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LIFE-CYCLE IMPACT ASSESSMENT OF RECYCLED PAVEMENT PROJECTS IN VIRGINIA

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16. Abstract:

This report describes a study conducted to evaluate the performance and quantify the potential environmental benefits of recycled asphalt pavement projects completed in Virginia. The performance of the recycled projects was assessed by evaluating collected stiffness data and by the development of performance prediction models based on data obtained from the Virginia Department of Transportation (VDOT) pavement management system. Quantifying the potential environmental impacts for these projects was completed following recommendations by Harvey et al. in *Pavement Life Cycle Assessment Framework*. Modeling of unit processes in the various pavement life cycle stages was tailored to represent conditions and practices used in Virginia to the extent possible.

The global warming (GW) score and a Single Score Index were used to assess pavement recycling projects completed in Virginia. The study found that approximately 98% of the total GW score result came from pavement smoothness during the use stage. During the cradle-to-laid (material production, transportation, and construction) stage, the results showed that pavement recycling projects used for interstate reconstruction and primary route restorative maintenance were more environmentally friendly—as they yielded lower GW scores—compared to the conventional approaches. The results found that full depth reclamation (FDR) projects used as reconstruction on primary routes sometimes had a higher GW score compared to conventional projects, especially in instances when cement was used as a stabilizing agent (cement production at the plants is associated with high greenhouse gas emissions). When considering the entire life cycle, most of the GW score impacts came from the use stage.

The results of the structural evaluation showed that there were no large changes in the stiffness of the recycled layers for FDR projects when comparing data from 36-month and 10-year testing periods. The predicted functional service life of all recycling projects ranged from 6 to more than 30 years using thresholds based on either ride quality or a distress index. For FDR projects, cement-stabilized projects were generally predicted to last longer when compared to the asphalt-stabilized projects.

The study recommends that VDOT consider reoccurring structural evaluation of all completed pavement recycling projects to better evaluate the trends observed in this report. To reduce environmental impacts, VDOT should encourage (or even incentivize) practices that improve the initial pavement smoothness for recycling projects and use structural designs that are expected to have a low annual rate of deterioration. To better account for the actual deterioration of pavement recycling projects with the agency pavement management system, VDOT should develop a set of recycling-specific deterioration models to better reflect their anticipated longer service lives. Finally, VDOT should develop a framework to implement life cycle assessment practices to complement the current selection and design process, for pavement maintenance and rehabilitation projects, that will result in reduced environmental impacts.

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ABSTRACT

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GLOSSARY

Terminology	Definition	Source
Analysis period	The time-period used in the LCA model to capture the influence of current and anticipated future decisions in the pavement life cycle that covers the expected service life under a particular set of use conditions which may form the basis of estimating the service life under other in-use conditions.	Harvey et al. 2016
Cradle-to-laid	Life cycle assessments with the construction stage added to the system boundary	Harvey et al. 2016
Estimated service life	Service life that an assembled system (part of works) would be expected to have in a set of specific in-use conditions, determined from reference service life data after considering any differences from the reference in use conditions	Harvey et al. 2016
Functional unit	Product system measurement of performance to provide a reference unit	Based on ISO 2006a
Global warming (also climate change)	Occurs when there is a rise in the global average temperature near the earth's surface because of greenhouse gases (GHGs); primarily associated with fuel combustion and some material production processes	Bare, 2012
Impact category	Category showing an environmental issue to which assignments of life-cycle inventory analysis may be made	Based on ISO 2006a
Impact category indicator	The measurable depiction of an impact category	Based on ISO 2006a
Life cycle	The successive stages of a product or system, from raw material to final disposal	Harvey et al. 2016
Life cycle assessment (LCA)	The compilation and evaluation of a system's inputs, outputs, and environmental impacts over the entire life cycle	Based on ISO 2006b
Life cycle impact assessment	The phase of an LCA that shows the extent and significance of a system's environmental impacts for the entire life cycle	Based on ISO 2006a
Life cycle interpretation	The phase of an LCA where inventory analysis and impact assessment results are compared to the defined goal and scope to obtain conclusions and recommendations	Based on ISO 2006b
Life cycle inventory analysis	The phase of an LCA that compiles and quantifies product inputs and outputs for the entire life cycle	Based on ISO 2006a
Output	Product, material, or energy that exits a process	Based on ISO 2006b
Performance	Expression relating to the magnitude of a particular aspect of the object of consideration relative to specified requirements, objectives, or targets	Harvey et al. 2016
Single Score Indicator	A unitless indicator based on calculations from normalization and weighting factors for each impact category indicator used to characterize the overall impact of the projects	Bare et al. 2006; Lautier et al. 2010
System boundary	A set of criteria that indicates unit processes associated with a part of a product system	Based on ISO 2006a
Uncertainty	A measure of the quality of LCA data. Uncertainty should be evaluated as a part of the LCA prepared to create an EPD based on this PCR	CLF 2013
Unit process	The smallest component of the life-cycle inventory analysis with quantification of input and output data	Based on ISO 2006a

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INTRODUCTION

Background

In-service pavements require maintenance and rehabilitation (M&R) interventions to keep them in compliance with structural and functional standards. With the increased focus on the sustainability of our roadway systems, it has become important to document the cost and environmental impacts of different M&R strategies over the life cycle of the pavement. In the last 10 years, the Virginia Department of Transportation (VDOT) has conducted various pavement recycling projects to evaluate the emerging M&R recycling techniques of Cold Recycling (CR) and Full-Depth Reclamation (FDR). Even though in most instances, pavement recycling techniques have clear environmental and construction cost benefits over traditional maintenance, rehabilitation, reconstruction, and construction techniques, the environmental benefits are seldom quantified. In general, only a few studies have documented the functional and structural long-term performances of pavement recycling projects. Among the existing studies that have analyzed and documented the performance of in-place pavement recycling techniques (Jones et al., 2015; Lewis et al., 2006; Miller et al., 2006; Romanoschi et al., 2004) only a few have provided a time-evolution of project performance exceeding 5 years (Amarh et al., 2019; Lane and Kazmierowski, 2012). Among other reasons, this lack of knowledge regarding the performance of pavement recycling projects has contributed to the slow adoption of the technology in the United States (Stroup-Gardiner, 2011).

Recycling practices have been shown to not only reduce life-cycle costs, but also improve the life-cycle environmental performance of pavements (Thenoux et al., 2007). In terms of asphalt surfaced roads, conventional paving primarily consists of the practice of milling an existing surface and transporting the removed material to an asphalt plant, where it is stockpiled as reclaimed asphalt pavement (RAP). The RAP is then incorporated into newly produced asphalt concrete (AC) in percentages typically ranging from 15% to 40%. Finally, the RAP containing AC is transported to a specific pavement section and used as a new asphalt pavement material. In contrast, pavement recycling reduces the amount of material hauling, increases the reuse of materials, and reduces the construction time by recycling the paving materials in situ. This reduction in construction time is critical in reducing delays (Santero et al., 2011), which have adverse business and environmental impacts (e.g., deterioration of goods, delays in deliveries, driver stress, gas consumption, and carbon dioxide production). Reducing the construction time also reduces worker exposure to traffic and work-zone accidents.

Diefenderfer and Apeagyei (2011) reported that pavement rehabilitation with FDR for selected projects could result in 50-year life-cycle cost savings of approximately $10 million and $30.5 million on the primary and secondary networks in Virginia, respectively. In addition, the properties of FDR materials on three trial sections (State Routes [SR] 40, 13, and 6 in Franklin, Powhatan, and Goochland Counties, respectively) were characterized for 2 years after construction in 2008. Site descriptions, details on the construction and reclamation processes, results of laboratory and field evaluations to assess mechanical properties, and the effective structural number and layer coefficients were documented (Diefenderfer and Apeagyei, 2011). Amarh et al. (2017) conducted a follow-up study to evaluate the layer moduli from Falling Weight Deflectometer (FWD) testing and assessed the in-service performance of FDR sections over an 8-year period after construction. Between 1986 and 2006, the Nevada Department of Transportation (DOT) built over 900 centerline miles of cold in-place recycling (CIR) and FDR, resulting in savings of $600 million compared to complete reconstruction without considering user costs (Bemanian et al., 2006). In terms of environmental impacts, Alkins et al. (2008) reported that implementing cold recycling has reduced emissions of carbon dioxide by 52%, nitric oxide and nitrogen dioxide by 54%, and sulfur dioxide by 61% compared to conventional-based rehabilitation strategies (Alkins et al., 2008). More recently, researchers are using life cycle assessment (LCA) to better measure the impacts of pavement M&R activities on the surrounding environment.

LCA is a standard methodology intended to assess the environmental performance of a product or system over its life cycle. Although LCA can consider a wide range of environmental impacts, pavement LCA generally measures the impact in terms of greenhouse gas (GHG) emissions, energy consumption, and material use. These impacts occur during the five different stages of a pavement's life: *(1)* material extraction and production, *(2)* construction, *(3)* maintenance and rehabilitation (M&R), *(4)* use, and *(5)* end-of-life (EOL). The majority of pavement-related LCA studies have been developed for processes covering only the material extraction and production, construction, and M&R stages of the pavement. In general, the pavement-related studies were conducted either to better understand the benefits of using alternative or recycled materials in the construction process, quantify the benefits of waste minimization during construction, or compare project types and construction techniques. LCA studies addressing the use of portland cement and AC pavements in non-recycling construction methods are common and have been extensively studied (Athena, 2006; Birgisdottir and

Christensen, 2005; Häkkinen and Mäkelä, 1996; Horvath and Hendrickson, 1998; Huang et al., 2009; Santero et al., 2011; Stripple, 2001). Other pavement LCA studies evaluated the use of recycled materials such as RAP, recycled waste glass, etc., in road projects (Bressi et al., 2019; Chiu et al., 2008; Farina, et al. 2017), either as a partial substitute for materials in hot mix asphalt (HMA) surface mixes or in the base layer. Only a few LCA studies evaluating traditional construction methods and pavement recycling alternatives have been conducted in the United States (Cross et al., 2011; Levis et al., 2011; Liu et al., 2014; Saboori et al., 2017; Santos et al., 2015; Senhaji, 2017) and around the world (Alkins et al., 2008; Cao et al., 2016; Cao et al., 2019; Eckmann et al., 2012; Giani et al., 2015; Miliutenko et al., 2013; Turk et al., 2016; Zarrinkamar and Modarres, 2020). The results from these studies vary and are difficult to compare for several reasons, including variations in the life cycle stages included in the system boundary, different functional units, varying transportation distances, and different impact assessment methodologies, among others. However, the common link that ties these studies together is the fact that the use-stage impacts are rarely evaluated, and in cases where this is done, actual pavement performance data from the pavement sections are not considered. Another common limitation with the studies described above is that the tools and datasets used are in some cases either proxies or outmoded, and thus do not cover unit processes/materials specific for pavement recycling techniques.

Within the context of VDOT's current rehabilitation decision process using Pavement Management System (PMS) data, the LCA can support decisions about pavement design and rehabilitation practices. The selection and design of maintenance and rehabilitation projects are fundamental project-level pavement management business processes. Typically, the selection strategy is based on the result of a life cycle cost analysis (LCCA) or the determination by a district pavement manager, the availability of local construction materials, and the familiarity of local contractors with construction using the materials (Hallin et al., 2011). However, many more factors can be included, and their tradeoffs considered, to make the project selection process more sustainable. For example, in a rehabilitation project, the performance of different rehabilitation alternatives along with the availability of local materials can be part of the assessment. Thus, a record of the long-term performance of VDOT's current inventory of recycled pavement projects—in addition to conventional-based rehabilitation methods—along with a database of environmental impacts estimated at each stage of the projects' life cycle, can be used to develop a set of guidelines or framework that will help decide which future projects are best suited for recycling. With this framework in place, VDOT will be able to consider both environmental impacts and pavement performance when evaluating future recycling options.

PURPOSE AND SCOPE

The purpose of this research was to document the functional and structural performance of various pavement recycling projects in Virginia and to quantify the potential environmental benefits of various pavement recycling projects completed in Virginia using an LCA approach.

The scope of the study includes those pavement recycling projects completed in Virginia between 2008 and 2018 using the FDR, CIR, and cold central plant recycling (CCPR) techniques. The pavement recycling projects were completed on a variety of roadway types, including interstate, primary, and secondary routes. The detailed processes leading to the development of the LCA tool—*pySuPave* software—and database of unit processes in the life cycle of a recycled pavement are partially documented in this report.

METHODS

Overview

The research objectives were achieved through the following specific tasks:

1) Document the location, type of materials used, costs, and initial performance of all pavement recycling projects completed between 2008 and 2018 in Virginia.
2) Evaluate the structural performance of different recycled pavement layers through backcalculation of FWD data to facilitate the evaluation of the structural condition over time.
3) Develop models to define the functional deterioration of load- and non-load-related distresses using data extracted from VDOT's PMS.
4) Develop the assessment framework, and LCA tool—*pySuPave* software—with a database covering unit processes for pavement recycling.
5) Analyze the results of the LCA.

Pavement Recycling Projects in Virginia

VDOT's Materials Division and the research team developed a list of all VDOT pavement recycling projects completed or ongoing between 2008 and 2018. The full list is provided in Appendix A. The list includes project data, location, recycling method used, and costs, where available.

Structural Performance Evaluation

The collected deflection data were analyzed in accordance with the backcalculation methodology and procedures outlined in Von Quintus et al. (2015), together with ASTM D5858, *Standard Guide for Calculating in situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory*. 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 recycled base layer, and a subgrade layer at the bottom (CIR and CCPR data files were analyzed as three-layered structures as well because the thicknesses of the underlying bases were not known). 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 (through a functionality in ELMOD) prior to the backcalculation. ELMOD calculates the accumulated differences of the center deflections and allows the user manually to identify and demarcate homogeneous segments for a more refined analysis. The accumulated difference at the i^{th} station was defined in Equation 1 as follows:

$$\sum_{i=1}^{k} \delta_i - k\mu \qquad (1)$$

where

$\sum \delta_i$ = sum of deflections from the 1st station to the k^{th} station inclusively,

i = number of stations from δ_1 to δ_k inclusively, and

μ = mean deflection of all stations.

A section was considered homogeneous when the cumulative differences continued in the same upward or downward trend. The boundaries of the homogeneous sections were marked when a significant change in trend was observed. The thickness of each layer in a homogeneous section was then input into ELMOD. 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 (Maher and Bennert, 2008; Masada et al., 2004).

Using the deflection basin fit method, the moduli of the HMA layer and FDR base were then determined through a series of iterations using the center deflection and the curvature or shape of the basin under the load plate. The subgrade modulus was then adjusted according to the estimated stress level under the load center. The outer deflections were checked, and additional iterations were carried out if necessary. The calculated deflection profile and measured deflection profile were then matched with the percentage difference (root mean square [RMS]) between the calculated and measured values reported.

The iterations were performed with the objective of minimizing the RMS as the convergence criteria. Acceptable backcalculation results were defined as results with an RMS less than or equal to 3%, and as backcalculated moduli values for each layer falling within an acceptable range for each layer type and category based on the default range of values used in the Mechanistic Empirical Design Guide (Von Quintus et al., 2015).

Data Collected

Table 1 reports the availability of FWD measurements by year for each project. The table shows that FWD data were limited, and the structural data collected soon after project completion are only available for the five projects completed in 2008 and 2011.

Development of Functional Deterioration Models

To quantify the expected deterioration of the pavement recycling projects, several deterioration models were needed, the first of which were used to describe the change in surface condition and distress indices with respect to time.

Table 1. Overview of FWD Data Collection since Project Completion (Shaded Cells Denote Periods when Project Was in Service)

County	Project	FWD Testing & Data Availability											
		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Accomack	SR709								▨	▨	▨	▨	▨
	SR609								▨	▨	▨	▨	▨
Augusta	I-81S				▨ ✓	▨ ✓	▨ ✓	▨	▨ ✓	▨	▨	▨ ✓	▨
Bedford	SR24E&W					▨	▨	▨	▨	▨	▨	▨	▨
Brunswick	SR85N&S										▨	▨	▨
Chesterfield	SR10W					▨	▨	▨	▨	▨	▨	▨	▨
Dinwiddie	SR85S								▨	▨	▨	▨	▨
Franklin	SR40E&W	▨ ✓	▨ ✓	▨ ✓	▨	▨	▨	▨	▨	▨	▨	▨	▨ ✓
Franklin	SR40E&W	▨ ✓	▨ ✓	▨ ✓	▨	▨	▨	▨	▨	▨	▨	▨	▨ ✓
Giles	SR460W												▨ ✓
Goochland	SR6E&W	▨ ✓	▨ ✓	▨ ✓	▨	▨	▨	▨	▨	▨	▨	▨	▨ ✓
Henrico	SR60E&W				▨	▨	▨	▨	▨	▨	▨	▨	▨
Isle of Wight	SR17N&S					▨	▨	▨	▨	▨	▨	▨	▨
Isle of Wight	SC620E&W					▨	▨	▨	▨	▨	▨	▨	▨
King William	SR30E&W												
Powhatan	SR13N&S	▨ ✓	▨ ✓	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨ ✓
Powhatan	US60W			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨ ✓
Prince George	SR35N&S				▨	▨	▨	▨	▨	▨	▨	▨	▨ ✓
Richmond	SR3E&W					▨	▨	▨	▨	▨	▨	▨	▨ ✓
Scott	SR224							▨	▨	▨	▨	▨	▨
York	SR620E&W												▨
York	I64												▨

Data Collected

The pavement condition data, maintenance history, and pavement age obtained from the VDOT PMS were used to develop pavement deterioration curves for the pavement condition parameters (critical condition index [CCI]), roughness, and other distresses (longitudinal cracking, transverse cracking, and rutting). For flexible pavements, the load-related distress rating (LDR) gives an indication of pavement condition concerning damage due to wheel loads applied to the pavement. It comprises distresses such as 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. Like 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 CCI is the lower of the LDR and NDR and is used as an indicator to measure the overall pavement condition. Details on the development of these indices are discussed elsewhere (McGhee, 2002). The variables were obtained at the highest available resolution from the PMS for model development. Data filtering was applied; any proposed filtering was discussed with the VDOT project panel during quarterly progress meetings.

Data Processing

Data for 14 FDR, two CIR, and one CCPR project were extracted from the VDOT PMS. Data preparation steps involving the identification and removal of erroneous data (e.g., unreasonably high, or low differences between consecutive data points with no known maintenance activity for instance, negative values) were carried out to clean the raw data using data visualization functionality in the JMP statistical software. For nonlinear modeling, a requirement of a minimum of three time-series data points (Baladi et al., 2017) was set to further clean the data. Therefore, all projects with less than 3 years of data were removed (projects removed included the only CCPR project) from the analysis. After the data processing/filtering steps a total of eight FDR and two CIR projects, as shown in Table 2, were used in the analysis.

Table 2. Details of In-Place Recycling Projects Used for the Analysis

Route (Length - mi)	Administrative Classification	Recycling Methods	AADTT 2017	Pavement Structure (above subgrade)				Total Thickness
				Layer 1	Layer 2	Layer 3	Layer 4	
IS81SB (3.7)	Interstate	FDR Cement/Lime + CCPR	6943	2.0 in SMA12.5A	4.0 in IM19.0A	6.0 in CCPR	12.0 in FDR	24.0 in[a]
SR3EB (3.0)	Primary	FDR Cement	92	2.0-in SM12.5A	2.0-in IM19.0A	9.5-in FDR	-	13.5 in
SR3WB (3.0)	Primary	FDR Cement	85	2.0-in SM12.5A	2.0-in IM19.0A	9.5-in FDR	-	13.5 in
SR6EB (3.6)	Primary	FDR Cement	127	1.5-in SM12.5A	2.0-in IM19.0A	9.0-in FDR	-	12.5 in
SR13EB (3.6)	Primary	FDR Cement	172	1.5-in SM12.5A	2.0-in IM19.0A	9.0-in FDR	-	12.5 in
SR24EB (2.9)	Primary	FDR Cement	61	1.5-in SM9.5A	9.0-in FDR	-	-	10.5 in
SR40EB (0.25)	Primary	FDR FA	48	2.5-in SM9.5A	9.8-in FDR	-	-	12.3 in
SR40EBa (0.25)	Primary	FDR EA	48	2.5-in SM9.5A	9.8-in FDR	-	-	12.3 in
US17NB (9.8)	Primary	CIR EA	127	1.5-in SM12.5A	2.0-in IM19.0A	5.0 in CIR	-	8.5 in
US17SB (9.8)	Primary	CIR FA	170	2.0-in SM12.5A	3.0-in IM19.0A	5.0 in CIR	-	10.0 in

IM19.0A = Intermediate Mix with 19.0 mm nominal maximum aggregate size (NMAS), A = performance grade (PG) 64-22 binder, SMA12.5A = Stone Matrix Asphalt with 12.5 mm NMAS, SM9.5A = Surface Mix with 9.5 mm NMAS, SM12.5A = Surface Mix with 12.5 mm NMAS, AADTT = Average Annual Daily Truck Traffic, FDR = Full Depth Reclamation, CIR = Cold In-place Recycling, CCPR = Cold Central Plant Recycling, FA = Foamed Asphalt, EA = Emulsified Asphalt.

[a] The configuration of the right lane of I-81 is not consistent for the entire 3.7 miles. The initial part is 4-in asphalt over 8-in CCPR while the rest is 6-in asphalt over 6-in CCPR. The left lane was composed of 5-in CIR with a 4-in asphalt overlay.

Exploratory Data Analysis

The filtered PMS data were analyzed using the curve-fitting tools and visual graphs in JMP statistical software. The data were comprised of the pavement age (computed from the project construction year) and condition descriptors such as fatigue cracking, rutting, International Roughness Index (IRI), transverse cracking, longitudinal cracking, and CCI. The correlation between these variables is presented in Table 3.

Table 3. Correlation between Condition Variable and Age

Variable	Correlation
CCI	-0.638
IRI (in/mi)	0.2037
Rut (in)	-0.1982
Fatigue Cracking Total (% total area)	0.557
Transverse Cracking Total (ft/lane mi)	0.6279
Longitudinal Cracking Total (ft/lane mi)	0.4285

The pooled data showed negative correlations between the CCI and age (-0.64), and positive correlation between the IRI and age (0.20). Except for rutting, the results in Table 3 were expected, as they are characteristic of pavement deterioration with time. Even though the negative correlation observed between rutting and age signals a reduction in rutting over time, the year-on-year differences were generally small. Summary statistics for the PMS data are presented in Table 4.

Table 4. Summary Statistics for Project Data Used in the Analysis

Variable	Mean from All Projects	Standard Deviation	Minimum	Maximum
CCI	92.7	9.0	65.0	100.0
IRI (in/mi)	93.3	22.0	47.0	171.0
Rut (in)	0.1	0.1	0.0	0.2
Fatigue Cracking Total (% total area)	0.8	1.6	0.0	9.1
Transverse Cracking Total (ft/lane mi)	254.3	445.1	0.0	1840.7
Longitudinal Cracking Total (ft/lane mi)	48.0	127.9	0.0	828.0
Age (yr)	6.6	2.1	5.0	9.0

Since there were only a few projects per recycling category, the analysis was by each project. There was high variation in the CCI and IRI data per project. The age of the projects ranged from a minimum of 5 years to a maximum of 9 years.

Regression Modelling for Pavement Deterioration

For brevity, this section focuses only on the development of the regression models on CCI and IRI. However, the same process was used in developing models for rutting and cracking (fatigue, thermal, and longitudinal). Regression analysis was performed to predict the CCI and IRI of the projects using the treatment age as the predictor variable. VDOT generally uses the CCI and other factors as a trigger to plan the type and frequency of pavement M&R schedules. In pavement LCA, IRI models are used to predict the evolution of surface roughness over time and subsequently assess the impacts on vehicle fuel consumption due to rolling resistance. Several model-shapes from various functions (Ercisli, 2015) (Table 5) were initially fitted to the data from individual projects to determine which models best fit the trends observed.

Table 5. General Forms for CCI Prediction Model Comparison

Function	**General Equation**
Negative Binomial	$a - Age^{b} \times Exp(c)$
Quadratic	$a + b \times Age + c \times Age^{2}$
Logistic 3P	$\frac{c}{1 + Exp(-a \times (Age - b))}$
Gompertz 3P	$a \times Exp\left(Exp\left((-b \times (Age - c)\right)\right)$
Exponential 3P	$a - b \times Exp(c \times Age)$
Linear	$a - b \times Age$
Exponential 2P	$a \times Exp(b \times Age)$

Note: a, b, c = model coefficients

The most plausible models were then selected using the second-order Akaike information criterion (AICc) weight (calculated from the AICc) assuming the error to be normally distributed (except for the negative binomial model). This estimator represents the relative likelihood of the “best” model (1.0 being most likely) when comparing several models. The curves were further assessed on how well they satisfied several boundary conditions. For CCI, the initial value should be 100 and not exceed 100 at any time in the prediction. The effect of constraining or restricting the appropriate model coefficients on the overall model was evaluated by checking if there was a statistical difference between the error sum of squares (SSE) of the restricted and unrestricted (original) models for the various functions. No boundary conditions for the maximum IRI value were set, though a pavement with an IRI greater than 500 in/mi is generally considered not rideable except at low speeds (American Concrete Pavement Association, 2002). The models satisfying the boundary conditions with AICc weights closest to 1 were then selected. Finally, to estimate the service life of the projects, the ages were computed from the final models generated by setting CCI and IRI condition triggers.

Life Cycle Assessment of Recycling Alternatives

VDOT has been pursuing pavement recycling on a selected basis as a part of the state’s pavement rehabilitation program since 2008. LCA provides a way to objectively quantify and thus compare the environmental impacts associated with various pavement alternatives. The LCA conducted for these projects was carried out in accordance with the framework described by Harvey et al. (2016) which conforms to guidelines in the ISO 14040 series (ISO, 2006).

The framework described by Harvey et al. (2016) incorporates five distinct life cycle stages (shown in Figure 1): (1) material extraction and production, (2) construction, (3) M&R, (4) use, and (5) EOL. Ideally, any LCA should examine each stage of the product life cycle in detail. However, given time, data, and knowledge constraints, this is difficult for most products, including pavements. The *material extraction and production* stage describes activities involved in pavement materials acquisition (e.g., mining, crude oil extraction) and processing (e.g., refining, manufacturing, mixing), including plant processes and transport. The *construction stage* describes processes and equipment associated with the construction of pavement systems, including both new construction and reconstruction efforts. The *use stage* evaluates pavement characteristics (e.g., roughness, stiffness/rigidity, and macrotexture) that affect vehicle energy consumption and corresponding emissions as well as the surrounding environment (e.g., hydraulic flow retention/detention and contamination, air emissions, noise, heat capacity/conductivity, solar absorptivity, sound absorptivity). The *maintenance and rehabilitation stage* evaluates the application of treatments to an existing pavement that slow the rate of deterioration or that address functional or structural deficiencies. The *EOL stage* describes the final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its performance life. In practice, pavements are usually left in place as an underlying layer in their state or recycled.

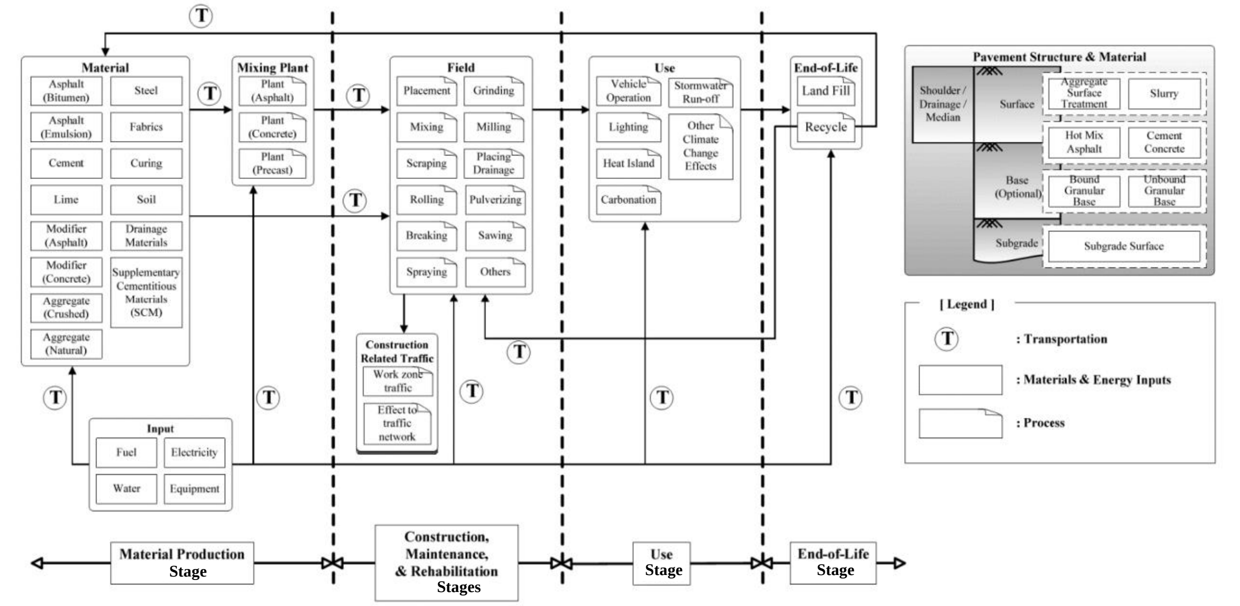


Figure 1. Typical Life Cycle Stages of a Pavement System (Harvey et al., 2016)

Performing an LCA, according to ISO14044 guidelines, includes four basic steps or phases (ISO, 2006a): *(1)* goal and scope definition, *(2)* inventory analysis, *(3)* impact assessment, and *(4)* interpretation, as shown in Figure 2. The LCA process starts with defining the goal of the study, which determines the system boundary (which pavement life cycle stages to include) and scope of the study, duration or analysis period of the study, a suitable functional unit (describing what is to be studied by defining a physical unit and performance specifications), and the target audience. The next step is the life cycle inventory (LCI) analysis, which quantifies all input flows (raw materials and energy consumption of resources) and output flows (waste flows and emissions) attributed to all processes within the life-cycle system boundaries. The life cycle impact assessment (LCIA) step is where the inventory results from the previous step are classified and categorized into various environmental characterizations for more meaningful assessment of the life-cycle inventory results. Specifically, resource inputs and emissions are organized into environmental impact categories (e.g., global warming, acidification, and primary energy use, etc.) to better understand their environmental significance. This classification of emissions into impact categories was done using the United States Environmental Protection Agency's (US EPA) Tool for Reduction and Assessment of Chemical and other environmental Impacts (TRACI) method. In addition to the TRACI indicators described, a unitless indicator based on calculations from normalization and weighting factors for each indicator was used to determine the overall impact of the projects (Bare et al., 2006; Lautier et al., 2010). The resulting point-based indicator is known as the *single score index***.** The complete list of impact categories—with weighting and normalization factors used in calculating the single score index—is shown in Appendix C. The *interpretation* step uses the results from the inventory analysis and/or the impact assessment to draw conclusions, make recommendations, identify analysis refinements, or otherwise aid in the decision-making process.

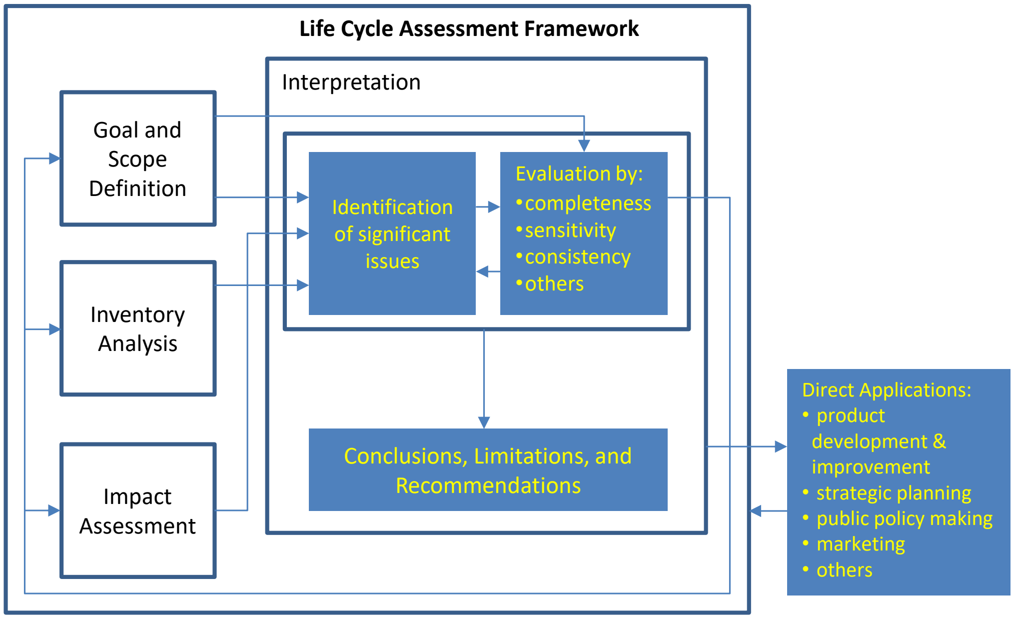


Figure 2. Updated LCA Framework (adapted from Harvey et al., 2016)

Goal and Scope Definition

The objective of this LCA was to quantify the potential environmental benefits associated with various recycled pavement projects completed in Virginia using the global warming (GW) indicator and single score index. This task was accomplished by comparing recycling-based projects to structurally similar theoretical designs using conventional techniques for three rehabilitation categories, as shown in Figure 3. The three categories include interstate reconstruction, primary route reconstruction, and restorative maintenance (i.e., mill and fill) for flexible pavements. In some cases, the conventional design may not be practical to implement; however, they were identified to match the structural capacity of the recycling-based projects. More specific goals include:

1. Estimate and document the GW score and the single score index of recycled projects and compare to structurally equivalent pavements rehabilitated with conventional methods in the state. The recorded scores per project will serve as benchmarks, providing baseline

results for future LCAs studies to compare various alternative decisions involving recycled pavement projects.
2. Evaluate which unit process across the life cycle stages of the compared projects contribute large environmental burdens over the analysis period.

The scope of the LCA and other assumptions are listed as follows.

1. The physical functional unit was 1 lane-mile of a pavement project with a width of 12 ft.
2. Details of actual recycling projects and theoretical conventional designs that had similar structural capacities are shown in Figure 4. These details include the types of mixtures, thickness of the layers, and the structural number of the projects. The structural numbers were calculated using structural layer coefficients from national averages obtained from the Pavement Recycling and Reclamation Alliance (Pavement Preservation and Recyling Alliance, 2021) and the I-81 in-place recycling project report (Diefenderfer and Apeagyei, 2014).
3. The system boundary includes the following pavement life cycle stages: material production, construction (work zone not included), transportation (raw materials to plant to site), and use. The M&R, and EOL stages were not included. The M&R stage was likely to introduce uncertainty in the results—a reason for normalizing the results by the respective ages. The pavements were assumed to be reused (left in place as an underlying layer in their state) at EOL stage. The environmental burdens from this EOL selection were assumed to be minimal; thus, the EOL stage was excluded from the system boundary.
4. The analysis period considered varied by project, using the estimated functional service life of each project based on the last rehabilitation.
5. The target audience was VDOT and its local districts, but other agencies with similar projects and environmental conditions may use the results.
6. It is assumed that the original pavement has already been built and was therefore beyond the scope of the analysis. Only the travel lanes are considered; all other pavement components such as shoulders, guard rails, markings, lighting, etc., fall outside the physical boundary.
7. Finally, the annualized environmental impact assessment results are limited to the GW score and the overall single score for the sake of simplicity. To ensure functional equivalence, the scores were normalized by dividing each project’s results with its estimated service life and/or the total route annual average daily traffic (AADT).

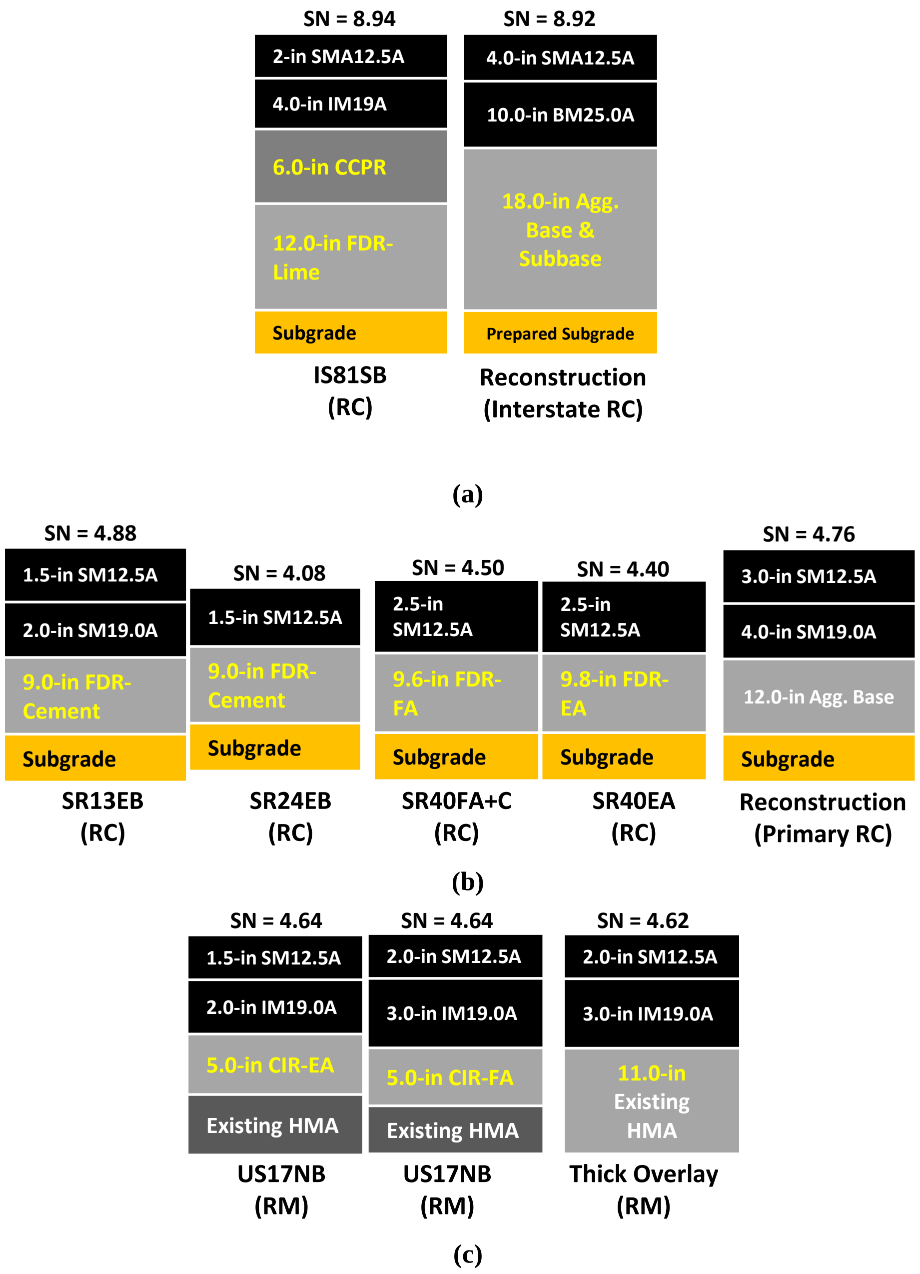
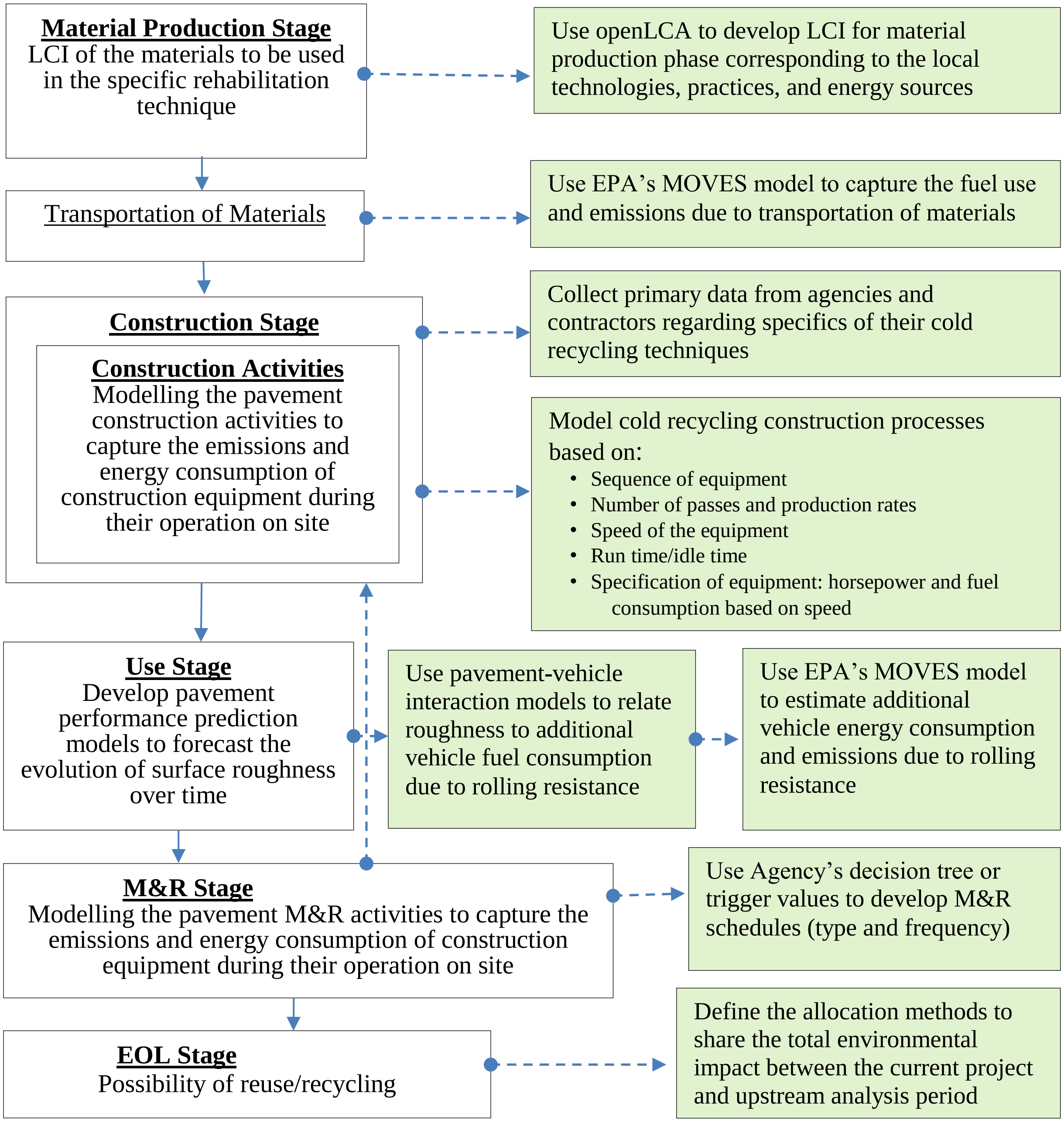


Figure 3. Details of Recycling and Reference Conventional Projects: (a) Interstate Reconstruction; (b) Primary Reconstruction; (c) Restorative Maintenance Projects. **SN = Structural Number, IM19.0A = Intermediate Mix with 19.0 mm nominal maximum aggregate size (NMAS), A = performance grade (PG) 64-22 binder, BM25.0A = Base Mix with 25.0 mm NMAS, A = PG 64-22 binder, SMA12.5A = Stone Matrix Asphalt with 12.5 mm NMAS, SM19.0A = Surface Mix with 19.0 mm NMAS, SM12.5A = Surface Mix with 12.5 mm NMAS, , FA = Foamed Asphalt, EA = Emulsified Asphalt, HMA = Hot mix asphalt, CCPR = Cold Central Plant Recycling, FDR = Full Depth Reclamation, CIR = Cold In-Place Recycling, RM = Restorative Maintenance, RC = Reconstruction.**

Life Cycle Inventory Analysis

The overall objective of the inventory analysis is to identify and calculate the environmental flows (e.g., inputs of material, energy and resources, and outputs of waste, pollution and co-products) of the various recycling treatment alternatives being studied. Figure 4 outlines the procedure used in developing the LCI for each LCA stage.



Material Production Stage
LCI of the materials to be used in the specific rehabilitation technique

Use openLCA to develop LCI for material production phase corresponding to the local technologies, practices, and energy sources

Transportation of Materials

Use EPA's MOVES model to capture the fuel use and emissions due to transportation of materials

Construction Stage

Collect primary data from agencies and contractors regarding specifics of their cold recycling techniques

Construction Activities
Modelling the pavement construction activities to capture the emissions and energy consumption of construction equipment during their operation on site

Model cold recycling construction processes based on:

- Sequence of equipment
- Number of passes and production rates
- Speed of the equipment
- Run time/idle time
- Specification of equipment: horsepower and fuel consumption based on speed

Use Stage
Develop pavement performance prediction models to forecast the evolution of surface roughness over time

Use pavement-vehicle interaction models to relate roughness to additional vehicle fuel consumption due to rolling resistance

Use EPA's MOVES model to estimate additional vehicle energy consumption and emissions due to rolling resistance

M&R Stage
Modelling the pavement M&R activities to capture the emissions and energy consumption of construction equipment during their operation on site

Use Agency's decision tree or trigger values to develop M&R schedules (type and frequency)

EOL Stage
Possibility of reuse/recycling

Define the allocation methods to share the total environmental impact between the current project and upstream analysis period

Figure 4. Flowchart Outlining the Procedure Used in Developing the LCI for Each Project Life Cycle Stage

Material Acquisition and Production

The list of materials used in the construction of the projects was compiled into a database and used for the inventory calculations. Material inventory covered the energy consumption and emissions of all processes starting with acquisition of raw materials through transportation to the plants for production until the final products were ready to be shipped from the asphalt plants. The bill of materials (BoM), i.e., the quantities and material composition for AC mixtures, were obtained from job mix formulas (JMF) that had been submitted by producing plants through VDOT's PLAID system for the projects covering 2015 to 2019. For each mix type (SM9.5D, SM12.5A, SMA12.5D, IM19.0A, IM19.0D, etc.), the average material quantities from JMFs from 10 asphalt plants in the VDOT Richmond District were used in developing the LCI for 1 short-ton of each product. Mix designs for various recycled base materials were obtained from the actual projects, as well as VDOT's and other agencies' manuals for an evaluation of typical stabilization agent/additive percentages. The unit processes involved in the acquisition and production of materials for the pavement systems built with these recycling treatment alternatives were modeled in the OpenLCA software along with the Ecoinvent 2.2 database (Wernet et al., 2016), tailored to location conditions in Virginia. The BoMs for the projects under study are given in Table 6.

Table 6. BoMs For 1 Ton of Asphalt Concrete Mixes and Recycled Base Mixes Used

Material	Unit	SM-12.5A	IM-19.0A	FDR - C	FDR - FA + C	FDR - EA	CIR - FA	CIR - EA	CCPR – FA + C
No.78 [0.170 mm]	Ton	0.310	0.320	-	-	-	-	-	-
No.10 [2.0 mm]	Ton	0.188	0.230	-	-	-	-	-	-
Recycled aggregates (RAP)	Ton	0.282	0.219	0.950	0.970	0.965	0.978	0.965	0.965
Sand	Ton	0.160	0.180	-	-	-	-	-	-
PG 64S-22 binder	Ton	0.056	0.047	-	-	-	-	-	-
Cement	Ton	-	-	0.050	0.010	-	-	-	0.010
Ad-here HP Plus	Ton	0.004	0.004	-	-	-	-	-	-
Emulsion	Ton	-	-	-	-	0.035		0.035	
Foamed Asphalt	Ton	-	-	-	0.020	-	0.023	-	0. 025

SM12.5 A = Surface Mix with 12.5 mm nominal maximum aggregate size (NMAS), "A" for binder with performance grade 64-22, IM19.0 A = Intermediate Mix with 19.0 mm NMAS
CCPR FA + C = Cold Central Plant Recycling with Foamed Asphalt and Cement as additive
CIR FA = Cold In-place Recycling with Foamed Asphalt
CIR EA = Cold In-place Recycling with Emulsified Asphalt
FDR FA + C = Full Depth Reclamation with Foamed Asphalt and Cement as additive
FDR EA = Full Depth Reclamation with Emulsified Asphalt
FDR C = Full Depth Reclamation with Cement
FA = Foamed Asphalt, EA = Emulsified Asphalt

Transportation of Materials

For each of the asphalt mix types used in the inventory calculations, the maximum estimated transportation distances from each component material source to the corresponding asphalt plants were estimated (Table 7). The resulting distances ranged from 17 miles to 52 miles for aggregates. RAP materials for AC mix production were assumed to have been stockpiled at the AC plants and were thus assigned a transportation distance of zero. Transportation distance for the stabilizers (cement, emulsion, and foamed asphalt) and other additives was assumed to be 25 miles from a transit terminal to the construction site. Virgin binders were assumed to be transported from a transit terminal (not refinery) to the AC plants through 25 miles. The produced AC mixtures were assumed to be transported through a maximum distance of 25 miles to the project sites. The recycled FDR and CIR materials (RAP) were produced on site, and thus assigned a transportation distance of zero miles, while the CCPR base material was assumed to be recycled at a mobile plant at most 5 miles from the construction site (multiplied by 2 in Table 7 to cover distance from construction site to mobile plant and back to construction site). The transportation of construction equipment was not included in this exercise. The materials were assumed to be transported with heavy-duty trucks running at their maximum capacity (20–28 tons) to the manufacturing plants and construction site. The US EPA's MOVES model was used to determine the average fuel consumption and airborne emission factors for operating diesel-powered, single-unit, short-haul trucks. These factors were computed for the typical climate conditions during the month of April in Virginia.

Table 7. Material Transportation Distances to Mixing Plants and Construction Sites

Material	Unit	SM-12.5A	IM-19.0A	FDR - C	FDR - FA + C	FDR - EA	CIR - FA	CIR - EA	CCPR - FA + C
No.78 [0.170 mm]	mile	52.0	24.0	-	-	-	-	-	-
No.10 [2.0 mm]	mile	52.0	52.0	-	-	-	-	-	-
Recycled aggregates (RAP)	mile	0	0	0	0	0	0	0	10.0
Sand	mile	52.0	45.3	-	-	-	-	-	-
PG 64S-22 (formerly PG 64-22)	mile	25.0	25.0	-	-	-	-	-	-
Cement	mile	-	-	25.0	25.0	-	-	-	-
Ad-here HP Plus	mile	25.0	-	-	-	-	-	-	-
Emulsion	mile	-	-	-	-	25.0	-	25.0	-
Foamed Asphalt	mile	-	-	-	25.0	-	25.0	-	-

SM12.5 A = Surface Mix with 12.5 mm nominal maximum aggregate size (NMAS), "A" for binder with performance grade 64-22, IM19.0 A = Intermediate Mix with 19.0 mm NMAS
CCPR FA + C = Cold Central Plant Recycling with Foamed Asphalt and Cement as additive
CIR FA = Cold In-place Recycling with Foamed Asphalt
CIR EA = Cold In-place Recycling with Emulsified Asphalt
FDR FA + C = Full Depth Reclamation with Foamed Asphalt and Cement as additive
FDR EA = Full Depth Reclamation with Emulsified Asphalt
FDR C = Full Depth Reclamation with Cement
FA = Foamed Asphalt, EA = Emulsified Asphalt

Construction

Energy consumption under the construction stage includes fuel consumed by construction equipment, electric power, and other energy sources used on site. A list of tasks for construction activities performed when applying the initial recycling-based treatments and subsequent maintenance activities was compiled. The equipment and production rates required were obtained from contractors known to have executed the projects under study and complemented with information from existing literature sources and available software (Athena, 2013; Skolnik et al., 2013) and are provided in Appendix C. VDOT's "Work Activity Base Production Rates," a worksheet containing production rates from work items compiled from five other states with assumed similar work conditions, was used to validate the production rates data obtained from the previous step in instances where there was wide variation or where little information was available for a specific work item. Based on the quantities (volume) of work to be done under each construction task estimated from the treatment design/pavement geometry, and the corresponding productivity rates, the total equipment run time was calculated and used to estimate the fuel consumed by each equipment. An example of the list of construction equipment and sequence of construction for FDR with foamed asphalt stabilization is shown in Figure 5.

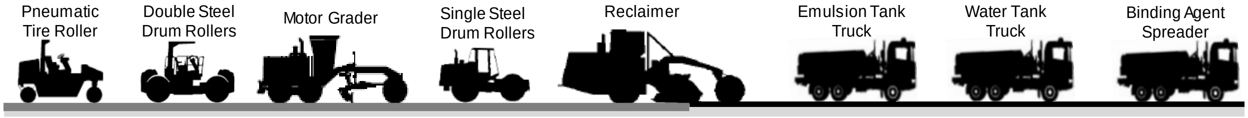


Figure 5. Typical Equipment Train for Pavement Recycling using FDR with Emulsified Asphalt and Cement Additives.

Use Stage

The rolling resistance is the vehicle energy loss associated with pavement-vehicle interaction (PVI), as the vehicles move over a pavement surface. Among other factors, it is affected by pavement surface texture, roughness, and deflection (stiffness). Generally, the higher the rolling resistance, the more fuel is consumed. Among the three mechanisms influencing rolling resistance, only roughness was considered. The roughness prediction models as a function of pavement surface age developed for the projects under study were used to predict the roughness over a 10-year analysis period. The roughness-speed impact (RSI) model (Ziyadi et al., 2018), was used to calculate environmental impacts and energy consumption as a function of pavement roughness and vehicle speed. The general form of the RSI model is given by Equation 2.

$$RSI_{t=0}^{Energy}: \quad \hat{E}(v, IRI) = \frac{p}{v} + (k_a.IRI + d_a) + b.v + (k_c.IRI + d_c).v^2 \qquad (2)$$

where:
$\widehat{E}$ = estimated energy consumption per vehicle distance (kJ/mile),
v = average speed (mph),
IRI = International Roughness Index (in/mile), and
k_a, k_c, d_a, d_c, p, b = model coefficients that depend on vehicle type as shown in Table 8.

Table 8. RSI Model Regression Coefficients per Vehicle Type (Ziyadi et al., 2018)

Coefficients	**Passenger Car***	**Small Truck***	**Medium Truck***	**Large Truck***
k_a	6.70E-01	7.68E-01	9.18E-01	1.40E+00
k_c	2.81E-04	1.25E-04	1.33E-04	1.36E-04
d_c	2.1860E-01	3.0769E-01	9.7418E-01	2.3900E+00
d_a	2.1757E+03	7.0108E+03	9.2993E+03	1.9225E+04
b	-1.6931E+01	-7.3026E+01	-1.3959E+02	-2.6432E+02
p	3.3753E+04	1.1788E+05	1.0938E+05	8.2782E+04

* FHWA Classification
Passenger car = Class 1, 2, 3
Small truck = Class 4, 5
Medium truck = Class 6, 7, 8
Large truck = Class 9, 10, 11, 12, 13

The model was reformulated and expanded to cover the complete list of the EPA's TRACI impact categories (Bare, 2012) resulting from an increment rate of pollutants as a function of vehicle speed and pavement IRI (Equations 3 and 4).

$$\Delta RSI_{t=0}^{Env.}: \quad \Delta\hat{I}(v, \Delta IRI) = \left[q_v . {}^{\Delta IRI}/_{63.36}\right] . I_i(v) \tag{3}$$

$$RSI_{t=0}^{Env.}: \quad \hat{I}(v, IRI) = I_i(v) + \Delta\hat{I}(v, \Delta IRI) \tag{4}$$

where
$\Delta\hat{I}(v, \Delta IRI)$ = estimated additional TRACI impacts *i* per vehicle distance (mile) at a given speed due to change in pavement roughness ΔIRI (in/mile),
q_v = % increase per one unit (63.36 in/mi) change in IRI, and
$I_i(v)$ = baseline TRACI impact *i* at a given speed and IRI = 0.

In selecting a baseline IRI, the threshold between an excellent and good rating of 60 in/mi was used (VDOT, 2019). For projects with an initial IRI below the 60 in/mi threshold (as in the case of Interstate 81), the initial IRI of that project was used as a basis in the estimation of the vehicles' energy consumption. The traffic information used as inputs to the RSI model is shown in Table 9.

Table 9. 2018 Traffic Information Inputs in the RSI Model

Traffic Information (one direction)	**I81**	**SR13**	**SR24**	**SR40EA&FA**	**US17NB&SB**
Total AADT	31,000	2,300	17,000	4,900	29,000
% Passenger cars	74	97.1	98.3	93.0	97.0
% Small trucks	2	0.9	0.8	0.8	0.4
% Medium trucks	21	1.4	0.3	2.2	1.1
% Large trucks	3	0.6	0.6	4.0	1.1
% Growth	5	3.0	3.0	3.0	3.0
Average Traffic Speed [mph]	70	45	60	45	55

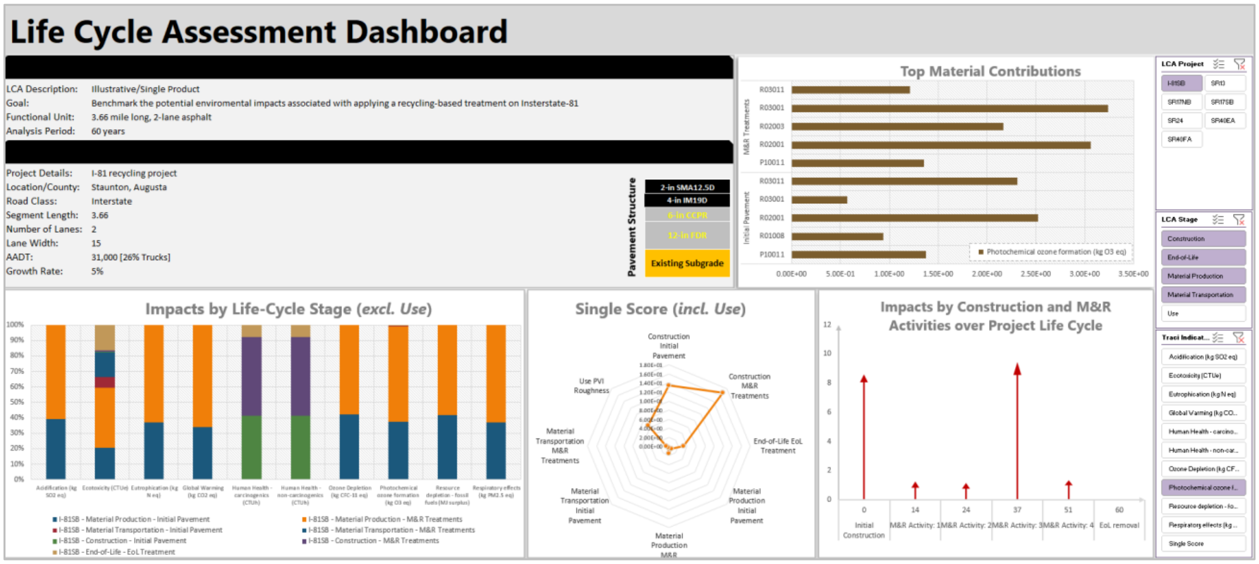
AADT = Average Annual Daily Traffic

Life Cycle Impact Assessment

The objective of the impact assessment is to translate the emission quantities (wastes and pollutants) obtained from the inventory analysis into meaningful and relatable indicators to facilitate interpretation of the results in relation to the LCA goal. The LCI results are characterized into various impact categories based on the potential effects that the resulting emissions have on humans, the natural environment, or the depletion of natural resources. The TRACI characterization model (incorporated in the in-house developed LCA tool—pySuPave) developed by the EPA was used. Even though most pavement LCAs report *energy use* and *global warming* as environmental indicators from the inventory analysis and impact assessment, respectively, including a broader set of impact category indicators, such as those defined in the TRACI methodology, is recommended (Bare, 2012).

Development of LCA Tool: PySuPave

As mentioned earlier, LCA tools and databases covering unit processes for pavement recycling methods are rare or not readily available. Thus, the LCA was performed with an in-house built tool—pySuPave—developed for pavement practices and materials in the state of Virginia. The LCA tool is capable of computing and reporting the potential environmental impacts associated with the main processes of each pavement life cycle stage (from material production to EOL). The tool is a Python-based application with an MS Excel user interface. MS Excel is also used to store a database of all key unit processes for the material extraction and production, construction processes and equipment, and typical transportation modes used to move materials and equipment used in various pavement-recycling treatments. The MS Excel interface has two main workbooks; a *user-inputs workbook* with multiple worksheets mimicking the phases defined in the pavement LCA framework, and a *database workbook* with multiple worksheets (libraries) covering unit processes for material extraction and production, construction tasks with corresponding machinery requirements, and various transportation modes, presented in the form of "Module-Product" matrices (Steubing et al., 2016). The Python scripts combine the user inputs with the inventory of environmental burdens from the Ecoinvent LCA databases and perform the LCA calculations. The tool also comes with a database comprising individual MS Excel files storing the environmental impacts related to all unit processes pertinent to a pavement LCA analysis (one per file), calculated according to the TRACI impact assessment methodology. Furthermore, the tool is capable of interfacing with commercial LCI databases, such as Ecoinvent, through the OpenLCA software to enable quick updates on inventory computations and impact assessment calculations. Figure 6 shows the dashboard displaying results from a sample LCA run using the pySuPave tool.


Life Cycle Assessment Dashboard

LCA Description: Illustrative/Single Product
Goal: Benchmark the potential enviromental impacts associated with applying a recycling-based treatment on Insterstate-81
Functional Unit: 3.66 mile long, 2-lane asphalt
Analysis Period: 60 years

Project Details: I-81 recycling project
Location/County: Staunton, Augusta
Road Class: Interstate
Segment Length: 3.66
Number of Lanes: 2
Lane Width: 15
AADT: 31,000 [26% Trucks]
Growth Rate: 5%

Figure 6. Dashboard from Developed LCA Tool Showing Results of Case Study

RESULTS AND DISCUSSION

Characteristic Moduli Values with Changes over Time

The backcalculation results are discussed in this section. The elastic modulus (E) values for the asphalt layer (temperature corrected), recycled base layer, and subgrade for the last set of FWD measurements collected in 2019 are reported in Figure 7.

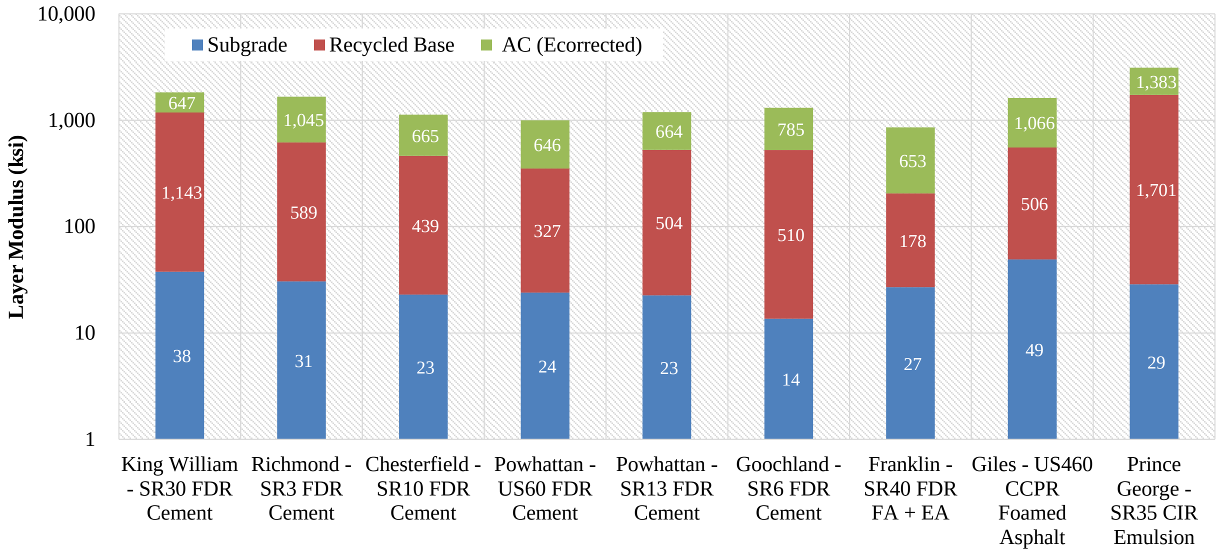
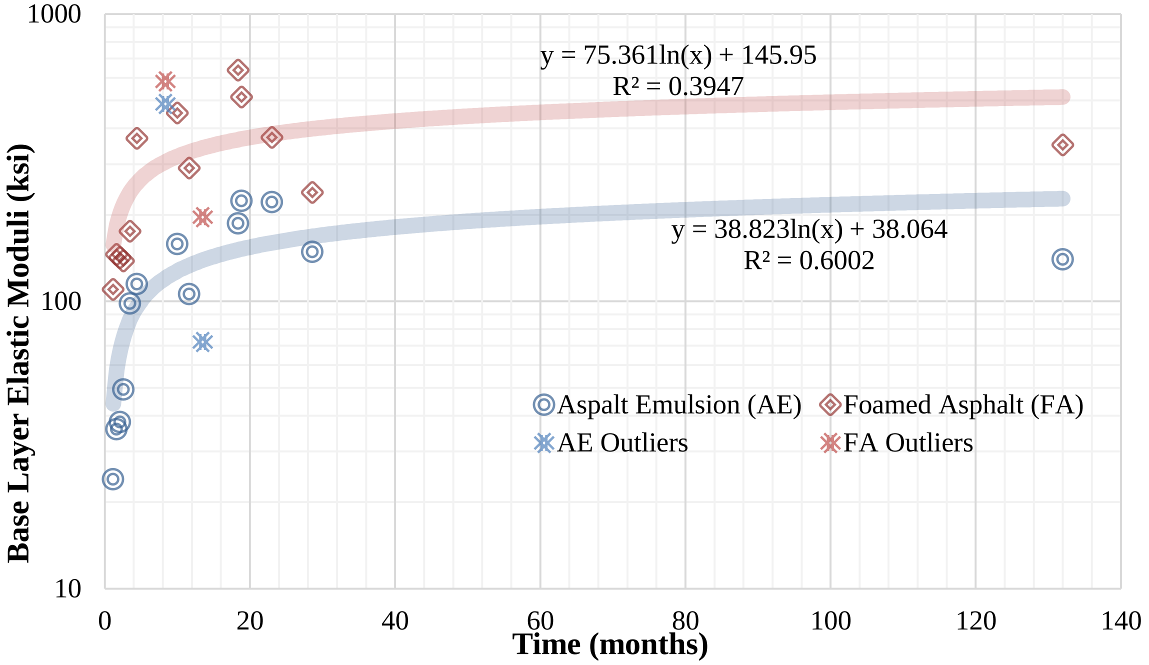
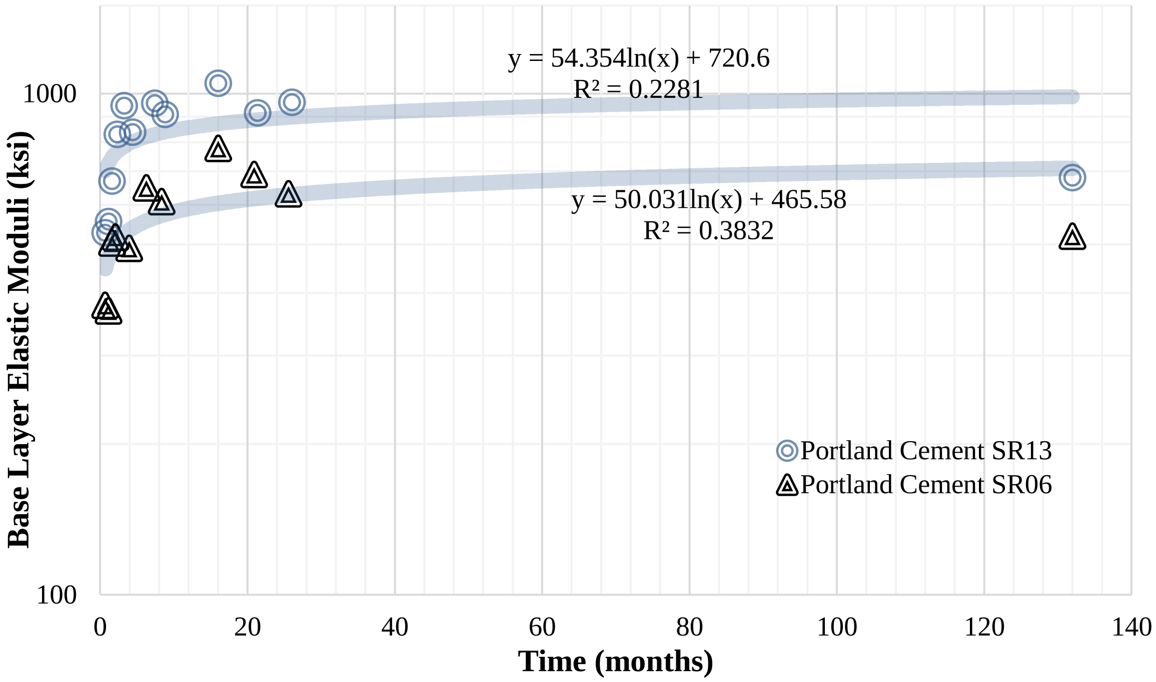


Figure 7. Backcalculated Layer Moduli (meeting acceptable RMSE) of 2019 FWD Measurements for Various Projects

Four FDR projects, two bitumen-stabilized (two adjacent sections on SR40) and two cement-stabilized (SR6 and SR13), completed in 2008 had additional FWD measurements collected at different times from 2008 to 2019. The changes in stiffness of the recycled FDR bases of the projects completed in 2008 are presented in Figure 8a (bitumen-stabilized) and Figure 8b (cement-stabilized).



(a)



(b)

Figure 8 Evolution of Backcalculated Elastic Modulus with Time: (a) Bitumen-Stabilized FDR Bases from SR40; (b) Cement-Stabilized SR6 and SR13 Projects

For the bitumen-stabilized projects (Figure 8a), an average 22% reduction in the layer modulus was observed—after approximately 10 years—from the initial strength gained after construction. A similar observation was made for the cement-stabilized FDR projects (Figure 8b), where a reduction in stiffness ranging from 14% to 24% of the initial 2-year strength gain is observed. The results in both cases are within the variability of the initial strength between 12 and 36 months after construction. Thus, it cannot be concluded that there is truly a reduction in the observed moduli after 10 years in service without additional testing. Recommended moduli values based on the averages of the backcalculated moduli according to the recycling methods after several years in service are provided in Table 10.

Table 10. Recommended Moduli Values for Recycling Method Estimated from Various Projects

Recycling Method	Age in Service	Subgrade (ksi)	Recycled Base (ksi)
FDR Cement	10	25	640
FDR Foamed Asphalt + Cement	12	27	340
FDR Emulsion	12	27	140
CCPR Foamed Asphalt	5	49	806
CIR Emulsion	9	29	[a]1,700

[a]values not temperature corrected

Pavement Deterioration Models

CCI Prediction Models

The AICc weight statistic was used to compare and select the best models. The closer a model's AICc weight is to 1 (or 100%), the higher the chances of it being closer to the true model among those being compared. Table 11 shows the test statistics from this step of the analysis; the negative binomial model was selected for further validation.

Table 11. Test Statistics for CCI Prediction Model Comparison

Function	General Equation	AICc	AICc Weight	SSE	RMSE
Negative Binomial	$a - Age^{b} \times Exp(c)$	270.7	54%	222.0	6.3
Quadratic	$a + b \times Age + c \times Age^{2}$	272.5	22%	228.2	6.5
Logistic 3P	$\frac{c}{1 + Exp(-a \times (Age - b))}$	272.8	18%	229.5	6.6
Gompertz 3P	$a \times Exp\left(Exp\left((-b \times (Age - c))\right)\right)$	275.1	6%	237.5	6.8
Exponential 3P	$a - b \times Exp(c \times Age)$	281.7	0%	262.9	6.6
Linear	$a - b \times Age$	338.6	0%	630.6	12.9
Exponential 2P	$a \times Exp(b \times Age)$	346.5	0%	713.1	14.6

Note: *a, b, c* = model coefficients

As the CCI is an index ranging from 0 to 100, the model was "refitted," this time with appropriate restrictions on the model coefficients. The effect of constraining or restricting the parameters (y-intercept) on the overall model was evaluated by checking if there is a statistical difference between the SSE of the restricted and original model. The results of the test statistics are presented in Table 12.

Table 12. Test Statistics for Evaluating Effects of Fixing Parameters on Original Model

Model		SSE	DFE	MSE	Restrictions	F Ratio	P value (Prob > F)
Negative Binomial	original	237.5	35	6.79		0.4930	0.8828
	a fixed	316.8	45	7.04	$a = 100$		

There is insufficient statistical evidence to conclude that the SSEs for the compared models (original and fixed parameters) are statistically different as the *p*-value was found to be greater than 0.05. Thus, one can conclude that models with the intercept set to 100 can be used without any significant changes to the model. The coefficients and test statistics from the regression and the final deterioration models are presented in Figure 8 and

Table 13, respectively.

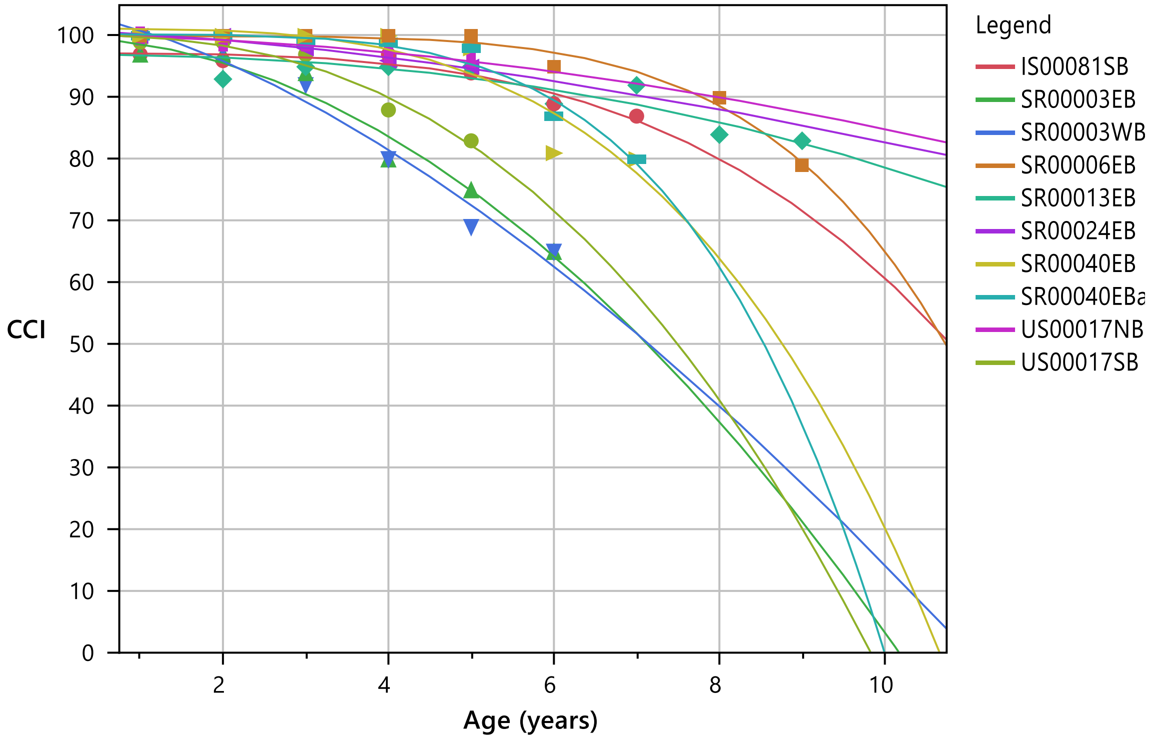


Figure 9. Deterioration Models for CCI

Table 13. Parameter Estimates and Statistics for CCI Prediction Model

Project ID	**Parameter Estimates**					
	a	**Standard Error**	***b***	**Standard Error**	***c***	**Standard Error**
IS81SB-CCPR/FDR	100	0	1.7	0.7	-0.7	1.3
SR3EB-FDR C	100	0	1.9	0.2	0.1	0.4
SR3WB-FDR C	100	0	1.8	0.2	0.3	0.3
SR6EB-FDR C	100	0	5.0	1.5	-8.1	3.3
SR13EB-FDR C	100	0	1.3	0.3	0.0	0.7
SR24EB-FDR C	100	0	2.1	1.7	-1.7	2.6
SR40EB-FDR FA+C	100	0	3.9	0.7	-4.4	1.3
SR40EBa-FDR EA	100	0	4.5	1.0	-5.8	1.9
US17NB-CIR EA	100	0	2.0	2.3	-1.8	3.5
US17SB-CIR FA	100	0	2.6	0.7	-1.3	1.1

IRI Prediction Models

In many PMS applications, the IRI is used together with the CCI to make rehabilitation decisions. In pavement LCA, modeling IRI values is commonly used to estimate a trigger for maintenance needs. Furthermore, these models are also used to relate pavement roughness to vehicle fuel consumption during the use stage because of the rolling resistance. The model functions and corresponding statistics are presented in Table 14.

Table 14. Test Statistics for IRI Model Comparison

Function	General Equation	AICc	AICc Weight	SSE	RMSE
Exponential 2P	$a \times Exp(b \times Age)$	495.4	73%	2927.9	8.1
Linear	$a + b \times Age$	497.4	27%	3019.0	8.2

Based on the AICc weight values, the exponential 2P model was found to be the model that best predicts the IRI from the treatment age compared to the linear model. Table 15 shows the estimates and test statistics for the final IRI model selected. The Interstate 81 project (IS81SB) was found to have a significantly lower initial IRI value (48 in/mi) compared to the overall average of 85 in/mi. The number of paved layers was highest for this project compared to the other projects analyzed. In turn, the SR40Ba project was found to have a significantly high rate of IRI deterioration (7 in/mi/year, *linear approx. of the term, b*) compared to the overall average of 2 in/mi/year. The average rate of change of IRI for the cement-stabilized and bitumen-stabilized FDR treatments was found to be 1.5 and 5.2 in/mi/year, respectively, while the bitumen-stabilized CIR treatments were found to deteriorate at a rate value of 0.7 in/mi/year (*also linear approx. of b*). Figure 10 presents the results in the analysis of means (ANOM) graphs. Observations in red are statistically different from the mean.

Table 15. Parameter Estimates and Statistics for IRI Prediction Models.

Project	Parameter Estimates			
	a	***p-value***	***b***	***p-value***
IS81SB-CCPR/FDR	48.5	<.0001	0.008	0.79
SR3EB-FDR C	79.2	<.0001	0.034	0.11
SR3WB-FDR C	89.9	<.0001	0.021	0.30
SR6EB-FDR C	90.0	<.0001	0.007	0.52
SR13EB-FDR C	91.9	<.0001	0.014	0.19
SR24EB-FDR C	105.0	<.0001	0.004	0.87
SR40EB-FDR FA+C	89.7	<.0001	0.035	0.02
SR40EBa-FDR EA	100.8	<.0001	0.058	<.0001
US17NB-CIR EA	74.2	<.0001	0.003	0.94
US17SB-CIR FA	84.2	<.0001	0.013	0.65

a = initial IRI
b = growth constant, the frequency (number of times per unit time) of growing by a factor ***e***

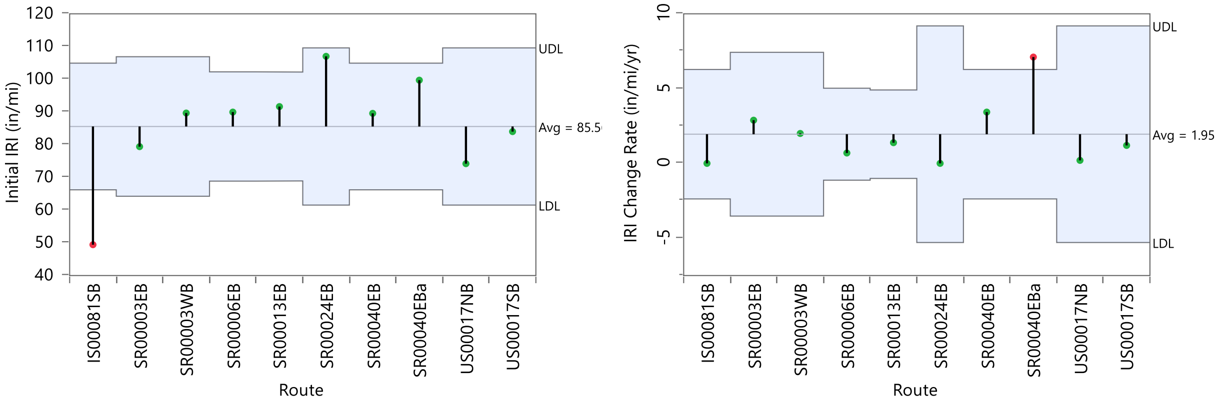


Figure 10. Comparison of the Initial IRI Values and Annual Linear Rate of Change across Projects (blue bands represent lower and upper limits of the confidence interval)

Estimation of Treatment Functional Service Life

Table 16 shows the results of the estimated service life of the various treatments from typical trigger values used by VDOT for rehabilitation decisions. Both the IRI and CCI models were used in the estimation, and the lower of the two results was selected as the final estimated service life for conservatism.

Table 16. Results of Treatment Service Life Estimation

Model Function	Project ID	ADTT	Parameter Predicted	Condition Trigger	Estimated Life
Negative Binomial	IS81SB-CCPR/FDR	6943	CCI	40	18
	SR3EB-FDR C	92		40	8
	SR3WB-FDR C	85		40	8
	SR6EB-FDR C	127		40	11
	SR13EB-FDR C	172		40	26
	SR24EB-FDR C	61		40	16
	SR40EB-FDR FA+C*	48		40	9
	SR40EBa-FDR EA*	48		40	9
	US17NB-CIR EA	127		40	19
	US17SB-CIR FA	170		40	8
Exponential 2 P	IS81SB-CCPR/FDR	6943	IRI (in/mi)	140	> 30
	SR3EB-FDR C	92		140	17
	SR3WB-FDR C	85		140	21
	SR6EB-FDR C	127		140	> 30
	SR13EB-FDR C	172		140	30
	SR24EB-FDR C	61		140	> 30
	SR40EB-FDR FA+C*	48		140	13
	SR40EBa-FDR EA*	48		140	6
	US17NB-CIR EA	127		140	> 30
	US17SB-CIR FA	170		140	> 30

FA = Foamed Asphalt, EA = Asphalt Emulsion
* short section lengths (0.25 miles)

Using a terminal CCI value of 40 (poor condition) and a threshold IRI value of 140 in/mi (VDOT, 2014), the service lives of the projects were estimated from an inverse prediction of the project age. It resulted in an average service life of 13 years with a standard deviation of 6 years. The average service life of the cement-treated FDR was estimated to be 14 years. The average service life of the bitumen-treated FDR projects was estimated to be 9 years, respectively. The bitumen-treated CIR sections' service life averaged 13 years with a standard deviation of 7 years. The IS81SB project, which combines FDR, CIR, and CCPR, was estimated to have a service life of 18 years. Finally, it is worth mentioning that these results are aligned with the values found in the literature (Asphalt Recycling and Reclaiming Association, 2015; Peshkin et al., 2004) and survey data from contractors reported by Senhaji (2017).

Comparison of Models

The model developed for predicting the CCI from pavement age was compared to existing PMS models. The model developed for the interstate recycling projects was compared to a default PMS interstate reconstruction model whose model coefficients are based on average performance (and expert opinion) using the Stantec model. Figure 11 shows that the predicted service life using the interstate recycling project performance model is greater than the service life estimated using the default interstate deterioration model for reconstructed pavements.

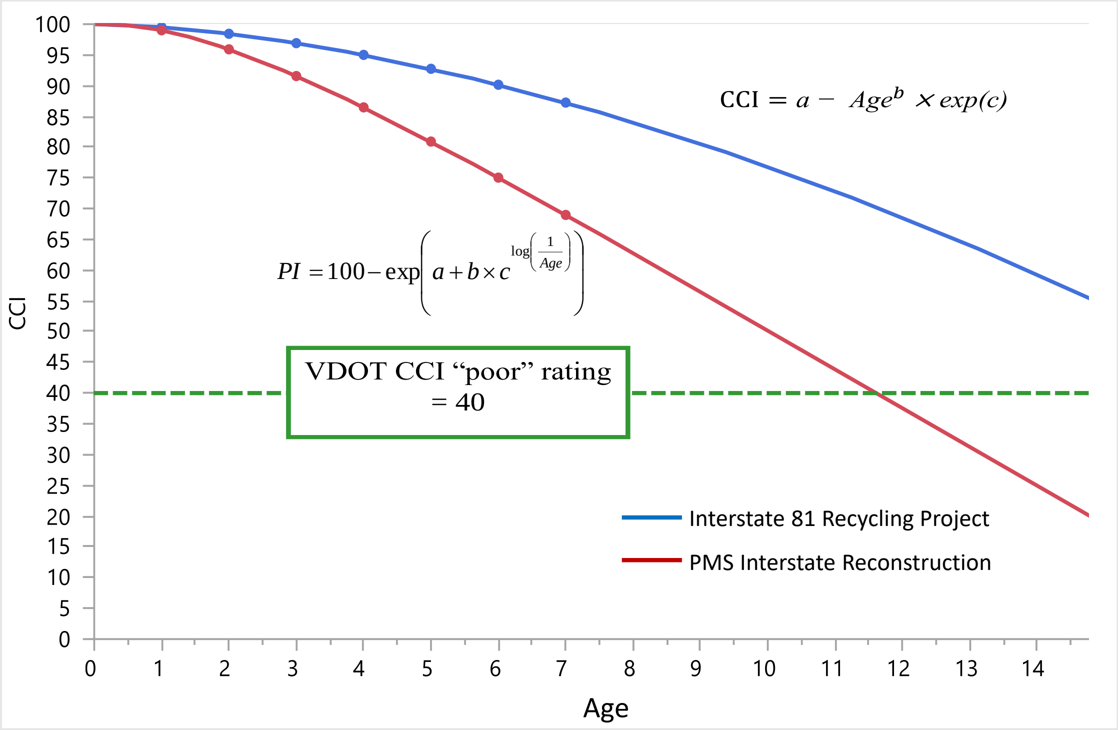


Figure 11. Comparison of Equivalent Interstate Reconstruction Models

Other Distress Prediction Models

The performance models developed for rutting, fatigue cracking, thermal cracking, and longitudinal cracking are presented in Appendix B.

Impact Assessment Results

Recycling Projects with Associated Global Warming Impact and Single Score Index

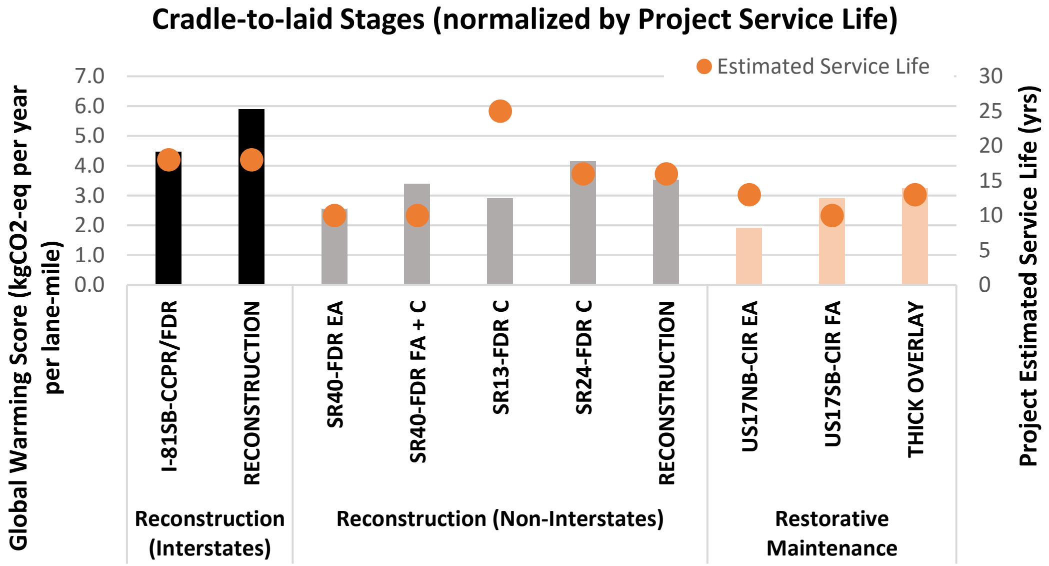
This section reports the GW scores for each recycling project normalized by dividing each project's result by its corresponding service life and ranks the projects (under each rehabilitation category, i.e., RM, RC) using the overall single score index. The total impacts considering all life cycle stages within the system boundary are reported and shown in Table 17. Further probing of the results indicated that the impacts of the use stage were orders of magnitude larger (approximately 98%) than the scores of the material production, transportation, and construction stages and would make these three latter scores practically insignificant if all four were added together. Thus, the cradle-to-laid impacts (considering material production, transportation, and construction) associated with the projects and the use-stage impacts per project were evaluated separately.

Table 17. GW Impact and Single Score Index across All Life Cycle Stages Considered in the System Boundary Normalized by Projects' Estimated Service Lives

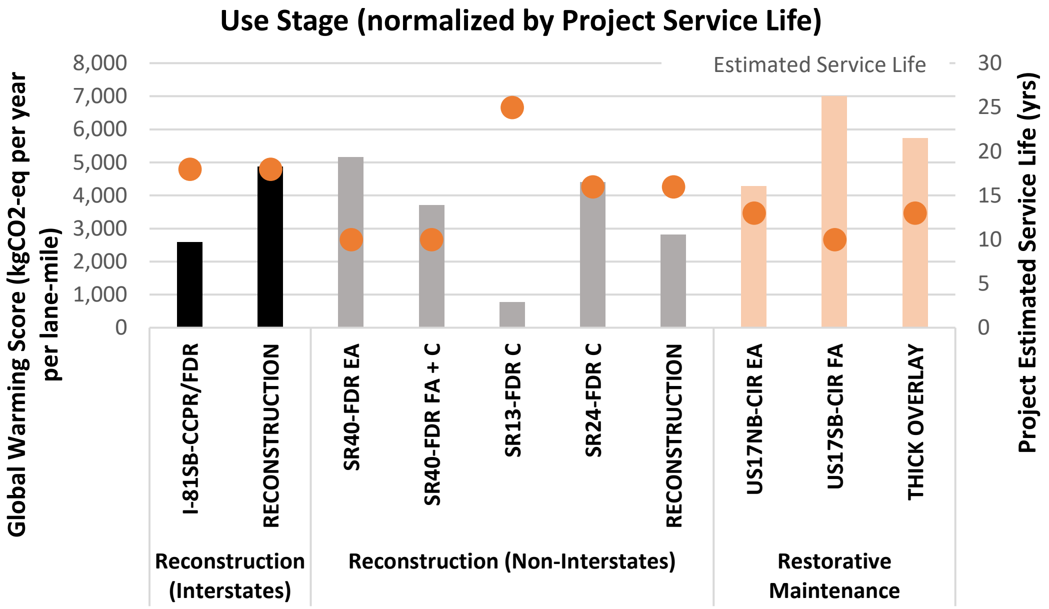
Rehabilitation Category	Rehabilitation Project	GW (kgCO2-eq per year per lane mile)	Single Score Index (pts per year)
Reconstruction (Interstates)	IS-81SB-CCPR/FDR	2592.89	0.12
	RECONSTRUCTION*	4875.96	0.25
Reconstruction (Non-Interstates)	SR40-FDR EA	5159.93	0.20
	SR40-FDR FA + C	3718.71	0.15
	SR13-FDR C	771.83	0.05
	SR24-FDR C	4402.50	0.30
	RECONSTRUCTION*	2824.67	0.22
Restorative Maintenance	US17NB-CIR EA	4283.17	0.21
	US17SB-CIR FA	7008.77	0.34
	THICK OVERLAY*	5739.62	0.29

* denotes the conventional alternative

The breakdown of the GW score by contribution of the various components in the life cycle stages is shown in Figure 12**.** Considering the cradle-to-laid stages of the projects' life cycle (Figure 12a), the I-81SB project combining CCPR and FDR had lower GW scores by approximately 24% compared to the alternative of reconstructing a new pavement with the conventional method. This is due to the higher thickness and therefore the large quantity of materials needed to reconstruct a pavement with equivalent strength as that attained by the I-81 project, and consequently the high number of trips needed to transport these materials to the construction site. For the other reconstruction projects considered for primary roads, projects with cement (as a primary stabilizer or as an additive) generally produced higher cradle-to-laid GW scores compared to the conventional reconstruction project of similar strength (as seen with the SR13 C and conventional RECONSTRUCTION projects). This is expected due to the large amount of CO_2 emissions generated during the calcination process in cement production (Santero, 2010). The use of portland limestone cement—shown to produce approximately 10% less greenhouse gas emissions but similar performance as ordinary portland cement—can be explored (Thongsanitgarn et al., 2012). The emulsified asphalt-stabilized FDR project produced the lowest GW score among the treatment categories. For projects in the restorative maintenance category, CIR projects yielded lower cradle-to-laid GW scores—approximately 26% (US17NB at 45% and US17SB at 10%)—compared to the conventional overlay (THICK OVERLAY) project. The transportation of materials for the construction of the conventional overlay project contributed to its higher GW score.



(a)



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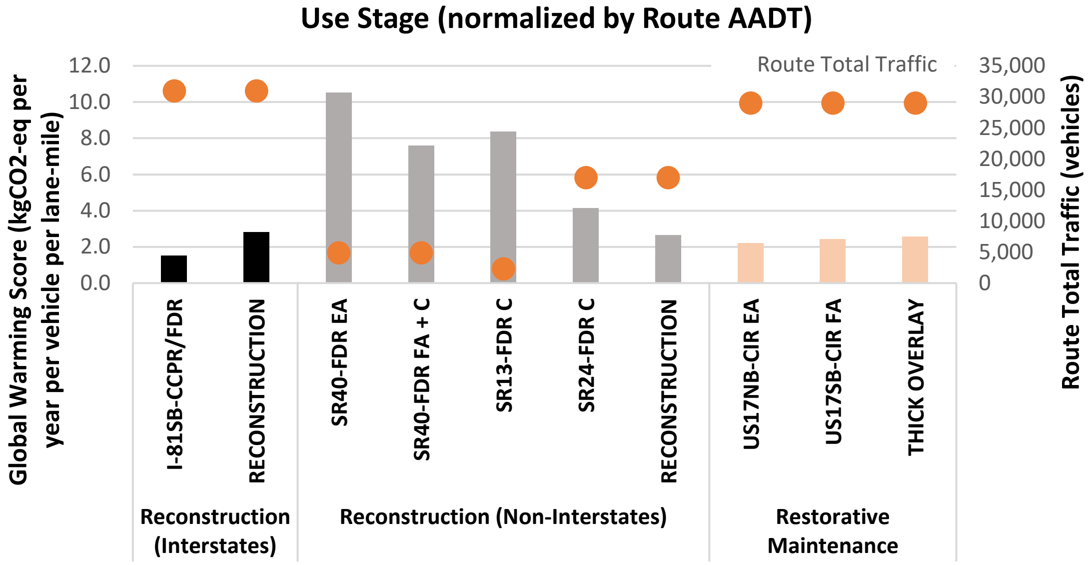

(c)

Figure 12. Comparison of GW Results for (a) Cradle-to-laid Normalized by Service Life (b) Use Stage Roughness Normalized by Service Life (c) Use Stage Roughness Normalized by Total Traffic

Figure 12b and Figure 12c show the use-stage GW scores normalized by each project's estimated service life and the route traffic volume. The trends are similar in both figures except for the SR13-FDR C project, where the lowest GW score is observed when normalized by service life compared to when the scores are normalized by the traffic volume. This is because the SR13-FDR C project is estimated to last longer (25 years) than all projects in the non-interstate reconstruction rehabilitation category and it also has the lowest traffic volume (2,300 vehicles). For the restorative maintenance projects, noticeable differences in use-stage GW scores are observed when normalized by service life: SR17-CIR EA with the longest estimated life yielding the lowest score. However, the differences are less pronounced when normalized by traffic. To further understand and explain the factors influencing the use-stage impacts, the 10-year GW score for each project and several input parameters were analyzed. Table 18 reports the 10-year GW score for the projects under consideration. Generally, the higher the route traffic, the higher the GW score. However, large trucks on low-volume roads traveling at low speeds between 45 and 55 mph can yield very large GW scores.

Table 18. Cumulative GW Score after 10 years in Service (Use Stage)

Rehabilitation Category	**LCA Project**	**Baseline IRI (in/mi)**	**Initial IRI (in/mi)**	**Change Rate (in/mi/yr)**	**AADT**		**Speed (mph)**	**GW (kgCO2-eq) per lane-mile**
					Passenger Cars	**Total Trucks**		
Reconstruction (Interstates)	I-81SB-CCPR/FDR	48	49	0.83	22,940	8,060	70	20,156
	RECONSTRUCTION	48	50	1.00	22,940	8,060	70	38,950
Reconstruction (Non-Interstates)	SR40-FDR EA	60	101	7.06	4,557	343	45	51,574
	SR40-FDR FA + C	60	90	2.69	4,557	343	45	37,153
	SR13-FDR C	60	92	1.38	2,233	67	45	6,359
	SR24-FDR C	60	107	0.54	16,711	289	60	41,403
	RECONSTRUCTION	60	90	1.80	16,711	289	60	26,506
Restorative Maintenance	US17NB-CIR EA	60	74	0.20	28,130	870	55	35,344
	US17SB-CIR FA	60	84	1.20	28,130	870	55	70,059
	THICK OVERLAY	60	79	2.37	28,130	870	55	55,752

For any two projects with the same traffic inputs, the GW score is higher for the project with higher initial IRI, as observed with the following project pairs: I-81SB/RECONSTRUCTION under the interstate reconstruction category; SR40-FDR EA / SR40-FDR FA+C, and SR24-FDR C / RECONSTRUCTION under the primary-roads reconstruction category; and the THICK OVERLAY / US17NB&SB restorative maintenance projects (Figure 13). The interstate project with the lowest initial IRI and low deterioration resulted in the lowest GW score even though it had a comparable number of passenger cars as the US17 projects. Since the initial roughness after projects were completed and their future deterioration rates can be controlled by the contractor and to some extent by the agency, measures should be taken to keep these factors low by incentivizing lower initial roughness attained by contractors even for low-volume primary and secondary roads. In addition to the low carbon footprint associated with low after-construction IRIs, other expected indirect benefits would include reduced vehicle maintenance and better fuel efficiency. Table 19 provides additional examples of techniques that could result in lower GW scores.

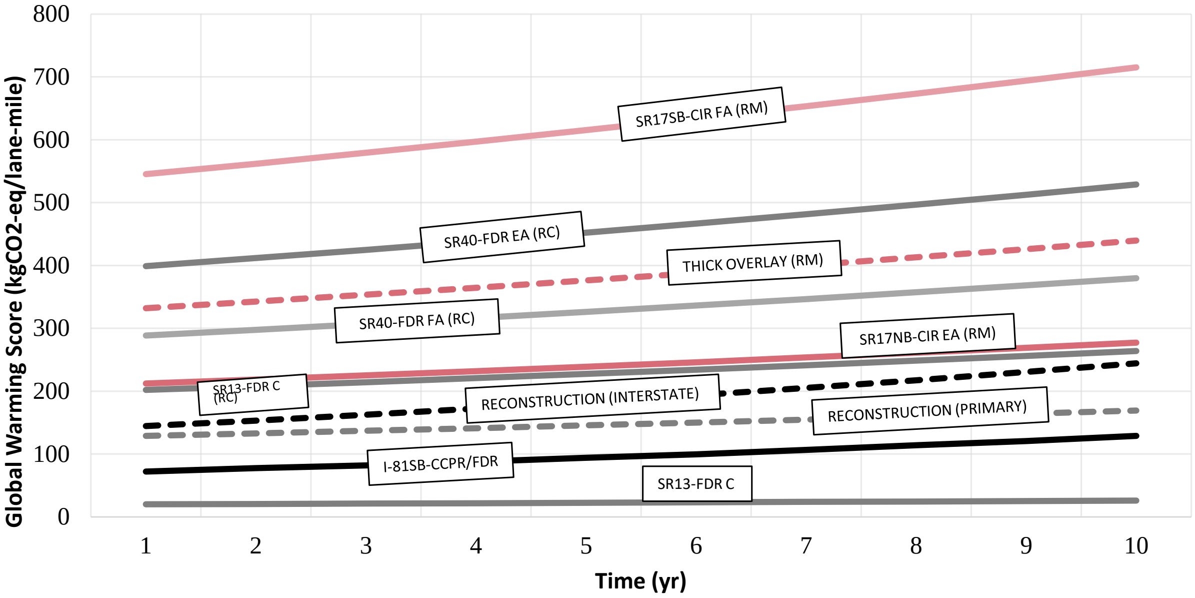

Figure 13. Ten-Year Evolution of GW Score for Various Recycling Projects

Table 19. Summary of Benefits and Drawbacks of Recycling Techniques Compared to Conventional Methods Based on the Research Findings

Recycling Method	Benefits / Drawbacks Observed from Study	Potential Solutions / Recommendation
Full Depth Reclamation (FDR) with Cement	• Onsite materials reduce GW through low transport distances • Stiffer base layer • Long estimated functional service life (8-30 yrs) • High initial IRI compared to state recycling average • High GW at cradle-laid stage due to use of ordinary portland cement	• Profile milling • Paver-laid FDR • Compressive strength limits • Use of cement alternatives such as portland limestone cement (PLC)
Full Depth Reclamation with Asphalt Stabilization (*based on one project*)	• Onsite materials reduce GW through low transport distances • Estimated functional service life between 6 and 13 yrs • Low GW at cradle-to-laid stage • Higher change in IRI for emulsion project (may be due to susceptibility to moisture)	• Explore PLC as active filler to emulsion projects • Profile milling • Paver-laid FDR
Cold In-place Recycling with Asphalt Stabilizers	• Onsite materials reduce GW through low transport distances • Low initial IRI and annual rate of change compared to state recycling average • Only suitable when distresses are limited to the bound layers	• Explore PLC as active filler to foam and emulsion projects
Cold Central Plant Recycling over Full Depth Reclamation	• Low initial IRI and annual deterioration rates compared to state recycling average • Can be used for high-volume/high priority roads • Considerably high GW at cradle-laid stage due (large quantity of works, CCPR haul distance) • Low overall GW due to low initial IRI and deterioration rate.	• Explore locating mobile plants close to project site to reduce hauling distances

GW = Global warming, IRI = International roughness index

Finally, assessing the projects by the single score index per year derived from weighting factors from the National Institute of Standards and Technology ranks the projects as follows (listed in order of decreasing impacts under their respective rehabilitation categories):

- Interstate reconstruction
    - Conventional approaches (0.25 pts)
    - I-81SB-CCPR/FDR (0.12 pts)
- Primary routes reconstruction
    - Conventional approaches (0.22 pts)
    - SR24-FDR C (0.3 pts)
    - SR40-FDR EA (0.2 pts)
    - SR40-FDR FA (0.15 pts)
    - SR13-FDR C (0.05 pts)

- Primary routes restorative maintenance
    - Conventional approaches (0.29 pts)
    - US17SB-CIR FA (0.34 pts)
    - US17NB-CIR EA (0.21 pts)

Overall, VDOT’s current practice of employing pavement recycling methods to rehabilitate distressed highways—even though it may yield higher environmental impact at the construction stage (in instances where CCPR is combined with FDR)— can yield lower environmental burdens over the life cycle when pavement designs are optimized for smoothness and traffic loads.

SUMMARY OF FINDINGS

- Deflection testing was found to be useful in describing the structural performance of pavement recycling projects. However, some projects had no structural data or large time gaps between subsequent tests.
- A slight reduction in the stiffness of the recycled bases for the 2008 FDR projects after 12 years in service was observed but it was within the variability of the strength between 12 and 36 months.
- The average initial IRI values and average rates of change in IRI for the treatments analyzed were found to be 85 in/mi and 2 in/mi/yr, respectively.
- The predicted service life of the FDR projects applied on primary/secondary roads (estimated from the lower of threshold values for CCI of 40 and IRI of 140 in/mi) ranged from 8–26 years, with cement-stabilized projects generally having longer predicted service lives compared to the asphalt-stabilized projects.
- The functional service life of the Interstate 81 project was estimated at 18 years (based on data for the right lane where FDR and CCPR were used).
- The estimated deterioration rate of the Interstate 81 project was found to be lower than the assumed deterioration rate for conventional interstate reconstruction projects used by VDOT.
- The cement-treated projects were found to have a longer estimated service life compared to asphalt-stabilized projects but also had a larger GW impact (during the material production stage) due to the large amounts of energy required during the production of ordinary portland cement.
- The use stage was found to contribute the largest proportion to the impact assessment indicators (GW and overall single score) included in this study. In particular, the roughness immediately after construction and annual deterioration rate were found to be key characteristics.

CONCLUSIONS

- *Regular structural testing of completed pavement recycling projects would help to better document their performance for future analysis.*

- *FDR/recycled bases retain initial stiffness after 10 years in service. The slight reduction in the stiffness of the recycled bases for the 2008 FDR demonstration projects after 12 years in service was within the variability of the initial strength between 12 and 36 months after construction.*

- *Compared to the overall project mean, there were no significant differences in the initial IRI values for the recycled projects except for the Interstate 81 project.*

- *The lower initial IRI and lower rate of change in IRI for the Interstate 81 project are attributed to the construction practices and thicker pavement employed.*

- *A larger relative cradle-to-laid GW impact for projects that incorporated cement-treated layers can be attributed to the relatively large quantities of energy needed for cement production. Other cement alternatives like portland limestone cement proven to produce low emissions can be explored.*

- *Based on the lower estimated deterioration rate of the Interstate 81 project, when compared to the assumed deterioration rate for conventional interstate reconstruction projects used by VDOT, the Interstate 81 project is expected to have a longer service life than typical interstate reconstruction projects.*

- *If a project is constructed having a lower initial IRI, this smoothness level is likely to persist for a longer period and ultimately contribute to much lower overall GW.*

RECOMMENDATIONS

1. *VTRC and VDOT's Materials and Maintenance Divisions should develop a testing plan to conduct reoccurring structural evaluation of all completed pavement recycling projects.*

2. *VDOT's Materials Division should encourage (or incentivize) practices that result in lower initial IRI values to reduce GW impacts for recycling projects.*

3. *VTRC and VDOT's Materials Division should list those components of pavement recycling that can reduce GW impacts over the project life cycle compared to conventional designs.*

4. *VTRC and VDOT's Maintenance Division should develop an additional set of deterioration models for pavement recycling projects to be used in the agency PMS.*

5. *VTRC and VDOT's Materials and Maintenance Divisions should develop a framework to assist with future implementation of LCA practices for pavements.*

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, a reoccurring structural evaluation plan for pavement recycling projects should include FWD or Traffic Speed Deflectometer (TSD) testing at approximately 6 and 18 months after construction and then every 3 to 5 years thereafter. VDOT's Materials and Maintenance Divisions and VTRC will develop this plan within Fiscal Year 2022.

With regard to Recommendation 2, the Rideability for Completed Pavement Projects Special Provision should continue to be applied by VDOT district pavement management and materials staff to pavement recycling projects where applicable.

With regard to Recommendation 3, VTRC and VDOT's Materials Division will develop and submit a research needs statement (RNS) for this topic to the appropriate PaveRAC subcommittee within Fiscal Year 2022.

With regard to Recommendation 4, VTRC and VDOT's Maintenance Division will develop and submit a RNS for this topic to the appropriate PaveRAC subcommittee within Fiscal Year 2022.

With regard to Recommendation 5, VTRC and VDOT's Materials and Maintenance Divisions will develop and submit a RNS for this topic to the appropriate PaveRAC subcommittee within Fiscal Year 2022.

Benefits

This study provides evidence that changes in practice can lead to significant reductions in VDOT's GW impact related to pavement M&R. With results from this research, VDOT decision makers can make more informed policy decisions, and pavement practitioners can select M&R alternatives that will result in more economical and sustainable practices. Regarding Recommendation No. 1, additional structural evaluation will help VDOT better understand the function and deterioration of pavement recycling projects and lead to more efficient designs. Regarding Recommendation No. 2, encouraging (or incentivizing) lower initial IRI values will help reduce GW impacts from pavement M&R practices and help VDOT in meeting goals within the MAP21/FAST Act. Previous research has already shown that projects having lower initial IRI values tend to retain those lower values over their service lives (McGhee and Gillespie, 2006). With regard to Recommendation No. 3, copying the design concepts used on the I-81 recycling project will result in pavement sections having a long service life, reduced future maintenance needs, and lower GW impacts. Regarding Recommendation No. 4, developing specific deterioration models for pavement recycling projects will help to accurately reflect their positive impact on the performance of the pavement network and further promote the use of pavement recycling. Regarding Recommendation No 5, developing an LCA framework will assist VDOT with implementing best practices that encourage reduced GW impacts within pavement M&R activities.

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APPENDIX A

PAVEMENT RECYCLING PROJECTS IN VIRGINIA

This section of the report describes completed and ongoing asphalt pavement recycling projects in the state of Virginia as of 2018.

Table A.1. Compilation of Completed or Ongoing Pavement Recycling Projects in Virginia as of 2018

District	County	Route(s)	Direction	Year Constructed	Estimated Lane Miles	Recycling Method
Bristol	Scott	224	Both	2014	0.43	FDR
Salem	Franklin	40	Both	2008	1.1	FDR
	Bedford	24	Both	2012	5.94	FDR
	Giles	460	W	2015	7.14	CCPR
Richmond	Powhatan	13	Both	2008	7.3	FDR
	Goochland	6	Both	2008	7.2	FDR
	Powhatan	60	W	2010	3.32	FDR
	Powhatan	13	Both	2016	n/a	FDR
	Henrico	60	Both	2011	3.72	CIR
	Prince George	35	Both	2011	4.7	CIR
	Chesterfield	10	W	2012	2.4	FDR
	Dinwiddie	I-85	S	2014-2015	21	CCPR
	Brunswick	I-85	Both	2017	6.53	FDR
Hampton Roads	Isle of Wight	17	Both	2012	19.5	CIR
	Isle of Wight	620	Both	2012	2.78	FDR
	Accomack	709	Both	2015	7.98	FDR
	Accomack	609	Both	2015	5.92	FDR
	York	I-64, Seg. II	Both	2017-2020	42	CCPR & FDR
	York	I-64, Seg. III	Both	2018-2021	49	CCPR & FDR
	York	620	Both	2014	2.5	FDR
	Surry	602	Both	2019	5.6	FDR
	Sussex	139	Both	2019	2.4	FDR
Fredericksburg	Richmond	3	Both	2012	5.96	FDR
	King William	30	Both	2013	8	FDR
Staunton	Augusta	I-81	S – Right Lane	2011	3.66	CCPR & FDR
			S – Left Lane	2011	3.66	CIR

E = Eastbound, W = Westbound, N = Northbound, S = Southbound, FDR = Full-Depth Reclamation, CCPR = Cold Central Plant Recycling, CIR = Cold In-place Recycling, FA = Foamed Asphalt, EA = Emulsified Asphalt

Full Depth Reclamation Projects

2008 (SR40, SR6, SR13)

SR40

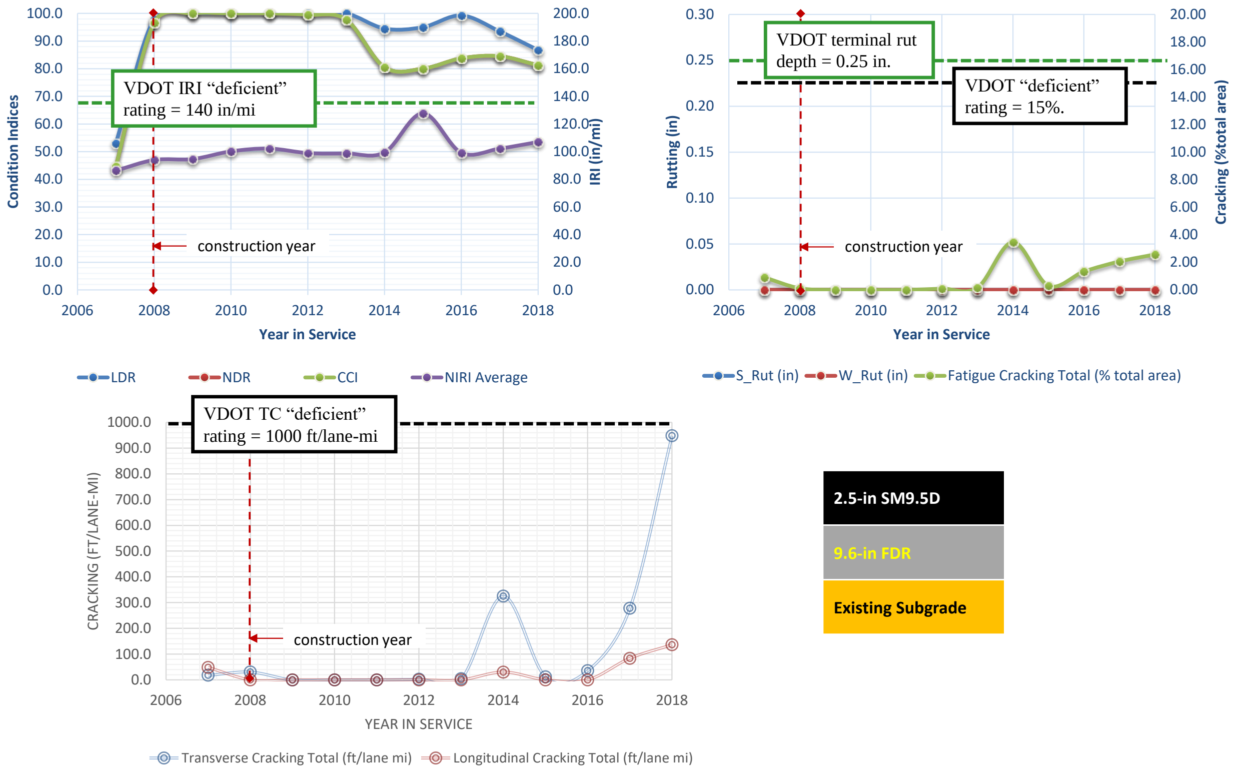


Figure A.1. Performance Plots and Structure for the SR40 FDR Foamed Asphalt Project (Franklin County)

Table A.2. SR40 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	Foam - $11.12/SY
Total recycled	4,356 SY
Stabilization agent	Foamed Asphalt (2.7%) + Cement (1%)
Unit cost of stabilizing agent	Included in unit cost of recycling
Total used	n/a
Project Length	0.5

SR40

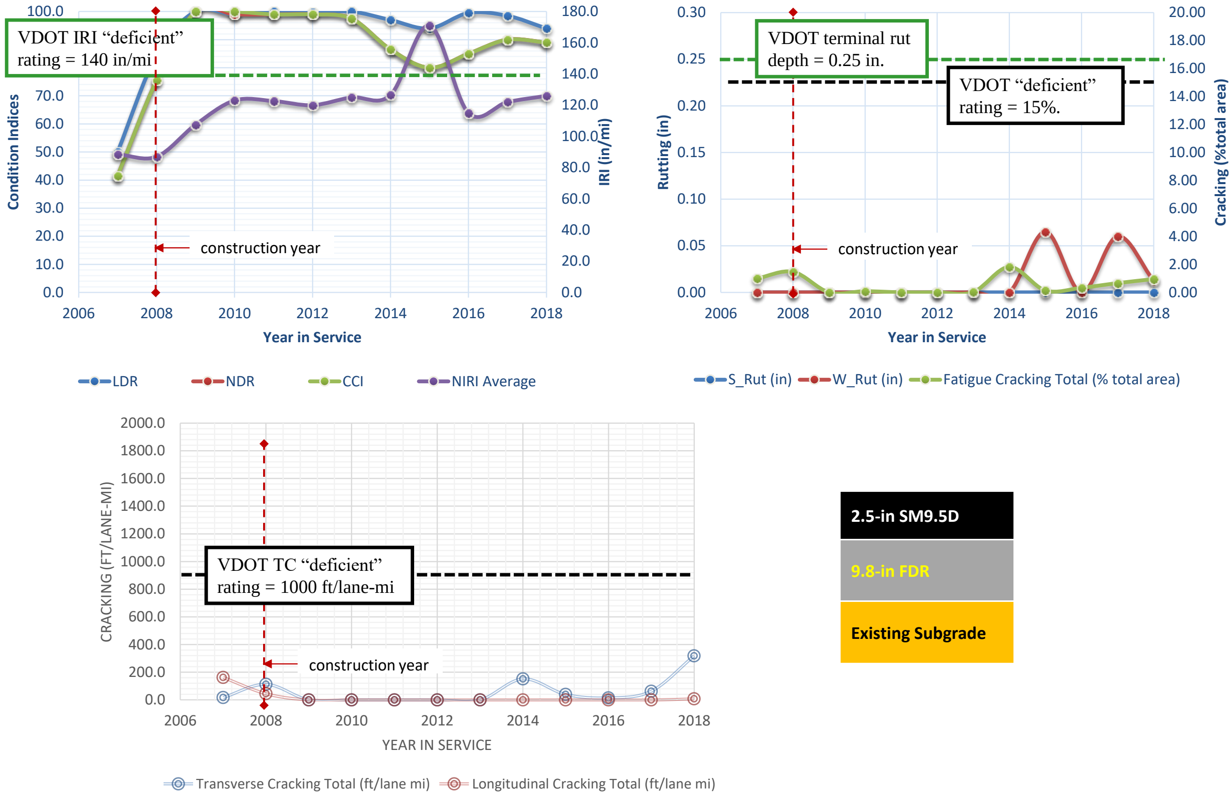


Figure A.2. Performance Plots and Structure for the SR40 FDR Emulsion Asphalt Project (Franklin County)

Table A.3. SR40 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	Emulsion - $15.49/SY
Total recycled	4,536 SY
Stabilization agent	Emulsion (3.5%)
Unit cost of stabilizing agent	Included in unit cost of recycling
Total used	n/a
Project Length	0.6

SR13

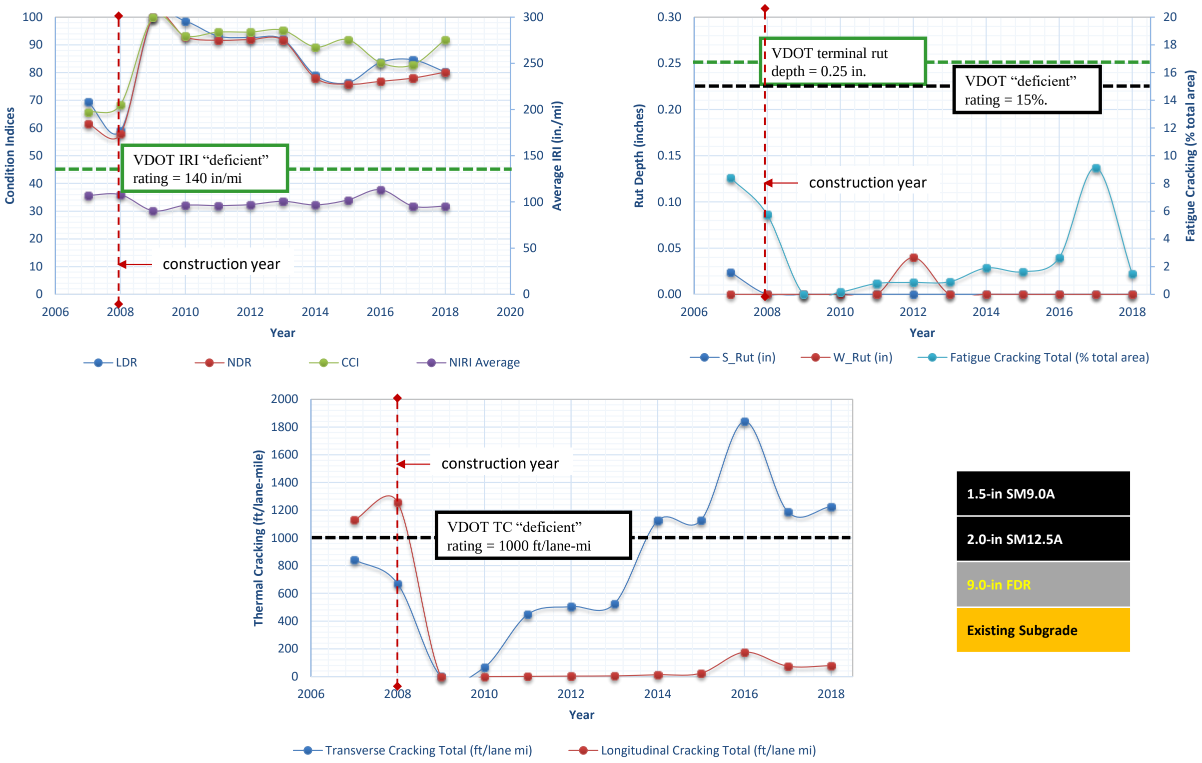


Figure A.4. Performance Plots and Structure for the SR13 FDR Project (Powhatan County)

Table A.3. SR13 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$3.52
Total recycled	50,060 SY
Stabilization agent	Cement (5%)
Unit cost of stabilizing agent	n/a
Total used	2746 tons (combined for SR13 and SR6)
Project Length	7.3

SR6

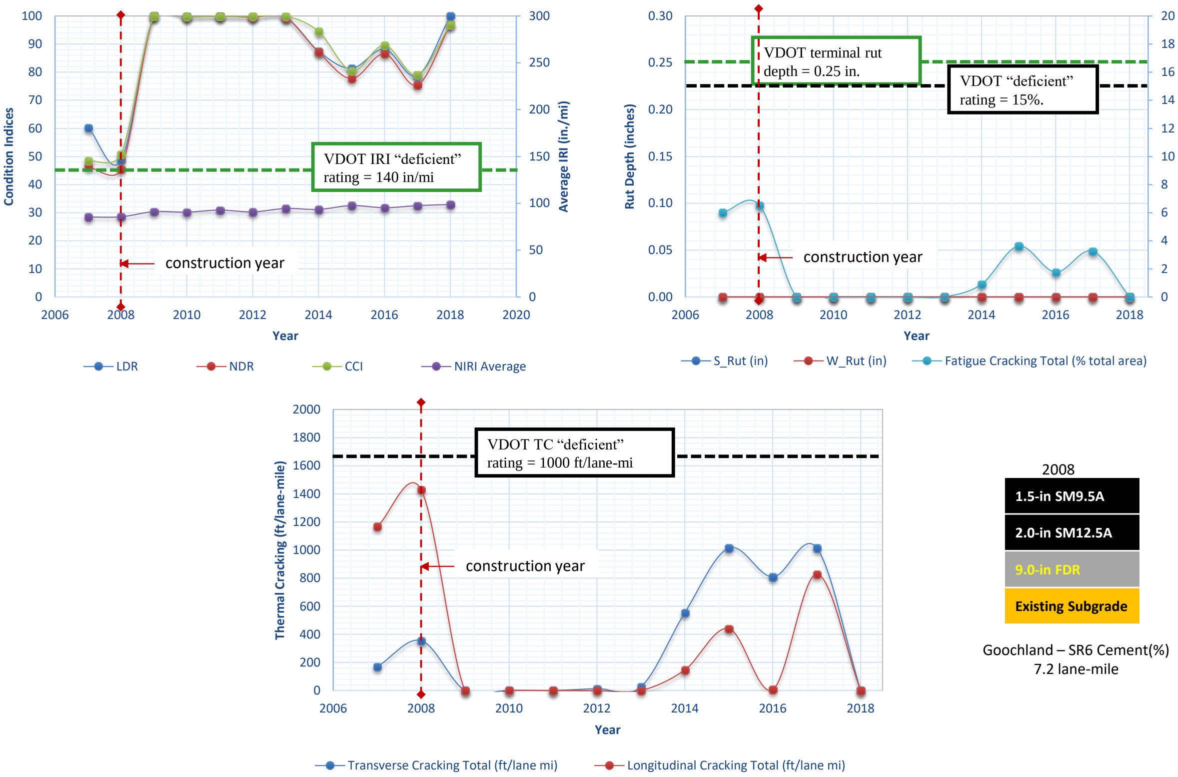


Figure A.4. Performance Plots and Structure for the SR6 FDR Project (Goochland County)

Table A.5. SR6 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$3.52/SY
Total recycled	53,680 SY
Stabilization agent	Cement (5%)
Unit cost of stabilizing agent	n/a
Total used	2746 tons (combined for SR13 and SR6)
Project Length	7.2 lane-mi

2010 (US 60)

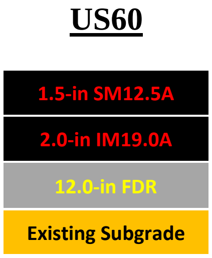


Figure A.5. Structure for US60 FDR Project (Powhatan County - Mulberry Drive)

Table A.6. US60 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$3.73/SY
Total recycled	32,256 SY
Stabilization agent	Cement
Unit cost of stabilizing agent	$127.19/ton
Total used	1,118 tons
Project Length	3.32 lane-mi

2011 (*I-81*)

I-81

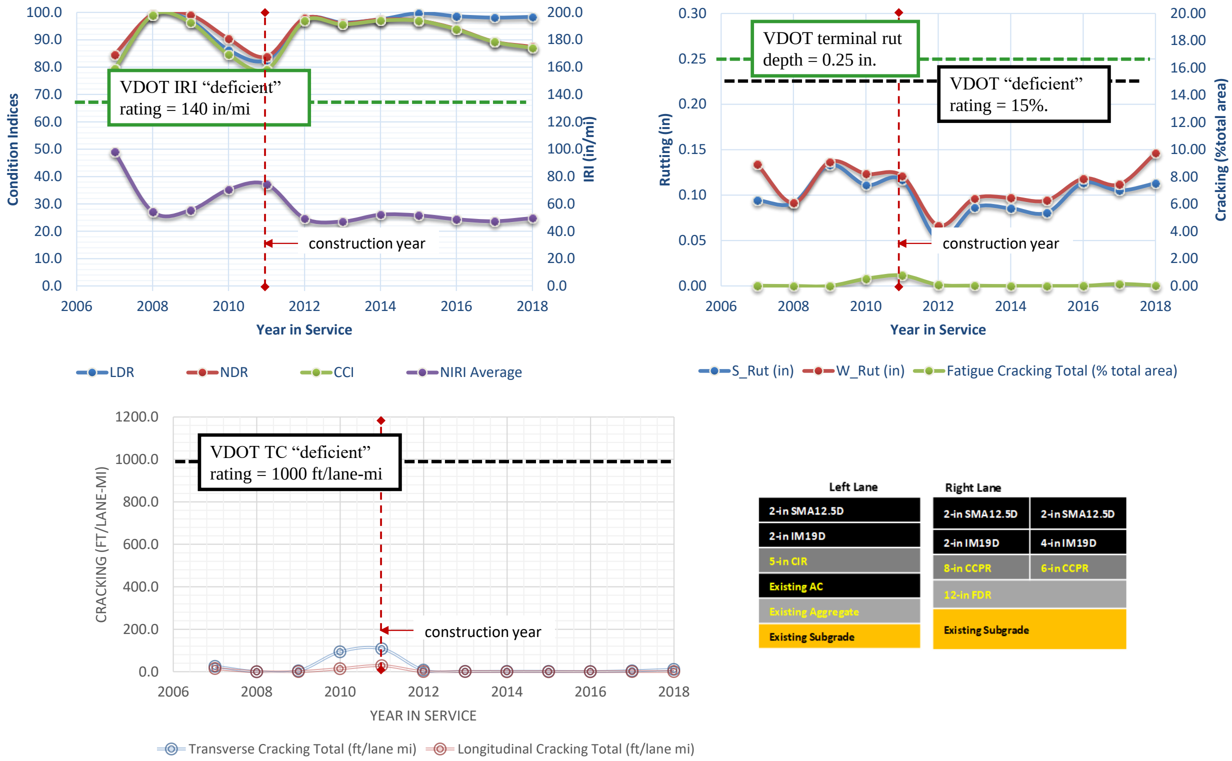


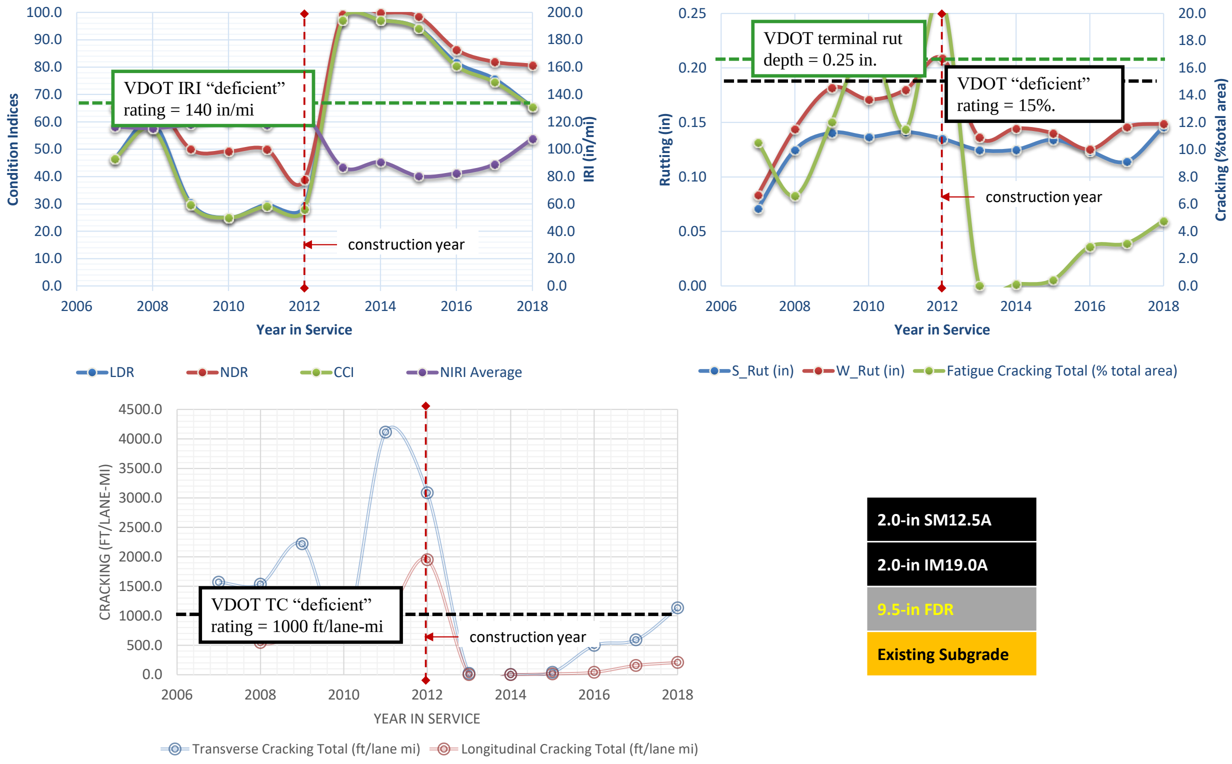
Figure A.6. Performance Plots and Structure for the I-81 CIR, CCPR, and FDR Project (Augusta County)

Table A.7. I-81 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$49.00/SY
Total recycled	30,061 SY
Stabilization agent	*Right Lane* – CCPRM: Foam AC + Cement, FDR: Cement (5%) *Left Lane* – CIR Emulsion
Unit cost of stabilizing agent	$573.00/Ton
Total used	564 Tons
Project Length	7.32 lane-mi

2012 (SR 3, SR 24, SR 10, SR 620)

SR3EB &WB



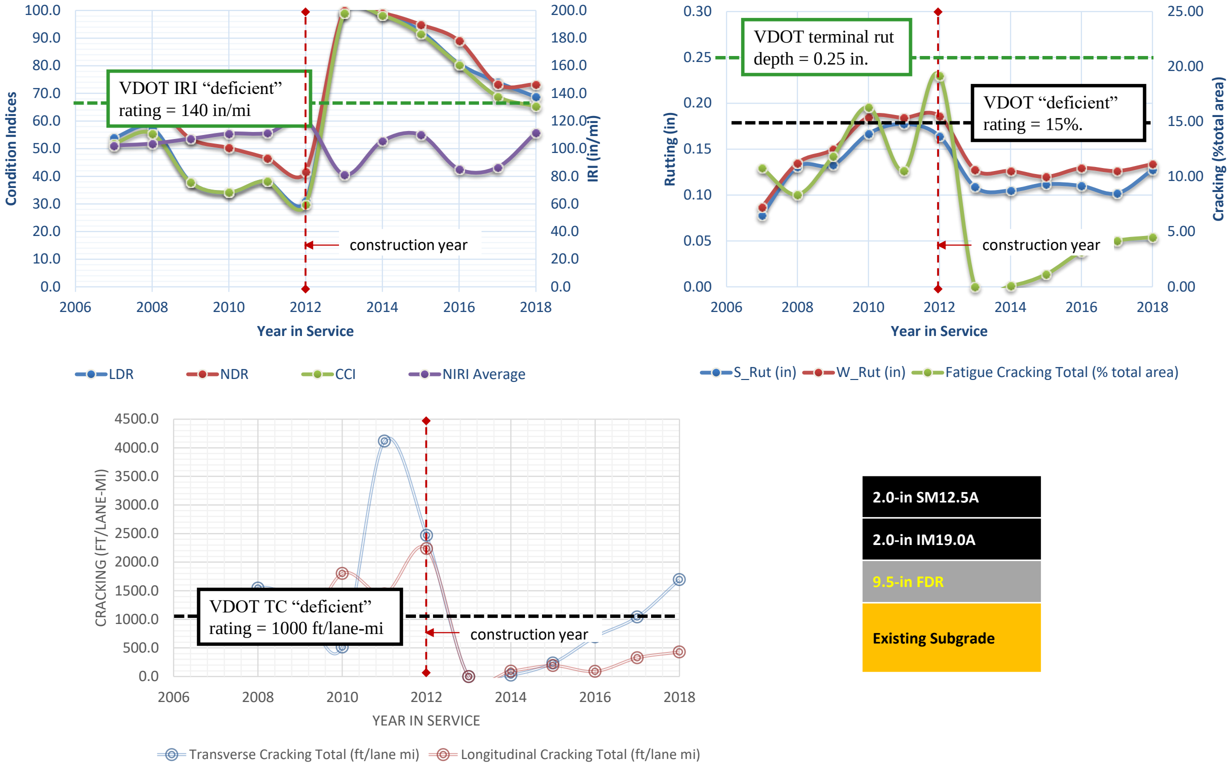
VDOT IRI "deficient" rating = 140 in/mi

VDOT terminal rut depth = 0.25 in.

VDOT "deficient" rating = 15%.

VDOT TC "deficient" rating = 1000 ft/lane-mi

(a)



(b)

Figure A.7. Performance Plots and Structure for the SR3 FDR Project: (a) Eastbound (b) Westbound (Richmond County)

Table A.8. SR3 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	n/a
Total recycled	n/a
Stabilization agent	Cement
Unit cost of stabilizing agent	n/a
Total used	n/a
Project Length	5.96

SR24

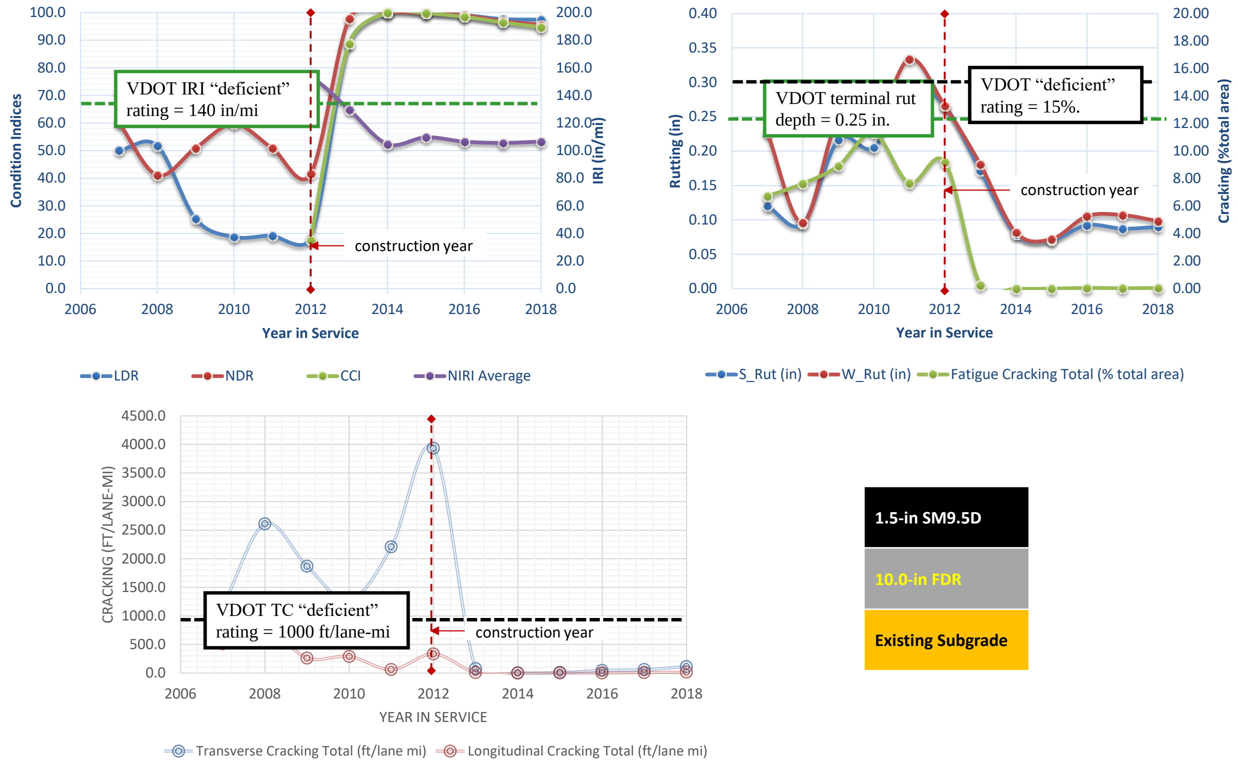


Figure A.8. Performance Plots and Structure for SR24 FDR Project (Bedford County)

Table A.9. SR24 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$8.68/SY (developed as a value engineering proposal)
Total recycled	17,351 SY
Stabilization agent	Cement
Unit cost of stabilizing agent	$166.91/ton
Total used	521 tons
Project Length	5.94 lane-mi

SR10

Figure A.9. Structure for the SR10 FDR Project (Chesterfield County)

Table A.10. SR10 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$15.00/SY
Total recycled	15,185 SY
Stabilization agent	Cement (5%)
Unit cost of stabilizing agent	Included in unit cost of recycling
Total used	n/a
Project Length	2.4 lane-mi

SC620

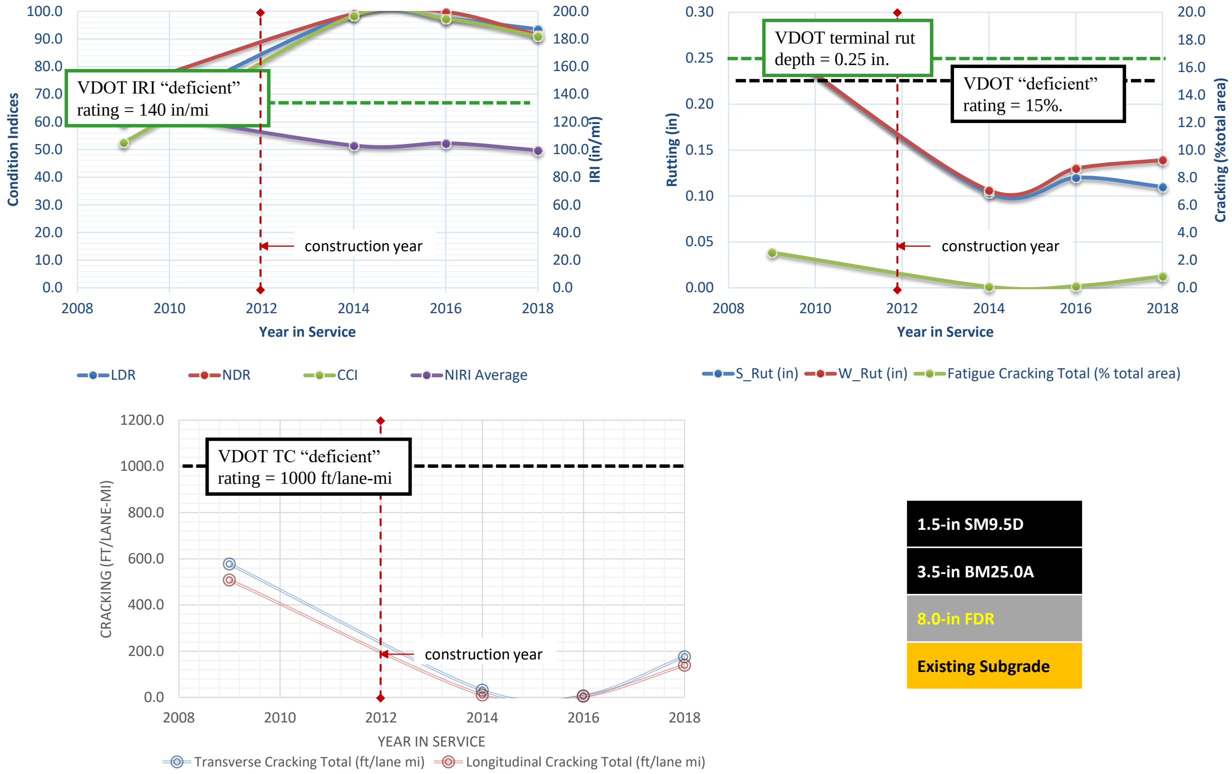


Figure A.10. Performance Plots and Structure for the SC620 FDR Project (Isle of Wight County)

Table A.11. SC620 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$11.70/ SY
Total recycled	16,155 SY
Stabilization agent	cement (6%)
Unit cost of stabilizing agent	Included in manipulation
Total used	n/a
Project Length	2.78

2013 (SR 30)

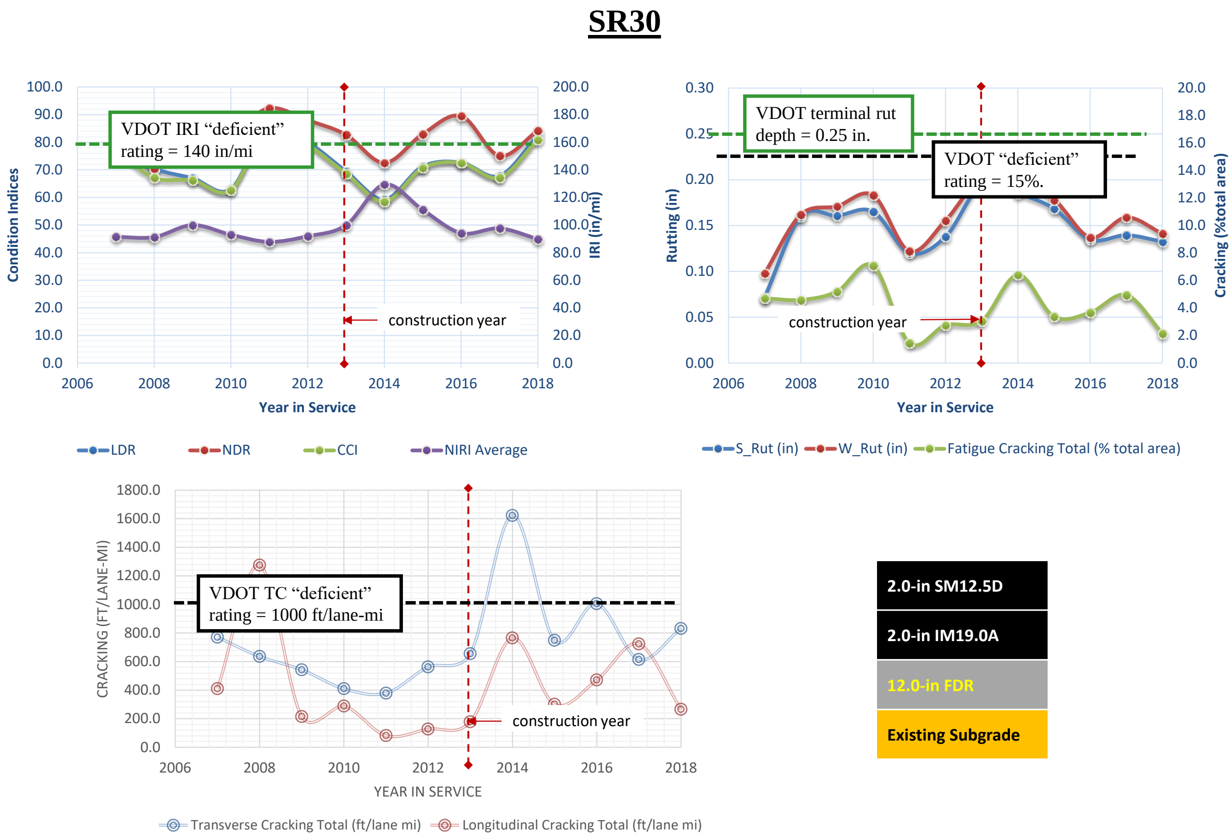


Figure A.11. Performance Plots and Structure for the SR30 Cement FDR Project (King William County)

Table A.12. SR30 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$6.96 /SY
Total recycled	91,000 SY
Stabilization agent	n/a
Unit cost of stabilizing agent	n/a
Total used	n/a
Project Length	8 lane-mi

2014 (SR 224, SR 620)

SR224

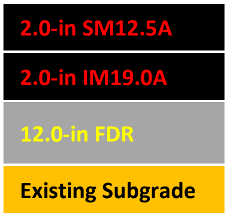


Figure A.12. Structure for the SR224 FDR Project (Scott County)

Table A.13. SR224 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$10.04/ SY
Total recycled	17,351 SY
Stabilization agent	cement
Unit cost of stabilizing agent	$166.91/ton
Total used	521 tons
Project Length	2.25 lane-mi

SR620

Figure A.13. Structure for the SR620 FDR Project (York County)

Table A.14. SR620 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$11.70/ SY
Total recycled	16,155 SY
Stabilization agent	cement (5%)
Unit cost of stabilizing agent	$169.13/ton
Total used	572 tons
Project Length	2.5 lane-mi

2016 (*SR 13, SR 609, SR 709*)

SR13

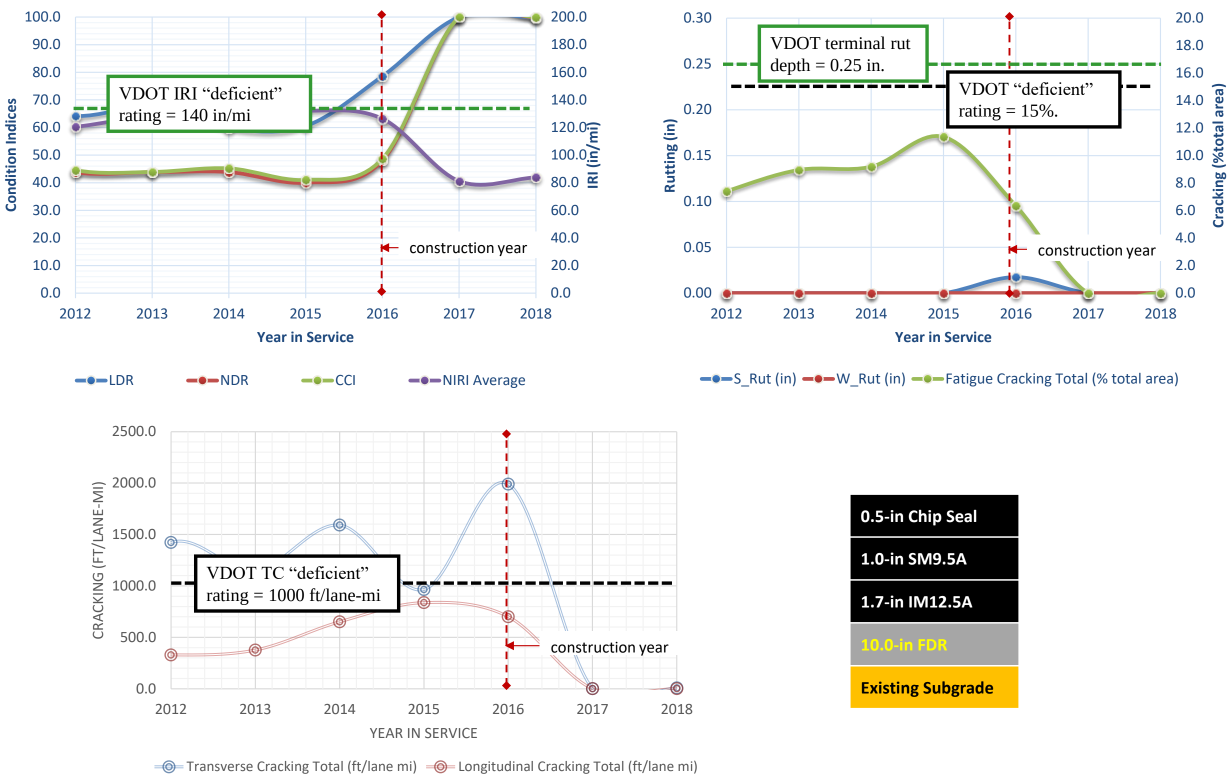


Figure A.14. Performance Plots and Structure for the SR13 FDR Project (Powhatan County)

Table A.15. SR13 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$7.86/SY for FDR Manipulation (project was developed as a on-call FDR contract)
Total recycled	n/a
Stabilization agent	Cement
Unit cost of stabilizing agent	$161.25/ton
Total used	n/a
Project Length	n/a

SR609

Figure A.15. Structure for the SR609 FDR Project (Accomack County)

Table A.16. SR609 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$5.30/SY
Total recycled	48,098 SY
Stabilization agent	cement (5%)
Unit cost of stabilizing agent	$250/ton
Total used	678 tons
Project Length	7.98 lane-mi

SR709

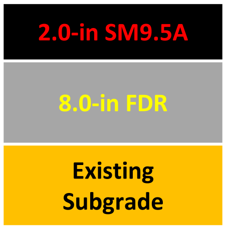


Figure A.16. Structure for the SR709 FDR Project (Accomack County)

Table A.17. SR709 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$ 5.9/SY
Total recycled	41,455 SY
Stabilization agent	cement (5%)
Unit cost of stabilizing agent	216.4/ton
Total used	917 tons
Project Length	5.92 lane-mi

2017 (*I-85, I-64*)

I-85

Figure A.17. Structure for the I-85 FDR Project (Brunswick County)

Table A.18. I-85 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$2.86/SY
Total recycled	53,633.10 SY
Stabilization agent	Cement
Unit cost of stabilizing agent	$135.00/ton
Total used	1,468 tons
Project Length	6.53 lane-mi

I-64

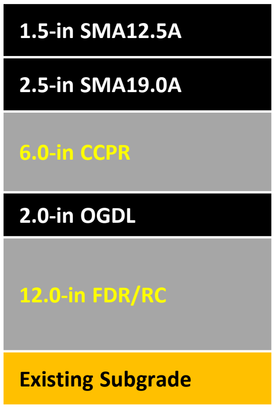


Figure A.18. Structure for the I-64 Segment II CCPR and FDR Project (York County)

Table A.19. I-64 Segment II Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	CCPR = $ 75.71/ton, FDR = 4.65 SY, CTRM = 50.95/ton
Total recycled	168,000 tons, FDR = 344,651 SY, CTRM = 146,000 tons
Stabilization agent	CCPRM: Foam AC + Cement, FDR: Cement (5%)
Unit cost of stabilizing agent	Design Build Lump Sum
Total used	
Project Length	42 lane-mi

2018 *(I-64)*

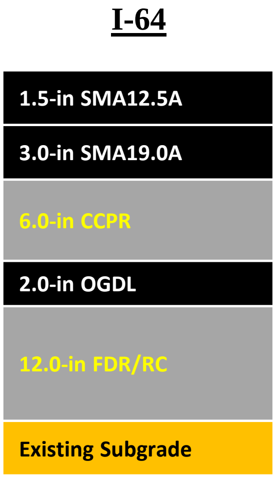


Figure A.19. Structure for the I-64 Segment III CCPR and FDR Project (York County)

Table A.20. I-64 Segment III Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	CCPR = $65/ton, FDR = $7/SY, CTRM = $37/ton
Total recycled	CCPR = 195,670 tons, FDR = 229,010 SY, CTRM = 201,050 tons
Stabilization agent	CCPRM: Foam AC + Cement, FDR: Cement (5%)
Unit cost of stabilizing agent	Design Build Lump Sum
Total used	
Project Length	49 lane-mi

Cold Central Plant Recycling Projects

2014-2015 (*I-85 South*)

I-85

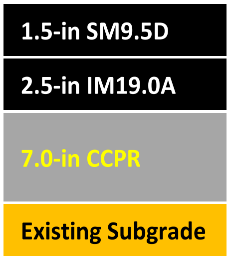


Figure A.20. Structure for the I-85 CCPR Project (Dinwiddie County)

Table A.21. I-85 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$ 8.50/ton
Total recycled	126615 tons
Stabilization agent	Foam asphalt + cement
Unit cost of stabilizing agent	$600/ton
Total used	628 tons
Project Length	21 lane-mi

2015 (*US 460*)

Figure A.21. Structure for the US460 CCPR Project (Giles County)

Table A.22. US460 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$ 21.10/ton
Total recycled	50,266 tons
Stabilization agent	Foamed asphalt + cement
Unit cost of stabilizing agent	$665.36/ton
Total used	498 tons
Project Length	7.14 lane-mi

Cold In-place Recycling Projects

2011 (*SR60, SR35*)

SR60 E&W

Figure A.22. Structure for the SR60 CIR Project (Henrico County)

Table A.23. SR60 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$ 8.30/ton
Total recycled	28,371 tons
Stabilization agent	Emulsion
Unit cost of stabilizing agent	$665/ton
Total used	260 tons
Project Length	3.72 lane-mi

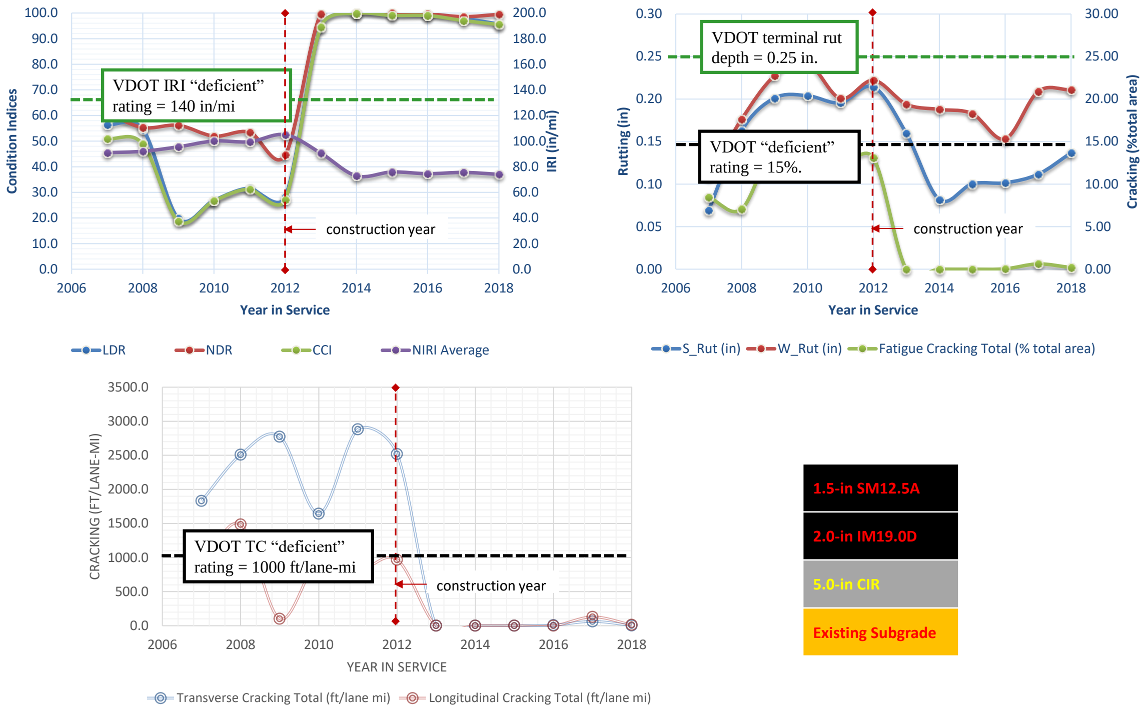
SR35

Figure A.23. Structure for the SR35 CIR Project (Prince George County)

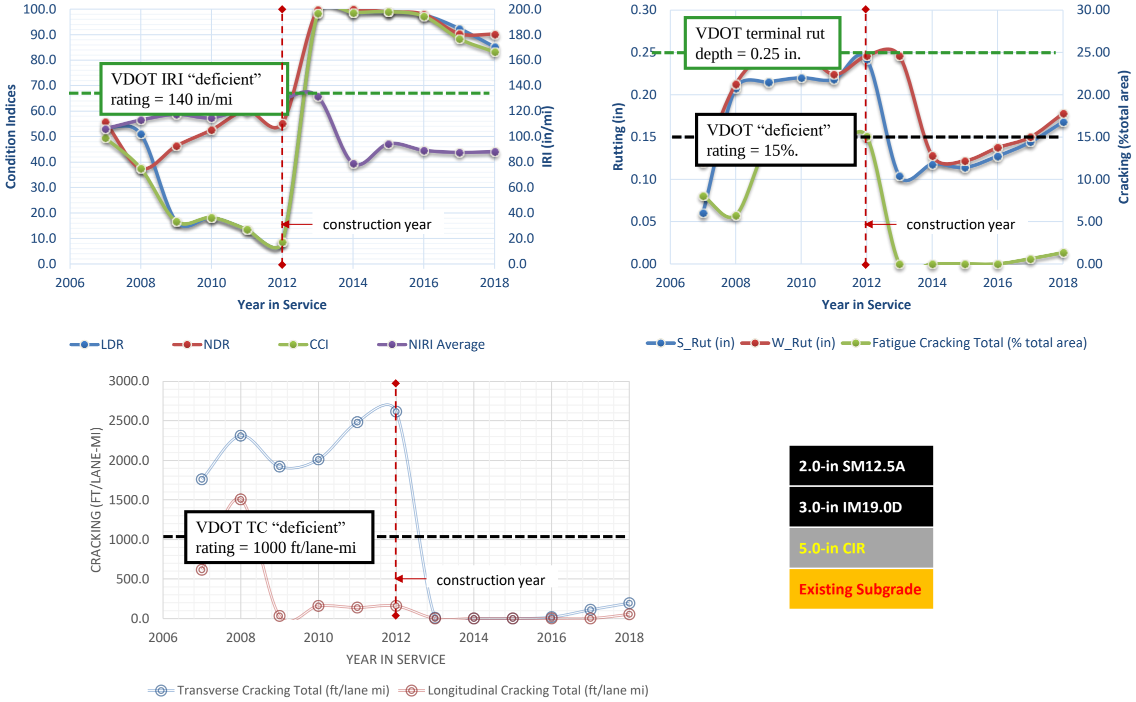
Table A.24. SR35 Project Details: Length, Costs, and Recycling Material Quantities

Unit cost of recycling process	$ 9.00/ton
Total recycled	52,800 tons
Stabilization agent	Emulsion
Unit cost of stabilizing agent	$675/ton
Total used	505 tons
Project Length	4.7 lane-mi

2013 (*US 17 North and South Bound*)



(a)



(b)

Figure A.24. Performance Plots and Structure for the SR17 CIR Project: (a) Northbound (b) Southbound (Isle of Wight County)

APPENDIX B

DISTRESS PREDICTION MODELS

This appendix presents results of the exponential models developed for rutting and cracking. The model function is of the form:

$$a \times Exp(b \times Age)$$

where: a = scale, b = growth rate

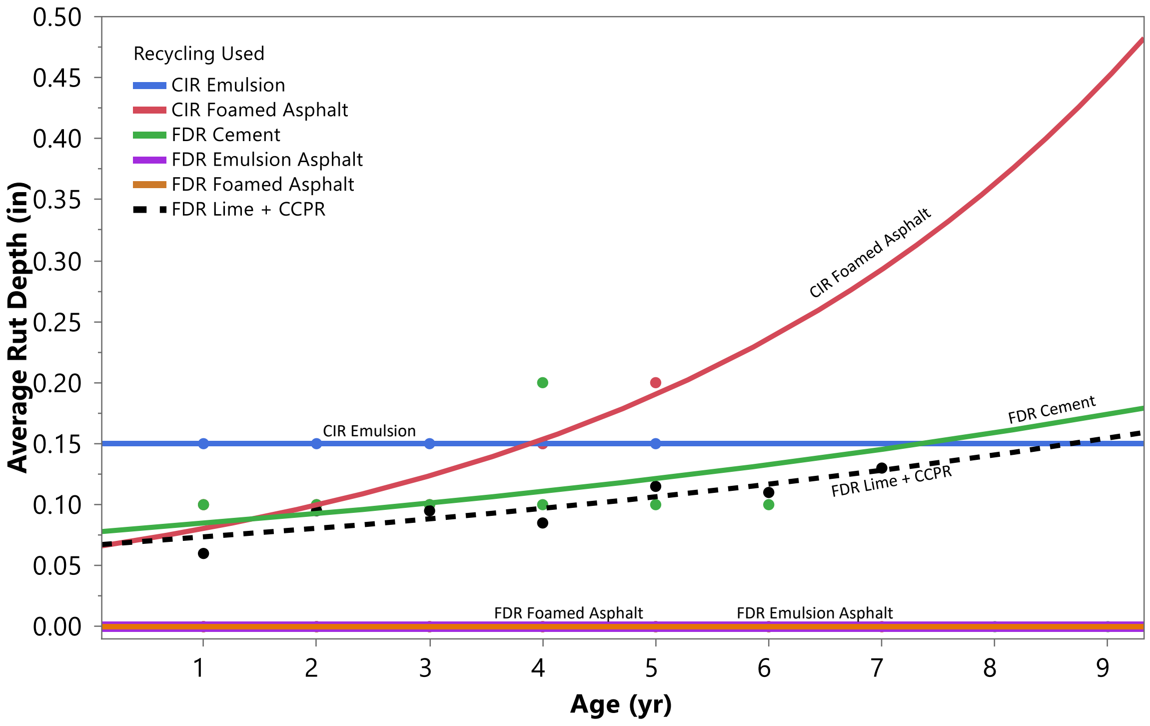


Figure B.1. Rutting Performance Prediction Models for Projects in Virginia

Table 20. Parameter Estimates and Test Statistics for Rutting Models

Model		AICc	BIC	SSE	MSE	RMSE	R-Square
Exponential 2P		-8.47	12.66	2.01	0.04	0.19	0.09
Parameter	**Group**	**Estimate**	**Std Error**	**Wald ChiSquare**	**Prob > ChiSquare**	**Lower 95%**	**Upper 95%**
a	CIR Emulsion	0.15	0.20	0.54	0.46	-0.25	0.55
b	CIR Emulsion	0.00	0.41	0.00	1.00	-0.80	0.80
a	CIR Foamed Asphalt	0.06	0.13	0.24	0.62	-0.19	0.32
b	CIR Foamed Asphalt	0.22	0.51	0.18	0.67	-0.78	1.21
a	FDR Cement	0.08	0.05	2.27	0.13	-0.02	0.18
b	FDR Cement	0.09	0.12	0.60	0.44	-0.14	0.32
a	FDR Emulsion Asphalt	0.00	0.07	0.00	1.00	-0.14	0.14
b	FDR Emulsion Asphalt	0.00	0.00	.	.	0.00	0.00
a	FDR Foamed Asphalt	0.00	0.07	0.00	1.00	-0.14	0.14
b	FDR Foamed Asphalt	0.00	0.00	.	.	0.00	0.00
a	FDR Lime + CCPR	0.07	0.13	0.26	0.61	-0.19	0.32
b	FDR Lime + CCPR	0.09	0.38	0.06	0.81	-0.66	0.84

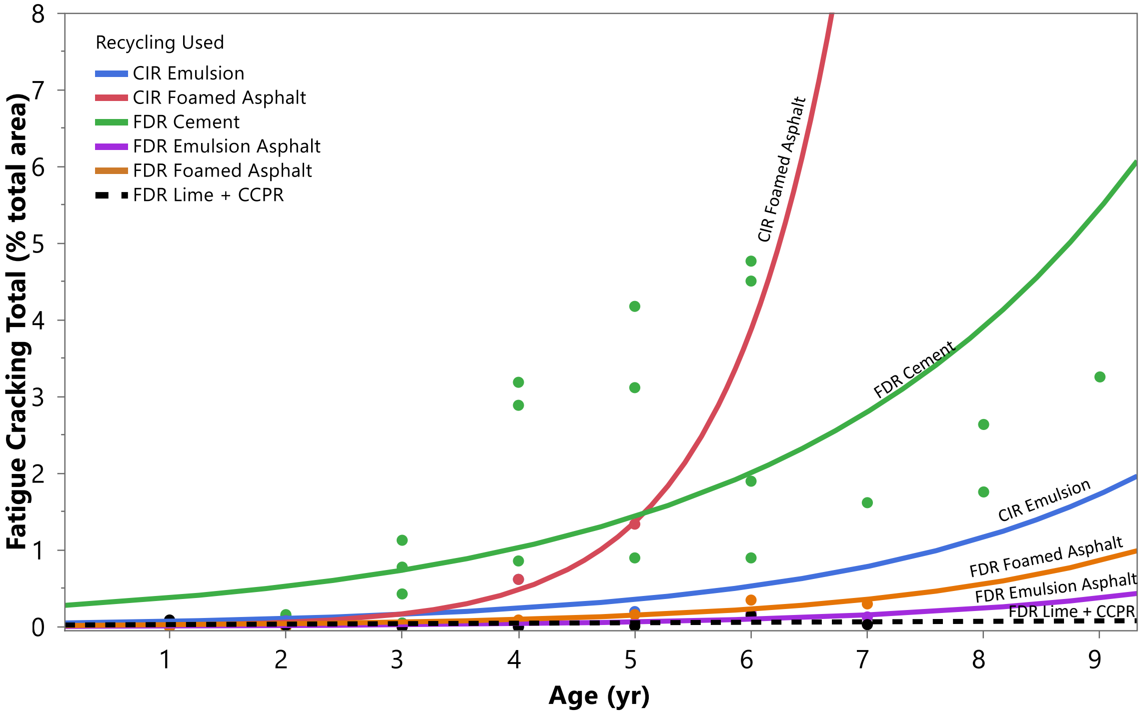


Figure B.2. Fatigue Cracking Performance Prediction Models for Projects in Virginia

Table 212. Parameter Estimates and Test Statistics for Fatigue Cracking Models

Model		**AICc**	**BIC**	**SSE**	**MSE**	**RMSE**	**R-Square**
Exponential 2P		221.74	242.87	69.27	1.31	1.14	0.58
Parameter	**Group**	**Estimate**	**Std Error**	**Wald ChiSquare**	**Prob > ChiSquare**	**Lower 95%**	**Upper 95%**
a	CIR Emulsion	0.05	0.51	0.01	0.92	-0.96	1.06
b	CIR Emulsion	0.39	2.36	0.03	0.87	-4.23	5.02
a	CIR Foamed Asphalt	0.01	0.07	0.01	0.92	-0.13	0.15
b	CIR Foamed Asphalt	1.04	1.95	0.29	0.59	-2.78	4.87
a	FDR Cement	0.27	0.12	5.55	0.0185*	0.05	0.50
b	FDR Cement	0.33	0.05	37.22	<.0001*	0.23	0.44
a	FDR Emulsion Asphalt	0.01	0.24	0.00	0.98	-0.47	0.48
b	FDR Emulsion Asphalt	0.44	5.32	0.01	0.93	-9.98	10.87
a	FDR Foamed Asphalt	0.02	0.25	0.00	0.95	-0.47	0.50
b	FDR Foamed Asphalt	0.44	2.29	0.04	0.85	-4.05	4.93
a	FDR Lime + CCPR	0.02	0.70	0.00	0.97	-1.34	1.39
b	FDR Lime + CCPR	0.13	5.34	0.00	0.98	-10.34	10.60

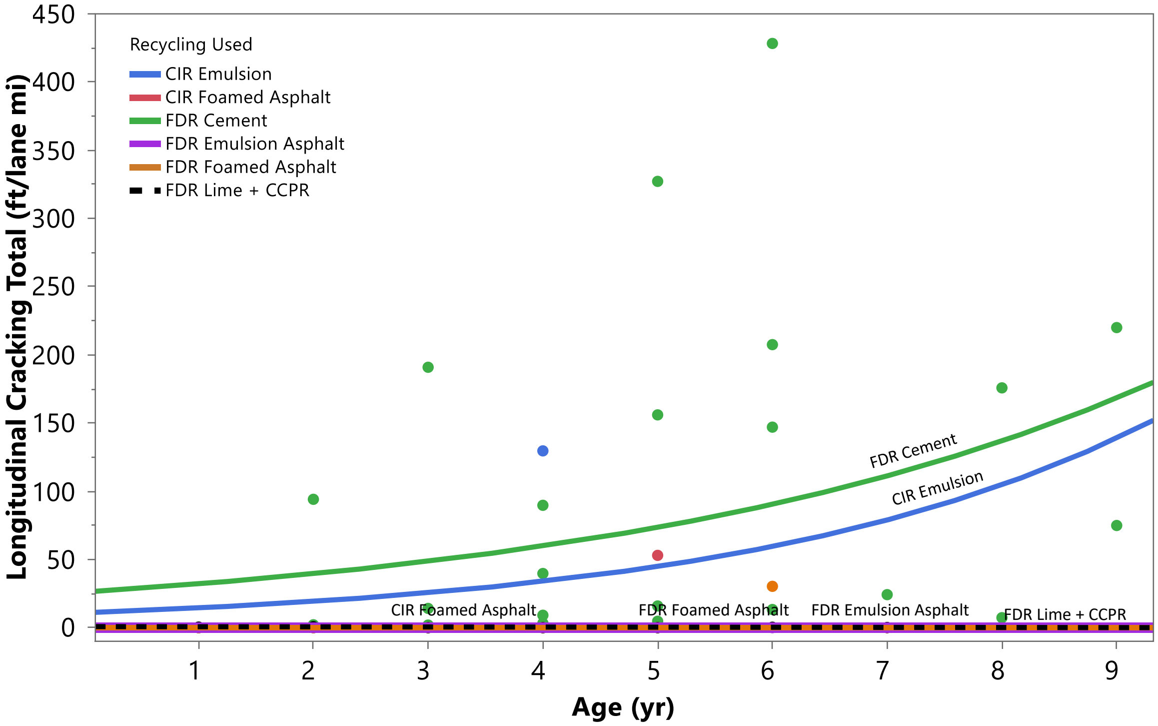


Figure B.3. Longitudinal Cracking Performance Prediction Models Projects in Virginia

Table 223. Parameter Estimates and Test Statistics for Longitudinal Cracking Models

Model		**AICc**	**BIC**	**SSE**	**MSE**	**RMSE**	**R-Square**
Exponential 2P		771.81	792.94	327997.28	6188.63	78.67	0.27
Parameter	**Group**	**Estimate**	**Std Error**	**Wald ChiSquare**	**Prob > ChiSquare**	**Lower 95%**	**Upper 95%**
a	CIR Emulsion	10.92	46.11	0.06	0.81	-79.46	101.3
b	CIR Emulsion	0.28	1.01	0.08	0.78	-1.7	2.27
a	CIR Foamed Asphalt	0	35.18	0	1	-68.95	68.95
b	CIR Foamed Asphalt	0	0	.	.	0	0
a	FDR Cement	26.11	13.58	3.69	0.05	-0.52	52.73
b	FDR Cement	0.21	0.08	7.49	0.0062*	0.06	0.36
a	FDR Emulsion Asphalt	0	29.73	0	1	-58.28	58.28
b	FDR Emulsion Asphalt	0	0	.	.	0	0
a	FDR Foamed Asphalt	0	29.73	0	1	-58.28	58.28
b	FDR Foamed Asphalt	0	0	.	.	0	0
a	FDR Lime + CCPR	0.76	162.21	0	1	-317.17	318.68
b	FDR Lime + CCPR	-0.4	100.9	0	1	-198.15	197.35

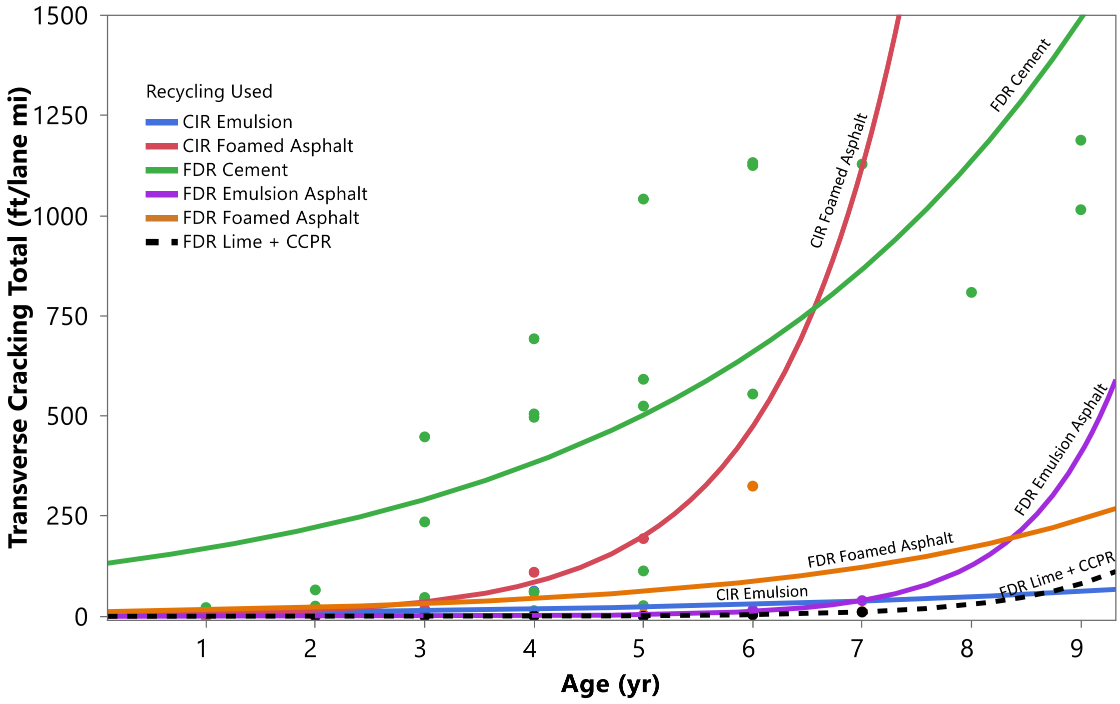


Figure B.4. Transverse Cracking Performance Prediction Models Projects in Virginia

Table 234. Parameter Estimates and Test Statistics for Transverse Cracking Models

Model		**AICc**	**BIC**	**SSE**	**MSE**	**RMSE**	**R-Square**
Exponential 2P		937.67	958.8	4207542	79387.59	281.76	0.66
Parameter	**Group**	**Estimate**	**Std Error**	**Wald ChiSquare**	**Prob > ChiSquare**	**Lower 95%**	**Upper 95%**
a	CIR Emulsion	6.84	179.48	0	0.97	-344.94	358.62
b	CIR Emulsion	0.25	6.43	0	0.97	-12.36	12.85
a	CIR Foamed Asphalt	2.7	32.46	0.01	0.93	-60.92	66.31
b	CIR Foamed Asphalt	0.86	2.5	0.12	0.73	-4.04	5.77
a	FDR Cement	128.93	37.31	11.94	0.0005*	55.8	202.05
b	FDR Cement	0.27	0.04	48.25	<.0001*	0.2	0.35
a	FDR Emulsion Asphalt	0.01	1.54	0	0.99	-3.01	3.04
b	FDR Emulsion Asphalt	1.16	19.51	0	0.95	-37.08	39.41
a	FDR Foamed Asphalt	11.39	88.44	0.02	0.9	-161.96	184.73
b	FDR Foamed Asphalt	0.34	1.26	0.07	0.79	-2.13	2.81
a	FDR Lime + CCPR	0.01	3.64	0	1	-7.12	7.14
b	FDR Lime + CCPR	1.01	58.24	0	0.99	-113.14	115.16

APPENDIX C

Supporting Information for Construction Stage Inventory Calculations

1. Construction Activity and Equipment Information

TABLE C-1. List of Construction Activities and Machinery Information

Construction Activity/ Productivity Rates	Construction Task	Equipment Used	Rated Power [hp]	Production/ Application Rates	Unit	No. Required	Allocation [%]
Cold Central Plant Recycling	Roadway Preparation	Broom or Sweeper	120	5,000	m2/hr	1	100
	Foamed Asphalt Supply	Bitumen Tanker	550	20,000	m2/day	1	100
	Milling	Milling Machine	610	40	m3/hr	1	100
		Haul Truck	350	1,000	tonne/day	6	100
	Pulverizing + Mixing	Front End Loader	66	1,000	tonne/day	1	100
		Mobile Asphalt Plant	173	53	tonne/day	1	100
	Recycled Mat. Placement	Paver	250	1,215	tonne/day	1	100
	Compaction	Pneumatic Tire Roller	75	1,215	tonne/day	1	100
		Double Steel Smooth Drum Roller	154	1,215	tonne/day	1	100
	Tack Coat Application	Emulsion Tanker	210	20,000	m2/day	1	100
	HMA Placement	Haul Truck	350	1,000	tonne/day	2	100
		Paver	250	1,215	tonne/day	1	100
	Compaction	Pneumatic Tire Roller	75	1,215	tonne/day	1	100
		Single Steel Smooth Drum Rollers	130	1,215	tonne/day	1	100
		Double Steel Smooth Drum Roller	154	1,215	tonne/day	1	100
Cold In-place Recycling	Roadway Preparation	Broom or Sweeper	120	5,000	m2/hr	1	100
	Bitumen Emulsion Supply	Water Tanker Truck or Distributor	350	20,000	m2/day	1	100
		Emulsion Tanker Truck	210	20,000	m2/day	1	100
	Milling + Pulverizing + Mixing	Cold Recycler	610	1,713	tonne/hr	1	90
	Recycled Mat. Placement	Paver	250	1,215	tonne/day	1	90
	Compaction	Pneumatic Tire Roller	75	1,215	tonne/day	1	80
		Double Steel Smooth Drum Roller	154	1,215	tonne/day	1	80
	Tack Coat Application	Emulsion Distributor	210	20,000	m2/day	1	100
	HMA Placement	Haul Truck	350	1,000	tonne/day	2	100
		Paver	250	1,215	tonne/day	1	100
	Compaction	Pneumatic Tire Roller	75	1,215	tonne/day	1	100
		Single Steel Smooth Drum Rollers	130	1,215	tonne/day	1	100
		Double Steel Smooth Drum Roller	154	1,215	tonne/day	1	100
	Roadway Preparation	Broom or Sweeper	120	5,000	m2/hr	1	100

Construction Activity/ Productivity Rates	Construction Task	Equipment Used	Rated Power [hp]	Production/ Application Rates	Unit	No. Required	Allocation [%]
Full Depth Reclamation with Cement Stabilization	Cement Pre-spreading	Binding Agent Spreader	320	20,000	m2/day	1	100
	Milling + Pulverizing + Mixing	Water Tanker Truck	350	20,000	m2/day	1	100
	Recycled Material Placement	Reclaimer	755	446	m2/hr	1	100
	Grading	Motor Grader	255	2,726	tonne/day	1	50
	Compaction	Pneumatic Tire Roller	75	1,215	tonne/day	1	100
		Single Steel Smooth Drum Rollers	130	1,215	tonne/day	1	100
		Double Steel Smooth Drum Roller	154	1,215	tonne/day	1	100
	Tack Coat Application	Emulsion Tanker Truck	210	20,000	m2/day	1	100
	Asphalt Concrete Placement	Haul Truck	350	1,000	tonne/day	2	100
		Paver	250	1,215	tonne/day	1	100
	Compaction	Pneumatic Tire Roller	75	1,215	tonne/day	1	100
		Single Steel Smooth Drum Rollers	130	1,215	tonne/day	1	100
		Double Steel Smooth Drum Roller	153504	1,215	tonne/day	1	100

Hours per day = 8 hrs

APPENDIX D

LIFE CYCLE ASSESSMENT INDICATORS

LCA impact categories may relate to inputs that reflect, for instance, the consumption of resources, or outputs that show the effects of a pollutant or a group of pollutants. There are numerous indicators, and those described below from TRACI only form a subset of indicators available to pavement LCA practitioners. In addition to the TRACI indicators described, a unitless indicator based on calculations from normalization and weighting factors (Table D.1) for each indicator was used to characterize the overall impact of the projects. The resulting point-based indicator is known as the Single Score.

Table 24. Impact Categories Reported in the VDOT LCA Case Study with Normalization and Weighting Factors for Calculation of Single Score Index

Impact Category	Abbreviation	Unit	Normalization	Weighting
Acidification	Ac	kg SO2 *eq*	0.011	0.036
Ecotoxicity	Ec	CTUe	0.0000905	0.084
Eutrophication	Eu	kg N *eq*	0.0463	0.072
Global Warming	GW	kg CO2-*eq*	0.0000413	0.349
Ozone Depletion	OD	kg CFC-11-*eq*	6.2	0.024
Photochemical Smog Formation	PSF	kg O3 *eq*	0.000718	0.048
Human Health - Carcinogenics	HH-C	CTUh	19,706	0.096
Human Health - Non-Carcinogenics	HH-nC	CTUh	952	0.06
Respiratory Effects, Average	RE	kg PM2.5-*eq*	0.0412	0.108
Resource depletion - fossil fuels (MJ surplus)	RD-FF	MJ surplus	0.0000579	0.121

Description of Impact Category Indicators

Acidification measures the increase in the concentration of hydrogen ions (H+) within a local environment (Bare, 2012). The deposition of air pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) on the earth's surface can damage ecosystems and man-made systems such as buildings and other structures. The combustion of fuels at various stages in the pavement LCA produces these acidifying pollutants.

Ecotoxicity, as it applies to pavement LCA, is relevant for background processes involving mining or specific chemistry processes. It refers to the harmful impacts on plant and animal life from the release of chemicals.

Eutrophication happens when an aquatic system sees accelerated growth of algae and weeds, and an unwanted accumulation of algal biomass. The presence of excess nitrogen and phosphorus result in this phenomenon, affecting coastal environments and freshwater lakes.

Global warming or climate change occurs when there is a rise in the global average temperature near the earth's surface because of greenhouse gases (GHG) primarily associated with fuel combustion, and some material production processes. The impacts of global warming include the melting of polar ice caps causing a rise in sea level, increased risk of extreme weather events, and distortion of natural habitats, agriculture, and human health.

Ozone depletion occurs when stratospheric ozone that protects the earth's surface from UV radiation is reduced by substances such as chlorofluorocarbons (CFCs). The phenomenon can lead to skin cancer, cause cataracts in the human population, and has been documented to damage plants and other man-made materials (Bare, 2012).

Photochemical smog formation occurs when tropospheric ozone (O_s) is created by reactions between volatile organic compounds (VOCs) and nitrogen oxides (NO_x) under sunlight. Emissions from traffic during the use stage are the main contributors to ozone and smog formation, which can damage human lungs and reduce productivity in plants (Bare, 2012).

The **human health (cancer and non-cancer)** indicator assesses the increase in morbidity caused by exposure to a pollutant.

Respiratory effects or human health (particulate matter) deals with particulate air pollution in the forms of PM_{10} and $PM_{2.5}$ (particles of diameter 10 and 2.5 micrometers or less) and emissions (NO_x and SO_x) causing the formation of these particulates through secondary reactions. Particulates in this category can cause asthma and increase mortality rates in humans. Diesel fuel particulates are seen in several processes in the pavement life cycle but are key in the use stage.

Resource depletion or fossil fuel use mainly focuses on the reduction in availability of fossil or nonrenewable resources. Research efforts to provide site-specific recommendations on land and water use are currently ongoing (Bare 2012).