RESEARCH & DEVELOPMENT

Comparing Performance of Full-depth Asphalt Pavements and Aggregate Base Pavements in NC

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16. Abstract

This report presents the findings from the performance analysis of two types of pavements commonly used in North Carolina, aggregate base course (ABC) pavements and full-depth asphalt (FDA) pavements. The main objective of this research project is to examine the NCDOT's assumptions that the required M&R strategies and life costs of the two types of the pavements are the same. In order to complete the inherent tasks to meet this objective, the North Carolina State University (NCSU) research team identified field sections in North Carolina that include both types of pavement (ABC and FDA) and analyzed and compared the performance data of the sections. In addition, the NCSU research team collected and tested material samples from the field using the performance test methods. The team established a database that contains information about the identified sections, for example, their material properties and performance data, as an additional product for the future recalibration of the AASHTO Pavement ME design program.

Analysis of the NCDOT's Pavement Management Systems (PMS) database revealed that the performance of the pavements is affected statistically by the pavement structure and traffic volume. This study employed two parameters, the so-called 'structural number' (SN) and asphalt layer thickness, to represent the structural effects. The study used the annual average daily traffic (AADT) data in the PMS database to show the effects of traffic volume on pavement performance. The NCSU researchers developed an index parameter, the pavement deterioration index (PDI) that is related to the SN, asphalt thickness, and design AADT, for analysis. The PDI can be used to determine the best time to apply M&R treatments. The PDI is proportional to the AADT and inversely proportional to the SN and asphalt concrete layer thickness. In other words, the pavements with higher PDI values have relatively short performance years for M&R treatment. The appropriate time to perform M&R treatment is when the pavement condition rating (PCR) decreases to the trigger value of 60 percent. The analysis results show that the PCR for each of the two types of pavement has a unique negative relationship with the PDI. As a result, the time for M&R treatment can be predicted by applying the trigger PCR value of 60 percent on the pavement type specific relationship between the PCR and the PDI. Once the M&R treatment time is determined, LCCA can be used to determine the costs of different types of pavements.

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EXECUTIVE SUMMARY

Aggregate base course (ABC) pavements and full-depth asphalt (FDA) pavements are two types of pavements commonly used in North Carolina. The North Carolina Department of Transportation (NCDOT) has a long history of building ABC pavements. The aggregate base layer in those pavements is made of relatively inexpensive materials and provides structural support for the top asphalt layers, which are usually under more severe loading and climate conditions than lower layers. In recent years, the NCDOT has begun to construct FDA pavements on high-volume routes. These FDA pavements consist of thick asphalt concrete layers placed directly on top of the subgrade soil, which typically is stabilized. The bounded asphalt layers at the bottom of the pavement system are stiffer and more moisture-resistant than the unbound aggregate base layer in ABC pavements. Currently, the NCDOT assumes that ABC pavements and FDA pavements have about the same service life and require about the same maintenance and rehabilitation (M&R) treatments. The NCDOT also now assumes that the costs of these two types of pavements are the same in life cycle cost analysis (LCCA).

The main objective of this research project is to examine the NCDOT's assumptions that the required M&R strategies and life costs of the two types of the pavements are the same. In order to complete the inherent tasks to meet this objective, the North Carolina State University (NCSU) research team identified field sections in North Carolina that include both types of pavement (ABC and FDA) and analyzed and compared the performance data of the sections. The NCSU team collected and tested material samples from the field. In addition, the team established a database that contains information about the identified sections, for example, their material properties and performance data, as an additional product for the future recalibration of the AASHTO Pavement ME design program.

Analysis of the NCDOT's Pavement Management Systems (PMS) database revealed that the performance of the pavements is affected statistically by the pavement structure and traffic volume. This study employed two parameters, the so-called 'structural number' (SN) and asphalt layer thickness, to represent the structural effects. The study used the annual average daily traffic (AADT) data in the PMS database to show the effects of traffic volume on pavement performance. The NCSU researchers developed an index parameter, the pavement deterioration index (PDI) that is related to the SN, asphalt thickness, and design AADT, for analysis. The PDI can be used to determine the best time to apply M&R treatments. The PDI is proportional to the AADT and inversely proportional to the SN and asphalt concrete layer thickness. In other words, the pavements with higher PDI values have relatively short performance years for M&R treatment. The appropriate time to perform M&R treatment is when the pavement condition rating (PCR) decreases to the trigger value of 60 percent. The analysis results show that the PCR for each of the two types of pavement has a unique negative relationship with the PDI. As a result, the time for M&R treatment can be predicted by applying the trigger PCR value of 60 percent on the pavement type specific relationship between the PCR and the PDI. Once the M&R treatment time is determined, LCCA can be used to determine the costs of different types of pavements.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 Introduction

Aggregate base course (ABC) pavements and full-depth asphalt (FDA) pavements are the two most commonly used types of pavements in North Carolina. Currently, the North Carolina Department of Transportation (NCDOT) assumes that the two types of pavements perform similarly and require the same maintenance and rehabilitation (M&R) treatments. The NCDOT also applies the same life cycle cost analysis (LCCA) model to both types of pavements. In this research project, the North Carolina State University (NCSU) research team compared the performance of the two types of pavements in North Carolina and recommends the proper time to conduct M&R treatments for each type of pavement. The products of this research project can be used for future pavement design, the development of M&R decision trees, and LCCA. The NCSU research team established a database that includes the performance data for the two pavement types and a recalibration design guide that the NCDOT can use for the recalibration of the Pavement ME design program.

1.1 Scope

This scope of this research project is to compare the performance of ABC pavements and FDA pavements and to compare their life cycle costs. In order to complete the tasks, the NCSU research team identified field sections constructed using the two types of pavements and collected performance data for the two pavement types. The performance data include information from projects located in the Mountain, Piedmont, and Coastal Plain regions of North Carolina. The study utilizes 59 sections.

1.2 Objectives

The objectives of this project are to:

1. Provide important performance information regarding ABC and FDA pavements that can be used to update the NCDOT's LCCA procedure.
2. Identify pavement sections with both ABC and FDA pavements for the recalibration of ME Design to fit North Carolina conditions.
3. Develop guidelines for the recalibration of ME Design and demonstrate the data collection process using new paving projects.

1.3 Organization of the Report

This report is organized into four chapters. The first chapter presents the introduction and research approach used in the study. The second chapter presents the major findings that include comparisons between the performance of the two types of pavements and the recommended maintenance time for each pavement type. Chapter Three presents and discusses the laboratory test data. The fourth chapter presents and discusses the database and guidelines for the recalibration of the Pavement ME program. Chapter Five provides the conclusion and offers final recommendations of this project.

1.4 Research Approach

The NCSU research team compared the performance data obtained from the Pavement Management Systems (PMS) database for the two pavement types, i.e., ABC and FDA pavements. The team used the performance condition rate (PCR) as the main index value. The team considered the factors that affect the performance of the pavements, i.e., pavement structure and traffic volume, for the comparisons. The recommended maintenance time is based on the performance of the pavements and the traffic and structural factors.

CHAPTER 2 Analysis of the Performance of Aggregate Base Course Pavements and Full-Depth Asphalt Pavements

2.1 Field Sections in PMS Database

This section discusses the analysis results and comparisons of the ABC and FDA pavement projects in North Carolina in terms of pavement performance. The NCSU research team evaluated the main factors that affect pavement performance, i.e., traffic volume and pavement structure, and proposes an index parameter, the so-called pavement deterioration index (PDI), which normalizes those effects. The proper time for M&R treatment is given at the end of this chapter and is based on PDI analysis. The recommended treatment time can be used in LCCA. The NCSU research team extracted the performance data used in its analysis from the PMS database provided by the NCDOT. The analysis utilized 65 pavement sections, i.e., 21 FDA pavements and 44 ABC pavements. Most of these sections were TIPs that were either newly constructed or reconstructed after 2000 when Superpave asphalt mixtures were introduced. Some of the TIP sections have several survey intervals with different mileposts. The research team considered each survey interval with continuously recorded performance data as an independent pavement section. The NCDOT Pavement Management Unit monitored the performance of the field sections. As aforementioned, these sections include both ABC and FDA pavements from the Mountain, Piedmont, and Eastern Coastal regions of North Carolina. The PMS database also includes pavements of different route classes, i.e., United States (US) highways, NC highways, and secondary roads.

Note that the NCSU research team initially received data for 100 pavement sections, i.e., 41 FDA pavements and 59 ABC pavements, from the NCDOT. However, some of these performance data could not be included in the analysis due to one or more of the following reasons:

- The distresses were not recorded/monitored continuously (causing a monotonic decrease in the PCR).
- No distresses were recorded for the section after a long service time.
- Only two data points were available for the section and thus were insufficient to develop a performance curve.
- The pavement's performance did not follow typical trends for performance deterioration and thus was difficult to interpret.

Screening of the data from 100 pavement sections using the reasons above resulted in 59 sections with reasonable performance data.

2.2 Information Extracted from the Pavement Management System Database

The information that NCSU researchers extracted from the PMS database includes general information (i.e., pavement type, TIP number, construction date, route number, number of lanes), pavement location, pavement structural information (i.e., asphalt mixture type and layer thickness), design annual average daily traffic (AADT), survey time, PCR, and individual distress information. The individual distress information includes the percentage of each severity level (none, low, moderate, and severe) for alligator cracking, transverse cracking, rutting, raveling, oxidation, bleeding, patching, and ride quality. The condition data were generated from a windshield survey conducted by the NCDOT before 2012 and by subcontractors after 2012 using an automated device. Figure 2.1 presents an example of a PCR versus pavement life curve. In Figure 2.1, the legend shows the TIP number and the pavement type (i.e., ABC vs. FDA) and milepost in parenthesis.

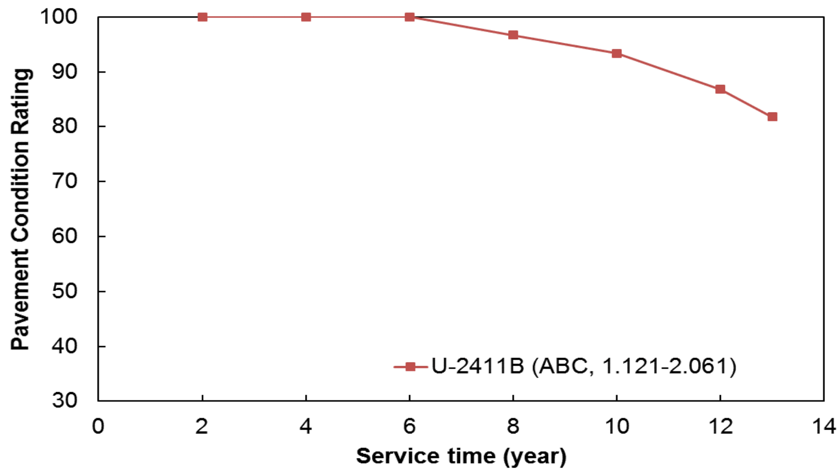

Figure 2.1 Typical pavement condition curve derived from information in the PMS database.

The information in the PMS database indicates that the reported amounts of distress are in the low range. The severity levels are mostly none or low for rutting, raveling, oxidation, bleeding, and patching. However, alligator cracking was reported as severe. Hence, the PCR was found to be a strong function of the amount of cracking. The NCSU research team thus selected the PCR recorded in the PMS database as the pavement condition evaluation factor for the following reasons:

- The PCR could be calculated using available data and the NCDOT model; therefore, no secondary computation was needed.
- M&R treatment decisions could be made directly based on the PCR.

2.3 Understanding Pavement Performance Data

2.3.1 Observations of Pavement Performance Data

Based on the performance data in the PMS database, the NCSU research team made a series of observations in order to model the pavement conditions in conjunction with the various factors, i.e., pavement type, pavement structure, and traffic volume. These observations are described in (a), (b), (c), and (d) below.

(a) The PCR decreases as the service time increases. Figure 2.1 illustrates the performance condition of a typical pavement in terms of a PCR curve.

(b) The NCDOT typically does not allow the PCR to decrease to 60. The pavement performance curves from the 59 sections indicate that the PCR is generally over 60 in North Carolina. In addition, Figure 2.2 through Figure 2.6 present the performance curves for pavements with a known maintenance history. Maintenance treatments were applied before the PCR of the pavements dropped to 60.

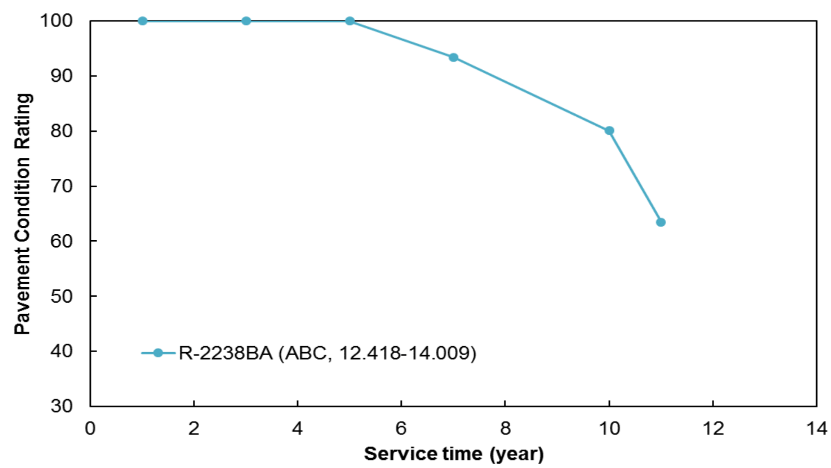

Figure 2.2 Pavement performance curve with maintenance history for R-2238BA.

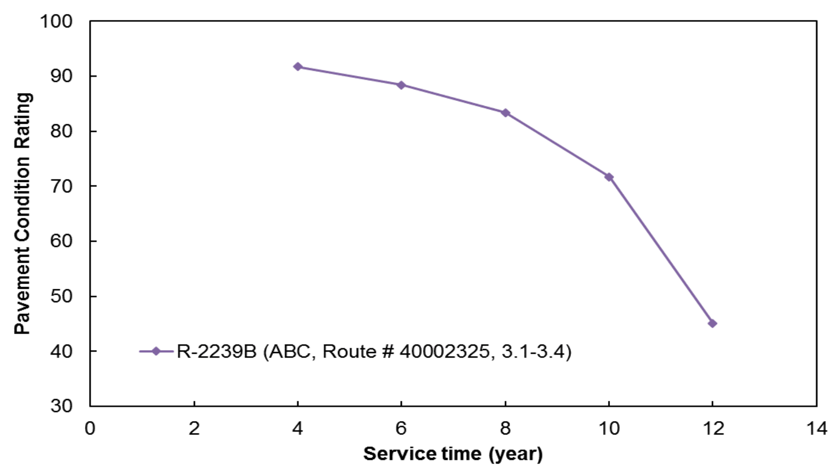

Figure 2.3 Pavement performance curve with maintenance history for R-2239B.

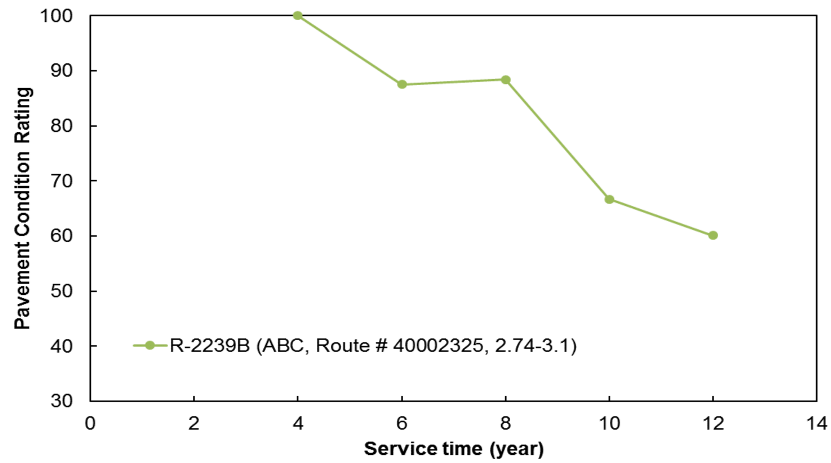

Figure 2.4 Pavement performance curve with maintenance history for R-2239B.

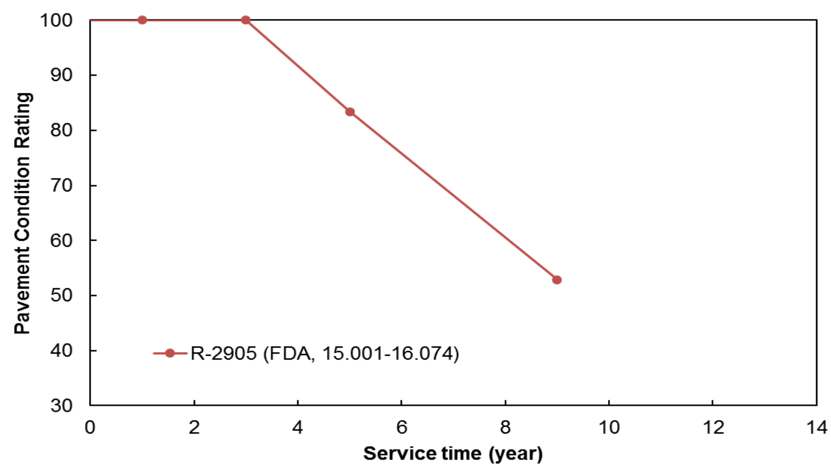

Figure 2.5 Pavement performance curve with maintenance history for R-2905.

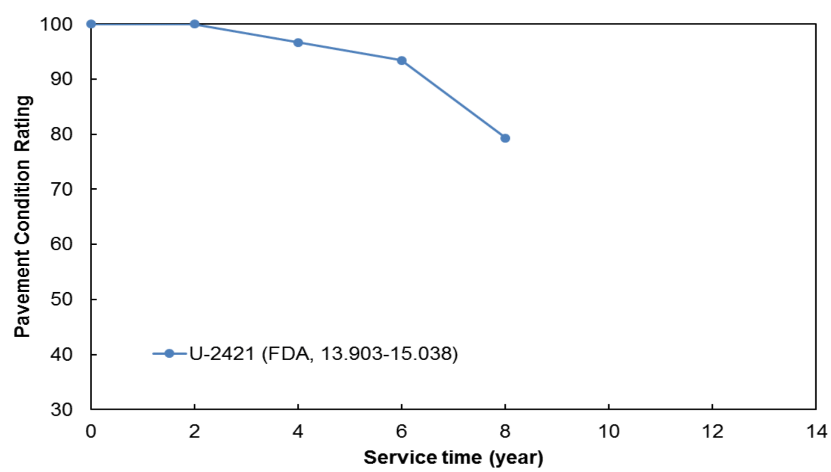

Figure 2.6 Pavement performance curve with maintenance history for U-2421.

After the NCSU research team consulted with the NCDOT engineers, the team determined that the PCR of 60 should be used to trigger M&R treatment. That is, PCR = 60 is the threshold for M&R.

(c) In terms of the shape of the performance curve (PCR vs. service time), the curve can be divided into two regions. The primary region typically represents the first few years after construction. In this region, the pavement condition deteriorates slowly. In the secondary region, which usually occurs five to twelve years after construction, the amount of distress on the pavement surface increases quickly, and the PCR likewise drops quickly. The pavement condition deteriorates in the secondary region until a maintenance treatment is applied. Note that, for a full PCR curve, a tertiary region usually is plotted in which the pavement distress growth rate decreases when the pavement condition deteriorates. However, in reality, highway agencies would not allow a tertiary region condition to occur. Therefore, Figure 2.7 presents only two regions (primary and secondary) for the pavement performance curve.

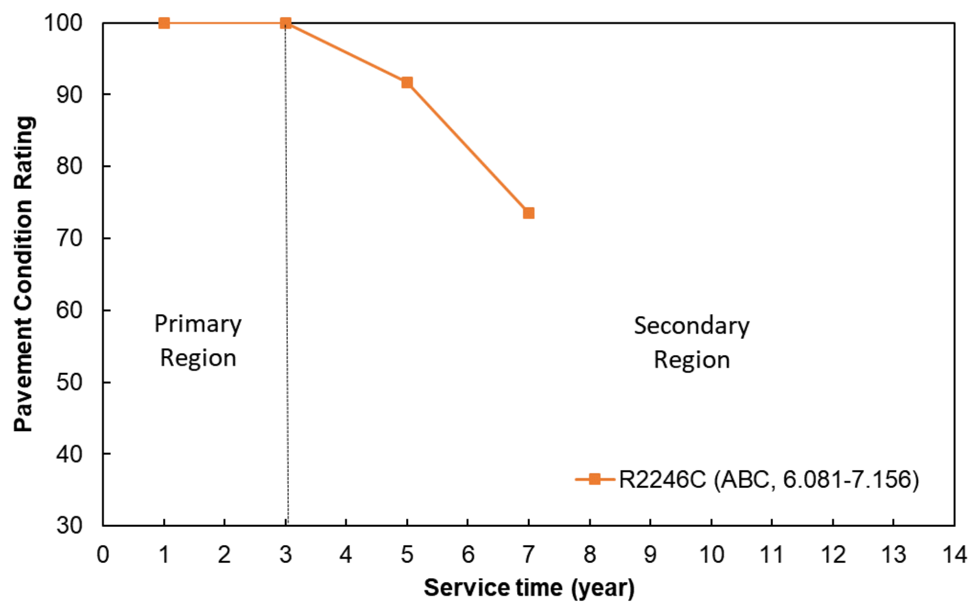

Figure 2.7 Schematic of divisions of pavement performance curve.

(d) The TIPs have different route classes. The route class of the pavement is indicated by the route number. To be specific, the route number is composed of 7 digits, and the first digit indicates the route class. For example, ‘1’ as the first digit represents an interstate highway, and ‘2’ indicates a US route. ‘3’ means that the route is a North Carolina highway, and ‘4’ means a secondary route. The pavement sections used in this study are mostly US highways, NC highways, and secondary routes. Figure 2.8 presents a bar chart that shows the number of highways (US routes and NC routes) and secondary roads that are composed of ABC pavements and FDA pavements.

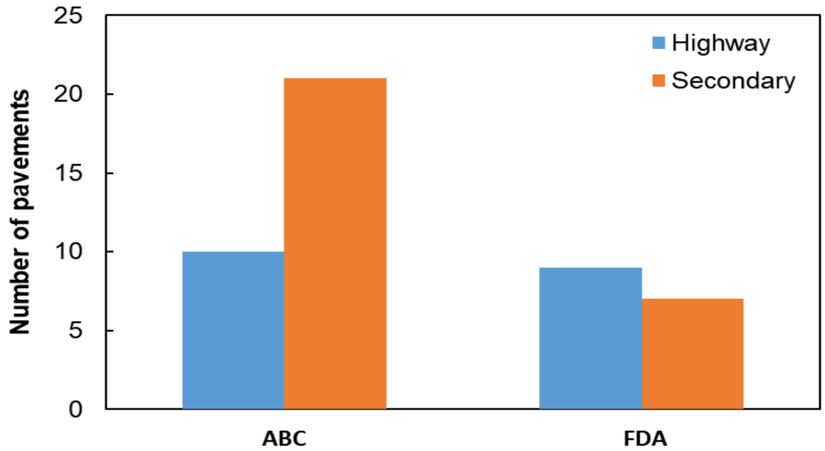

Figure 2.8 Number of highways and secondary routes in pavement sections used in this study.

According to Figure 2.8, the ABC pavements among the study sections are mostly secondary roads, whereas more FDA pavements are found from US or NC routes. It is reasonable to design ABC pavements for secondary roads because the cost is relatively low. In other words, among the sections obtained from the PMS database, almost all the secondary roads belong in the ABC category. Similarly, the FDA pavement structure is used primarily for high-volume route class roads, i.e., US highways and NC highways. The difference in the performance of the pavements in the different route classes is believed to be a result of the different traffic volumes and load levels of passing traffic for each. Therefore, traffic volume should be used as one of the modeling parameters in order to take into account pavements in different route classes.

2.3.2 Modeling of Pavement Performance Curve

In order to understand pavement performance as a function of various factors, the NCSU research team developed performance curves using mathematical models. As described in Section 2.3.1, a primary region and a secondary region can be observed on the performance curves extracted from data in the PMS database. Therefore, the team used power form functions to model the performance curves. Figure 2.9 presents an example of measured performance data and the fitted curve and shows good correlation between the two. Figure 2.10 and Figure 2.11 present the fitted curves for the ABC and FDA pavements, respectively.

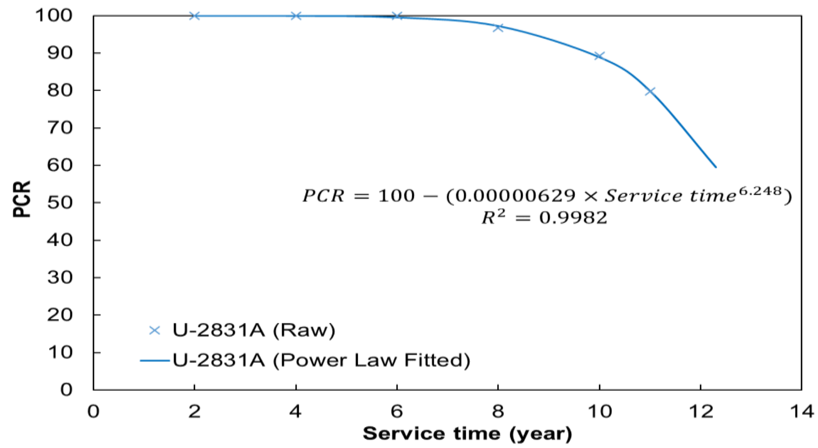

Figure 2.9 Performance curve fitted using power law function.

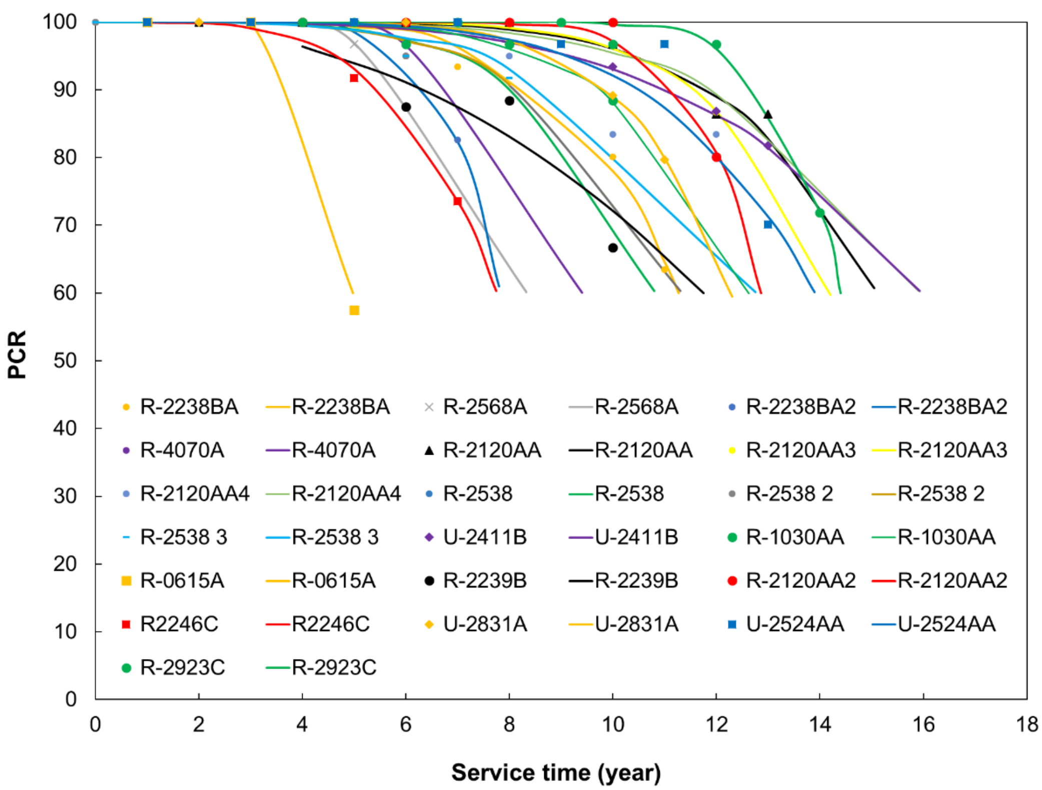

Figure 2.10 Fitted pavement performance curves for ABC pavement sections.

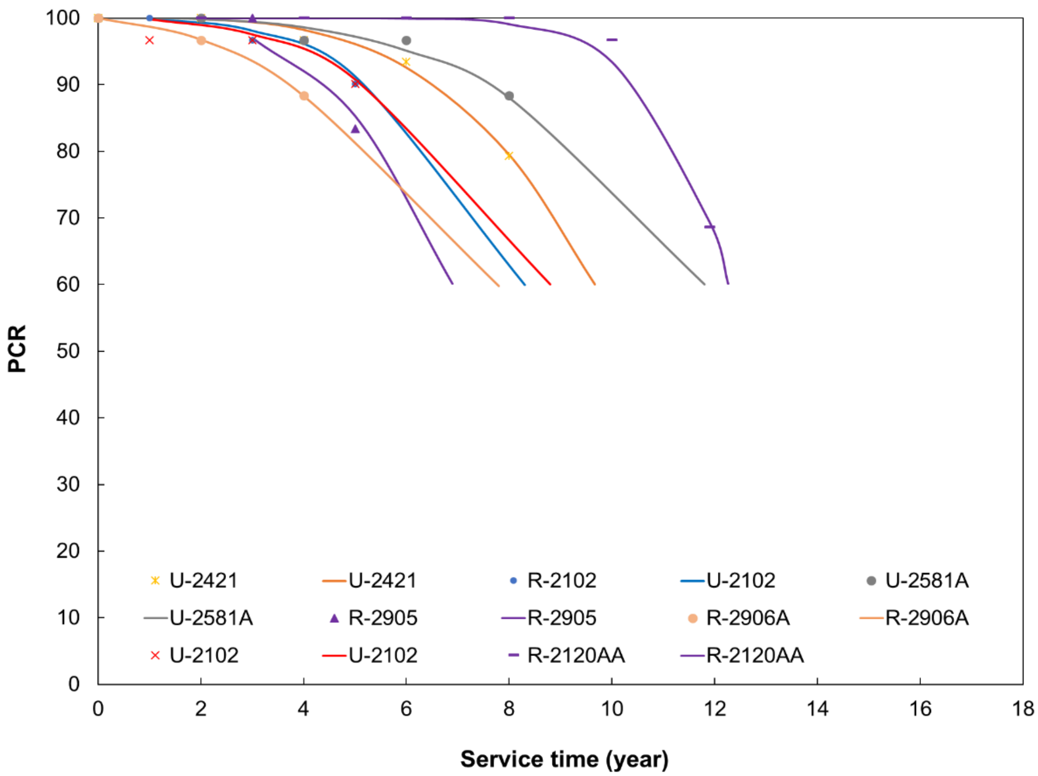

Figure 2.11 Fitted pavement performance curves for FDA pavement sections.

Note that, although most of the performance curves could be modeled using a power law function, the performance of some of the sections could not be explained using the mathmatical model. In those sections, the primary and secondary regions were not clear. For example, when the performance history had only two similar data points, the power law model could not characterize the performance sufficiently. Figure 2.12 presents the pavement sections that could not be fitted using the power law model. Also six additional sections are not presented in Figure 2.12 because the predicted M&R treatment times for these sections resulted in longer than 40 years, which is unrealistic.

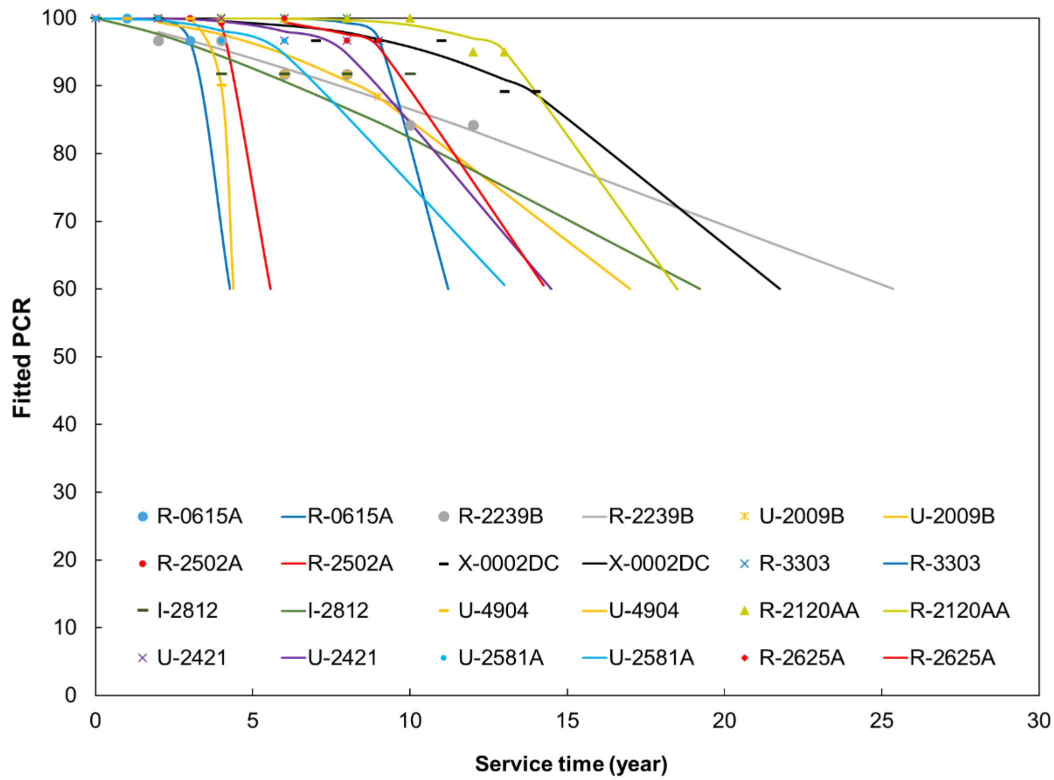

Figure 2.12 Performance curves that could not be fitted using power law function.

2.4 Time for Maintenance and Rehabilitation Treatment

Except for the five sections presented in Figure 2.2 through Figure 2.6, M&R treatment histories are not explicitly recorded in the PMS database. Among the recorded performance data in the database, the PCR rarely decreased to the level of 60. The NCDOT panel and NCSU research team agreed that PCR deterioration to 60 can be used to trigger M&R treatment. Thus, using the M&R trigger value, the treatment time for the pavements could be determined, as the performance curves could be extended using the power law functions. Figure 2.13 and Figure 2.14 illustrate the computation of the M&R treatment times for the ABC and FDA pavements, respectively.

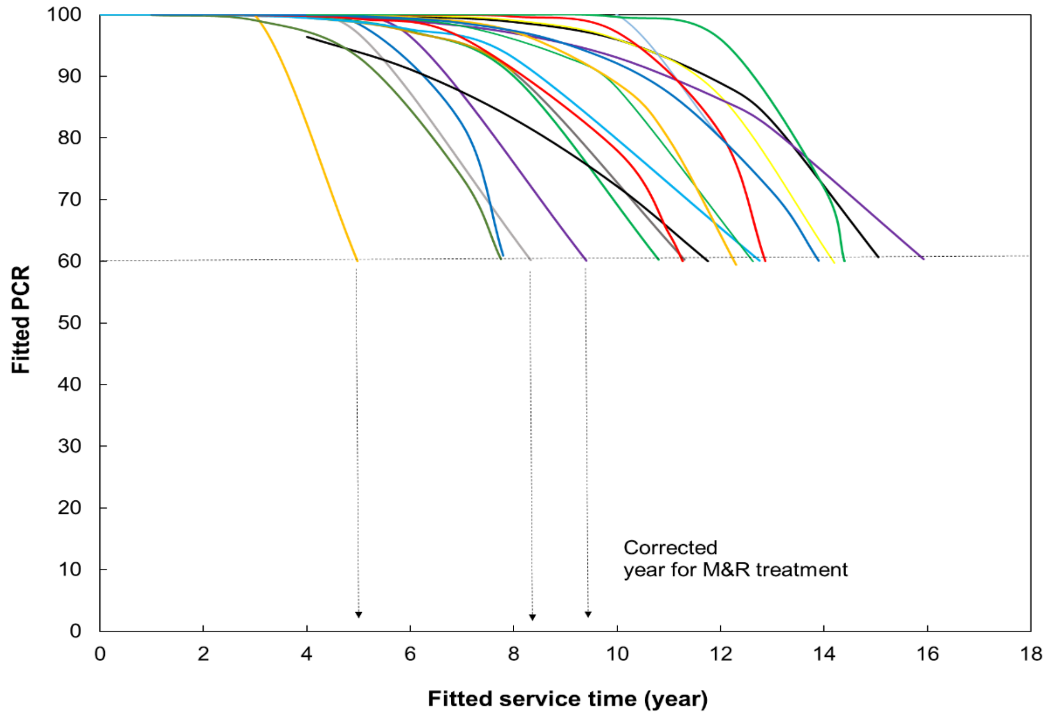

Figure 2.13 M&R treatment times on extended performance curves for ABC pavements.

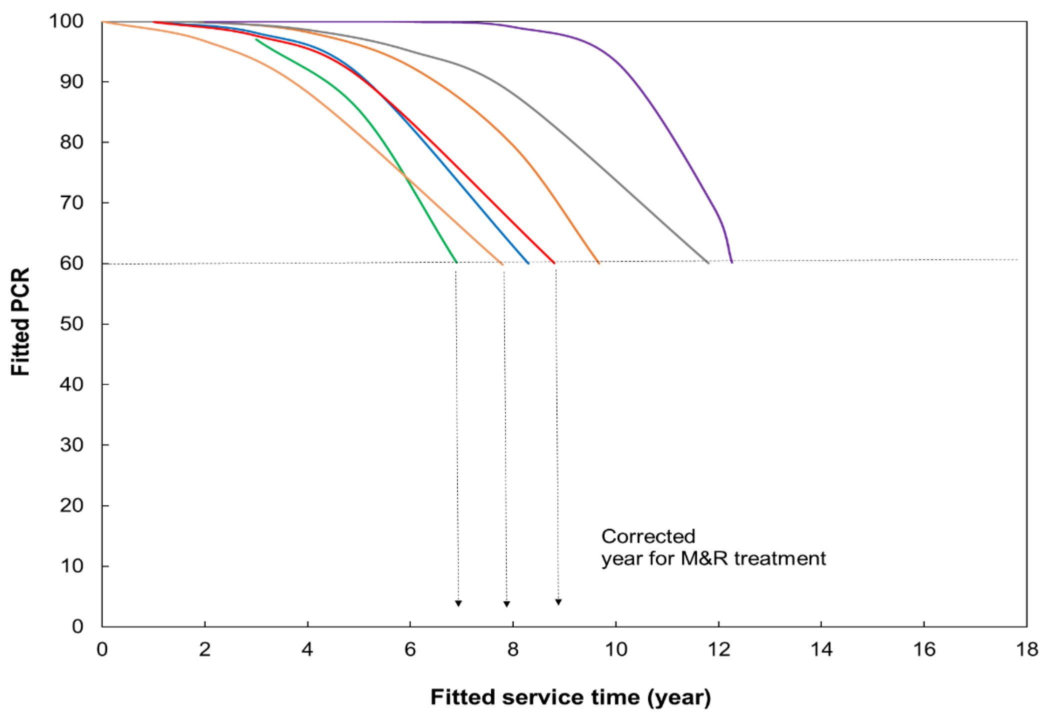

Figure 2.14 M&R treatment times on extended performance curves for FDA pavements.

Figure 2.15 presents the calculated average treatment times for the two types of pavements. The estimated treatment times for individual pavements are summarized in Table 1 and Table 2 for

ABC pavements and FDA pavements, respectively. The bar chart in Figure 2.15 shows that the FDA pavements have a slightly shorter service life than the ABC pavements prior to treatment application. However, as discussed earlier, the two types of pavements usually are placed under different circumstances. That is, FDA pavements are used more often for route classes where the traffic volume is high. Therefore, additional factors must be considered when deciding which type of pavement has the longer service life than the other.

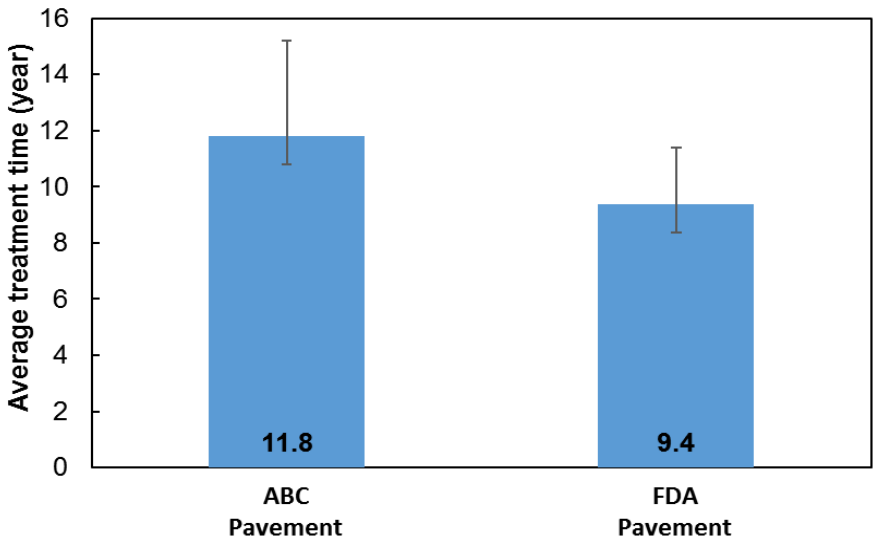

Figure 2.15 Average M&R treatment times for ABC and FDA pavements.

Table 1. Estimated M&R Treatment Times for ABC Pavements

TIP number	Project MP (Start)	Project MP (End)	Route number	Corrected age at PCR 60 (year)
R-0615A	0	0.026	30000024	5.0
R-0615A	0.026	1.771	30000024	5.0
R2246C	6.081	7.156	40001430	7.8
R-2120AA	3.89	4.21	40001150	15.0
R-2239B	2.74	3.1	40002325	11.8
R-2219AD/U-3630	0	0.32	40001992	18.1
U-2411B	1.121	2.061	40002433	15.9
U-2831A	0	1.634	40001954	12.3
R-2238BA	12.418	14.009	30000087	11.3
U-2524AA	5.212	7.207	40001546	13.9
R-2538	5.082	5.903	30000054	12.8
R-2538	6.844	8.144	30000054	10.8
R-2538	5.903	6.844	30000054	11.3
R-2538	5.212	7.207	30000054	12.2
R-1030AA	0	0.552	40002153	12.6
U-3329	0	0.53	40001412	13.0
R-2568A	28.867	28.962	30000109	8.3
R-4070A	15.983	18.043	30000012	9.4
R-2120AA	0	0.19	40001209	14.2
R-2238BA	11.631	12.418	30000087	7.8
R-2923C	0	0.55	40001765	14.4
R-2120AA	0.42	0.73	40001444	15.9
R-2120AA	0	0.18	40001210	12.9
Average				11.8

Table 2. Estimated M&R Treatment Times for FDA Pavements

TIP number	Project MP (Start)	Project MP (End)	Route number	Corrected age at PCR 60 (year)
R-2906A	19.388	21.403	30000055	7.8
R-2905	15.001	15.132	30000055	6.9
U-2102	2.083	2.503	30000157	8.3
U-2421	13.903	15.038	20000070	9.7
U-2102	0.772	2.503	30000157	8.8
R-2120AA	0	0.24	40001125	12.3
U-2581A	23.432	23.909	20000070	11.8
Average				9.4

2.5 Critical Factors for Pavement Performance

In order to make a full and fair comparison of the performance of the two types of pavements, two primary factors must be considered: the effects of traffic and the effects of pavement structure. The effects of these two factors are discussed in the following subsections.

2.5.1 Effects of Traffic

The main function of pavements is to carry the traffic load. As the service life and amount of traffic increase, distresses start to appear on the pavement surface, and the remaining service life diminishes. This report has discussed the deterioration of the pavement's performance in terms of service life; the report now presents another dimension, i.e., the pavement's performance in terms of cumulative traffic.

The NCSU research team obtained design traffic volumes for each pavement section from the PMS database. The parameter that represents the design traffic volume is the AADT. The cumulative traffic volume (CTV) at a certain year can be computed using Equation (2.1).

$$CTV = AADT \times ServiceTime\left(year\right) \times 365 \tag{2.1}$$

Figure 2.16 and Figure 2.17 present the PCR versus CTV curves for the ABC pavements and FDA pavements, respectively. Figure 2.18 presents a comparison of the cumulative traffic between the ABC pavements and the FDA pavements. Figure 2.19 presents a bar graph that shows the average cumulative passing traffic prior to M&R treatment for the two types of pavements. This comparison shows that, in terms of cumulative traffic, the FDA pavements can carry more traffic than the ABC pavements by 147 percent on average. This observation is counter to the conclusion drawn from the comparison of the performance of the two types of pavements in terms of service life (time).

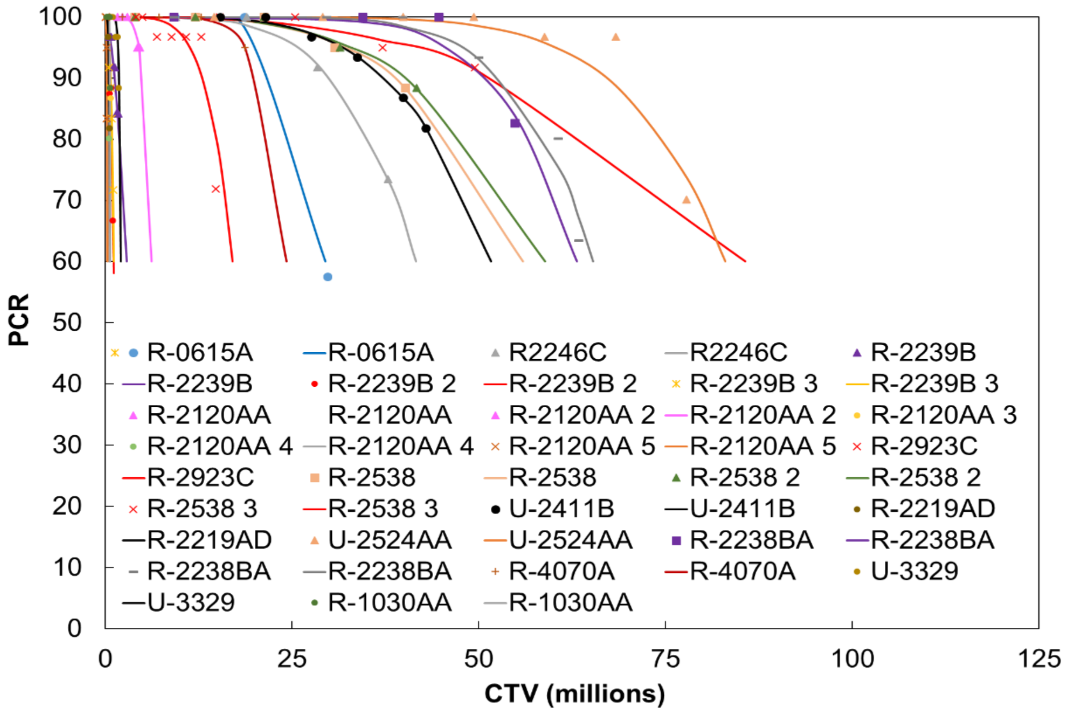

Figure 2.16 Performance condition rates vs. cumulative traffic volume for ABC pavements.

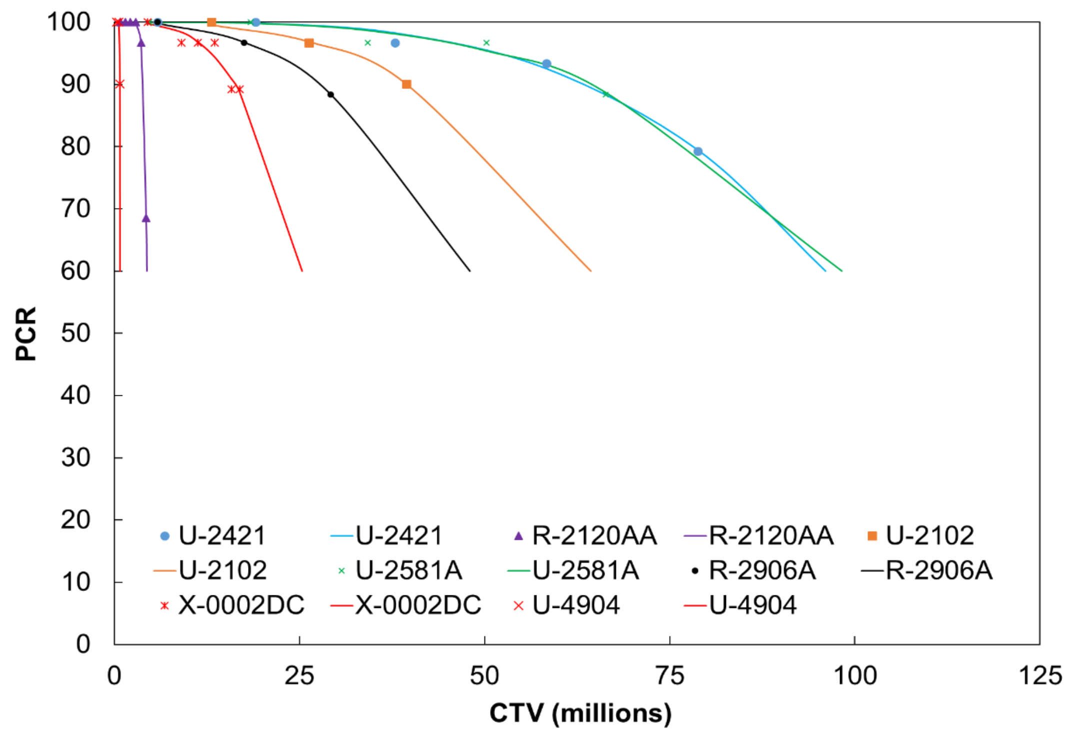

Figure 2.17 Performance condition rates vs. cumulative traffic volume for FDA pavements.

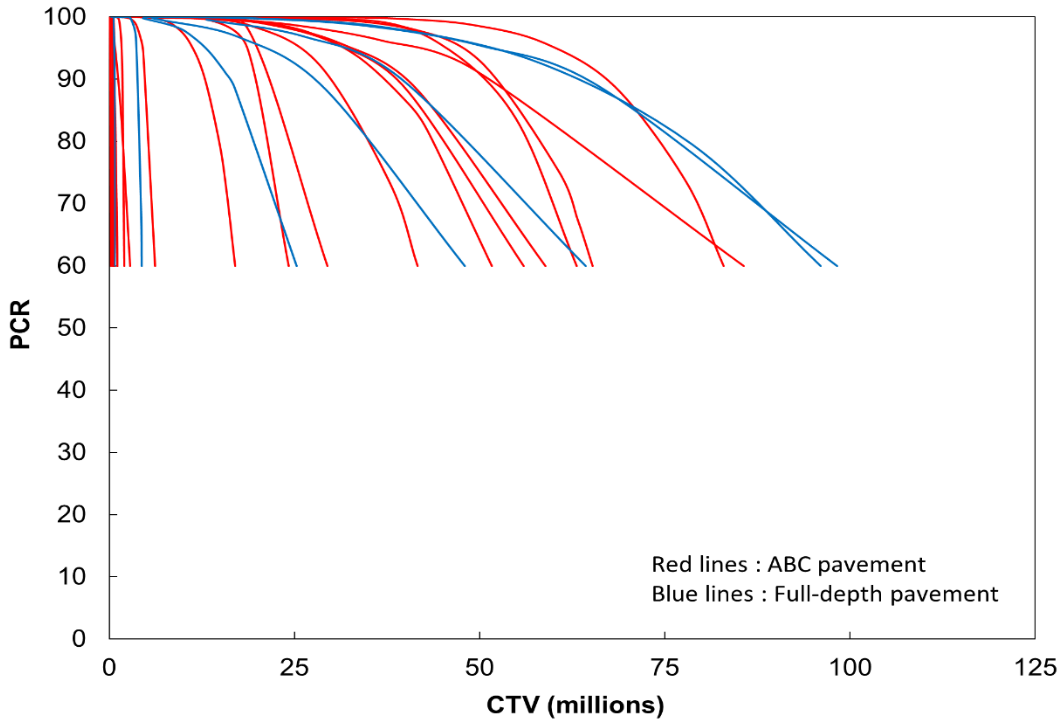

Figure 2.18 Performance condition rates vs. cumulative traffic volume for ABC and FDA pavements.

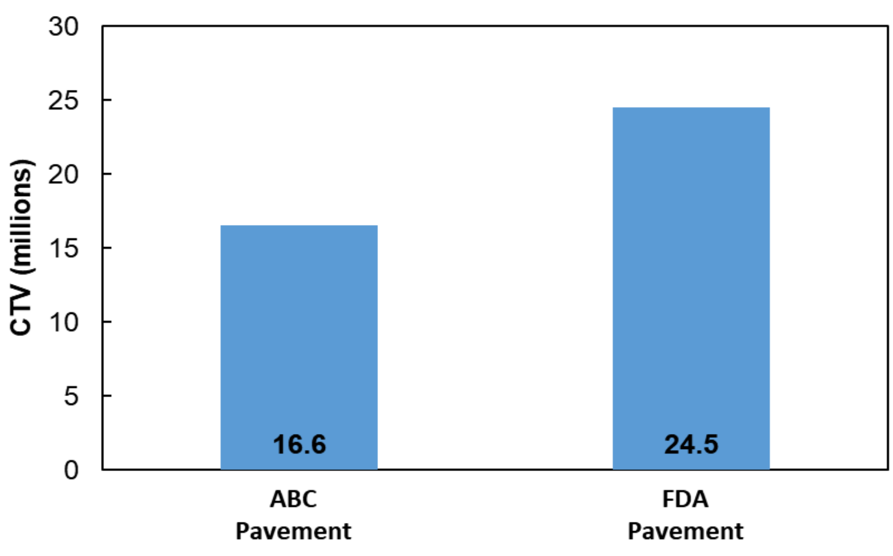

Figure 2.19 Average cumulative passing traffic prior to M&R treatment for ABC and FDA pavements.

Thus, the NCSU research team compared the performance of the two types of pavements in two different domains, i.e., service time and cumulative traffic. The study results show that the ABC pavements have a longer service life whereas the FDA pavements can bear more traffic loading.

2.5.2 Effects of Pavement Structure

The structure of a pavement has a significant effect on its performance and the cost of construction. In FDA pavements, the asphalt layers carry most of the load on the pavement so that the vertical stress from the traffic load is distributed throughout the subgrade. The relatively thick bound layers also protect FDA pavements from moisture from the pavement surface. In ABC pavements, the asphalt layers are built upon an aggregate base layer that is 4 to 10 inches thick; the asphalt layers and the base layer together provide structural support. Pavement distresses, e.g., fatigue cracking, may appear during the early stages of a pavement's service life. The early occurrence of fatigue cracking is due to the effects of bending and shear stresses under heavy traffic on the relatively thin asphalt layers. Once the pavement surface cracks, water can enter the pavement and accelerate the deterioration. Moreover, the designed structure can directly affect the initial cost of the pavement. Therefore, pavement structure is considered as an important factor in this study.

In order to quantify the effect of the type of pavement structure, the concept of 'structural number' (SN) is used in this study. The SN is a pavement design parameter found in the AASHTO 1993 Pavement Design Guide, which is currently used by the NCDOT for pavement design. The SN is computed from Equation (2.2) based on the layer coefficients and layer thicknesses.

$$SN = a_1 D_1 + a_2 D_2 M_2 + a_3 D_3 M_3 \tag{2.2}$$

where

a_1, a_2, a_3 = structural layer coefficients of the wearing surface, base layer, and sub-base layer, respectively,

D_1, D_2, D_3 = thickness of the layers, and

M_2, M_3 = drainage coefficients for the base and sub-base, respectively.

The layer coefficients represent the contribution of the layers in the pavement and differ for different types of materials. For example, asphalt layers have higher layer coefficients than aggregate base layers, and surface asphalt mixtures have higher layer coefficients than bottom asphalt mixtures. Table 3 presents the layer coefficients for different structural types.

Table 3. Layer Coefficients for Structure Number Coefficients

AC surface course, Types S9.5X, SF9.5A	AC surface course, Type S12.5X	AC intermediate course, Type I19.0X	AC base course, Type B25.0X
0.44 (per inch)	0.44 (per inch)	0.44 (per inch)	0.30 (per inch)
Permeable asphalt drainage course	Aggregate base course	Cement-treated aggregate base course	Cracked and seated concrete
0.14 (per inch)	0.14 (per inch)	0.23 (per inch)	0.28 (per inch)
Rubblized concrete	Full-depth reclaimed asphalt	200-mm lime-stabilized subgrade	175-mm cement-stabilized subgrade
0.28 (per inch)	0.20 (per inch)	1.0 (for layer)	1.0 (for layer)

Figure 2.20 presents the average SNs for the ABC and FDA pavements with standard deviation. The FDA pavements have a higher SN than the ABC pavements on average, which is reasonable because the structures of both types of pavements are designed to match their respective anticipated traffic volumes.

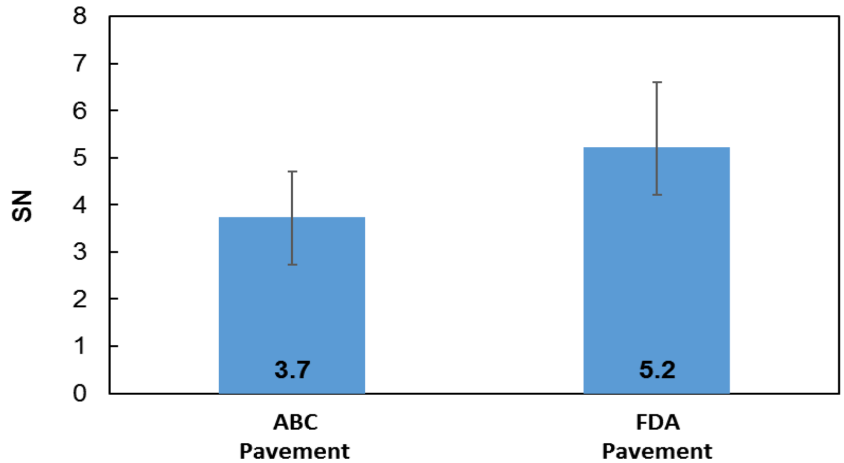

Figure 2.20 Average structural numbers for ABC and FDA pavements.

A unique power law relationship exists between the design SN and the AADT for both types of pavement structure, as presented in Figure 2.21. The correlation in this relationship indicates two points of interest. First, although the design variable for traffic in the AASHTO 1993 Design Guide is the equivalent stand axle load (ESAL), using available AADT data in the PMS database is sufficient to represent the different traffic volumes for each pavement type. Second, the NCDOT pavement design using the AASHTO 1993 Design Guide seems to address the anticipated traffic volumes adequately. However, because fairly significant differences in the performance of ABC pavements and FDA pavements are evident, the SNs in the AASHTO 1993 Design Guide may not be sufficient to balance the contributions from the asphalt layers and base layers. Therefore, other variables that describe pavement structural properties should be considered as well.

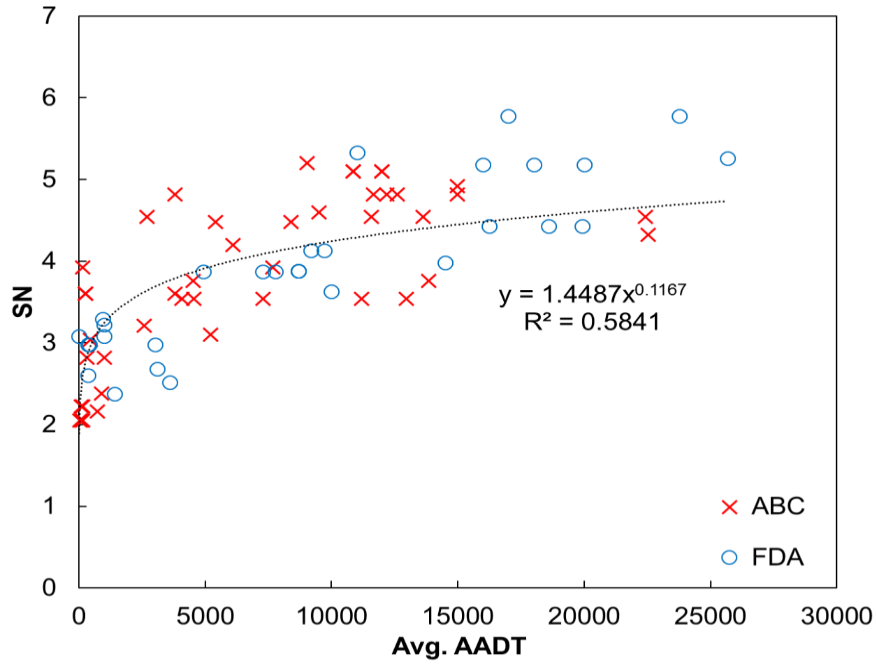

Figure 2.21 Relationship between structural number and AADT for ABC and FDA pavements.

The NCSU research team calculated the total asphalt concrete thickness for each pavement section. Figure 2.22 presents the averaged asphalt concrete thicknesses of the ABC and FDA pavements and shows that the thicknesses differ significantly. The asphalt concrete thickness of the pavement is thus considered an important structural factor in this study in addition to the SN.

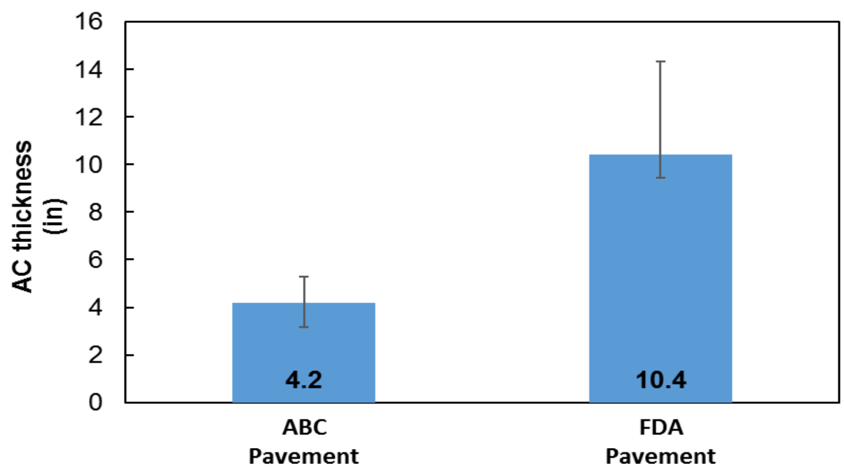

Figure 2.22 Average asphalt concrete thicknesses for ABC and FDA pavements.

Table 4 and Table 5 present summaries of the critical parameters for the ABC pavements and FDA pavements, respectively.

Table 4. Summary of Pavement Properties of ABC Pavement Sections

TIP number	Route number	SN	AC (in.)	Average AADT
R-0615A	30000024	3.76	6	13,837
R2246C	40001430	3.54	5.5	12,960
U-2929	40001323	3.76	6	4,514
R-2240A	40001154	2.82	4.5	1,006
R-2239B	40002323	2.82	4.5	310
R-2239B	40002325	3.6	5	260
R-2239B	40002325	3.6	5	260
R-2239B	40002325	3.6	5	260
R-2120AA	40001150	3.6	5	3,800
R-2120AA	40001199	2.38	3.5	900
R-2120AA	40001209	2.05	2.75	150
R-2120AA	40001210	2.05	2.75	100
R-2120AA	40001444	2.05	2.75	40
U-2009B	40001430	4.54	5.5	22,431
R-2923C	40001765	4.54	5.5	2,700
R-0977A	20000064	4.82	5.5	3,800
U-2712	40002200	4.32	5	22,533
U-3307B	40003632	4.48	6	5,400
R-2538	30000054	4.82	7	12,193
R-2538	30000054	4.82	7	12,593
R-2538	30000054	4.82	7	14,973
R-2538	30000054	4.82	7	11,667
U-2411B	40002433	4.48	6	8,400
R-2219AD/U-3630	40001992	2.22	2.5	100
R-2568A	30000109	5.2	7	9,034
U-2831A	40001954	4.2	7	6,100
U-2524AA	40001546	4.92	7	14,978
R-2238BA	30000087	4.54	5.5	13,628
R-2238BA	30000087	4.54	5.5	11,585
R-2502A	20000001	3.54	5.5	4,067
R-4070A	30000012	3.54	5.5	7,277
U-3329	40001412	3.04	5	450
R-1030BA	40001002	3.1	4.5	5,206
R-1030AA	40002153	2.22	2.5	154
Average		3.7	5.2	6,696.0

Table 5. Summary of Pavement Properties of FDA Pavement Sections

TIP number	Route number	SN	AC (in.)	Average AADT
R-2625A	40002705	3.88	7.5	8,695
U-2421	20000070	5.78	16	17,000
U-2421	20000070	5.78	16	23,773
R-2120AA	40001125	3.29	8.75	931
R-2625A	40002705	3.88	7.5	8,695
X-0002DC	40001933	2.68	8	3,090
U-2102	30000157	5.18	14	18,000
U-2102	30000157	5.18	14	20,000
U-2581A	20000070	4.43	11.5	16,243
U-2581A	20000070	4.43	11.5	18,591
U-2581A	20000070	4.43	11.5	19,914
R-3303	40001452	3.22	6	996
R-2905	30000055	5.26	14.5	25,667
R-2906A	30000055	5.18	14	16,000
I-2812	40001211	2.6	7.5	360
U-4904	40001324	2.98	4.5	400
U-4904	40001324	2.98	4.5	350
Average		4.2	10.4	11,688

2.6 Analysis of Pavement Performance and Critical Parameters

The NCSU research team identified three critical factors, i.e., AADT, SN, and asphalt concrete thickness, which impact pavement performance. Information regarding these factors is available in the PMS database and in the design documents. The objective of this section is to examine the relationship between the critical factors and pavement performance so that, in future, pavement performance and life cycle costs can be estimated as the pavements are designed.

2.6.1 Relationships between Simple Critical Factors and Pavement Performance

In order to investigate the effects of each critical factor, the research team evaluated the relationship between the factors and pavement performance individually. The team used the estimated M&R treatment times presented in Section 2.4 to represent pavement performance because (1) pavements with poor performance would require early treatment and (2) the estimated M&T treatment time is related directly to the life cycle cost of the pavement. The relationships between the critical factors and pavement performance are discussed in the following sections.

2.6.1.1 Estimated M&R Treatment Time vs. Traffic Volume

Figure 2.23 shows the relationship between the estimated M&R treatment times and the estimated AADT in the PMS database. The figure shows that, the higher the AADT, the sooner the pavement will require treatment. This trend is expected because a considerable amount of traffic can accelerate the damage evolution in pavements. Another observation that can be made from the plot is that the FDA pavements, in general, may require treatment sooner than the ABC pavement sections due to the heavier traffic on FDA pavements compared to ABC pavements. However, this trend also indicates that the effect of traffic loading may not be addressed sufficiently in the current pavement design method.

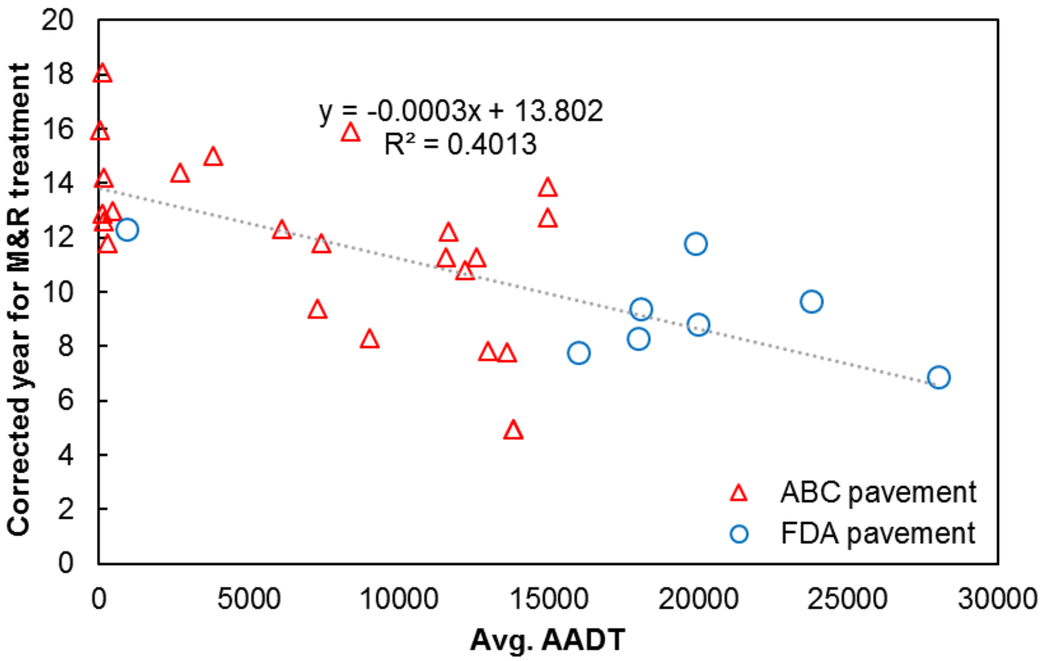

Figure 2.23 Relationship between estimated M&R treatment time and AADT.

2.6.1.2 Estimated M&R Treatment Time vs. Pavement Structure Factors

Figure 2.24 presents the relationship between the estimated M&R treatment times and SN for the ABC and FDA pavement sections, and Figure 2.25 shows the M&R treatment times vs. the total asphalt concrete layer thickness for both pavement types. The M&R treatment time has an inverse linear relationship with both the SN and total asphalt concrete layer thickness. However, it is expected that a better structure can alleviate the evolution of pavement distresses. This unexpected relationship is believed to be attributed to the stronger effect of traffic volume on pavement performance compared to the effects of SN and AC layer thickness.

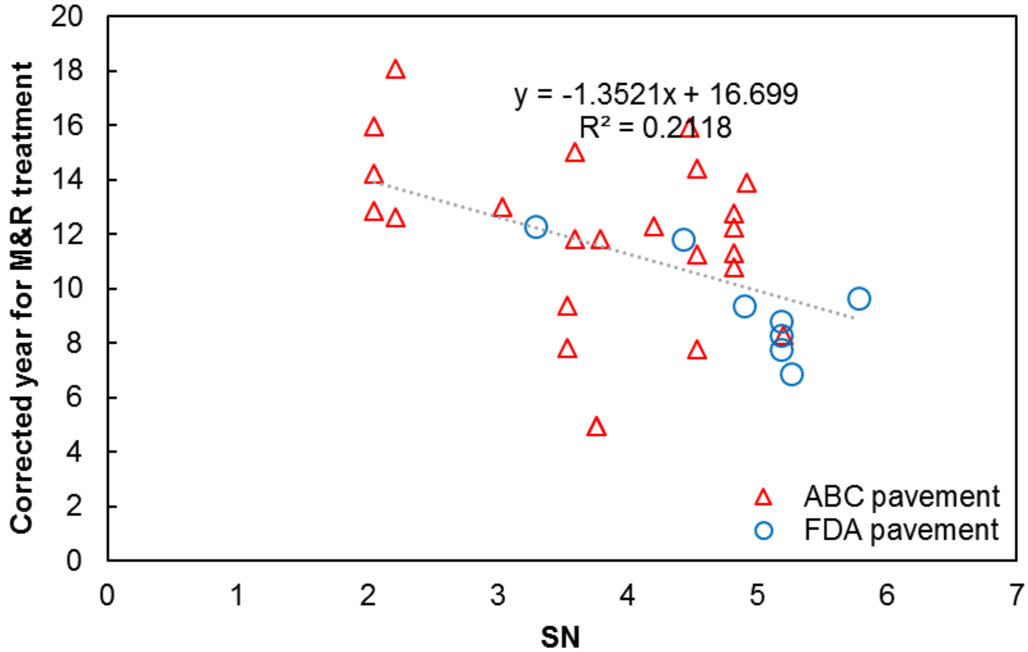

Figure 2.24 Relationship between estimated M&R treatment time and structural number.

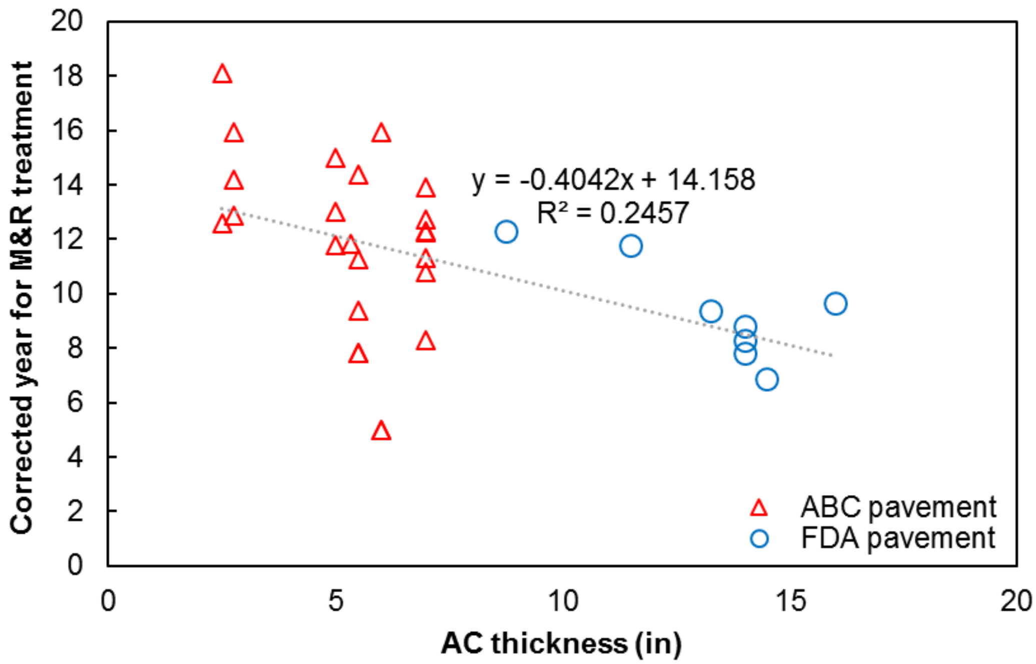

Figure 2.25 Relationship between estimated M&R treatment time and total asphalt concrete layer thickness.

2.6.2 Development of a Pavement Deterioration Index

The previous sections present the relationships between pavement performance and traffic and structural factors. The analysis results indicate that the designed pavement structure may not be sufficient to overcome the effects of traffic loading on pavements. Therefore, the structural factors, i.e., the SN and total asphalt concrete layer thickness, are even more important when considering the existing designed pavement and its cost. To this end, the research team developed a simple pavement deterioration index (PDI) for this study using the critical factors. Equation (2.3) describes the development of this deterioration index.

$$PDI = \frac{AADT}{SN \times H_{AC}} \tag{2.3}$$

where PDI = pavement deterioration index,
$AADT$ = annual average daily traffic,
SN = structural number of the pavement, and
H_{AC} = total asphalt concrete layer thickness, inch.

Figure 2.26 presents the relationship between the PDI values and corrected year for M&R treatment (i.e., pavement performance). A relatively high correlation is shown. In the PDI, the traffic volume is normalized by the structural factors; thus, the fitting results indicate decrease in pavement performance. Also, the range of the PDI values for the FDA pavements is close to that for the ABC pavements, thus indicating the ability of the PDI in accounting for the effects of traffic volume on pavement performance properly.

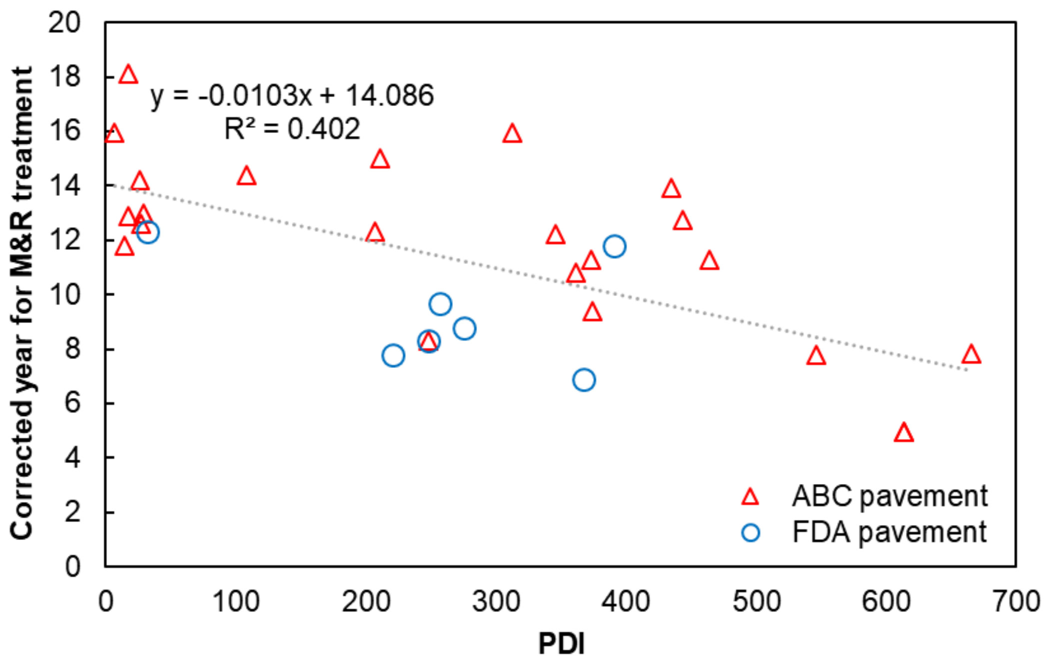

Figure 2.26 Relationship between pavement performance and pavement deterioration index values.

Although the difference is not large, the data points for the FDA pavements seem to be positioned slightly lower than those for the ABC pavements in Figure 2.26. Therefore, the corrected year for M&R treatment and PDI values for the ABC and FDA pavement sections are plotted separately in Figure 2.27 and Figure 2.28 respectively. For Figure 2.28, one point that was located much higher than the rest of the data points for the FDA pavements in Figure 2.26 was an outlier and thus is excluded from the graph.

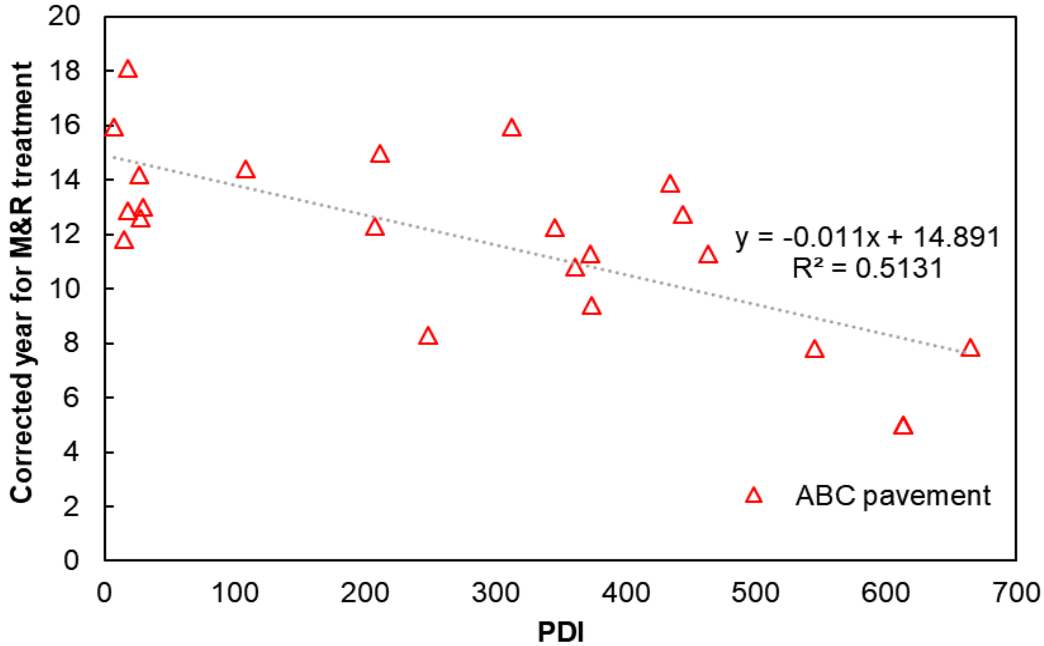

Figure 2.27 Relationship between pavement performance and pavement deterioration index values for ABC pavements.

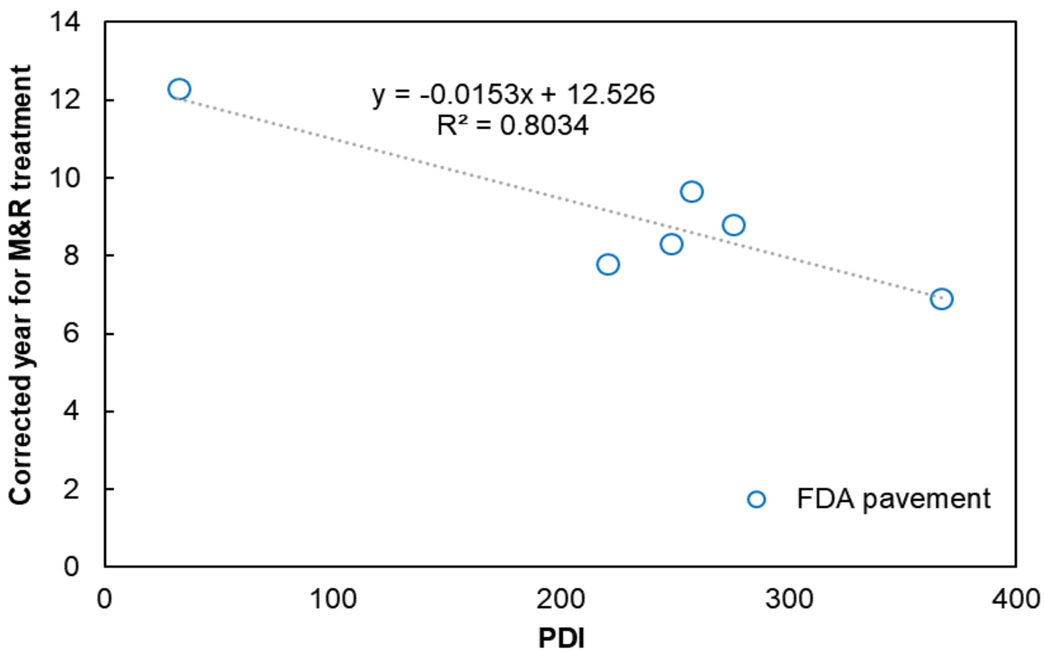

Figure 2.28 Relationship between pavement performance and pavement deterioration index values for FDA pavements.

2.7 Prediction of M&R Treatment Time

A linear relationship exists between the estimated M&R treatment time and the proposed PDI values. Because the PDI is composed of parameters that are available as the pavement is designed, the treatment time of the pavement can be estimated quickly using the linear relationship. Equation (2.4) expresses the formula that is used to predict the treatment time for both types of pavements (ABC and FDA), and Equations (2.5) and (2.6) are used respectively to predict the treatment times for the ABC and FDA pavements separately.

$$Est.Trt.Time = (-0.0103 \times \frac{AADT}{SN \times H_{AC}}) + 14.086 \tag{2.4}$$

$$Est.Trt.Time = (-0.011 \times \frac{AADT}{SN \times H_{AC}}) + 14.891 \tag{2.5}$$

$$Est.Trt.Time = (-0.0153 \times \frac{AADT}{SN \times H_{AC}}) + 12.526 \tag{2.6}$$

where Est. Trt. Time = estimated M&R treatment time, year.

Figure 2.29 and Figure 2.30 present comparisons between the predicted treatment times and the estimated pavement treatment times for when the three equations, i.e., Equation (2.4) for the ABC and FDA pavements together (Fig. 2.29) and Equations (2.5) and (2.6), respectively, for the ABC and FDA pavements individually (Figure 2.30), are applied. The comparisons indicate that, for most of the pavement sections in the PMS database, the predicted treatment time is reasonably acceptable. This prediction can help improve LCCA by knowing the proper treatment time for different pavements with various traffic loads and structures.

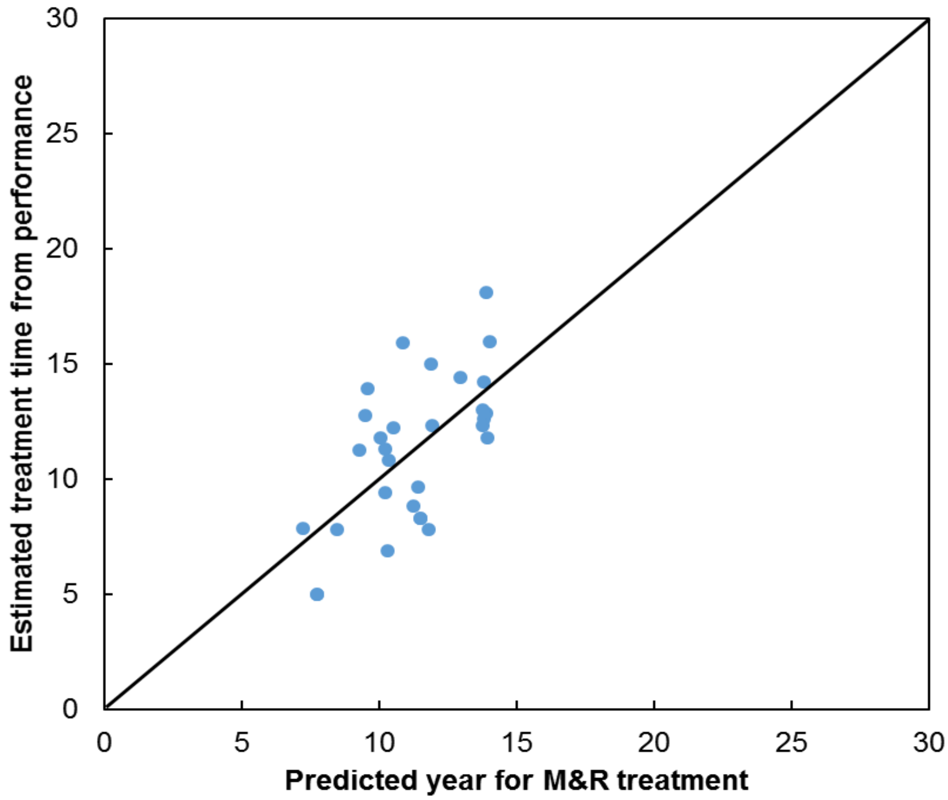

Figure 2.29 Predicted treatment time vs. estimated treatment time calculated using Equation (2.4) for both ABC and FDA pavements.

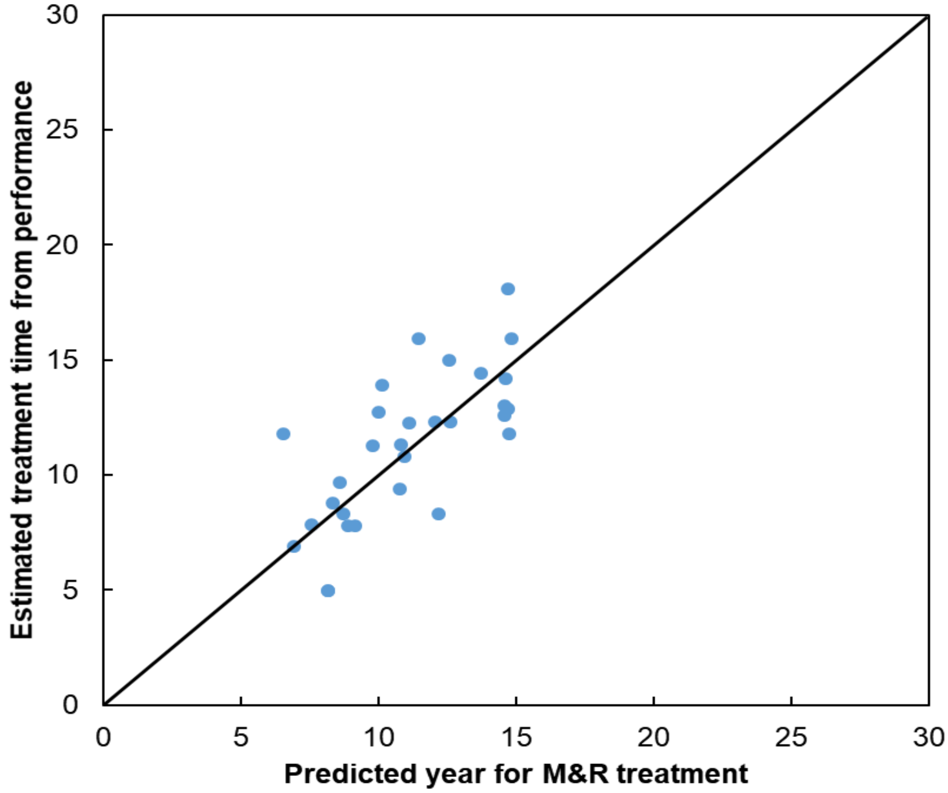

Figure 2.30 Predicted treatment time vs. estimated treatment time calculated using Equations (2.5) and (2.6), respectively, for each pavement type (ABC and FDA) individually.

In addition, the NCSU research team verified the prediction results using the rehabilitation histories for four sections that the NCDOT provided. Figure 2.31 and Figure 2.32 present the verification results.

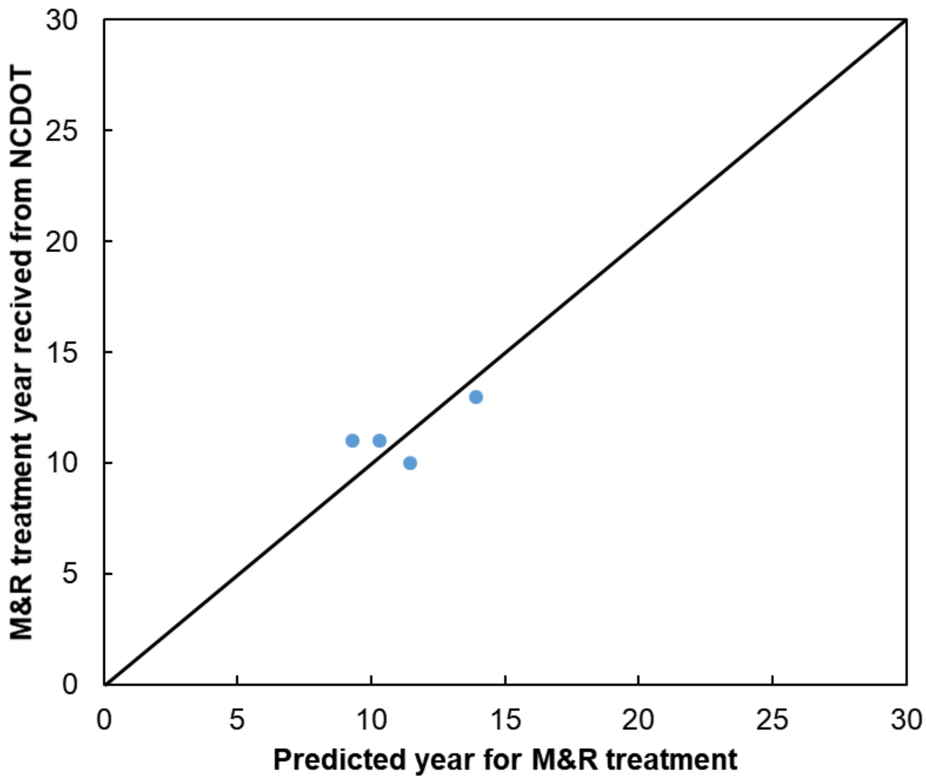

Figure 2.31 Verification of the predictive equation for M&R treatment time obtained from Equation (2.4) used for both pavement types (ABC and FDA).

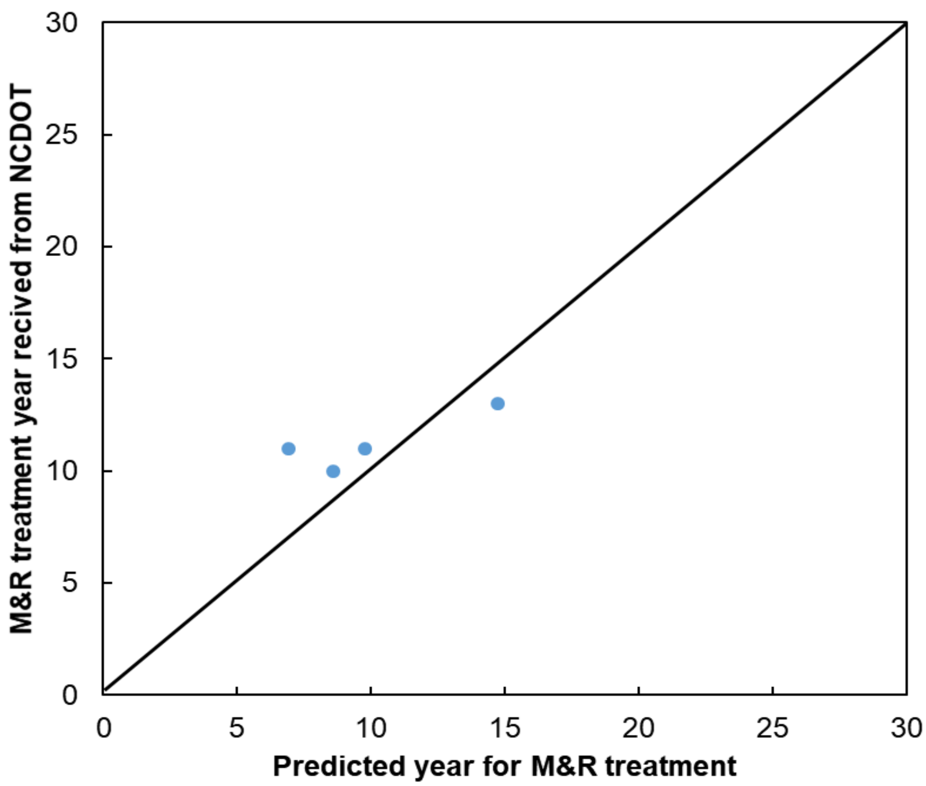

Figure 2.32 Verification of the predictive equation for M&R treatment times obtained from Equations (2.5) and (2.6) used for individual pavement types (ABC and FDA).

2.8 Comparison between ABC Pavements and FDA Pavements

The main objective of this study is to compare the performance of ABC pavements and FDA pavements and to investigate the cost-effectiveness of the two types of pavements. According to the analyses presented in the previous sections, the volume of traffic and the structure of the pavement significantly affect pavement performance. A unique linear relationship exists for both types of pavement (ABC and FDA) between pavement performance and the PDI that is composed of the AADT, SN, and total asphalt concrete layer thickness. The relationships for both types of pavements together and the individual types of pavement separately suggest that one type is not distinguishably better than the other in terms of pavement performance. However, the ABC pavements tend to have relatively longer rehabilitation times than the FDA pavements; this finding makes sense given the lighter traffic volumes that ABC pavements experience compared to FDA pavements. Thus, life cycle costs should be calculated and compared for each given project. When the cost of the pavement is estimated, the required treatment time and the structure of the pavement should be taken into account.

CHAPTER 3 Conclusions and Recommendations for Future Research

This study investigated the performance of ABC pavements and FDA pavements. A summary of the analyses is as follows.

1. The NCSU research team compared the ABC and FDA pavements in the time domain and cumulative traffic domain. These comparisons show that, in general, the ABC pavements deteriorate more slowly in the time domain but more quickly in the cumulative traffic domain than the FDA pavements.

2. The NCSU research team modeled pavement performance curves using a power law function. The team was able to estimate the M&R treatment time for each pavement section based on a predefined M&R trigger, which is the PCR of 60.

3. The NCSU research team identified the critical factors that are related to pavement performance: AADT, SN, and total asphalt layer thickness.

4. The NCSU research team proposed a PDI that can be calculated using the parameters for pavement design. The PDI and pavement performance have reasonable relationships for the ABC and FDA pavements together and individually. Using these relationships, the proper time to apply M&R strategies can be estimated.

5. Based on the analysis results, in order to compare the life cycle costs of ABC pavements and FDA pavements, the design for each project must be compared individually. In the comparison, the proper time to apply M&R and the structural factors must be taken into account in the LCCA.

The following recommendations are made for future research:

- Reasons for the underestimation of the detrimental effects of traffic on FDA pavements need to be investigated and any necessary revisions to the current pavement design procedure should be developed.

- The developed M&R treatment time vs. PDI relationships for FDA and ABC pavements need to be further verified using a wide range of pavements.

APPENDIX A Guidelines for Pavement ME Recalibration

Part I. Introduction and General Information

1. Introduction

The Pavement ME design program, formerly known as the MEDPG, is a mechanistic-empirical program. It allows users to apply mechanical and semi-mechanical models to design new pavements or rehabilitate old pavements, instead of applying empirical methods, i.e., the AASHTO 1993 Design Guide. The Pavement ME program can predict pavement distresses for a trial design. The predicted performance of the trial design then can be compared with predetermined distress thresholds. After a trial and error process, the design candidates are obtained. The predicted distresses are limited within the highway agency's tolerance. However, the Pavement ME was calibrated using performance data that were measured throughout the United States. Thus, when the pavement design process is conducted by local agencies, Pavement ME should be calibrated for local pavements and conditions. The North Carolina Department of Transportation (NCDOT) sponsored work to calibrate the Pavement ME program through the following series of research projects:

- HWY-2003-09 *Typical Dynamic Moduli for North Carolina Asphalt Concrete Mixes*
- HWY-2006-23 *Implementation Plan for the New Mechanistic-Empirical Pavement Design Guide*
- HWY-2007-07 *Local Calibration of the MEPDG for Flexible Pavement Design*
- HWY-2008-11 *Development of Traffic Data Input Resources for the Mechanistic-Empirical Pavement Design Process*
- HWY-2012-01 *MEPDG Inputs for Warm-Mix Asphalts*

The input data specific for North Carolina were generated through these research projects. Since these projects, Pavement ME has been revised with new models and needs to be recalibrated using more recently recorded local performance data. In this task, guidelines for this recalibration using more recent data were developed and are provided herein, and an enhanced database for the calibration was established.

2. Background

The recalibration effort employs the calibration method developed in the HWY-2007-07 project and utilizes an enhanced database. The database consists of the 41 Long-Term Pavement Performance (LTPP) program and Pavement Management Systems (PMS) sections that were identified in the previous research projects and the newly identified pavement sections in this research project. The new sections were selected originally to compare the performance of ABC pavements and FDA pavements. The guidelines introduce a method to convert the performance data in the PMS database into a useable form for the calibration database.

2.1. Steps included in the calibration:

a. Complete the database. Collect the project-specific input information as listed in the guidelines and the corresponding performance information obtained from the PMS database. The performance data obtained from the PMS database should be converted to the form for LTPP data that can be used for calibration.

b. Prepare the input files for each project to run Pavement ME.
c. Prepare the computer program script according to guideline instructions.
d. Run the script. The optimized calibration factor will be reported after the computation in the script is completed.
e. Check the reasonableness of the calibration coefficients and the predicted results.

2.2. MEPDG input levels

The MEPDG offers three hierarchical traffic data input levels (Levels 1, 2, and 3). These levels indicate how well the pavement designer can estimate future truck traffic characteristics for the roadway being designed (NCHRP, 2004a). The selected level of input detail typically is governed by two factors: (1) the resources available to collect the detailed traffic data that are required for accurate future traffic characteristics prediction and (2) the size and functional importance of the project. Users can choose from the following three hierarchical input levels:

Level 1

Level 1 input reflects the designer's high degree of knowledge of the materials used in the pavement design. Level 1 input parameters are measured either directly from the site or near the site under study, or are determined through laboratory testing.

Level 2

Level 2 input reflects a medium level of knowledge of the materials used in the pavement design. Level 2 input parameters are determined based on state-wide averages or estimated based on known parameters through statistical correlations and relationships.

Level 3

Level 3 input reflects the least amount of knowledge of the materials used in the pavement design. Level 3 input parameters are estimated based on regional values or national values, i.e., MEPDG default values.

2.3. Calibration level

Because the laboratory testing program within this research work does not include any of the actual materials that were used in construction, no true input Level 1 exists for any of the layer materials, as mentioned earlier. The hot mix asphalt (HMA) material properties, including binder and mixture, are considered Level 2 inputs. Similarly, the base and subgrade materials are Level 3 and Level 2 inputs, respectively. Traffic information, on the other hand, is Level 1 input because such information should be based on the calibration/validation sections.

2.4. Project-specific information

a. Traffic
b. Structure

c. Materials
d. Climate
e. Performance

2.5. Introduction of the required input information for running Pavement ME

a. Performance criteria:

Input Parameter	Allowable Range	
Initial IRI, inches/mile	0	200
Terminal IRI, inches/mile	63	1260
Longitudinal cracking, feet/mile	500	2000
Alligator cracking percentage of lane area	0	100
Thermal fracture, feet/mile	0	10000
Chemically stabilized layer fatigue fracture, %	0	100
Permanent deformation, total pavement, inches	0	3
Permanent deformation, AC only, inches	0	3

Note: IRI is international roughness index.

b. Traffic:

Input Parameter	Information Source	Note
Initial two-way AADTT	Traffic survey unit	from 48-hour counting
Number of lanes in design direction	Traffic planning branch	or state-wide recommended values
Percentage of trucks in design direction	Traffic planning branch	or state-wide recommended values
Percentage of trucks in design lane	Traffic survey unit	or state-wide recommended values
Operational speed, mph	Pavement design unit	or national default values
Mean wheel location, inches from	Using national default	
Traffic wander standard deviation, inches	Using national default	
Design lane width, feet	Using national default	
Average axle width, feet	Using national default	
Dual tire spacing, inches	Using national default	
Tire pressure, psi	Using national default	
Tandem axle spacing, inches	Using national default	
Tridem axle spacing, inches	Using national default	
Quad axle spacing, inches	Using national default	
Average axle spacing, inches	Using state-wide recommended values	
Percentage of trucks per category (short, medium, long)	Using state-wide recommended values	
Axle load distribution factors (ALDFs)	Excel-based tool	Significant, site-specific information is required
Axles per truck (APT)	Using state-wide recommended values	
Monthly adjustment factors (MAFs)	Using state-wide recommended values	

Vehicle class distribution (VCD) factors	Excel-based tool	Significant, site-specific information is required
Traffic growth factors	Traffic forecasting group	

c. Climate:

Input Parameter	Information Source
Project longitude, degrees. minutes	Select the weather station
Project latitude, degrees. minutes	Select the weather station
Project elevation, feet	Select the weather station
Depth of water table at project location, feet	Geotechnical Unit or USGS website

d. Materials and structure, asphalt:

Material		Source
HMA Mixtures	Dynamic modulus	State-wide recommended values based material type
	Reference temperature (°F)	National default
	As-built effective binder content by volume (%)	
	As-built air voids (%)	
	As-built total unit weight (pcf)	
	Poisson's ratio	
	Thermal conductivity of asphalt (BTU/hr-ft-°F)	
	Heat capacity of asphalt (BTU/lb-ft)	
Asphalt Binder	Shear modulus, Pa, and phase angle at 10 radians/sec	State-wide recommended values based material type

Materials and structure, unbound layer:

Input Category	Input Parameter	Information Source
Soil gradation	Passes on each sieve	Excel-based tool developed based on the products of the NCHRP 9-23A project
Atterberg limits	Plasticity index (PI)	
	Liquid limit (LL)	
Compacted soil properties	Max. dry unit weight (pcf)	
	Soils specific gravity, Gs	
	Saturated hydraulic conductivity (permeability) (ft/hr)	
	Opt. gravimetric water content (%)	
SWCC parameters	SWCC parameters	

Note: SWCC is soil-water characteristic curve.

2.6. Computer routine script

The optimization should be conducted by running a program. In the HWY-2007-07 project, a MATLAB script was used. Because some changes have been made in the data, a new program script should be prepared. The new program can be written in MATLAB or any other computing language. For calibrating the model coefficients of the rutting/fatigue performance predictions, the following steps should be included in the program:

Step 1: The program reads the '.csv' or the '.dat' files that contain the initial values of the calibration coefficients. The program first calls the Apads.exe file for the first section and executes it. As a result of its execution, Apads.exe generates a file called '.rut' or '.fag' that contains the total predicted rut depth values for the section.
Step 2: The script reads the '.rut' file or '.fag' file and extracts only certain predicted total rut depth values or cracked areas (%) that correspond to the measured rut depth values previously saved in a file inside the section directory.
Step 3: Knowing the measured total rut depth or the percentage of cracking area and the corresponding predicted total rut depth, the program calculates the sum square error (SSE) between the two values.
Step 4: Steps 1 through 3 should be repeated for all the sections. Once the SSE values are available for all the sections, the program sums the SSEs from all the sections to calculate the total SSE. The total SSE is then forwarded to the Genetic Algorithm module within the script.
Step 5: Based on the calculated total SSE, the GA generates new values for the calibration coefficients and writes these new values to the text files of a '.csv' or '.dat' file.
Step 6: Steps 1 through 5 are repeated until the changes in the total SSE become minimal. Because of the nature of optimization and the time-consuming runs, the halting criterion can be based mainly on changes in the total SSE as well as changes in the values of the calibration coefficients.

Part II. Calibration Manual

1. Open the database file. Check the sections included in the database.
2. Collect project-specific information about the sections and complete the database.
   - 2.1 Performance information
     - 2.1.1 Extract performance information about the new PMS section from the PMS database.
     - 2.1.2 Convert the fatigue performance data recorded in the PMS database to the LTPP database recording method. For the fatigue data, the cracking area (%) will be calculated using Equation (1). For the rutting data, the rut depth should be converted using Equation (2).
     - 2.1.3 Complete the database.
   - 2.2 Other general project information
     - 2.2.1 Collect the project information:
       - Project name
       - Design life, years
       - Base/subgrade construction, month and year
       - Pavement construction, month and year
       - Traffic opening, month and year
       - Site/project identification

- Location
- Project ID
- Section ID
- Date
- Station / milepost format
- Station/ milepost beginning
- Station/ milepost end
- Traffic direction

2.2.2 Complete the database.

2.3 Traffic

2.3.1 Collect traffic information:

- Two-way average annual daily truck traffic (AADTT)
  - Find the data from the database.
  - If the database is not completed, obtain the data from the Traffic Survey Unit (TSU) or the design unit.
- Number of lanes in design direction
  - Find the data from the database.
  - If the database is not completed, obtain the data from the Traffic Planning Branch (TPB); if the data are not available from the TPB, use the default value, 2.
- Percentage of trucks in design direction
  - Find the data in the database.
  - If the database for the target section is not completed, obtain the site-specific data from the TPB Forecast Unit. If the site-specific data are unavailable, select the number based on the predominant type of vehicle that uses the roadway, as follows:
    - ➢ Class 4, except for local or municipal routes, use 50 percent.
    - ➢ Class 4, for local or municipal routes, use 80 percent to 100 percent.
    - ➢ Classes 5, 6, 7, use 62 percent.
    - ➢ Classes 8, 9, 10, use 55 percent.
    - ➢ Classes 11, 12, 13, use 50 percent.
  - If the predominant type of vehicle is unclear, use the national default value, which is 50 percent.
- Percentage of trucks in design lane (lane distribution factor, or LDF)
  - Find the data in the calibration database.
  - If the database for the target section is not completed, obtain the site-specific data from the TSU. If local data are unavailable, the following national default values can be used:
    - ➢ Single-lane roadways in one direction, use 100 percent.
    - ➢ Two-lane roadways in one direction, use 90 percent.
    - ➢ Three-lane roadways in one direction, use 60 percent.
    - ➢ Four-lane roadways in one direction, use 45 percent.

- Operational speed
  - Find the data in the calibration database.
  - If the database for the target section is not completed, obtain the site-specific data from the Pavement Design Unit. The data can be found in the Transportation Research Board Highway Capacity Manual. If local data are unavailable, use the national default value, which is 60 mph.
- Monthly adjustment factors (MAFs)
  - Research has found that the prediction results for performance are not sensitive to MAFs. A set of state-wise MAF values are recommended:

Month	**Class 4**	**Class 5**	**Class 6**	**Class 7**	**Class 8**	**Class 9**	**Class 10**	**Class 11**	**Class 12**	**Class 13**
January	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
February	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
March	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
April	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
May	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
June	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
July	1	1	1	1	1	1	1	1	1	1
August	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
September	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
October	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
November	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
December	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93

- Vehicle class distribution (VCD) factors
  - The VCD factors can significantly affect performance predictions. Site-specific information is required. Find the information in the database.
  - If local data are not available, use the decision trees in the Excel-based tool to general the VCD factors. The decision trees can be used based on two factors, the single-unit (Classes 4 to 7) truck percentages and the multiple-unit (Classes 8 to 13) truck percentages from 48-hour classification counts.
  - Check the generated VCD factors using engineering judgement. If the factors are reasonable, use the generated factors for the section.
- Traffic growth factor
  - Find the corresponding data in the database.
  - If local data are not available, use the data provided by the Traffic Forecasting Group.
- Axle load distribution (ALD) factors
  - The ALD factors can significantly affect the performance prediction. Site-specific information is required. Find the information in the database.

- If the local data are not available, use the decision trees in the Excel-based tool to generalize the ALD factors. The decision tree implements the percentages of Class 5 and Class 9 vehicles obtained from 48-hour counts.
- Check the generated ALD factors using engineering judgement. If the factors are reasonable, use the generated factors for the section.

- Mean wheel location (inches from lane marking)
  - Use the default value.
- Traffic wander standard deviation (in.)
  - Use the national default value.
- Design lane width (ft)
  - Use the national default value.
- Number of axles per truck
  - Use the recommended state-wise values:

Vehicle Class	Axle Type			
	Single	Tandem	Tridem	Quad
Class 4	1.77	0.23	0	0
Class 5	2	0	0	0
Class 6	1.12	0.93	0	0
Class 7	1.12	0.19	0.79	0
Class 8	2.44	0.57	0	0
Class 9	1.18	1.9	0	0
Class 10	1.04	1.25	0.52	0.15
Class 11	4.87	0.01	0	0
Class 12	3.82	0.96	0	0
Class 13	1.61	1.64	0.32	0.2

- Average axle width (edge-to-edge)
  - Use the national default value.
- Dual tie spacing (in.)
  - Use the national default value.
- Tire pressure (psi)
  - Use the national default value.
- Axle spacing (in.)
  - Replace the national default values with the recommended North Carolina state-wise values: 48.9 (tandem), 52.7 (tridem), and 50.0 (quad).
- Wheelbase
  - Use the default values for the inputs in this category.

2.4 Location, depth of water table, and climate

2.4.1 Climate station

- Find the corresponding climate station(s) from the calibration database.
- If the data are not available in the database, choose the most reasonable one or multiple climate stations according to the site location.

2.4.2 Depth of water table

- Find the corresponding data in the database.
- If local data are not available, use the data provided by the Geotechnical Unit. Alternatively, those data are also available from a tool on the United States Geological Survey (USGS) website – simply enter longitude and latitude information.

2.5 Structure and thermal cracking

2.5.1 Pavement structure and material

- Find the corresponding pavement structure of the pavement project in the database.
- Identify the material type of each layer, i.e., flexible, non-stabilized base, or subgrade. The information should be available in the database.
    - If the material type is non-stabilized base or subgrade, the category should be specified. Find the category information (soil type) in the database.
    - If local data are not available, the information can be obtained using the Excel-based tool developed based on the products of the NCHRP 9-23A project.
    - Check the reasonableness using engineering judgement and complete the database.

3. Generate input information for each individual section selected for the calibration.

3.1 Input the sensitivity criteria for flexible distresses in North Carolina, as shown in the following sections.

3.2 Input the general information for the project:

Pavement Type	Performance Measure	Measuring Unit	Failure Point (Maintenance Trigger)	Sensitivity	
				% of Failure Point	Threshold
Asphalt Concrete	IRI	inch/mile	140	10	14
	Total Rutting	inch	0.5	20	0.1 inch
	Alligator Cracking	% lane area	10	10	1% of lane
	Longitudinal cracking is considered by the NCDOT as light severity alligator cracking	feet/mile	2640 (50% of section length)	10	264 feet/mile

3.3 Input the traffic information as collected in the database.

3.4 Input the climate condition information for the project, including location, climate station, and depth of water table.

3.5 Generate the structural information as collected in the database. The layer thickness and layer type can be selected in this step.

3.5.1 Asphalt layers

- Identify the mixture type as recorded in the database.
- Input the dynamic modulus value for the mixture in the layer.
  - Choose Level I input.
  - Input the corresponding dynamic modulus values recorded in the database for the corresponding mixtures.
- Input the binder content for the mixture in the layer.
  - Choose the corresponding performance grade for the mixture as recorded in the database.
  - Choose and input the shear modulus values recorded in the database from the database for the corresponding mixture.
- Input the volumetric properties as recorded in the database for the corresponding mixture.
- For other input parameters, use the default values.

3.5.2 Unbound layers

- Input the unbound layer properties as recorded in the database.

4. Run the local calibration.

4.1 Method 1 (optional)

4.1.1 Replace default *k* values with material-specific *k* values.

4.1.2 Find beta values that minimize the SSE for total rut depth.

- Run Pavement ME with different combinations of beta 2 and beta 3 values.

- Run Excel Solver to find the global minimized SSE with the final beta 1 and other values.
- Compare the predicted performance before and after the calibration. Check the reasonableness and determine the final calibration coefficients.

4.2 Method 2 (selected)

4.2.1 Input the material-specific coefficients in one text file, for example, 930_Calibration_Layer1.csv. The subroutine program Apads.exe searches the project directory for the coefficients and extracts them from these files.

4.2.2 Input the unbound layer properties, i.e., Beta gb and Beta sg into the text file, CalibrationFactor.dat file. The file is generated automatically by executing Pavement ME. The file will be read by the Aquads.exe.

4.2.3 In addition to material-specific *k* values for the HMA layers, national *k* values for the unbound layers, and the five local calibration coefficients (βr1, βr2, βr3, βgb, and βsg), a text file must be created in a MATLAB®-readable format and must contain the measured total rut depth values for each section at the different available distress survey dates. The text file must be saved in the main directory where the MATLAB® script and all the section directories exist. By the end of this step, MATLAB® is ready to run, and the following steps explain how MATLAB® finds the optimized values of βr1, βr2, βr3, βgb, and βsg that minimize the bias between the predicted and measured total rut depth values.

4.2.4 Determine the boundary of the coefficients.

4.2.5 For this study, in order to make use of multiple computers, the absolute range for each of the calibration coefficients was divided into multiple zones. For each of these zones, the initial boundaries option was bypassed and only the absolute lower boundaries (LB) and absolute upper boundaries (UB) were defined. The zone selection for each of the calibration coefficients is based in part on the rutting optimization experience and on results from some initial GA runs. The progress of the optimization process within each zone was monitored individually throughout the optimization process. The zone that yielded the smallest total SSE was the zone of focus. Four computers (Dual core 3.33 GHz, 8 GB of RAM, 64-bit) were used for the rutting optimization study. These computers were allowed to run for approximately 32 days until the change in total SSE and corresponding calibration factors became acceptable, based on different runs. Again, the change in total SSE was monitored continuously throughout the optimization by plotting the data of the total SSE with time.

4.2.6 Run the MATLAB program.

4.2.7 Compare and determine the final coefficients.

APPENDIX B Material Characterization Test Results

Two field pavement sections were identified as part of this research project. One section was an ABC pavement located in the outer loop from east of the All American Freeway (SR 1007) to US 401 in Fayetteville, North Carolina (NC). The other section was a FDA pavement on US 501 from NC 49 to SR 1521 in Roxboro, NC. Both of the sections were newly constructed pavements. During the course of the research project, the NCSU research team and the NCDOT crew conducted several field trips to these construction sites. During the field trips, the research team identified sections that were about 1,000 feet long at each location, extracted 10 asphalt pavement cores at each location, sampled the aggregate base and subgrade soil, and performed dynamic cone penetrometer (DCP) tests. The NCSU research team also acquired aggregate and binder from asphalt plants. The asphalt mixtures were tested at NCSU, and the test results will be used as part of the material database for the recalibration of the Pavement ME program.

The asphalt mixture tests performed on the mixes included dynamic modulus tests, cyclic fatigue tests, and stress sweep rutting (SSR) tests. In addition, the NCSU research team performed triaxial repeated loading permanent deformation (TRLPD) tests on the mixtures. After the team calibrated the material properties from those tests, the dynamic modulus ($|E^*|$) values and the mixture-specific coefficients (k_1, k_2, k_3) of the rutting and fatigue models in Pavement ME could be generated. In addition, the team could predict the performance of these mixtures once the pavement structural information was known.

Part I. Field Section Information

The FDA pavement section identified in this project was part of US 501 in Roxboro, NC from NC 49 to SR 1521; Table B-1 presents the GPS coordinates. The ABC pavement section was part of the outer loop from east of the All American Freeway (SR 1007) to US 401 in Fayetteville, NC; Table B-2 presents the GPS coordinates.

Table B-1 GPS Coordinates of the FDA Pavement Field Project in Roxboro

	Coordinates		Station Number
Start Point	N 36°25.062'	W 078°57.064'	33+18
End Point	N 36°25.491'	W 078°56.778'	42+25

Table B-2 GPS Coordinates of the ABC Pavement Field Project in Fayetteville

	Coordinates		Description
Start Point	N 35°06.880'	W 078°57.399'	5M 4-pole light support
End Point	N 35°06.929'	W 078°57.215'	5M 4-pole light support

Figure B-1 presents several pictures that were taken during sampling in the field. Table B-3 presents the designed structures of the two pavement sections.

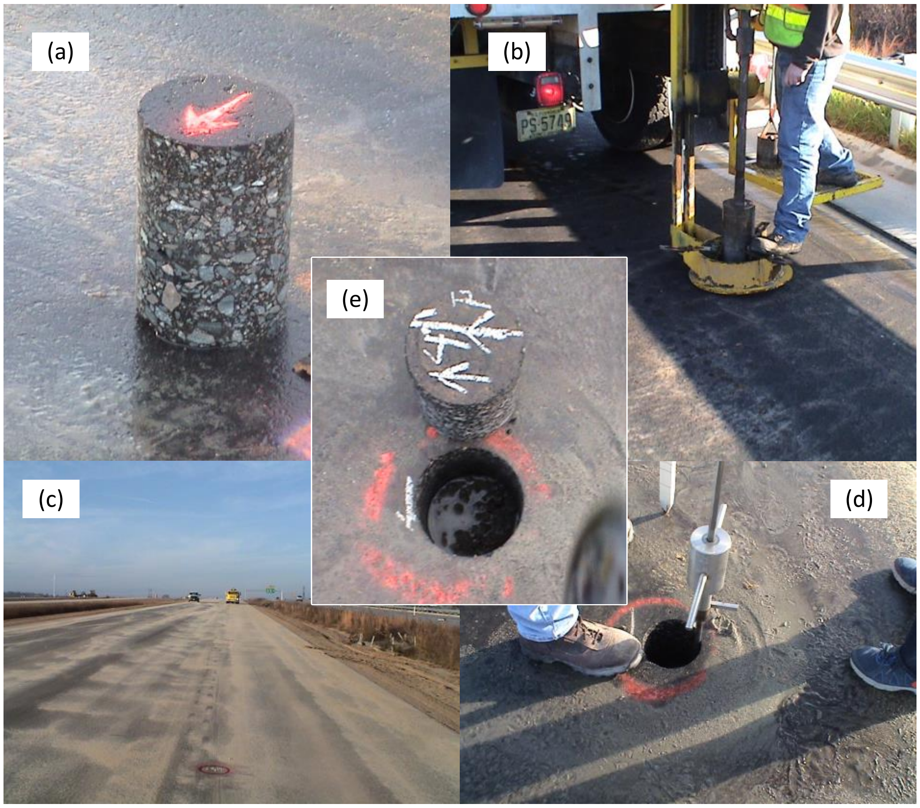

Figure B-1 Representative photos from the field: (a) core from Project R-2241A in Roxboro, (b) coring in Roxboro, (c) identified section and marked spots for coring for Project X-002CC in Fayetteville, (d) DCP measurements, and (e) core and core hole from Project X-002CC, I-295.

Table B-3 Design Information for the Identified Pavement Sections

		FDA Pavement		ABC Pavement	
		Material	Thickness (mm)	Material	Thickness (mm)
Structure	Layer 1	S9.5B	80	S9.5C	80
	Layer 2	I19.0B	110	I19.0C	80
	Layer 3	B25.0B	110	B25.0C	75
	Layer 4	-	-	ABC	200
	Total AC Thickness (mm)	300		235	
	Total Thickness (mm)	300		435	
Design ESALs (million)		2.1		10.2	

Part II. Mix Verification Prior to Laboratory Testing

Before the laboratory tests were performed, the NCSU research team verified the acquired materials that were obtained from the asphalt plant based on the NCDOT's Quality Management System (QMS) Manual 2016. The verification included the gradations, maximum specific gravities, and the bulk specific gravities of the laboratory-mixed, laboratory-compacted (LMLC) mixtures. This appendix presents the verification results of the FDA pavement mixtures. Figure B-2, B-3, and Figure *B-4* present the gradations of the Roxboro RS9.5B, RI19B, and RB25B mixtures, respectively. Table B-4 presents the verification results of the volumetric properties of the mixtures. The control limits listed in Table 609-1 of the QMS Manual were satisfied. The same tests also were performed on the mixtures in the ABC project. The control limits for those mixtures were satisfied as well.

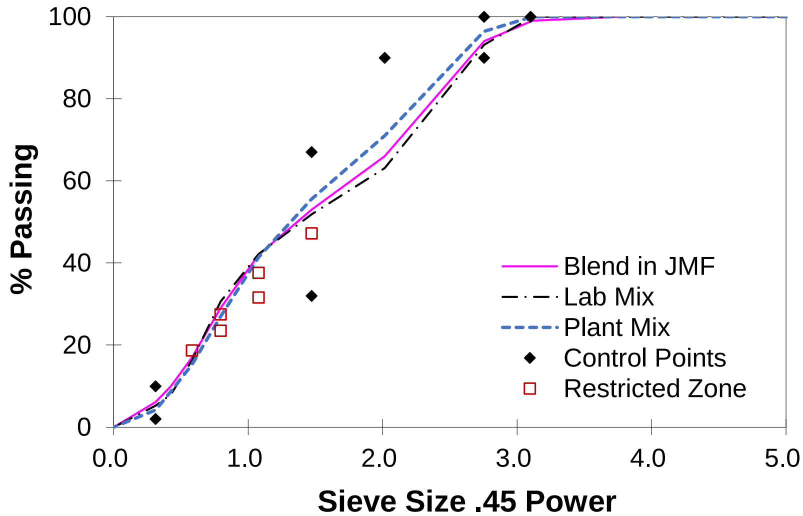

Figure B-2 Gradation verification for laboratory-fabricated and plant-fabricated mixtures (Roxboro RS9.5B).

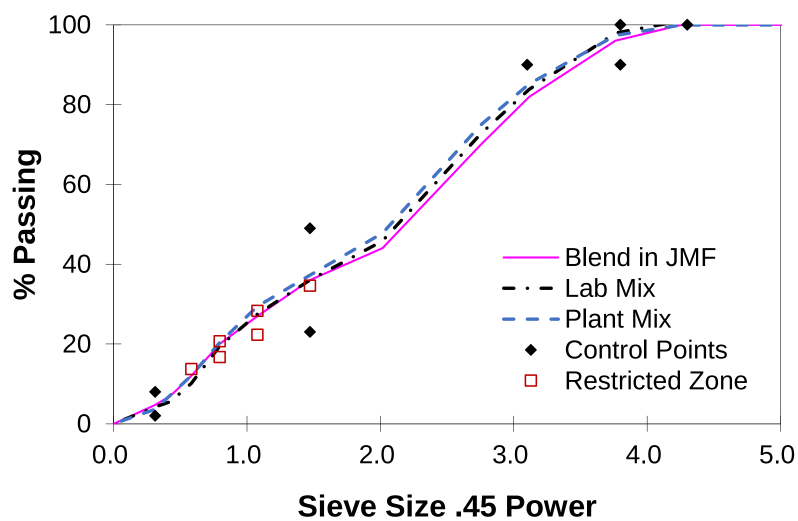

Figure B-3 Gradation verification for laboratory-fabricated and plant-fabricated mixtures (Roxboro RI19B).

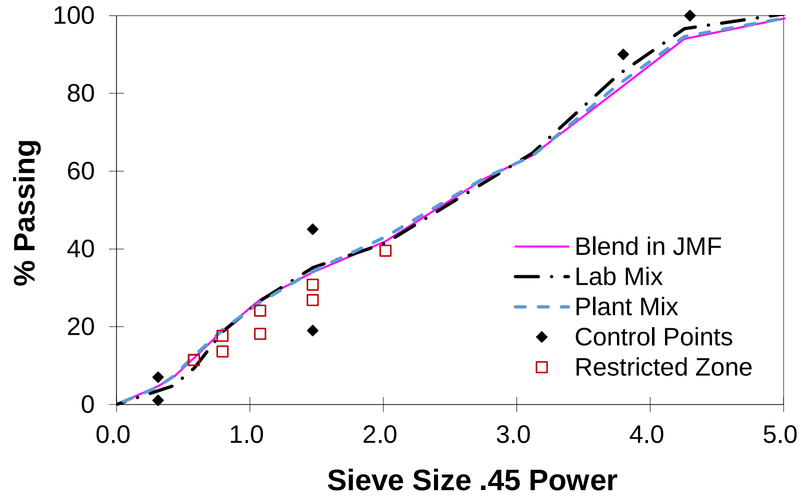

Figure B-4 Gradation verification for laboratory-fabricated and plant-fabricated mixtures (Roxboro RB25B).

Table B-4 Verification of Mixture Volumetric Properties

	G_{mm}		$G_{mb}@N_{des}$	
	JMF	Lab-mixed	JMF	Lab-fabricated
RS9.5B	2.463	2.460	2.364	2.355
RI19B	2.522	2.524	2.421	2.412
RB25B	2.551	2.556	2.449	2.396

Note: G_{mm} is maximum specific gravity; $G_{mb}@N_{des}$ is bulk specific gravity at N_{des}; JMF is job mix formula.

Part III. Laboratory Test Results

The laboratory tests performed on the mixtures include the following:

- Rutting resistance of each asphalt pavement layer
  - Tests of 100-mm x 150-mm laboratory-fabricated specimens using component materials
- Dynamic modulus of each asphalt pavement layer
  - Tests using horizontally extracted small specimens obtained from individual layers of field cores
- Fatigue behavior of each asphalt pavement layer
  - Tests using horizontally extracted small specimens obtained from individual layers of field cores

1. Rutting resistance of each asphalt pavement layer

Two different rutting tests, the TRLPD test (AASHTO T 378) and the SSR test, were performed on the study mixtures. The test results from both tests will be used in mechanistic-empirical pavement analysis programs. Prior to sample fabrication, the LMLC mixtures were verified based on NCDOT QMS Manual 2016.

The results of the TRLPD tests at different temperatures can be regressed into a mechanical-empirical model that is used in Pavement ME Design analysis. Figure B-5 presents the TRLPD test results for the FDA pavement mixtures.

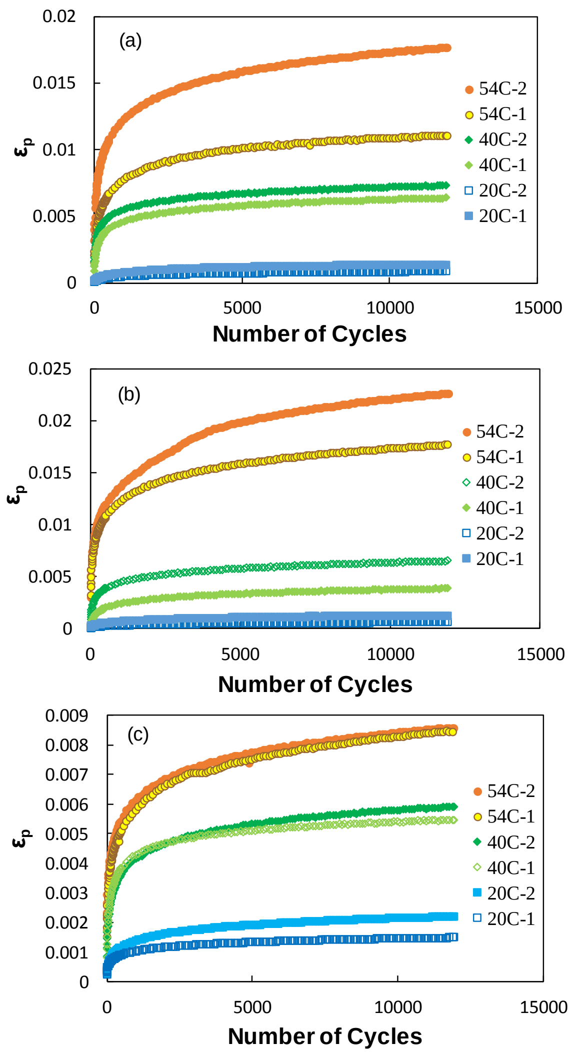

Figure B-5 TRLPD test results for FDA pavement project mixtures: (a) RS9.5B surface layer mixture, (b) RI19B intermediate layer mixture, and (c) RB25B bottom layer mixture.

The SSR test was developed at NCSU to calibrate the Shift Model. Using the calibrated coefficients, the permanent deformation of an asphalt mixture at any loading condition and temperature can be predicted using the Shift Model. Equations (B.1) - (B.4) present the formulas used in the Shift Model.

$$\varepsilon_{vp} = \frac{\varepsilon_0 \cdot N_{red}}{\left(N_I + N_{red}\right)^{\beta}} \tag{B.1}$$

$$a_{\xi_p} = p_1 \log(\xi_p) + p_2 \tag{B.2}$$

$$a_{\sigma_v} = d_1 \log(\sigma_v / P_a) + d_2 \tag{B.3}$$

$$N_{red} = A \cdot N \left(\frac{\xi_p}{1}\right)^{p1} \left(\frac{\sigma_v}{P_a}\right)^{d1} \tag{B.4}$$

where

ε_{vp}	= viscoplastic strain (i.e., permanent strain),
ε_0, N_I, β	= coefficients of the incremental model,
N_{red}	= reduced number of cycles at reference loading condition, and
N	= physical number of cycles for a certain loading condition.
a_{ξ_p}	= reduced load time shift factor,
p_1, p_2	= coefficients of reduced load time shift factor,
ξ_p	= reduced load time,
a_{σ_v}	= vertical stress shift factor,
d_1, d_2	= coefficients of vertical stress shift factor,
σ_v	= vertical stress,
P_a	= atmospheric pressure to normalize stress, and
A	= $10^{p_2} \cdot 10^{d_2}$

To calibrate the model coefficients, the SSR tests require two replicates at each of the two test temperatures, and in total, four specimens should be tested. The high temperature and the low temperature are selected based on the climate region where the mixture will be applied. The tests are conducted under confined pressure (10 psi). The deviatoric stress levels of 100, 70, and 130 psi, and 70, 100, and 130 psi at high and low temperatures, respectively, are applied. At each stress level, the load is applied for 200 cycles. Figure B-6 and Table B-5 present the test results and model coefficients for the FDA pavement mixtures, respectively.

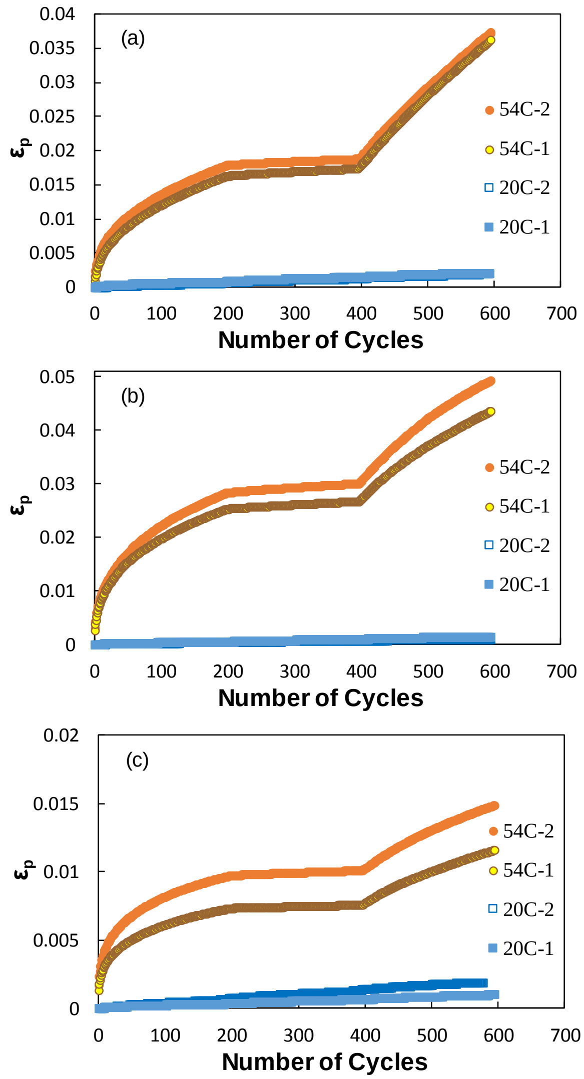

Figure B-6 SSR test results for FDA pavement mixtures: (a) RS9.5B surface layer mixture, (b) RI19B intermediate layer mixture, and (c) RB25B bottom layer mixture.

Table B-5 Shift Model Coefficients for FDA Pavement Mixtures

Mixture	Reference Temp.	beta	e0	NI	p1	p2	d1	d2
RS9.5B	54	0.588954	0.001933	1.571532	0.664597	0.28741	1.494263	-1.2878
RI19B	54	0.628501	0.003787	1.204612	0.86074	0.358383	2.69763	-2.34618
RB25B	54	0.725601	0.002014	0.875178	0.823929	0.337463	1.293949	-1.14459

The TRLPD and SSR tests also were conducted using the LMLC mixtures. Figure B-7 presents the TRLPD test results for the ABC pavement project. Figure B-8 and Table B-6 present the test results and model coefficients for the ABC pavement mixtures, respectively.

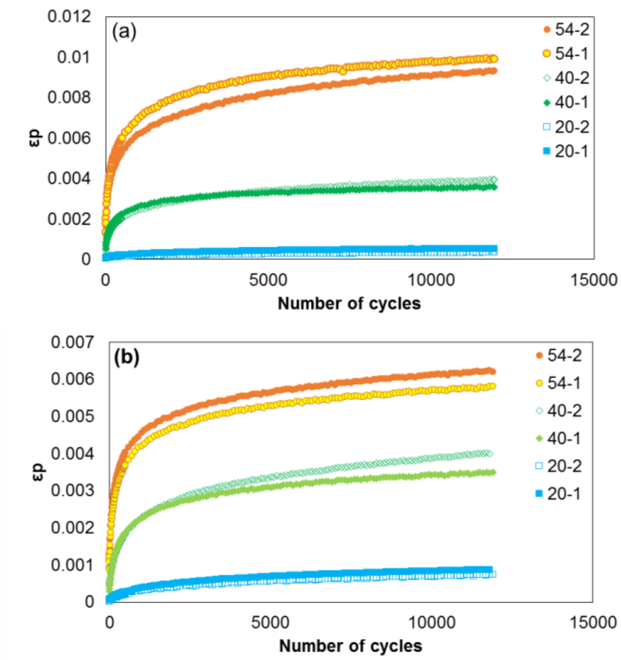

Figure B-7 TRLPD test results for ABC pavement project: (a) RS9.5C surface layer mixture and (b) RI19C intermediate layer mixture.

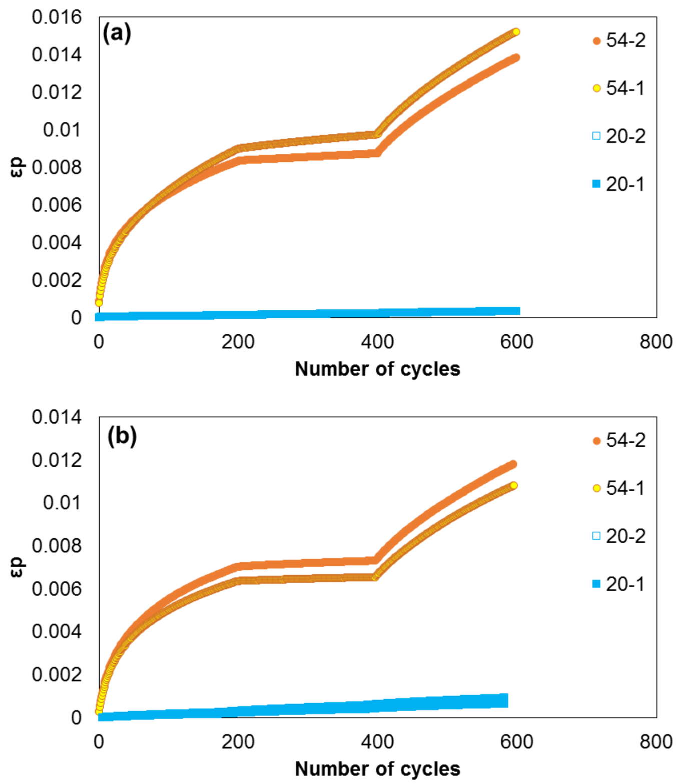

Figure B-8 SSR test results for ABC pavement project: (a) RS9.5C surface layer mixture and (b) RI19C intermediate layer mixture.

Table B-6 Shift Model Coefficients for the ABC Pavement Mixtures

Mixture	Reference Temp.	beta	e0	NI	p1	p2	d1	d2
RS9.5C	54	0.626714	0.001203	1.611067	0.871617	0.369871	2.636843	-2.29992
RI19C	54	0.666059	0.001181	8.078289	0.620184	0.279985	1.760596	-1.90708

2. Dynamic modulus test results

The dynamic modulus tests (AASHTO T 378) for the FDA and ABC pavement projects were performed on the mixtures obtained from the pavement sections; the results can be used in mechanistic-empirical programs. For these tests, small specimen samples were extracted horizontally from individual layers of field cores. For the FDA pavement project, the surface layer thickness was around 40 mm with one lift placed. Prismatic samples were used instead of cylindrical specimens because extracting cylindrical specimens from the field cores, for this case RS9.5B, would have been difficult. For the other five mixtures, cylindrical samples could be obtained from the field cores. These tests were performed at three temperatures (4°C, 20°C, and 40°C) and six frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz). Figure B-9 presents the dynamic modulus test results.

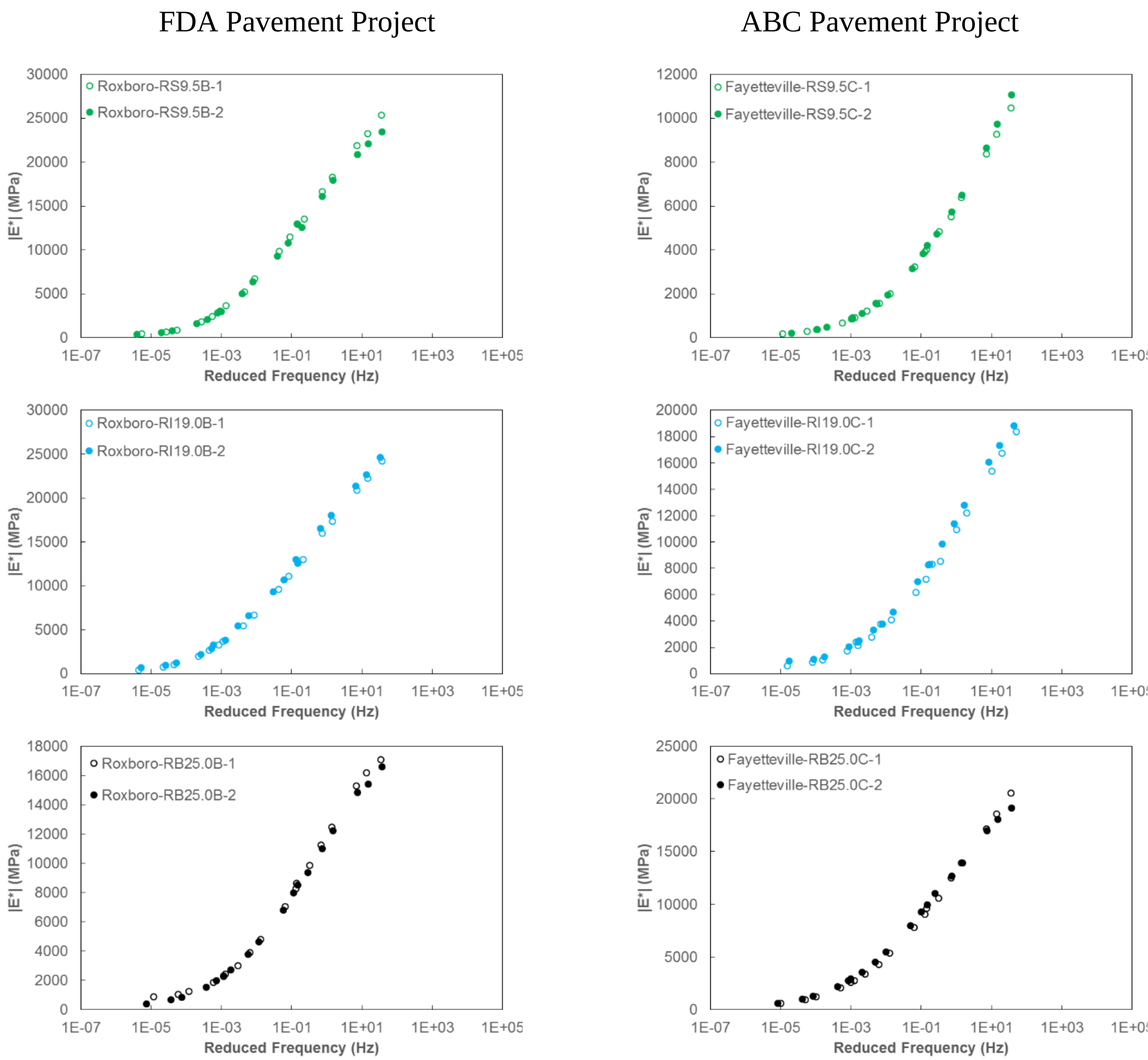

Figure B-9 Dynamic modulus test results for FDA pavement and ABC pavement projects.

Figure B-10 summarizes the dynamic modulus test results for both pavement projects. For the FDA pavement project, the dynamic modulus values of the base layer (RB25.0B) are lower than for the other layers. In this study, the field cores were stored in plastic containers, and it was found that the base layer specimens were submerged in the water at the bottom of the container. The water apparently caused some moisture damage to the specimens, which caused the dynamic modulus values to drop significantly. For the ABC pavement project, the surface layer shows the lowest dynamic modulus values of the three different layers, and the base layer has the highest dynamic modulus values.

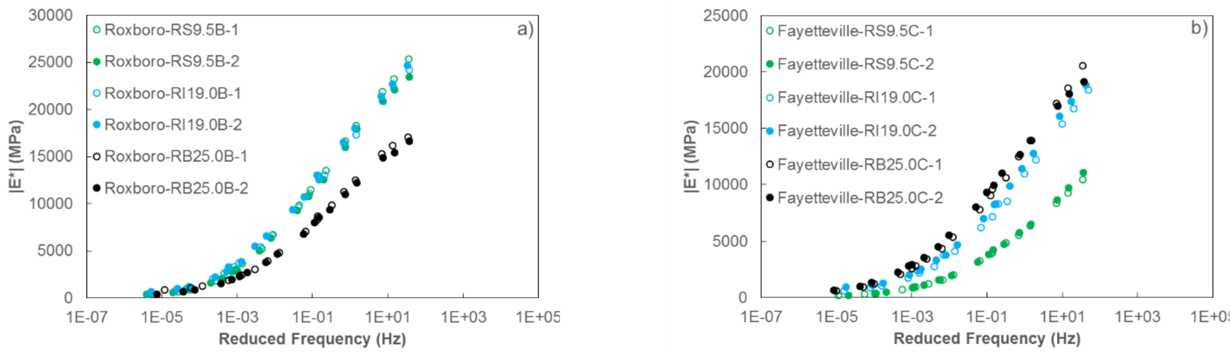

Figure B-10 Dynamic modulus test results for: (a) full-depth pavement and (b) ABC pavement projects.

3. Cyclic fatigue test results

The NCSU research team also performed cyclic fatigue tests (AASHTO TP 107) for the FDA and ABC pavement projects. For these tests, small specimen samples were extracted horizontally from individual layers of field cores. Similar to the dynamic modulus test results, the modulus values of the base layer in the FDA pavement are low (see Figure B-10, Roxboro RB25.0 B). As for the dynamic modulus tests, the field cores were stored in plastic containers and the base layer specimens were submerged in the water at the bottom of the container. The water apparently caused some moisture damage to the specimens, so cyclic fatigue tests for this layer were skipped.

Figure B-11 and Figure B-12 present the damage characteristic curves for these cyclic fatigue tests. Note that fatigue tests were not performed using the surface mix from the Roxboro project. The field cores extracted from that project contained only the first lift of the surface layer, which was less than 40 mm. Thus, prismatic specimens instead of cylindrical specimens had to be extracted. The research group believes that the fatigue behavior of this mixture would be similar to that of the surface mixture from Fayetteville due to the similarity of their dynamic modulus values.

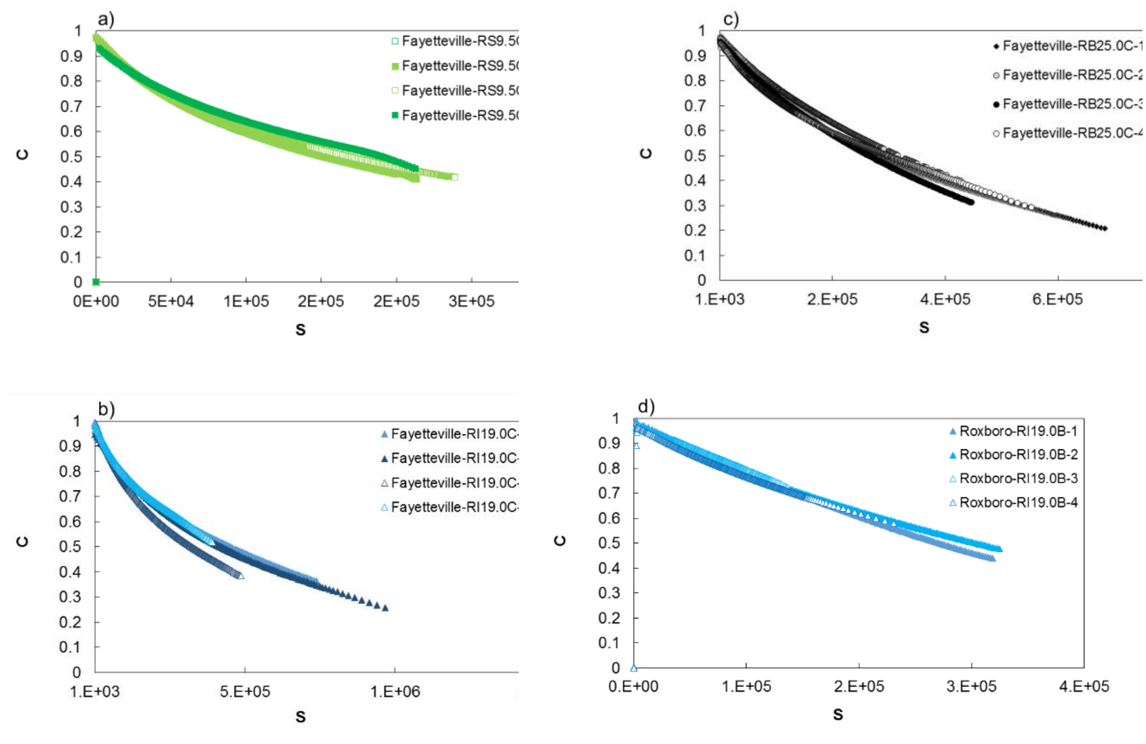

Figure B-11 Damage characteristic curves obtained from cyclic fatigue tests. For the ABC pavement project: (a) RS9.5C surface layer mixture, (b) RI19C intermediate layer mixture, and (c) RB25C base layer mixture. For the FDA pavement project: (d) RI19B intermediate layer mixture.

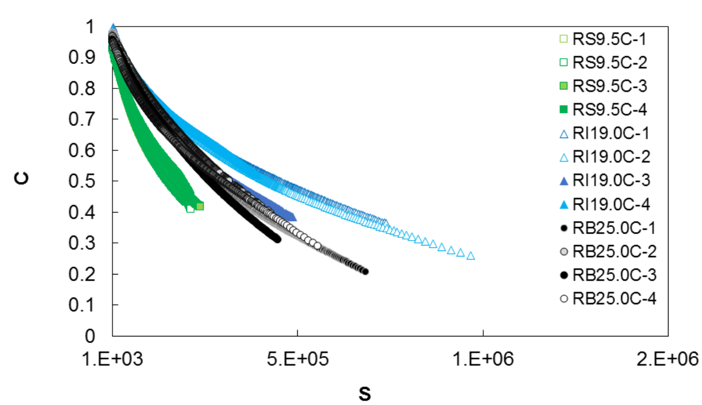

Figure B-12 Damage characteristic curves obtained from cyclic fatigue tests for the ABC pavement project (Fayetteville).

After determining the damage characteristics, the NCSU research team fitted the data to plots of the pseudo secant modulus and damage for all the fatigue tests using Equation (B-5). Table B-7 presents the coefficients for the exponential model.

$$C = e^{aS^b} \tag{B.5}$$

where *a* and *b* = the fitting coefficients for the exponential model.

Table B-7 Fitting Coefficients for the Exponential Model

Mixture	*a*	*b*
RS9.5C	-2.57E-04	6.55E-01
RI19.0C	-5.44E-05	7.27E-01
RB25.0C	-1.20E-05	8.74E-01
RI19.0B	-1.55E-05	8.42E-01

Two approaches were taken in this study to determine the failure criteria: the average released pseudo strain energy per cycle (G^R) and pseudo ductility (D^R).

Average released pseudo strain energy per cycle

In this approach, the G^R values were calculated based on Equations (B-6) and (B-7):

$$W_C^R = \frac{1}{2}(\varepsilon_{ta}^R)_n^2(1 - C_n^*) \tag{B.6}$$

$$G^R = \frac{1}{2}\int_0^{N_f}(W_C^R)dN / N_f^2 \tag{B.7}$$

where

W_C^R	=	released pseudo strain energy per cycle,
G^R	=	average released pseudo strain energy per cycle,
N_f	=	number of cycles to failure,
ε^R_{ta}	=	tension amplitude of pseudo strain,
n	=	time step used in the calculation, and
C^*_n	=	the cyclic pseudo secant modulus at the current analysis cycle.

Figure B-13 and Figure B-14 show the cyclic fatigue test results that were obtained based on the G^R approach for the ABC pavement project and FDA pavement project, respectively.

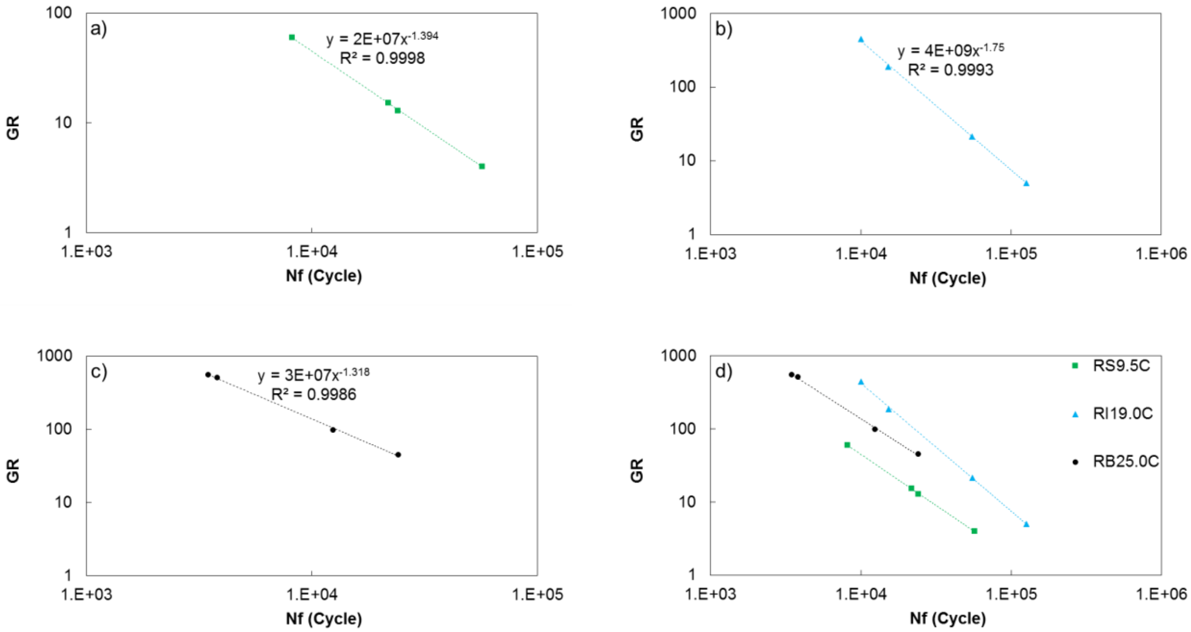

Figure B-13 G^R vs. N_f lines obtained from cyclic fatigue tests for ABC pavement project: (a) RS9.5C surface layer mixture, (b) RI19C intermediate layer mixture, (c) RB25C base layer mixture, and (d) all three different layers.

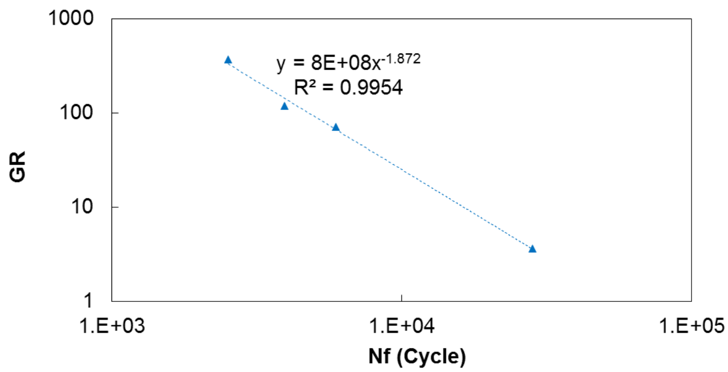

Figure B-14 G^R vs. N_f line obtained from cyclic fatigue tests for FDA pavement project: RI19C intermediate layer mixture.

Pseudo ductility

In this approach, pseudo ductility was calculated based on Equation (B-8):

$$D^R = \frac{\int_0^{N_f} (1-C)\, dN}{N_f} \tag{B.8}$$

where D^R = pseudo ductility.

It is noted that the numerator of Equation (B-8) is the sum of *(1-C)* for the entire life of the mixture. This term is denoted as *sum(1-C)* for the rest of this report. Figure B-15 and Figure B-16 show the cyclic fatigue test results that were obtained based on the pseudo ductility approach for the ABC pavement project and FDA pavement project, respectively.

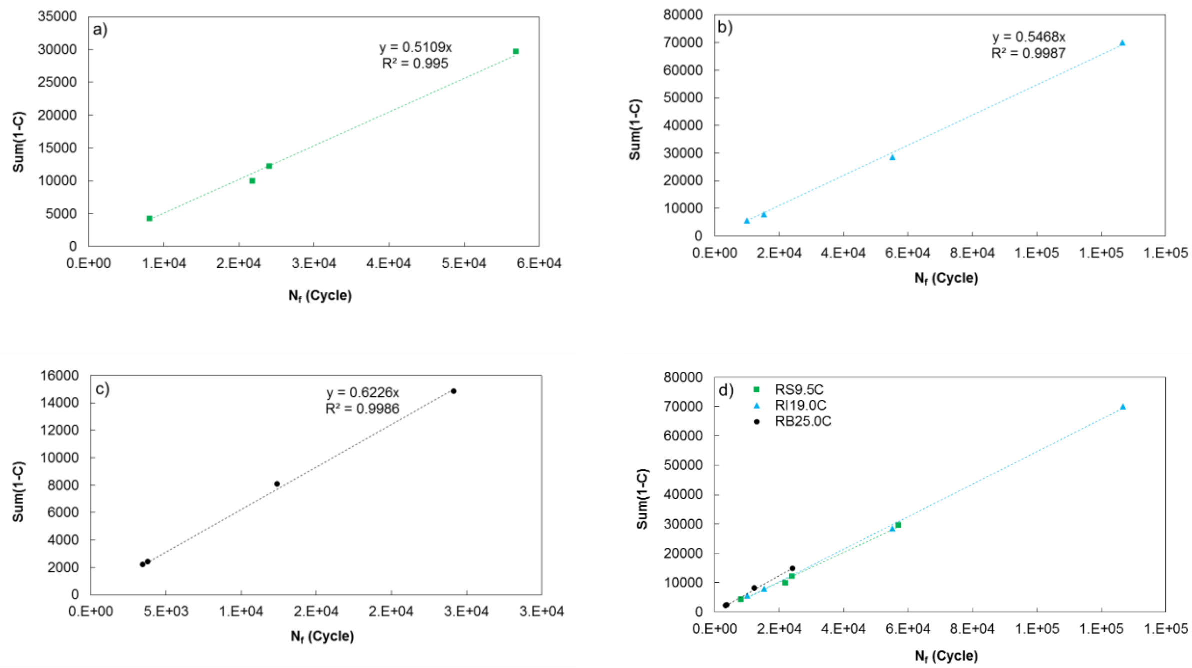

Figure B-15 *Sum(1-C)* vs. N_f obtained from cyclic fatigue tests for ABC pavement project: (a) RS9.5C surface layer mixture, (b) RI19C intermediate layer mixture, (c) RB25C base layer, and (d) all three different layers

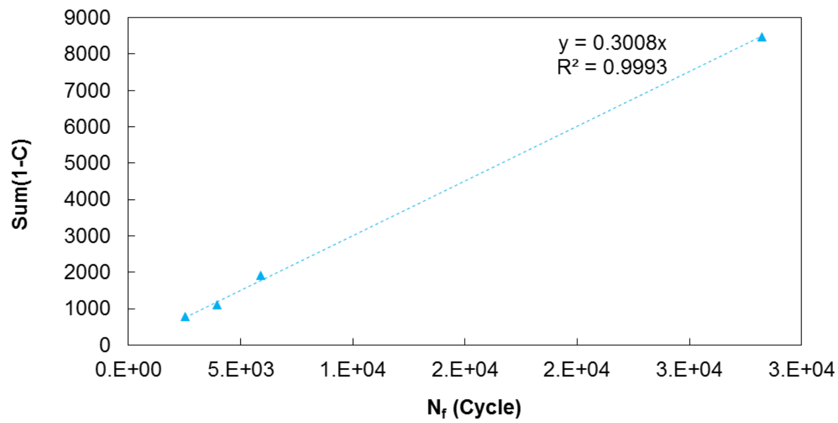

Figure B-16 *Sum*(*1-C*) vs. N_f obtained from cyclic fatigue tests for FDA asphalt pavement project: RI19C intermediate layer mixture.

Table B-8 presents the pseudo ductility values. Specifically, Table B-8 presents the D^R and S_{app} values for the different mixtures; the D^R values were obtained using Equation (B-8) for each mixture. S_{app} is defined as the corresponding S value to the $1\text{-}D^R$ value in a damage characteristic curve divided by 10,000. The S_{app} value is a good indicator of fatigue resistance and thus can be used to compare the fatigue performance of the different mixtures. A higher S_{app} value represents better fatigue resistance. Among these four mixtures, RI19C shows the best performance, as it is the most resistant against fatigue cracking. The tests were performed on specimens extracted from field cores and, therefore, some testing variability should be expected. Furthermore, the RI19B mixture from the Roxboro project showed low fatigue resistance. One possible reason for this outcome is that this mixture is a warm mix asphalt mixture that uses foaming technology.

Table B-8 D^R Values and S_{app} Values for Different Mixtures

Mixture	D^R	S_{app}
RS9.5C	0.51	8.5
RI19C	0.55	23
RB25C	0.62	19
RI19B	0.30	6.1