulus with time for (a) bitumen-stabilized FDR bases and (b) cement-stabilized FDR bases.**

As the trend does not show any significant damage within the analysis period, it was not possible to develop equations to predict long-term damage as applied in the MEPDG for rehabilitation design. Diefenderfer and Apeagyei (*6*) used similar logarithmic regression equations

to predict the variations in the structural layer coefficient over time. The following regression equations with their corresponding goodness-of-fit (R^2) values were obtained for the SR 40 project.

Foamed asphalt: $y = 110.7\ln(x) + 94.4$ ($R^2 = 0.53$)
Asphalt emulsion: $y = 57.71\ln(x) + 10.5$ ($R^2 = 0.83$)

SR 13 and SR 6

Figure 6b shows the variation of the average eastbound and westbound moduli for the Portland cement-stabilized projects over time. The long-term strength gain for the SR 13 project was similar to that for the SR 6 project. The moduli of the SR 6 project at the end of the 2 years were comparable to those obtained for the foamed asphalt (plus 1% cement) sections from the SR 40 project even though the initial stiffness was higher for the SR 6 project. Similar logarithmic regression equations were developed to predict the moduli as a variation of time. The regression equations and corresponding R^2 values are presented below:

Portland cement (SR 13): $y = 123.72\ln(x) + 640.76$ ($R^2 = 0.75$)
Portland cement (SR 6): $y = 94.018\ln(x) + 416.78$ ($R^2 = 0.80$)

A prediction relationship using the logarithmic regression through all points for SR 13 and SR 6 over time was developed:

Portland cement: $y = 127.14\ln(x) + 521.42$ ($R^2 = 0.50$)

("x" and "y" in the logarithmic regression equations are the pavement age and elastic modulus with units months and ksi respectively)

3.4.5 Long-Term Performance

Figure 7 shows predictions of the functional performance of the FDR projects over time. The model coefficients calibrated for the CCI curves (Equation 4) are as follows;

Foamed asphalt: $a = 21.86$, $b = -22.06$, $c = 1.521$ ($SSE = 4.13$)
Asphalt emulsion: $a = 22.01$, $b = -29.02$, $c = 1.652$ ($SSE = 3.89$)
Portland cement: $a = 22.13$, $b = -21.95$, $c = 1.193$ ($SSE = 7.97$)

A pavement with a CCI value of 100 has no discernible distresses, while pavement sections with a CCI value of zero indicates a heavily deteriorated pavement condition. Typically, VDOT considers pavement sections with a CCI value below 30 (very poor) as deficient, requiring further evaluation for corrective action. The analysis shows that all three projects are comparable in terms of performance. The bitumen-stabilized project remained in excellent condition for a longer period of time compared to the cement projects. The cement projects however, were projected to be approximately 4 years more durable than the bitumen-stabilized projects using the CCI of 30 as a trigger for rehabilitation.
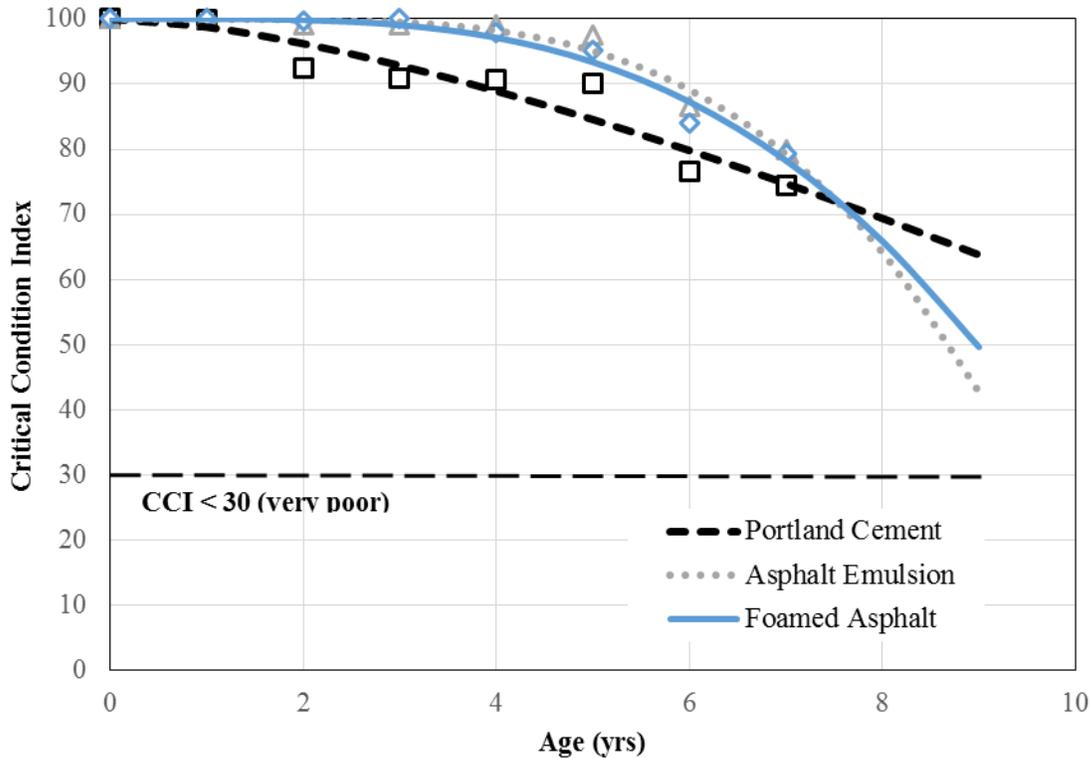
FIGURE 7: CCI curves showing pavement deterioration with age for the FDR projects

3.5   SUMMARY

The strength of the stabilized FDR bases for all three projects varied over time. The FDR sections having bitumen-stabilized bases showed more sensitivity to seasonal changes than those having Portland cement-stabilized bases. The cement-stabilized bases were stiffer and provided better support to the subgrade than the bitumen-treated bases. Based on the Critical Condition Index (CCI) for each recycling project from before and after the reclamation process (obtained from the VDOT PMS and shown in Table 1), the functional condition of the pavements was significantly improved as the pavements were restored to above 98 CCI 1 year after reclamation.

Of the three projects, the bitumen-stabilized sections showed the most sensitivity to temperature effects. However, the section having foamed asphalt (plus 1% cement) was less sensitive compared with the section having an emulsion-stabilized base. The Portland cement-stabilized bases showed little to no sensitivity to temperature, leading to the conclusion that the addition of cement as a chemical additive compared with other stabilizers not only improves the strength but also reduces the temperature sensitivity of the material. The analysis also suggested that the field evaluations of the structural capacity of bitumen-stabilized bases must consider temperature. If evaluations are undertaken only once after construction, the results may underestimate the actual condition if conducted at a high temperature for bitumen-stabilized projects.

The stiffness of the FDR bases in all three projects increased over time. FDR bases stabilized with Portland cement had the highest initial stiffness, taking about 2 months to attain the average maximum strength over the 2-year analysis period. The bitumen-stabilized bases took a

33

longer time to cure, with asphalt emulsion showing lower initial stiffness and lengthier time to gain maximum strength than the foamed-asphalt-stabilized bases. This trend may be, in part, due to the softer PG 58-22, as suggested by Diefenderfer and Apeagyei (6, 7). Also, the presence of cement may have slightly improved the curing time for the foamed asphalt sections. Pavement design engineers should note this curing trend for FDR projects and implement measures to improve short-term and overall long-term performance of these projects. Increasing the design strength or design traffic (AADT), exploring mix designs with combined stabilizing using emulsion asphalt bases with cementitious materials in appropriate contents, delaying the opening to traffic, or limiting usage to light traffic in the short term may be measures to consider.

The regression equations developed to predict the evolution of the elastic modulus with time for the three projects can be used to predict short-term strength gains. The equations predict an ever increasing strength with passage of time.

The preliminary condition modeling suggested that the Portland cement-stabilized projects had approximately four years of remaining service life compared to the bitumen-stabilized sections using a CCI of 30 as a trigger for rehabilitation. The durability and long-term condition of the bitumen-stabilized sections were similar even though the foamed asphalt (plus 1% cement) sections were significantly stiffer than the asphalt emulsion section. A longer time analysis is needed to confirm these findings because of the high variability of the CCI measurements.

3.6   CONCLUSIONS

The following conclusions and recommendations were made based on the results of this study.

- The effect of temperature should not be overlooked in the evaluation of the structural capacity of bitumen-stabilized FDR projects. The authors propose further work on developing more robust temperature models to improve the current practice.
- A general enhancement in the material properties from the initial strength after construction was noticed with time in all the stabilized FDR projects studied. These time-dependent variations in strength are significant for FDR projects and must be considered in the mechanistic-empirical analysis.
- The addition of cement as a primary stabilizing agent or as a chemical additive in bitumen-stabilized FDR bases not only increases strength but also reduces the effects of temperature on the moduli for FDR projects.
- Based on the stiffness trends of all three projects and their overall comparable performance in the long term, design moduli of approximately 170 ksi and 720 ksi for asphalt emulsion and Portland cement respectively are recommended for use in MEPDG for the FDR layer of projects with similar stabilizing agent content. When foamed asphalt, with Portland cement as a chemical additive is used, 450 ksi is recommended for design.
- Condition modeling was used to estimate the long-term performance of the projects and the analysis suggested that FDR projects with stiffer base materials do not necessarily perform better even though they may have slightly longer remaining service life in this research.

3.7 ACKNOWLEDGEMENT

REFERENCES

1. FHWA. Highway Statistics 2000 Table HM-51, Federal Highway Administration 2000.
2. ASCE. *2013 Report Card for America's Infrastructure*. American Society of Civil Engineers, 2013.
3. lkins, A.E., Lane, B., Kazmierowski, T. (2008). Sustainable Pavements – Environmental, Economic, and Social Benefits of In Situ Pavement Recycling. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2084*. Transportation Research Board of the National Academies, Washington, DC, pp. 100-103.
4. Bemanian, S., P. Polish, and G. Maurer. Cold in-place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1949*, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 54-71.
5. Berthelot, C., B. Marjerison, G. Houston, J. McCaig, S. Warrener, and R. Gorlick. Mechanistic comparison of cement-and bituminous-stabilized granular base systems. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2026,* 2007, pp. 70-80.
6. Diefenderfer, B., and A. Apeagyei. Time-dependent structural response of full-depth reclamation. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2253*, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 3-9.
7. Diefenderfer, B. K., and A. K. Apeagyei. Analysis of full-depth reclamation trial sections in Virginia.In FHWA/VCTIR Report 11-R23, 2011.
8. Guthrie, W., A. Brown, and D. Eggett. Cement stabilization of aggregate base material blended with reclaimed asphalt pavement. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2026*, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 47-53.
9. Hilbrich, S. L., and T. Scullion. Evaluation of Laboratory Mix Design and Field Performance of Asphalt Emulsion and Cement Stabilized Full-Depth Reclamation Project in Texas. In *Transportation Research Board 87th Annual Meeting*, 2008.
10. Lane, B., and T. Kazmierowski. Ten-Year Performance of Full-Depth Reclamation with Expanded Asphalt Stabilization on Trans-Canada Highway, Ontario, Canada. In*Transportation Research Record: Journal of the Transportation Research Board*, *No. 2306*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 45-51.
11. Lewis, D., D. Jared, H. Torres, and M. Mathews. Georgia's use of cement-stabilized reclaimed base in full-depth reclamation. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1952*, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 125-133.

12. Mallick, R., D. Bonner, R. Bradbury, J. Andrews, P. Kandhal, and E. Kearney. Evaluation of performance of full-depth reclamation mixes. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1809*, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 199-208.

13. Mallick, R., M. Teto, P. Kandhal, E. Ray Brown, R. Bradbury, and E. Kearney. Laboratory study of full-depth reclamation mixes. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1813*, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 103-110.

14. Maurer, G., S. Bemanian, and P. Polish. Alternative strategies for rehabilitation of low-volume roads in Nevada. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1989*, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 309-320.

15. Mohammad, L., M. Y. Abu-Farsakh, Z. Wu, and C. Abadie. Louisiana experience with foamed recycled asphalt pavement base materials. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1832*, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 17-24.

16. Romanoschi, S., M. Hossain, A. Gisi, and M. Heitzman. Accelerated Pavement Testing Evaluation of the Structural Contribution of Full-Depth Reclamation Material Stabilized with Foamed Asphalt. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1896*, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 199-207.

17. Saleh, M. Effect of Aggregate Gradation, Mineral Fillers, Bitumen Grade, and Source on Mechanical Properties Of Foamed Bitumen-Stabilized Mixes. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1952*, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 90-100.

18. Wen, H., M. Tharaniyil, B. Ramme, and S. Krebs. Field Performance Evaluation of Class C Fly Ash In Full-Depth Reclamation: Case History Study. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1869*, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 41-46.

19. Diefenderfer, B. K., and A. M. Overton. Research Pays Off: Pavement Recycling: An Effective Reuse of Resources. *TR News*, *No. 299*, 2015.

20. Dai, S., G. Skok., T. Westover, J. Labuz, and E. Lukanen. Pavement Rehabilitation Selection. Report No. MN/RC 2008-06 Minnesota Department of Transportation, St. Paul, 2008.

21. Marquis, B., D. Peabody, and R. Malick. Using Foamed Asphalt as a Stabilizing Agent in Full Depth Reclamation of Route 8 in Belgrade, Maine. *Recycled Materials Resource Center, Maine Department of Transportation and Worcester Polytechnic Institute (October)*, 2002.

22. AASHTO. Mechanistic-Empirical Pavement Design Guide-A Manual of Practice. American Association of State Highway Transportation Officials, 2008.

23. *AASHTO Guide for Design of Pavement Structures*. American Association of State Highway Transportation Officials, 1993.

24. Von Quintus, H. L., C. Rao, and L. Irwin. Long-Term Pavement Performance Program Determination of In-Place Elastic Layer Modulus: Backcalculation Methodology and

Procedures. Publication FHWA-HRT-15-037. FHWA, U.S. Department of Transportation, 2015.

25. Guidance Notes on Backcalculation of Layer Moduli and Estimation of Residual Life Using Falling Weight Deflectometer Test Data. *Research & Development Division*, Highway Department, Hong Kong., 2009.

26. Masada, T., S. Sargand, B. Abdalla, and J. Figueroa. Material properties for implementation of mechanistic-empirical (ME) pavement design procedures. No. FHWA/OH-2003/021, FHWA, U.S. Department of Transportation, 2004.

27. Maher, A., and T. Bennert. *Evaluation of Poisson's Ratio for Use in the Mechanistic– Empirical Pavement Design Guide (MEPDG)*. FHWANJ-2008-004. FHWA, U.S. Department of Transportation, 2008

28. Ullidtz, P. *Pavement analysis. Developments in civil engineering*. Elsevier, Amesterdam, Vol. 3, No. 5556, 1987, p. 034.

29. Quick, T., and W. Guthrie. Early-Age Structural Properties of Base Material Treated with Asphalt Emulsion. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2253, 2011, pp. 40-50.

30. Budge, A. S., and W. J. Wilde. Monitoring Curing of Emulsion-Stabilized Roadways Using the Dynamic Cone Penetrometer. *Proceedings of GeoDenver 2007,* Vol. 7, 2007.

4. SEVEN-YEAR FIELD PERFORMANCE OF PORTLAND CEMENT AND ASPHALT STABILIZED FULL-DEPTH RECLAMATION PROJECTS

Eugene A. Amarh
M.Sc. Student, Virginia Tech Transportation Institute
3500 Transportation Research Dr, Blacksburg, VA 24061
Tel: 540-998-9802; Email: amarheu2@vt.edu

Wilmar Fernandez-Gómez, Ph.D.
Postdoctoral Research Associate, Center for Sustainable Transportation Infrastructure, VTTI
Associate Professor, Universidad Distrital Francisco José de Caldas.
Tel: 540-577-4593 Email: wfernandez@udistrital.edu.co

Gerardo W. Flintsch, Ph.D., P. E.
Director, Center for Sustainable Transportation Infrastructure, VTTI
Professor, Department of Civil & Environmental Engineering, Virginia Tech
Tel: 540-231-9748 / 231-1569; Email: flintsch@vt.edu

Brian K. Diefenderfer, Ph.D., P. E.
Associate Principal Research Scientist, Virginia Transportation Research Council
530 Edgemont Rd, Charlottesville, VA 22903
Tel: 434-293-1944; Fax: 434-293-1990; Email: Brian.Diefenderfer@VDOT.Virginia.gov

Benjamin F. Bowers, Ph.D., P. E.
Research Scientist, Virginia Transportation Research Council
530 Edgemont Rd, Charlottesville, VA 22903
Tel: 434-293-1423; Fax: 434-293-1990; Email: Ben.Bowers@VDOT.Virginia.gov

Word count: 5477 words text + 12 tables/figures x 250 words (each) = 8477 words

Submission Date

4.1 ABSTRACT

The long-term performance of in situ recycled pavements under service loads has rarely been documented. Several questions regarding the performance remain unanswered for different pavement recycling methods in comparison with traditional techniques such as mill and overlay. This research investigated and compared the structural and functional condition of three full-depth reclamation (FDR) projects. Rutting, fatigue cracking, transverse cracking and IRI performance were used to assess the functional condition. FDR is a deep in situ pavement recycling method that involves pulverizing and reusing existing materials from distressed pavements. Trial sections were constructed as part of a Virginia Department of Transportation (VDOT) FDR demonstration project in 2008. Foamed asphalt (2.7% with 1% cement), asphalt emulsion (3.5%), and Portland cement (5%) were used as stabilizing treatments for the base layers. Several distress surveys were conducted for the pavement sections before and after construction. An automated road analyzer (ARAN) was used to collect distress data over a period of 7 years. Rutting was higher for the foamed asphalt and emulsion sections. The structural and functional capacities of the pavements improved irrespective of the stabilizing treatment used. The load related distresses seem to be more critical to the overall condition of the asphalt sections while the non-load related distresses played a key role in the cement sections. The International Roughness Index (IRI) was better for the cement sections compared to the asphalt stabilized sections.

Keywords: recycled base, full-depth reclamation, time-dependent response, rutting, Critical Condition Index

4.2   INTRODUCTION

A recent ASCE report suggested that approximately 20% of the nation's highways were in poor condition in 2014. According to the report, a staggering 32% of urban roads are in poor condition compared to 14% of rural roads resulting in repair needs estimated at about $420 billion (*1*). Considering the high cost estimates and impact to the environment due the volume of roads needing repair, it is not practical or sustainable to rehabilitate or reconstruct these roads using traditional methods. In place recycling of distressed pavements offers an innovative option of restoring the service life of pavements with medium to high traffic for many State Departments of Transportation (DOT) in the United States. The recycling is performed in situ, reusing materials from the existing pavement to form a base layer usually requiring an HMA or hydraulic concrete overlay or other surface treatments such as chip or slurry seal. The technology offers many advantages over traditional rehabilitation methods; reduced construction costs, ensuring a safe environment by reducing the use of virgin materials and eliminating the need to haul materials to landfill or other disposal sites (*2*). Pavement recycling may be performed as hot or cold recycling or as full depth reclamation (FDR). Cold recycling consists of cold in-place recycling (CIR) or cold central plant recycling (CCPR). The decision on which technique to use depends on the location and severity of the pavement distresses and the traffic volume. FDR is better suited for deteriorated pavements with distresses found deep within the pavement. FDR involves pulverizing the existing pavement materials, usually to a depth of up to 12 inches, remixing and finally compacting the mixture to form a uniform base. Stabilizers, such as foamed asphalt or asphalt emulsion, Portland cement, lime or fly ash, are added to the pulverized base mixture to improve the strength of the mixture before compacting. Many state DOTs have used FDR to successfully restore the structural capacity of pavements (*3-17*) with the Virginia DOT using all 3 cold recycling techniques together in a stratified configuration (strategically layered configuration) to rehabilitate a section of Interstate 81 in 2011 (*18*).

With growing interest from state DOTs in the implementation of mechanistic-empirical (ME) design, data is needed to develop and validate distress prediction models for inclusion in ME rehabilitation design. In spite of the growing interests and research studies, the long term in-service performance of the FDR applications with different stabilizers has been rarely compared and documented. Lane and Kazmierowski (*9*) studied FDR projects stabilized with foamed asphalt using three different mix designs and compared the projects with a control FDR section without foamed asphalt stabilization. The authors reported roughness data over 10 years of service, and pavement distress condition indices showing a significant difference between the test sections and the control sections. The foamed asphalt test sections delivered superior results over the control sections. Jones et al. (*19*) compared the performance of a Portland cement stabilized section with an unstabilized FDR section in an accelerated loading test facility. The authors reported the Portland cement sections outperformed the unstabilized sections most notably in terms of rutting performance. After approximately 490,000 equivalent single axle loads (ESALs), the unstabilized sections had reached a terminal rut depth of 0.5 in. compared to the cement stabilized section that recorded a rut depth of only 0.12 in. after 43.3 million ESALs. There were no visible cracks on

40

either of the projects at the end of the test period. Romanoschi et al. (*15*) conducted similar accelerated pavement tests on foamed asphalt stabilized bases and reported the rutting performance compared to a conventional pavement with a granular base material. The authors reported that a 1 in. foamed asphalt–stabilized FDR base material is equivalent to 1.0 in. of conventional Kansas AB-3 granular base on the basis of the permanent deformation and rut depth measurements obtained at the end of the tests. Miller et al. (*2*) compared the performance of two FDR projects (a section with cement stabilization and the other without any stabilization) and a conventional (box-cut) reconstruction after five years in service. The authors reported no rutting in any of the projects after five years. However, some cracking was reported in all three test sections stemming from thermal cracking. Lewis et al. (*10*) reported the performance of a cement stabilized FDR pilot project in Georgia. The authors measured pavement rutting and conducted visual inspections after nine months in service. Out of a total of 152 rutting measurements taken, ten showed a 1.6mm (1.6 inches) deformation with 4 of these readings reported caused by the asphalt spreader at the time of paving. The authors also observed signs of cracking in isolated areas which were assumed to be shrinkage cracks as a result of slightly excessive cement content in the base material.

While several state DOTs and other agencies have studied the performance of FDR, there has been little consistency in the stabilizers, parameters, and the performance measures studied. A side-by-side comparison or evaluation of the performance of the different stabilizers have been seldom reported. Most of the studies did not monitor the performance on a yearly basis. Accelerated pavement testing has been used in some of the cases but further validation with field performance is needed.

Amarh et al. (*20*) recently evaluated the elastic modulus as a strength indicator for FDR projects stabilized with foamed asphalt (1% cement additive), asphalt emulsion and Portland cement for consideration in the mechanistic empirical design methodology. The authors examined and reported the trends in the modulus over a period of 2 years placing emphasis to variations with time, temperature and moisture sensitivity. This paper extends the research undertaken by Amarh et al. (*20*), evaluating the long-term performance of these projects by analyzing distress data. The road condition data, along with age and construction history were obtained from the VDOT Pavement Management System (PMS). A PMS mostly employs pavement condition data to prioritize road rehabilitation and maintenance projects. The road condition data is also used to predict pavement performance and to develop cost effective strategies for future projects. A general trend analysis using the performance data of the sections over the last seven years was completed.

4.3   METHODOLOGY

4.3.1   **Overview**
Three trial sections were constructed in 2008 using the FDR technique with different stabilizing agents. These sections were initially monitored over a 2-year period to assess the feasibility of implementing FDR in future road maintenance projects under the climatic conditions in the state of Virginia. The trial sections were located on State Routes (SRs) 40, 13, and 6 in Franklin, Powhatan, and Goochland Counties, respectively. Foamed asphalt (with 1% cement) and asphalt

emulsion were used as stabilizing agents for two adjacent sections in the SR 40 project, while Portland cement was used in sections along SR 13 and SR 6. Diefenderfer and Apeagyei (5) assessed the performance of the projects at early ages. Amarh et al. (20) conducted a follow up study using data from this project to evaluate the mechanical properties of FDR projects using the elastic modulus as an indicator. This research extends their work and presents the in service performance of the projects using pavement distress data collected over a period of seven years after construction.

4.3.2 **Project Description**

State Route 40, Franklin County

SR 40 lies approximately 35 miles south of Roanoke, running east-west through south central Virginia. Subjected to a combined annual average daily traffic (AADT) of approximately 4400 (4% trucks), the trial section was originally two lanes at 10 feet wide each composed of a 6 to 10 inch unbound granular (crushed aggregate and uncrushed gravel) base overlaid with 5 to 6 inch HMA and surface treatments. Structural distresses such as longitudinal cracking and fatigue cracking within the wheel paths were prevalent in the original pavement. Multiple thin layers with complete debonding was evident in cores collected during site investigations prior to reclamation. According to VDOT's pavement distress rating, the critical condition index at the time was 41% (poor).

Reclamation was done to a depth of approximately 10 inches and subsequently overlaid with a 1.5 inch HMA (SM-9.5D) as a wearing course, following a leveling course. The lanes were widened by 2 feet per lane during reclamation. The widening was accomplished by trenching the edges of the pavement and using a motor grader to shape the reclaimed material across the existing pavement width and the trench. Two bitumen stabilizers were used at the site for both lanes. Foamed asphalt (PG 64-22) with 1% cement as an active filler was used in the western half of the section while asphalt emulsion (PG 58-22) was used in the eastern half during reclamation.

Reclamation was performed in two steps; the first pass pulverized the existing pavement to an approximate depth of 10 inches while addition of the stabilizers (at 2.7% and 3.5% content for foamed asphalt and asphalt emulsion, respectively) and mixing of the reclaimed materials was undertaken in the second pass. As mentioned earlier, 1% cement was added to the foamed asphalt section as an active filler. After mixing, the resulting materials were shaped by a motor grader and compacted with pad foot, steel-wheeled and rubber-tired rollers. The foamed asphalt section was reclaimed May 13 through 15, 2008 while the asphalt emulsion was done May 19 through 22, 2008. The HMA layer was placed three weeks after reclamation. The critical condition index one year after reclamation was 99/100 (excellent).

State Route 13, Powhatan County

Located approximately 25 miles west of Richmond, SR 13 (Old Buckingham Road) runs east-west in Powhatan County. The trial section was originally composed of a 4.5 to 6 inch HMA overlaying an aggregate base, with a combined annual average daily traffic (AADT) of approximately 2300 (5% trucks). Minor fatigue cracks and widespread longitudinal cracking were evident in the wheel

paths of the original pavement. Cores taken during site investigations prior to reclamation revealed debonded and stripped layers. The critical condition index was 58/100.

The existing pavement was pulverized to a depth of 8 inches followed by the addition of Portland cement at a content of approximately 5.0% and mixing in a second reclaimer pass. A motor grader was used to shape the resulting uniform mixture and it was subsequently compacted with pad foot, steel-wheeled and rubber-tired rollers. The reclamation was completed on July 21 and was overlaid with 3.75 inch HMA 1 week later. The critical condition index after reclamation was 100/100.

State Route 6, Goochland County
SR 6 (known for most of its length as River Road) is an east-west facility located about 25 miles west of Richmond. The test section was originally composed of approximately 9 inches HMA over an aggregate base subjected to a combined AADT of approximately 3,900 (7% trucks). The pavement exhibited similar distresses to SR 13 with cores extracted during the pre-reclamation site investigation revealing stripping and layer debonding. The critical condition index was 47/100 prior to reclamation.

Prior to the reclamation, the top 2 inches of the existing pavement were milled and removed. The remaining pavement was then pulverized to a depth of approximately 10 inches in a first reclaimer pass. The second added 5% Portland cement as a stabilizing agent and mixed the materials. Shaping and compaction of the reclaimed materials was carried out with construction equipment as in the 2 other projects. The reclamation exercise was carried out July 21, 2008 through August 7, 2008 and was overlaid with 3.5 inch HMA approximately 1 week later. The critical condition index was improved to 99/100 1 year after reclamation.

Reference Section
A section of pavement along State Route 13, rehabilitated in the 2005 construction year (2 years before construction of the FDR sections), was selected as a reference. The section had been routinely rehabilitated at an average 8 year interval. Prior to 2005, the sections was last maintained in the late 1990's with a 1.5 inch SM-2D asphalt concrete overlay. During the 2005 construction cycle, the section was again rehabilitated with an improved 1.5 inch SM-12.5D overlay. A summary of the projects is provided in Table 2. Table 3 summarizes the condition of the various project sections prior to reclamation.

TABLE 2 Summary of VDOT Full Depth Reclamation Project Site

Project	SR 40	SR 40	SR 13	SR 6	Reference
County	Franklin	Franklin	Powhatan	Goochland	Powhatan
State Route	40	40	13	6	13
Rehab Type	FDR Foamed Asphalt	FDR Asphalt Emulsion	FDR Portland Cement	FDR Portland Cement	Traditional Overlay
Relative Milepost	21.70 – 21.97	21.97 – 22.24	16.25 – 19.93	67.48 – 71.11	14.81 – 15.79
Approx. Project Length (miles)	0.25	0.25	3.7	3.65	0.98
Base Layer					
Type	FDR	FDR	FDR	FDR	n/a
Thickness (in)	9.4	9.8	9.2	9.1	n/a
AC Overlay					
Mix Type*	SM9.5D	SM9.5D	SM-12.5A /SM-19.0A	SM-9.5A/ SM-12.5A	SM9.5D
Thickness(in)	2.4	2.4	3.6	3.6	1.5
Year completed	2008	2008	2008	2008	2005

*Mix Type Definitions
SM9.5**A** = **S**urface **M**ix with 9.5 mm maximum nominal aggregates, "**A"** for binder with performance grade 64-22
SM9.5**D** = **S**urface **M**ix with 9.5 mm maximum nominal aggregates, "**D"** for binder with performance grade 70-22
SM12.5**A** = **S**urface **M**ix with 12.5 mm maximum nominal aggregates, "**A"** for binder with performance grade 64-22
SM19.0**A** = **S**urface **M**ix with 19.0 mm maximum nominal aggregates, "**A"** for binder with performance grade 64-22

TABLE 3 Condition of VOTs FDR Trial Sections prior to Reclamation

	SR 40	SR 40	SR 13	SR 6
Stabilizing Agent	Foamed Asphalt	Asphalt Emulsion	Portland Cement	Portland Cement
Major Distresses				
Transverse Cracking (ft/lane-mile)	17.50	16.67	714.97	193.68
Longitudinal Cracking (ft/lane-mile)	103.50	36.10	1113.10	1289.20
Fatigue Cracking (% total area)	1%	1%	7%	5%
IRI (in/mi)	91.50	126.25	115.95	112.35
Rut Depth (in)	0.12	0.12	0.09	0.11
Patching (sq.ft)	2449.20	1316.25	1.40	814.79
Condition Indices				
Load Related Distresses (LDR)	41/100	48/100	66/100	49/100
Non-Load Related Distress (NDR)	50/100	57/100	60/100	49/100

4.3.3 **Data Collection**

Overview of VDOT PMS

The pavement condition data has been collected and processed since 2006 by a private contractor specialized in providing data collection services for infrastructure asset management using continuous digital imaging and automated crack detection technology. A total yearly data collection of approximately 20,400 directional miles covering 100% of interstates (2,200 directional miles), 100% of Primary roads (10,500 directional miles) and approximately 20% of Secondary roads (7700 directional miles). Automobiles equipped with special cameras are used to capture downward pavement images to detect cracks. Other sensors mounted on the vehicle capture roughness and rutting data simultaneously as the vehicles are driven at highway speeds along the pavement. The images are then processed with *Wise-Crax®*, an automated crack detection software for identifying cracks and further supported with digital images to identify other distresses.

The collected data is summarized into three pavement distress indices. For flexible pavements, the load related distress rating (LDR) gives an indication of pavement condition with regards to damage due to wheel loads applied to the pavement. It comprises distresses such as alligator (fatigue) cracking, wheel path patching and rutting. The LDR is a deduct-based index with a value of 100 when there are no discernible load related distresses on the pavement being evaluated. Deduct points are assigned for each of the distresses that are load related depending on the type as well as severity and frequency of occurrence. Similar to the LDR, the non-load related distresses rating (NDR) represents the functional condition of the pavement but the distresses assigned here are not load related. Longitudinal and transverse cracking, non-wheel path patching and bleeding are examples of the quantities measured to calculate NDR. The critical condition index is the lower of the LDR and NDR and is used as an indicator to measure the overall pavement condition (*21*).

Parameters Evaluated

The pavement surface condition data used in the project was extracted from VDOT's Pavement Management System (PMS) database. The data were extracted for the mileposts corresponding to the lengths of each project. For the SR40 project, the asphalt emulsion section spanned from milepost 21.70 to 21.97 while the foamed asphalt section spanned milepost 21.97 to 22.24. The cement stabilized projects spanned milepost 16.25 to 19.93 for SR 13, milepost 67.48 to 71.11 for SR6 and milepost 14.81 to 15.79 for the reference section selected along state route 13. The lengths of the SR 40 projects were relatively short, thus limiting the number and variability of data points obtained for these sections. The overall performance of the test sections was compared with the reference section. To assess the performance of the each of the projects under study, the pavement distresses discussed in the following paragraphs were examined.

Rutting is the longitudinal surface depression in the wheel path of an in-service pavement associated with either transverse displacement caused by consolidation or lateral movement of the materials due to traffic loading. Rutting is reported as the average severity for the 0.1-mile section

on a transverse profile collected at prescribed intervals along the pavement. The maximum left and right rut depths are computed from the profiles using two different methods; the six-foot straightedge process and the wire-line method. The results reported in the VDOT PMS were computed with the six-foot straightedge process (*22*)

Fatigue cracking occurs in areas along the pavement subjected to repetitive wheel loads. The process initiates as longitudinal cracking in the wheel paths and eventually develops into a series of interconnected cracks with an "alligator skin" pattern. With the left and right wheel paths under consideration, the affected areas were measured and each severity level was reported for the section in square feet (*22*). For the purpose of this research the percentage total fatigue crack area for the average of severity level 1 and 2 was reported.

Transverse cracks are cracks that run predominantly perpendicular to the pavement centerline. These are usually caused by the reflection of a crack or joint in an underlying pavement layer or low temperature cracking of a brittle asphalt layer (not usually a concern in Virginia). It is assumed that the transverse cracking noted during this study on Routes 6 and 13 were shrinkage cracks of the cement treated FDR layer but the source was not investigated by coring. Transverse cracking were reported in linear feet per lane mile.

The International Roughness Index (IRI) is the standard measure of ride quality used by VDOT. The FHWA also uses the IRI in the monitoring of the Highway Performance Monitoring System (HPMS) which the administration uses to distribute funds to the states. It is generally defined as an expression of the accumulation of irregularities in the pavement surface per linear mile that adversely affects the ride quality of the vehicle (*23*).

Performance Curves

The pavement condition data and maintenance history along with the pavement age was used to develop performance curves. The parameters discussed in the preceding paragraphs were averaged over the corresponding project lengths made up of 0.2 lane mile sections. No data points were filtered from the information extracted from the PMS.

Deterioration models were developed and analyzed to assess the long-term performance of the projects using the pavement condition index along with the pavement age. VDOT currently uses the generalized form:

$$PI = 100 - \exp\left(a + b \times c^{\log\left(\frac{1}{Age}\right)} \right) \tag{1}$$

where

PI = Pavement Index (100 when pavement age is zero)
a, b, c = model coefficient
Age = age of pavement after treatment was last applied

The model was calibrated with the LDR, NDR and age data for the sections to obtain numerical values for the coefficients a, b, and c. The values of a, b, and c reported by Amarh et al. (*20*) for the CCI curves for the FDR sections were used as initial values in the calibration process. The

46

average condition data of the two cement projects (SR 13 and SR 6) was used in the calibration for cement treated bases for the NDR and LDR.

Other models were explored to assess which trends or shapes best predict deterioration of the FDR projects over time. The following models were used:

$$\text{Inverse Exponential: } PI = 100 - a \times \exp(b \times Age) \tag{2}$$

$$\text{Linear model: } PI = 100 - a \times Age \tag{3}$$

4.4 RESULTS AND DISCUSSION

4.4.1 Rutting

Figure 8 shows the average rut depth on the pavement sections over time. Overall, the projects with the cement treated bases showed lower rutting compared to the asphalt treated base projects. The average rut depth of all the projects a year after reclamation was 0.06 in. The trend for the cement projects differed significantly in the first four years after reclamation. Rutting in the SR 13 project increased sharply from 0.06 to 0.16 inches in the first year. Even though the design truck traffic was exceeded in the early periods in service of the SR 13 project, there is no explanation for the decreasing trends noticed afterwards. There was however, very high variability in the data extracted for the affected periods as shown by the box plots in Figure 8.
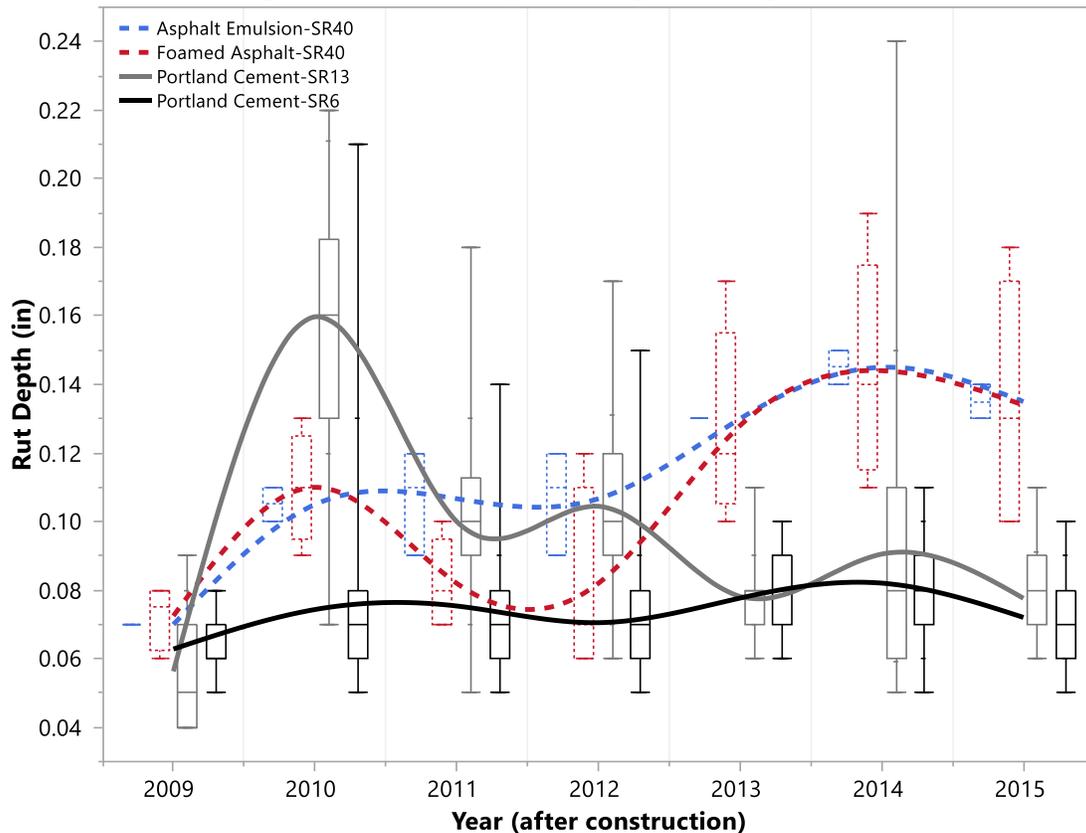

FIGURE 8: Comparison of rutting performance for bitumen stabilized FDR sections and Portland cement stabilized FDR sections

47

For the asphalt treated bases, the rutting increased slightly over the analysis period from an average of 0.07 in. after reclamation to 0.13 in. at the end of the study period. Overall, the average rut depth for the asphalt-stabilized sections was 0.11 in. with a standard deviation of 0.03in. The presence of cement as an additive in the foamed asphalt section or the softer PG58-22 binder used in the emulsion sections did not seem to play a significant role in the overall performance of the asphalt-stabilized sections despite the emulsion sections showing slightly higher rutting. The slightly higher rutting cannot be associated with the traffic in this case, as the design traffic was not exceeded in the asphalt emulsion project. All the FDR sections were below the terminal rut depth of 0.25 in. used by the VDOT.

4.4.2 Fatigue Cracking

Figure 9 illustrates the fatigue cracking trend for the projects. The foamed asphalt and emulsion stabilized sections showed little to no fatigue cracks prior to the 6th year in service. The percentage total lane area fatigue cracking in the 6th year for foamed asphalt and emulsion sections was 1.8% and 3.3% respectively. The survey carried out in the 7th year however, showed majority of these cracks had disappeared. Further study is required to understand this "unusual" observation. However, it is possible that the survey in the 6th year was taken under wet conditions. Cracks are easily visible when filled with water. Perhaps the survey taken the following year was under dry conditions, which may explain the drop in the percentage cracks observed that year. The fatigue cracking trend for the SR 6 cement project was similar to the two asphalt stabilized sections. However, a substantial increase in the amount of level 1 and 2 severity cracks was observed in both the 6th and 7th year for the SR 6 project, at 0.9% and 3.6% respectively. The SR 13 project showed the highest amount of level 1 and 2 severity cracks only after 2 years in service from a low 0.7% to a high 2.7% at the end of the survey period. Again, this may be attributed to the high traffic recorded for these cement sections.
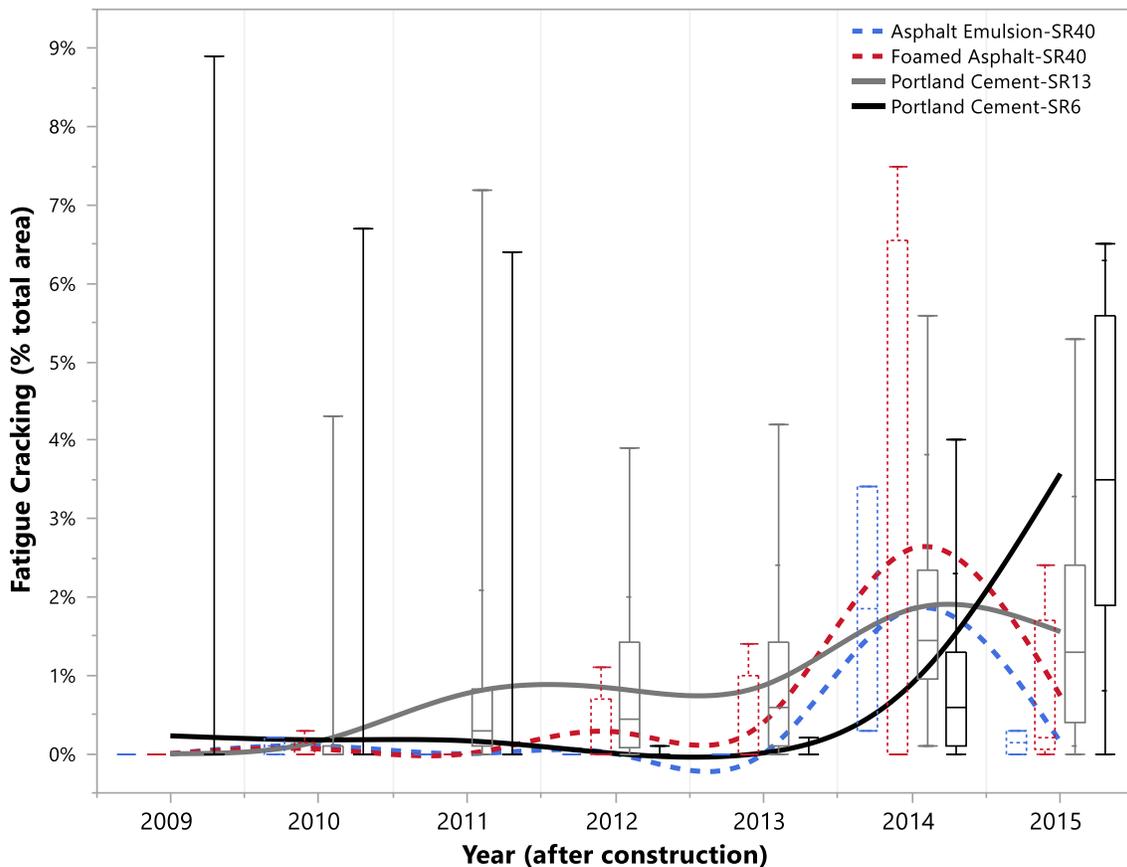
FIGURE 9: Fatigue cracking distribution for bituminous stabilized FDR sections and Portland cement treated FDR sections

4.4.3 Transverse Cracking

Transverse cracking measurements taken for the projects are shown in Figure 10. The trends are similar to the fatigue cracking pattern shown previously. The length of transverse cracks was generally higher for the cement-stabilized projects in comparison to the asphalt-stabilized projects with the latter showing almost no cracks the entire evaluation period. The average crack length for the SR 13 and SR 6 projects was 514 ft/lane mile and 234 ft/lane-mile with standard deviations of 424 and 372 ft/lane-mile respectively. A previous study on the stiffness of differently stabilized bases by Amarh et al. (*20*) using data from this project in the first two years reported higher stiffness for the SR 13 project compared to the SR 6 project. The trends seen in Figure 5 may be because of reflective cracks stemming from the shrinkage of the stiffer cement FDR base. A high percentage of cracks was noted for the SR 13 projects in isolated sections notably between mileposts 17.7 and 17.9. The contractor indicated some construction anomalies that led to applying excess cement in some sections during the project but did not confirm the exact sections that were affected.

49
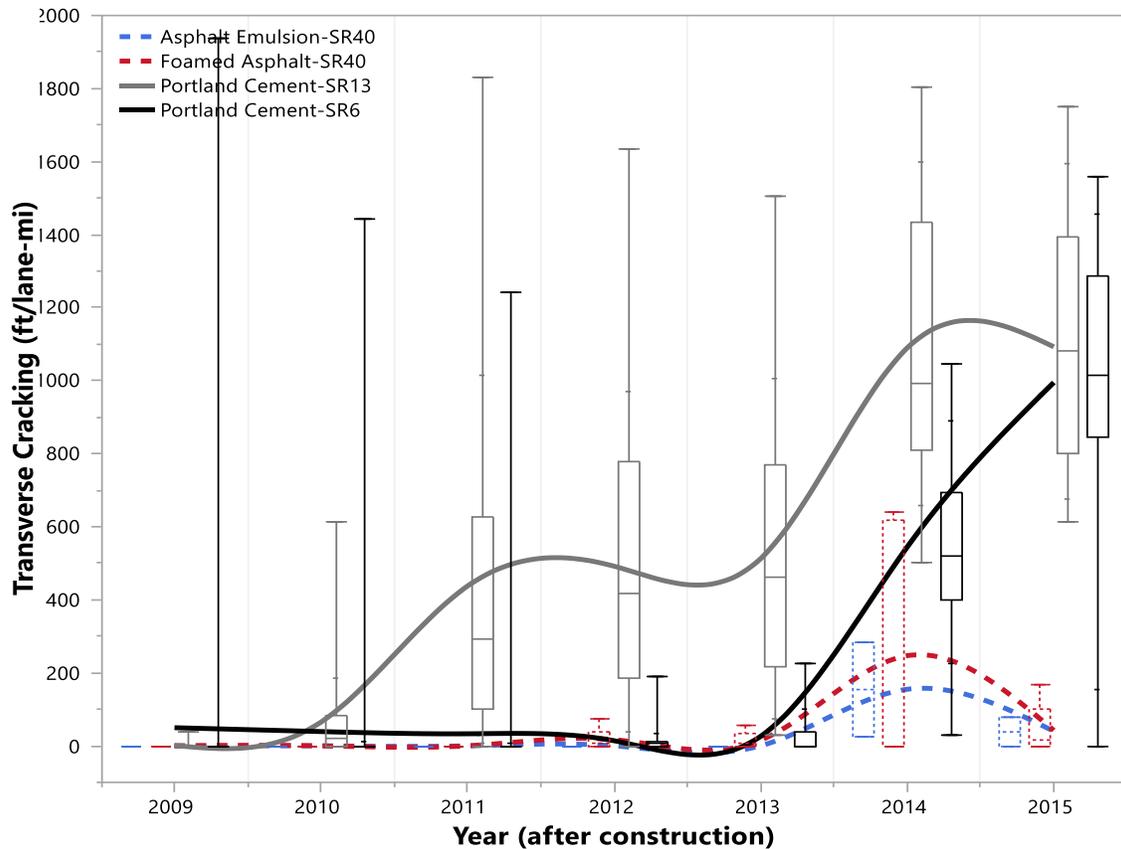
FIGURE 10: Transverse cracking distribution for bituminous stabilized FDR sections and Portland cement treated FDR sections

4.4.4 Roughness

Results of the changes in IRI measurements for the trial sections are shown in Figure 11. Overall, the cement stabilized sections recorded less roughness compared to the asphalt sections from the field measurements over the entire survey period. The average IRI for the cement-stabilized bases was 100.6 in/mi after a year in service and increased slightly to 111 in/mi at the end of the survey period. In the SR 40 project, the IRI was higher in the asphalt-stabilized sections compared to the foamed asphalt stabilized sections with both showing increasing trends in the seven-year period. The average IRI was 128.6 and 118.7 in/mi with standard deviations of 17.4 and 11.2 in/mi for the asphalt emulsion and foamed asphalt stabilized sections, respectively.
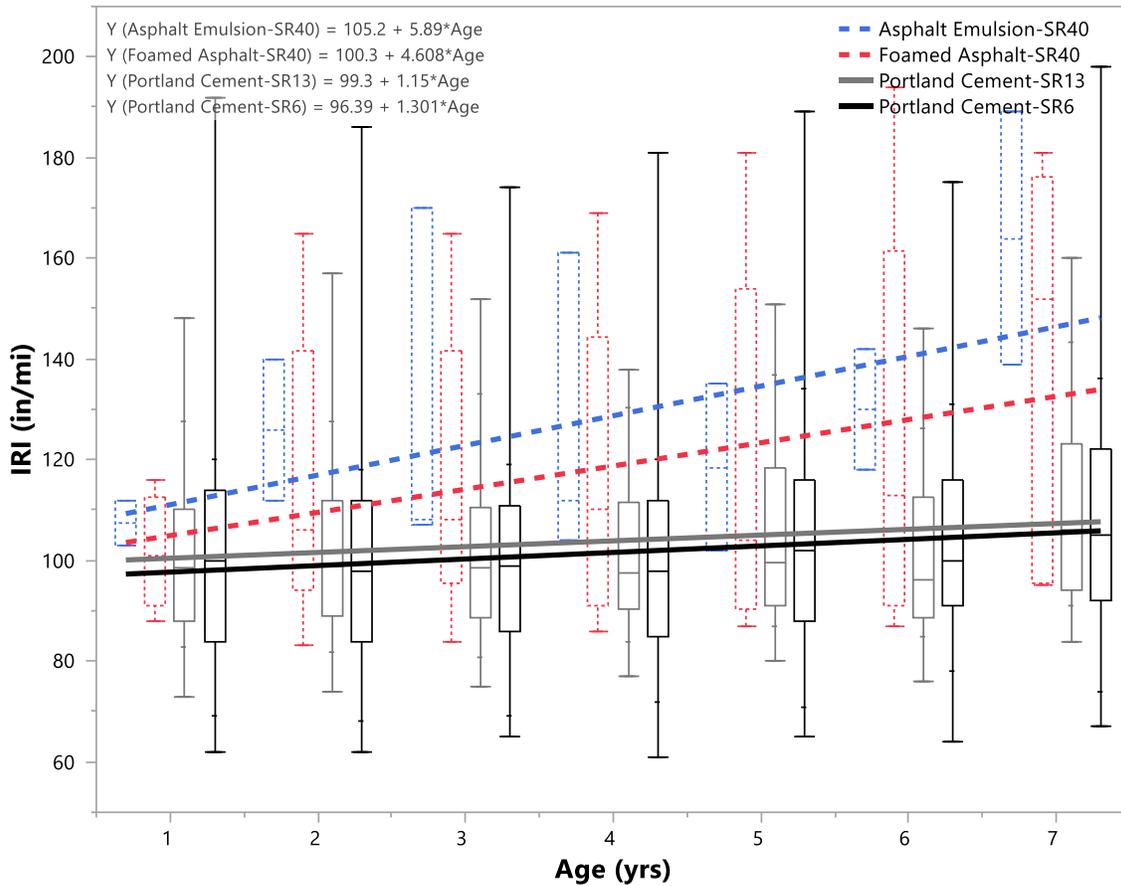
FIGURE 11: IRI trend for asphalt-treated and cement stabilized FDR sections

4.4.5 Performance Curves

The model coefficients calibrated for the performance curves using Equation 1 (current VDOT model) for the LDR and NDR distress indices are shown in Table 4.

TABLE 4: Coefficients for VDOTs LDR and NDR Performance Model

Treatment Type	Load Related Distress Model					Non-Load Related Distress Model				
	a	b	c	RMSE	R^2	a	b	c	RMSE	R^2
Asphalt Emulsion-SR40	9.6	-21.0	4.0	1.6	0.72	9.3	-24.2	4.0	0.5	0.65
Foamed Asphalt-SR40	8.3	-16.9	4.0	1.7	0.79	7.3	-18.4	4.0	0.9	0.67
Portland Cement-SR13/SR6	30.0	-32.5	1.2	2.3	0.69	30.0	-33.3	1.3	2.5	0.78
Reference	5.84	-7.70	4.00	9.68	0.76	4.12	-6.19	1.5	4.29	0.56

Figure 12 shows trends of the LDR and NDR performance of the FDR projects over time.

51

The deterioration trends for the asphalt emulsion and foamed asphalt sections are equivalent for both indices. The cement-stabilized sections compared to the asphalt sections showed slightly better performance for the load related distress rating. After seven years in service, the LDR index for the cement section had deteriorated to 85/100 while the asphalt treated section reached 79/100. This result is expected, as there was higher rutting and fatigue cracking (major contributors to this index) in the asphalt sections compared to the cement sections discussed in the preceding paragraphs. On the other hand, the asphalt-stabilized sections outperformed the cement sections for the non-load related index. Compared to the reference section, the FDR sections showed better performance, remaining in excellent condition for a longer period for the LDR index. For the NDR index, performance of the reference section was intermediate between the trial projects; outperforming the cement section but underperforming against the asphalt stabilized sections.
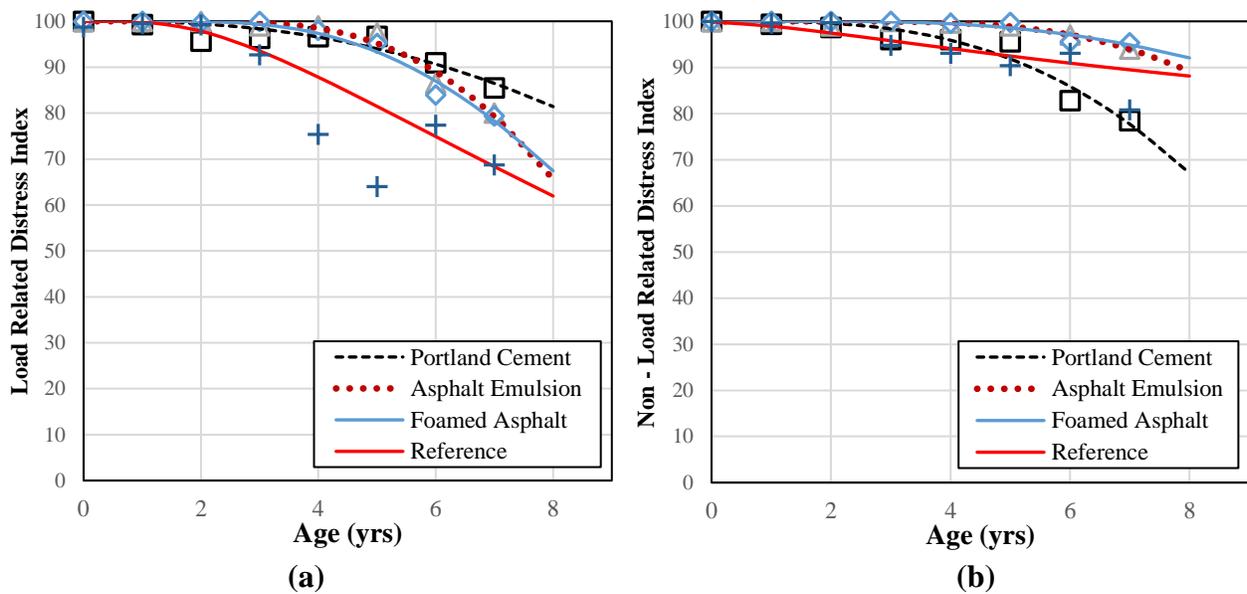

FIGURE 12: Performance curves using VDOTs adjusted Stantec model for (a) LDR and (b) NDR for differently stabilized FDR sections

The coefficients for the inverse exponential (equation 2) and linear (equation 3) models with the resulting performance curves are shown in table 5 and figures 13 and 14 respectively.

TABLE 5: Coefficients for Linear and Inverse Exponential Performance Models

| Model Type	Treatment Type	Load Related Distress Model				Non-Load Related Distress Model			
		a	b	RMSE	R^2	a	b	RMSE	R^2
Inverse Exponential	Asphalt Emulsion-SR 40	0.10	0.52	2.69	0.89	0.10	0.32	1.26	0.67
	Foamed Asphalt-SR 40	0.10	0.54	2.52	0.91	0.10	0.30	1.43	0.55
	Portland Cement-SR 13/SR 6	0.44	0.48	1.82	0.85	0.38	0.55	2.46	0.91
	Reference	0.10	0.62	14.41	0.03	0.24	0.51	2.99	0.78
Linear Model	Asphalt Emulsion-SR 40	1.72	-	5.96	0.45	9.28	-	1.66	0.43
	Foamed Asphalt-SR 40	1.95	-	5.92	0.51	7.33	-	1.67	0.39
	Portland Cement-SR 13/SR 6	1.47	-	2.97	0.60	2.19	-	5.28	0.59
	Reference	3.78	-	9.77	0.55	1.16	-	5.46	0.28
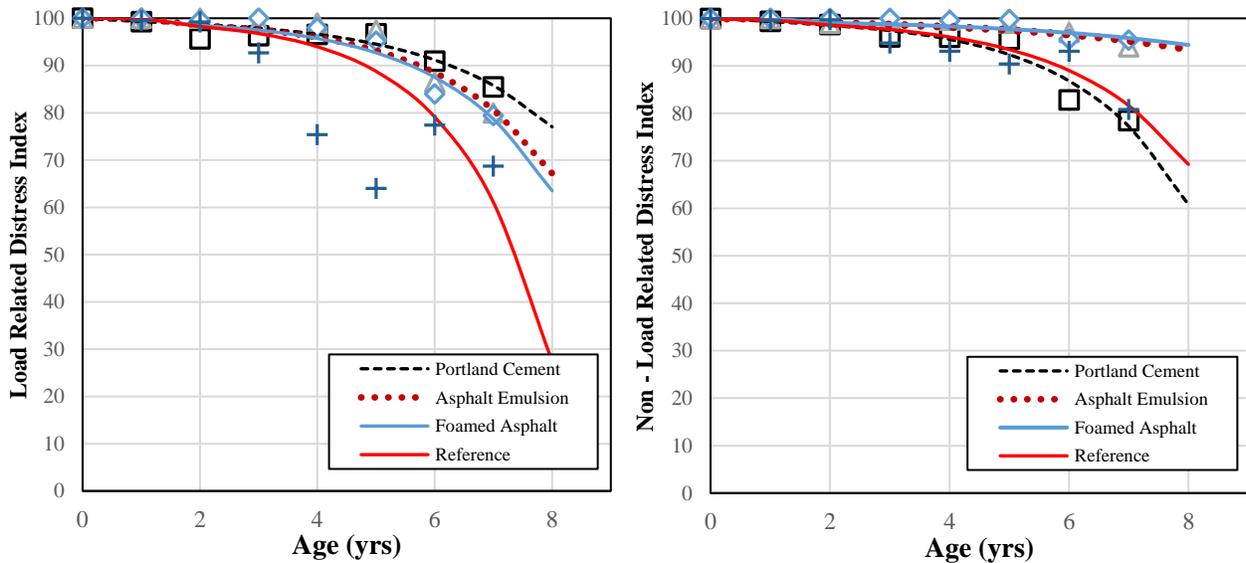
FIGURE 13: Performance curves using an inverse exponential model for (a) LDR and (b) NDR indices for differently stabilized FDR sections
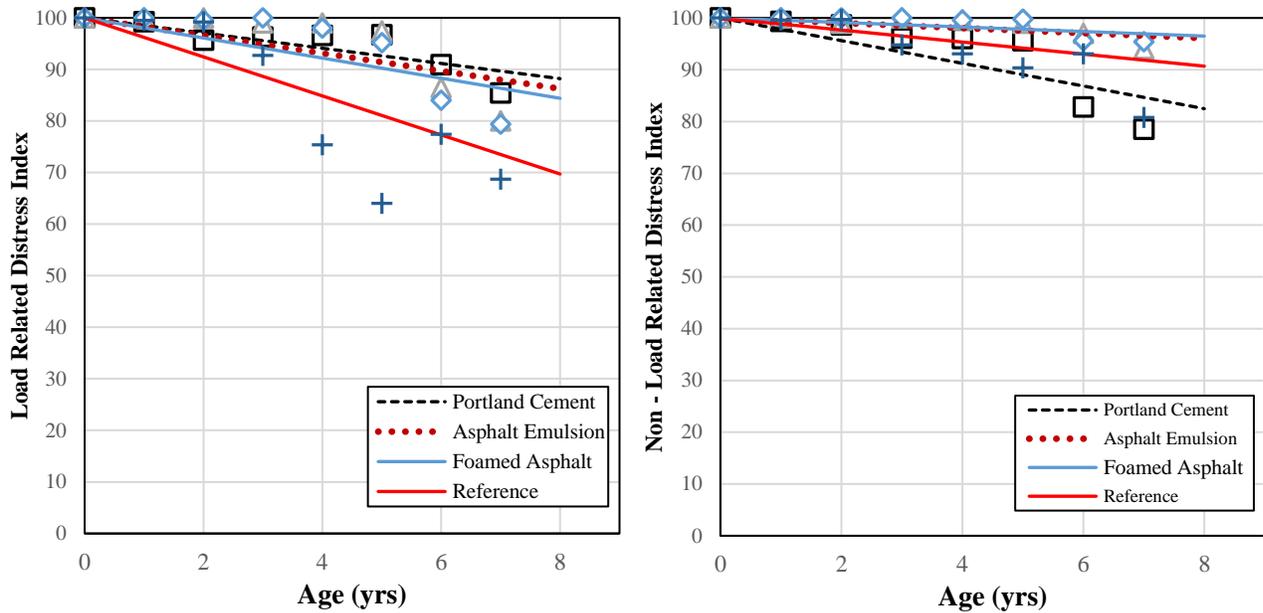
FIGURE 14: Performance curves using a linear model for (a) LDR and (b) NDR indices for differently stabilized FDR sections

4.5   SUMMARY

The long-term performance of the projects varied significantly based on the type of stabilizing agent used and potentially the truck volume and overlay thickness. In general, the cement based projects performed better with distresses that are induced by traffic loads such as rutting and fatigue cracking while the asphalt stabilized projects performed better with distresses that are usually caused by environmental effects or use of improper materials (transverse cracking). The pavement roughness measured for the projects showed better IRI results for cement-stabilized sections compared to the asphalt sections. Table 6 summarizes the results of the pavement distresses and ride quality for the study.

Rut depth was comparable for the foamed asphalt and asphalt emulsion sections but generally higher compared to the cement stabilized sections. The cement stabilized SR 13 projects showed unexpectedly high rutting in the first four years compared to all the other projects and this was traced to higher traffic than design capacity recorded for the affected period. Rutting in all the projects after seven years was below VDOTs typical terminal rut depth of 0.25 in. for primary roads.

The percentage total area of fatigue cracking was relatively low, with the projects showing little to no cracks in the first five years of the analysis period. However, with the design traffic on the SR 13 cement project exceeded in the early ages in service, the section showed 0.7% total area fatigue cracks as early as the second year in service to a high of about 2.7% cracks, six years into service.

The cement treated bases were more susceptible to transverse cracking compared to the asphalt stabilized sections. Stiffness of the FDR layers may have played a key role in the transverse cracking performance observed. A previous study on the stiffness of differently stabilized bases

by Amarh et al. (20) using data from this project in the first two years listed the following treatments in order of decreasing stiffness: Portland cement (SR 13), Portland cement (SR 6), Foamed asphalt with 1% cement (SR 40) and Asphalt emulsion (SR 40). The difference in the stiffness for the two cement projects may be attributed to the stabilizers used.

For the pavement roughness measurements, the two cement projects were smoother to start with but they also showed a slower decrease in smoothness as compared to the asphalt projects. The asphalt emulsion sections were deficient (IRI > 140 in/mile) after seven years in service.

TABLE 6 Major Distresses and Ride Quality for VDOT's FDR Demonstration Projects

Performance Indicator	FDR Project	2009	2010	2011	2012	2013	2014	2015
Fatigue Cracking (% total area)	Asphalt Emulsion-SR 40	0.0%	0.1%	0.0%	0.0%	0.0%	1.8%	0.1%
	Foamed Asphalt-SR 40	0.0%	0.0%	0.0%	0.2%	0.3%	3.3%	0.5%
	Portland Cement-SR 13	0.0%	0.2%	0.7%	0.9%	1.1%	2.1%	1.7%
	Portland Cement-SR 6	0.2%	0.2%	0.1%	0.0%	0.0%	0.9%	3.6%
Transverse Cracking (ft/lane mile)	Asphalt Emulsion-SR 40	0	0	0	0	0	155	40
	Foamed Asphalt-SR 40	0	0	0	11	9	247	29
	Portland Cement-SR 13	3	64	422	492	493	1061	1069
	Portland Cement-SR 6	45	35	30	14	24	522	968
Rutting (inches)	Asphalt Emulsion-SR 40	0.07	0.11	0.11	0.11	0.13	0.15	0.14
	Foamed Asphalt-SR 40	0.07	0.11	0.08	0.08	0.13	0.14	0.13
	Portland Cement-SR 13	0.06	0.16	0.10	0.11	0.08	0.09	0.08
	Portland Cement-SR 6	0.06	0.07	0.08	0.07	0.08	0.08	0.07
IRI (inch/mile)	Asphalt Emulsion-SR 40	107.5	126.0	128.3	125.7	118.5	130.0	164.0
	Foamed Asphalt-SR 40	101.5	115.4	116.4	116.2	118.6	123.6	139.0
	Portland Cement-SR 13	101.4	106.1	105.5	106.6	109.9	105.7	115.3
	Portland Cement-SR 6	99.7	98.7	99.2	99.2	103.9	103.5	107.1

In summary, the cement stabilized FDR projects better performed against distresses that are induced by traffic loads compared to the asphalt stabilized projects. For distresses that are caused by non-load related factors such as environmental effects or construction deficiencies, better performance was observed for the asphalt-stabilized projects compared to the cement sections. Cement used as a stabilizer in FDR projects helps improve strength but may be prone to distresses caused by adverse effects of the environment. Therefore it may be important to consider maximum strength criteria in design. Used as an additive with other asphalt stabilizers in FDR projects, cement can increase the strength, reduce the potential for rutting and improve the ride quality for asphalt stabilized FDR projects. Further research should therefore be conducted to find the optimum cement content to be used in combined stabilization projects involving asphalt and Portland cement to achieve maximum strength without compromising on resilience to adverse effects of the environment.

4.6   CONCLUSION

VDOT constructed three trial sections using the FDR technique with different stabilizing agents: foamed asphalt with 1% cement, asphalt emulsion, and Portland cement in 2008 to gain more

insight into the performance of recycled materials under the climatic conditions in the state of Virginia and assess the feasibility of recycled materials in future rehabilitation projects. This paper extends previous work done by Amarh et al. (*20*) by evaluating the long-term performance of the FDR projects. The database used for the research was developed by combining pavement condition data and maintenance history information extracted from the VDOT PMS. The following conclusions and recommendations were made based on the results of this study.

- Rutting for all three projects was less than VDOTs terminal rut depth of 0.25 in. Rutting in the emulsion sections was slightly higher than for the foamed asphalts but was not statistically significant. The cement sections showed the least rutting with significant differences between the asphalt projects. This may be an indication that the addition of cement in the appropriate amount could improve the rutting performance for FDR pavements.
- The number of years of stiffness data collected in the previous study was not enough to test a correlation between stiffness of the projects and their resulting performance. However, the analysis from this study showed that FDR projects with stiffer bases may be more prone to transverse cracking.
- The performance results in terms of distresses related to traffic loads are somewhat comparable between the asphalt and cement stabilized sections. For non-load related distresses however, the asphalt stabilized sections outperformed the cement stabilized sections.
- Further research should therefore be conducted to find the optimum cement content to be used in combined stabilization projects involving asphalt and Portland cement to achieve maximum strength without compromising on resilience to adverse effects of the environment.
- The overall long-term performance of all three projects measured with the pavement ride quality (IRI), showed the cement projects outperforming the asphalt stabilized projects.

4.7 ACKNOWLEDGEMENT

REFERENCES

1. ASCE. *2017 Report Card for America's Infrastructure*. American Society of Civil Engineers, 2017.
2. Miller, H. J., W. S. Guthrie, R. A. Crane, and B. Smith. Evaluation of cement-stabilized full-depth-recycled base materials for frost and early traffic conditions. 2006. Final Report Project #28. Recycled Materials Resource Center, University of New Hampshire. http://www.rmrc.unh.edu/Research/past/P28/p28final.pdf

3.   Bemanian, S., P. Polish, and G. Maurer. Cold in-place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1949, 2006, pp. 54-71.

4.   Berthelot, C., B. Marjerison, G. Houston, J. McCaig, S. Warrener, and R. Gorlick. Mechanistic comparison of cement-and bituminous-stabilized granular base systems. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2026, 2007, pp. 70-80.

5.   Diefenderfer, B., and A. Apeagyei. Time-dependent structural response of full-depth reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2253, 2011, pp. 3-9.

6.   Diefenderfer, B. K., and A. K. Apeagyei. Analysis of full-depth reclamation trial sections in Virginia.In, 2011. In FHWA/VCTIR Report 11-R23, 2011.

7.   Guthrie, W., A. Brown, and D. Eggett. Cement stabilization of aggregate base material blended with reclaimed asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2026, 2007, pp. 47-53.

8.   Hilbrich, S. L., and T. Scullion. Evaluation of Laboratory Mix Design and Field Performance of Asphalt Emulsion and Cement Stabilized Full-Depth Reclamation Project in Texas.In *Transportation Research Board 87th Annual Meeting*, 2008.

9.   Lane, B., and T. Kazmierowski. Ten-Year Performance of Full-Depth Reclamation with Expanded Asphalt Stabilization on Trans-Canada Highway, Ontario, Canada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2306, 2012, pp. 45-51

10.   Lewis, D., D. Jared, H. Torres, and M. Mathews. Georgia's use of cement-stabilized reclaimed base in full-depth reclamation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1952, 2006, pp. 125-133.

11.   Mallick, R., D. Bonner, R. Bradbury, J. Andrews, P. Kandhal, and E. Kearney. Evaluation of performance of full-depth reclamation mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1809, 2002, pp. 199-208.

12.   Mallick, R., M. Teto, P. Kandhal, E. Ray Brown, R. Bradbury, and E. Kearney. Laboratory study of full-depth reclamation mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1813, 2002, pp. 103-110.

13.   Maurer, G., S. Bemanian, and P. Polish. Alternative strategies for rehabilitation of low-volume roads in Nevada. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1989, 2007, pp. 309-320.

14.   Mohammad, L., M. Y. Abu-Farsakh, Z. Wu, and C. Abadie. Louisiana experience with foamed recycled asphalt pavement base materials. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1832, 2003, pp. 17-24.

15.   Romanoschi, S., M. Hossain, A. Gisi, and M. Heitzman. Accelerated Pavement Testing Evaluation of the Structural Contribution of Full-Depth Reclamation Material Stabilized with Foamed Asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1896, 2004, pp. 199-207.

16.   Saleh, M. Effect of Aggregate Gradation, Mineral Fillers, Bitumen Grade, and Source on Mechanical Properties Of Foamed Bitumen-Stabilized Mixes. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1952, 2006, pp. 90-100.

17. Wen, H., M. Tharaniyil, B. Ramme, and S. Krebs. Field Performance Evaluation of Class C Fly Ash In Full-Depth Reclamation: Case History Study. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1869, 2004, pp. 41-46.

18. Diefenderfer, B. K., and A. M. Overton. Research Pays Off: Pavement Recycling: An Effective Reuse of Resources. *TR News*, No. 299, 2015.

19. Jones, D., R. Wu, and S. Louw. Comparison of Full-Depth Reclamation with Portland Cement and Full-Depth Reclamation with No Stabilizer in Accelerated Loading Test. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2524, 2015, pp. 133-142.

20. Amarh, E. A., W. Fernandez-Gómez, G. W. Flintsch, B. K. Diefenderfer, and B. F. Bowers. Nondestructive In Situ Characterization of Elastic Moduli of Full-Depth Reclamation Base Mixtures. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 2641, 2017, pp. 1-11.

21. McGhee, K. Development and Implementation of Pavement Condition Indices for the Virginia Department of Transportation, Phase I: Flexible Pavement. *Virginia Department of Transportation, Maintenance Division*, 2002.

22. VDOT. *A Guide to Evaluating Pavement Distress Through the Use of Video Images*. Virginia Department of Transportation, Maintenance Division, 2012.

23. State of the Pavement. Virginia Department of Transportation, 2016.

5. CONCLUSION AND RECOMMENDATIONS

5.1 SUMMARY

This thesis conducted studies on the mechanical properties of full depth reclamation base layer materials and subsequent long term performance of these materials using data from a 2008 VDOT demonstration project. Foamed asphalt (2.7% with 1% cement), asphalt emulsion (3.5%), and Portland cement (5%) were used as stabilizing treatments for base works. The study of the mechanical properties was carried out by evaluating the trends of the elastic modulus under varying temperature, seasonality and moisture content with the passage of time. A series of in situ deflection tests were undertaken starting 3 weeks after the reclamation for approximately 28 months. ARAN surveys were conducted as part of VDOT's annual road condition monitoring and the results over the past 7 years for rutting, fatigue cracking, transverse cracking, IRI and modeled performance curves have been presented here.

5.2 FINDINGS

The following observations were made from the project.

- The effect of temperature should not be overlooked in the evaluation of the structural capacity of bitumen-stabilized FDR projects. The authors propose further work on developing more robust temperature models to improve the current practice.
- A general enhancement in the material properties from the initial strength after construction was noticed with time in all the stabilized FDR projects studied. These time-dependent variations in strength are significant for FDR projects and must be considered in the mechanistic-empirical analysis.
- Based on the stiffness trends of all three projects and their overall comparable performance in the long term, design moduli of approximately 170 ksi, 450 ksi, and 720 ksi for asphalt emulsion, formed asphalt and Portland cement FDR respectively are recommended for use in MEPDG.
- After 7 years, rutting for all 3 projects was below VDOTs terminal rut depth of 0.25 in. Rutting in the emulsion sections was slightly higher than for the foamed asphalts. The cement sections showed the least rutting.
- FDR projects with stiffer bases, as observed with the cement stabilized sections, may be more prone to transverse cracking.
- The performance results in terms of distresses related to traffic loads are similar between the asphalt and cement stabilized sections even though asphalt stabilized sections seem to have slightly higher rutting.. For non-load related distresses however, the asphalt stabilized sections outperformed the cement stabilized sections.

5.3 CONCLUSIONS

Characterization of the differently stabilized FDR base layers or mixtures using the elastic modulus was done to provide more insight to pavement engineers and state departments of transportation who have implemented or are planning to implement the mechanistic empirical design guide. The elastic modulus was found to vary significantly over time, with the initial values after construction depending on the type of stabilizing agent used. The stiffness of the FDR base layer is sensitive to temperature (stiffness reduces with increasing temperature) when asphalt-based stabilizers are used. Therefore, emphasis should be placed on time of day when tests are undertaken to evaluate the strength of completed projects. Portland cement increases stiffness and reduces temperature sensitivity of the FDR base layer when used as a standalone stabilizer or as an additive with asphalt stabilizers.

The long term in-service performance of the FDR projects showed promising results which were comparable to similar projects rehabilitated with an AC overlay. Distresses that are generally caused by traffic loads were more prevalent on the asphalt stabilized projects compared to the cement projects. However, the cement based projects were more prone to non-load related distresses (transverse cracking). As result, VDOT has modified the specification for cement stabilized FDR to include lower cement content. Combined stabilization using cement and asphalt stabilizers would seem a better stabilization approach for FDR projects in order to obtain a mixture that is durable and can withstand adverse effects of the environment. Furthermore, using the pavement ride quality to judge the overall performance of the projects, cement stabilization seemed a more superior alternative.

5.4 RECOMMENDATIONS

While the comparisons made in this thesis for the different projects provide an overall insight into the different objectives, it is recommended that more data is collected from other state DOTs to compare similar or equivalent projects (projects with same pavement thicknesses, stabilizer contents, similar traffic usage and under same environmental conditions, etc.) to ensure more detailed analysis is carried out to aid decision makers in selecting stabilizers that are more sustainable.

Also, further work should be conducted to evaluate which of these stabilizers provide a more environmentally friendly alternative using life cycle assessments.