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Structural Study of Cold Central Plant Recycling Sections at the National Center for Asphalt Technology (NCAT) Test Track: Phase III

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BRIAN K. DIEFENDERFER, Ph.D., P.E.
Principal Research Scientist
Virginia Transportation Research Council

DAVID H. TIMM, Ph.D., P.E.
Brasfield & Gorrie Professor
Auburn University

ILKER BOZ, Ph.D.
Research Scientist
Virginia Transportation Research Council

BENJAMIN F. BOWERS, Ph.D., P.E.
Assistant Professor
Auburn University

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530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginiadot.org

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16. Abstract:

The Virginia Department of Transportation (VDOT) contracted with the National Center for Asphalt Technology (NCAT) in 2012 to install, instrument, and monitor three pavement test sections at the NCAT Test Track. The purpose of this current study was to assess the performance of two of the original three test sections after approximately 30 million 18-kip single equivalent axle loads (ESALs). Both of these test sections, Sections N4 and S12, included a 5-in-thick cold central plant recycling (CCPR) layer placed on top of either a compacted aggregate base (Section N4) or a cement-stabilized foundation (Section S12) produced using equipment and procedures used in full depth reclamation (FDR). The test sections were assessed using pavement instrumentation and periodic performance monitoring to capture the response and any distresses developing from truck loading.

The study concluded that the two test sections are examples of new or reconstructed pavement structures that include CCPR or CCPR and a stabilized base layer (similar to FDR) that can achieve a long service life under heavy truck traffic. Section S12, containing the stabilized base layer (similar to FDR), was found to have very low strain levels and no deterioration evident at the surface after 30 million ESALs. The superior performance of this section was attributed to the use of the stabilized base layer. Section N4, having an aggregate base, was found to have cracking that was evident at the surface at approximately 29.6 million ESALs. This was expected at some point during the testing given the evidence of reduced moduli values for the asphalt/CCPR layer; greater and more erratic strain values; and increasing vertical base and subgrade pressures noted during the 2015-2018 NCAT Test Track cycle. Further trafficking of Section N4 is expected to provide additional information that might be used to determine a suitable design approach for similar pavement sections. Following trafficking, a forensic investigation of the test sections should be conducted to identify the specific layers in which any deterioration occurred.

The study recommends that VDOT modify their design manuals to include using a stabilized base layer (similar to FDR) beneath a CCPR layer when CCPR is included on pavement sections having high traffic volumes. It is also recommended that VDOT investigate if designing a pavement section consisting of both CCPR and a stabilized base layer (similar to FDR) is more appropriate using a flexible or a semi-rigid approach. The study further recommends that VDOT continue to sponsor trafficking on Section N4 for the 2021 NCAT Test Track cycle to understand better the behavior of the CCPR material in terms of its eventual deterioration. Following completion of testing on these sections, a forensic study should be conducted to help identify the specific layers in which any deterioration occurred.

The benefits to VDOT of implementing the study recommendations include the anticipated longer service life of a pavement section built using pavement recycling techniques where CCPR and a stabilized base layer (similar to FDR) are included. Determination of an appropriate design methodology; additional trafficking of Section N4 containing the aggregate base layer; and a forensic study of both sections following trafficking will provide VDOT a better understanding of the behavior of the CCPR material in terms of its eventual deterioration.

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FINAL REPORT

STRUCTURAL STUDY OF COLD CENTRAL PLANT RECYCLING SECTIONS AT THE NATIONAL CENTER FOR ASPHALT TECHNOLOGY (NCAT) TEST TRACK: PHASE III

Brian K. Diefenderfer, Ph.D., P.E.
Principal Research Scientist
Virginia Transportation Research Council

David H. Timm, Ph.D., P.E.
Brasfield & Gorrie Professor
Auburn University

Ilker Boz, Ph.D.
Research Scientist
Virginia Transportation Research Council

Benjamin F. Bowers, Ph.D., P.E.
Assistant Professor
Auburn University

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ABSTRACT

The Virginia Department of Transportation (VDOT) contracted with the National Center for Asphalt Technology (NCAT) in 2012 to install, instrument, and monitor three pavement test sections at the NCAT Test Track. The purpose of this current study was to assess the performance of two of the original three test sections after approximately 30 million 18-kip single equivalent axle loads (ESALs). Both of these test sections, Sections N4 and S12, included a 5-in-thick cold central plant recycling (CCPR) layer placed on top of either a compacted aggregate base (Section N4) or a cement-stabilized foundation (Section S12) produced using equipment and procedures used in full depth reclamation (FDR). The test sections were assessed using pavement instrumentation and periodic performance monitoring to capture the response and any distresses developing from truck loading.

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Virginia Transportation Research Council

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Assistant Professor
Auburn University

INTRODUCTION

Pavement recycling is a series of pavement rehabilitation techniques that can be used to rehabilitate a deteriorated asphalt pavement effectively while reducing costs and environmental impacts and improving performance (Asphalt Recycling and Reclaiming Association [ARRA], 2015). These techniques reuse existing materials in a portion of a rehabilitated or newly constructed pavement structure or pavement layer. Some of the most commonly cited benefits of using pavement recycling techniques for pavement rehabilitation and construction include reduced use of virgin materials, reduced fuel consumption, reduced lane closure time, reduced emissions related to construction, reduced cost, and improved performance (Al-Qadi and Ozer, 2020; Nataatmadja, 2001; Stroup-Gardiner, 2011; Thenoux et al., 2007). Specifically, pavement recycling techniques include the following processes: cold planing, hot in-place recycling, cold recycling (CR), and full depth reclamation (FDR). CR includes the techniques of cold in-place recycling (CIR) and cold central plant recycling (CCPR) (ARRA, 2015).

FDR is used to address structural deficiencies deep within a pavement structure. As shown in Figure 1, a reclaimer is often used to mix the bound layers and a predetermined portion of the underlying unbound layers into a homogeneous material that is often between 4 and 12 in thick (ARRA, 2015).

Figure 1. Reclaimer Used for Full Depth Reclamation

FDR may consist of simply pulverizing and remixing the roadway foundation, termed mechanical stabilization, but it most often incorporates one or several stabilizing agents. Typical FDR stabilizing agents include chemical stabilizers such as portland cement, lime, fly ash, cement, and lime kiln dust and asphalt-based stabilizers such as emulsified and foamed asphalt. Another way in which FDR can be used is described by the concept of *imported FDR*. This concept includes the use of materials originating from outside an existing project. An extensive example of the use of imported FDR includes the process for the I-64 Segments II and III lane widening/reconstruction projects where the FDR layer was completed using crushed concrete (Virginia Department of Transportation [VDOT], 2021).

CCPR is a process in which reclaimed asphalt pavement (RAP), obtained from roadway millings from a single project or existing stockpiles of RAP from many projects, is recycled and used to create a new bound base layer. Figure 2 shows a mobile CCPR plant where RAP is combined with a recycling agent (such as emulsified or foamed asphalt) and possibly an active filler (such as portland cement) and is sometimes supplemented with virgin aggregates to improve the gradation. The CCPR plant is designed to be portable and can be set up at a construction project or remain stationary at a fixed location.

VDOT has used both FDR and CCPR in three major interstate reconstruction projects. The first, completed in 2011 on I-81 in Augusta County, included milling most of the existing asphalt pavement and stockpiling the millings; stabilizing the foundation using FDR; and processing the milled material into a base layer using CCPR that was paved on top of the FDR layer (Diefenderfer et al., 2015). The second and third examples included Segments II and III on the I-64 pavement reconstruction/widening projects where CCPR was created from existing RAP stockpiles and was placed on top of an FDR layer constructed by using either imported or existing materials (VDOT, 2021).

Figure 2. Mobile Plant Used for Cold Central Plant Recycling

To study the performance of pavement sections constructed with different recycling techniques, VDOT contracted with the National Center for Asphalt Technology (NCAT) in 2012 to install, instrument, and monitor three pavement test sections at the NCAT Test Track. These sections, designated Sections N3, N4, and S12, were subjected to approximately 20 million 18-kip equivalent single axle loads (ESALs) over two track cycles between 2012 and 2017. During a third track cycle, with trafficking between 2018 and 2021, VDOT sponsored Sections N4 and S12. The total traffic level at the end of the third track cycle for Sections N4 and S12 was approximately 30 million ESALs. These sections include some of the first attempts in the United States to study the performance of CCPR and the combination of CCPR and FDR using instrumented pavement sections subjected to full-scale accelerated loading.

Both Sections N4 and S12 included a 5-in-thick CCPR layer placed on top of either a compacted aggregate base (Section N4) or a cement-stabilized foundation (Section S12) produced using equipment and procedures used in FDR. Both sections were surfaced with two layers of an asphalt mixture at the time of construction. The CCPR materials were produced using foamed asphalt (produced using a performance grade [PG] 67-22 asphalt binder) as the recycling agent at a dosage rate of 2.0% and hydraulic cement as a chemical additive at a dosage rate of 1.0%. The cement-stabilized foundation (composed of the existing aggregate base and the upper portion of the existing subgrade) was produced using hydraulic cement as the stabilizing agent at a dosage rate of 4.0%,

PURPOSE AND SCOPE

The purpose of this study was to evaluate the structural and functional performance of Virginia's recycled pavement sections as built at the NCAT Test Track after 30 million ESALs. Further, an objective was to compare the performance of pavement sections constructed with and without a stabilized foundation.

The scope of the study included performance monitoring and assessment of two of the recycled pavement sections at the NCAT Test Track constructed during the 2012 track cycle, specifically Sections N4 and S12. The performance was assessed during three track cycles (covering a period from 2012-2021) by analyzing the results of field testing and the response of temperature, pressure, and strain sensors placed during construction.

METHODS

The following tasks were undertaken to achieve the study objectives:

1. Conduct a review of literature on the performance of recently documented full-scale recycled test sections.

2. Summarize the design and construction of the recycled test sections at the NCAT Test Track.

3. Evaluate the performance of the recycled test sections at the NCAT Test Track through field tests and embedded instrumentation.

Performance Summary of Other Recycled Test Sections

The performance of other recycled test sections was summarized following a review of the available literature. The literature review was restricted to those documents published within approximately the last 5 years.

Summarize Design and Construction of NCAT Test Track Recycled Sections

The construction processes were summarized by NCAT and VDOT staff who were present during the construction of the test sections in 2012. These processes were described by Diefenderfer et al. (2016). The “Results and Discussion” section also includes a discussion of the design of the three test sections.

Evaluate Field Performance of NCAT Test Track Recycled Sections

Trucking Operations

Trafficking at the NCAT Test Track occurs through the use of a series of triple-trailer trucks, as shown in Figure 3. Each tractor pulls three trailers that are loaded with steel plates. The plates are arranged so that each axle (other than the steering axle) carries approximately 20,000 lbf. The trucks are run on the track in two shifts each day for approximately 17 hours per day, 5 days per week, over a 2-year test cycle in which approximately 10 million ESALs are applied.

Figure 3. Trucking Operation at the NCAT Test Track. NCAT = National Center for Asphalt Technology.

To compare this traffic level with local conditions, most of I-81 carries the highest truck volumes per day in Virginia (VDOT, 2019a), with portions carrying approximately 6,300 to 8,500 trucks per day in the right lane. With an assumption of an average ESAL value of 1.05 ESALs per truck (Smith and Diefenderfer, 2009), a load application of approximately 2.4 to 3.3 million ESALs per year was calculated.

Ride Quality and Rut Depth

Ride quality data and rut depth measurements were simultaneously collected on a weekly basis with vehicle-mounted sensors on an inertial profiler operated by NCAT staff. Data were collected in accordance with ASTM E950-09, Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference (ASTM International [ASTM], 2013); AASHTO R 43-07, Standard Practice for Determination of International Roughness Index (IRI) to Quantify Roughness of Pavements (American Association of State Highway and Transportation Officials [AASHTO], 2013); and AASHTO R 48-10, Standard Practice for Determining Maximum Rut Depth in Asphalt Pavements (AASHTO, 2013). The data were reported as average values over the entire 200-ft length of each section.

Elastic Modulus of Asphalt/CCPR Layers

Deflection testing to assess structural capacity was performed every 2 to 3 weeks by NCAT staff using a Dynatest Model 8000 falling weight deflectometer (FWD) in accordance with ASTM D4694-09, Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device (ASTM, 2013). Testing was conducted at four locations within each test section (one of which coincided with the location of the instrumentation). The FWD was equipped with nine sensors at radial distances of 0, 8, 12, 18, 24, 36, 48, 60, and 72 in from the center of a load plate. Deflection testing was conducted at four load levels (6,000; 9,000; 12,000; and 16,000 lbf) during the 2012 research cycle and three load levels (6,000; 9,000; and12,000 lbf) during the 2015 and 2018 research cycles. The 16,000 lbf load level was removed in the second cycle to help reduce testing costs. Following two unrecorded seating drops, three deflection basins were recorded at each load level. The deflection data were analyzed in accordance with AASHTO's *Guide for Design of Pavement Structures* (AASHTO, 1993). The analysis included calculating the combined modulus of the asphalt/CCPR layers. The results are presented as average values for each test date.

Instrumentation

Instruments to measure pavement temperature, strain, and pressure were placed within the three test pavement sections during construction. The temperature was measured at the top of the surface layer, at the mid-depth of the combined thickness of the CCPR material and asphalt layers, and at the bottom of the CCPR layer. Since the maximum tensile strain is greatest at the bottom of the asphalt/CCPR layers, strain gauges were included at the bottom of the CCPR layer. In addition, pressure cells were placed at the top of the aggregate layer and at the top of the subgrade. Additional details regarding the instrumentation used at the NCAT Test Track were provided by Timm (2009).

RESULTS AND DISCUSSION

Performance of Recently Documented Full-Scale Recycled Test Sections

The researchers conducted a literature review to identify publications documenting the performance of similarly configured test sections where results were published in the last 5 to 6 years. Despite a review of domestic and international research publications, no other test pavement sections were identified that included CCPR along with instrumentation and periodic performance measurements.

The researchers identified several publications that presented an assessment of CIR (Buss et al., 2017; Islam et al., 2019; Wacker et al., 2020); FDR (Ghasemi et al., 2018; Godenzoni et al., 2018; Guatimosim et al. 2019; Hunsucker et al., 2017; Lee et al., 2017; Zhang et al., 2018); or both (Cox et al., 2016) using pavement management–level performance observations. A majority of these studies included sections that either carried lower volumes or were early in their service lives and thus the performance assessments were preliminary. In general, for these studies, those pavement sections using pavement recycling techniques were found to have performance and/or service lives that were similar or longer, with regard to service lives, than their non-recycling control sections. Additional details for the most relevant publications are provided here.

Gutiérrez Klinsky et al. (2020) presented early findings from a CCPR section built in Brazil where emulsified asphalt was used as the recycling agent. The CCPR layer was 5.9 in thick and was surfaced with a 2-in-thick asphalt layer and a microsurfacing treatment. The section carried approximately 9,000 vehicles per day. After 1.5 years of service, no distresses and no early increases in ride quality and rutting measurements were observed. As seen with other studies (Diefenderfer and Apeagyei, 2011; Godenzoni et al., 2018), FWD measurements indicated an increase in pavement stiffness during early ages.

Wacker et al. (2020) reported the performance of three different types of CR sections after 7 years of service in Germany. The CR sections used emulsified asphalt as a recycling agent and cement as a chemical additive in two sections and foamed asphalt as a recycling agent and cement as a chemical additive in a third section. The pavement structure consisted of a 1.4-in-thick stone matrix asphalt (SMA) surface course; a 2.5-in-thick asphalt intermediate course; either a 3.1- or a 3.9-in-thick asphalt base layer; and a 7.9-in-thick CR layer. The daily traffic volume at the time of the construction was approximately 26,000 vehicles, with 15% heavy trucks. Structural testing with the FWD did not show any signs of deterioration, and in some cases, improvements in the FWD response were observed.

Islam et al. (2019) compared the field performance of 10 CIR pavement sections with 10 control pavement sections constructed using conventional hot mix asphalt in Colorado. The CIR materials were produced using emulsified asphalt as the recycling agent. The project sections were chosen to maximize similarity in pavement structure, traffic and environmental conditions, and location. The daily traffic volumes for the pavement sections ranged from 2,200 to 20,000. The field performance data including fatigue cracking, rutting, transverse cracking, and ride quality were obtained from the sections at a service life ranging from 5 to 11 years. The authors concluded that the performance of the pavement sections including CIR was similar to that of the non-recycling pavement sections.

In a continued effort through the accelerated test program, the performance of a cement-stabilized FDR section tested under dry and wet conditions was recently reported (Louw et al., 2020). The test section was constructed with a 9.8-in-thick cement-stabilized FDR layer surfaced with a 2.4-in-thick asphalt layer. The loading was performed using a linear accelerated pavement testing frame having a dual truck tire under dry and wet conditions. The test section was instrumented with numerous sensors (e.g., strain gauges, pressure cells, and thermocouples) embedded within the various locations of the pavement structure. In addition, FWD measurements before and after the loading were completed. The study results indicated severe cracking (shrinkage and fatigue) in both wet and dry sections because of a combination of material, environmental, and trafficking effects. The study also recommended reducing the maximum design strength of cement-treated layers in California from approximately 600 psi to approximately 430 psi in order to reduce the prospects of severe shrinkage cracking.

Design and Construction Summary of NCAT Test Track Recycled Sections

The CCPR material used in Sections N4 and S12 was produced using foamed asphalt and portland cement. The design foamed asphalt content was 2% using a PG 67-22 binder, and 1% Type II portland cement was added as a chemical additive. The optimum cement content for the cement-stabilized base used in Section S12 was found to be 4% Type II portland cement. The cement-stabilized base, composed of a mixture of existing aggregate and subgrade from the track, had an average compressive strength of 256 psi after 7 days, a maximum dry density of 130.0 lb/ft^3, and an optimum moisture content of 8.0%. A compressive strength of 350 psi after 7 days was used as a maximum limit during the design process. Additional mix design details, including the mix design process, were provided by Diefenderfer et al. (2016).

The configuration and as-planned thickness of each layer within Sections N4 and S12 are shown in Figure 4. Each test section featured an SMA surface layer, on a dense-graded intermediate asphalt mixture layer, and then the CCPR layer. The SMA surface layer had a nominal maximum aggregate size of 12.5 mm and used a PG 76-22 binder. The dense-graded intermediate mixture had a nominal maximum aggregate size of 19.0 mm and used a PG 67-22 binder. The CCPR material was made from 100% RAP. All of the aggregate/RAP materials for the SMA, dense-graded asphalt mixture, and CCPR material were shipped from Virginia to NCAT prior to construction in 2011.

The bound pavement layers (SMA, dense-graded asphalt mixture, and CCPR) in Section N4 were constructed on top of a crushed granite aggregate base layer; Section S12 was built on a cement-stabilized base layer. Both sections were constructed on the same native subgrade, which was classified as an A-4(0) soil and described further by Taylor and Timm (2009). During construction of the CCPR layer, the CCPR material was produced at a mobile plant (shown in Figure 2) located on-site. After processing, the CCPR material was hauled to the track using dump trucks. The CCPR material was placed using a conventional asphalt paver and paved to a depth of approximately 6 in. After completion of the CCPR layer, it was then profile-milled to the desired thickness. Diefenderfer et al. (2016) provided additional construction details.

Figure 5 shows the average as-built thickness of each test section and reflects the natural variation attributable to standard construction practices at the NCAT Test Track. The thickness of each layer was measured at 12 different locations within each section and averaged.

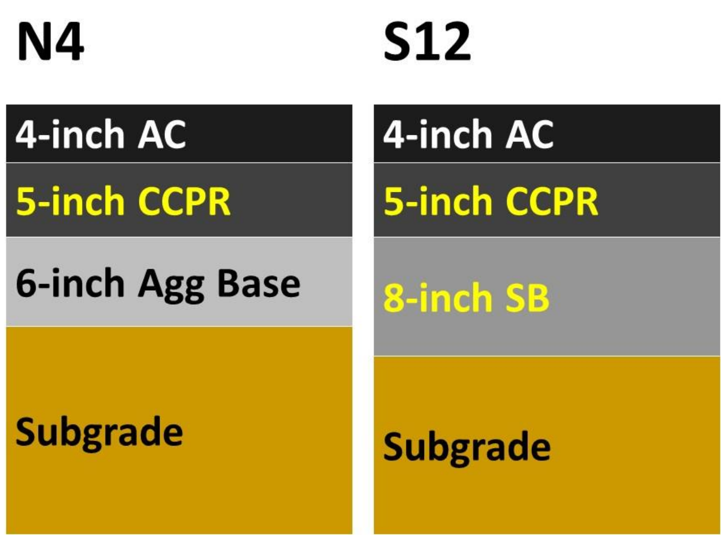

Figure 4. Schematic of NCAT Test Track Sections Including CCPR. NCAT = National Center for Asphalt Technology; CCPR = cold central plant recycling; AC = asphalt concrete; Agg = aggregate; SB = stabilized base.

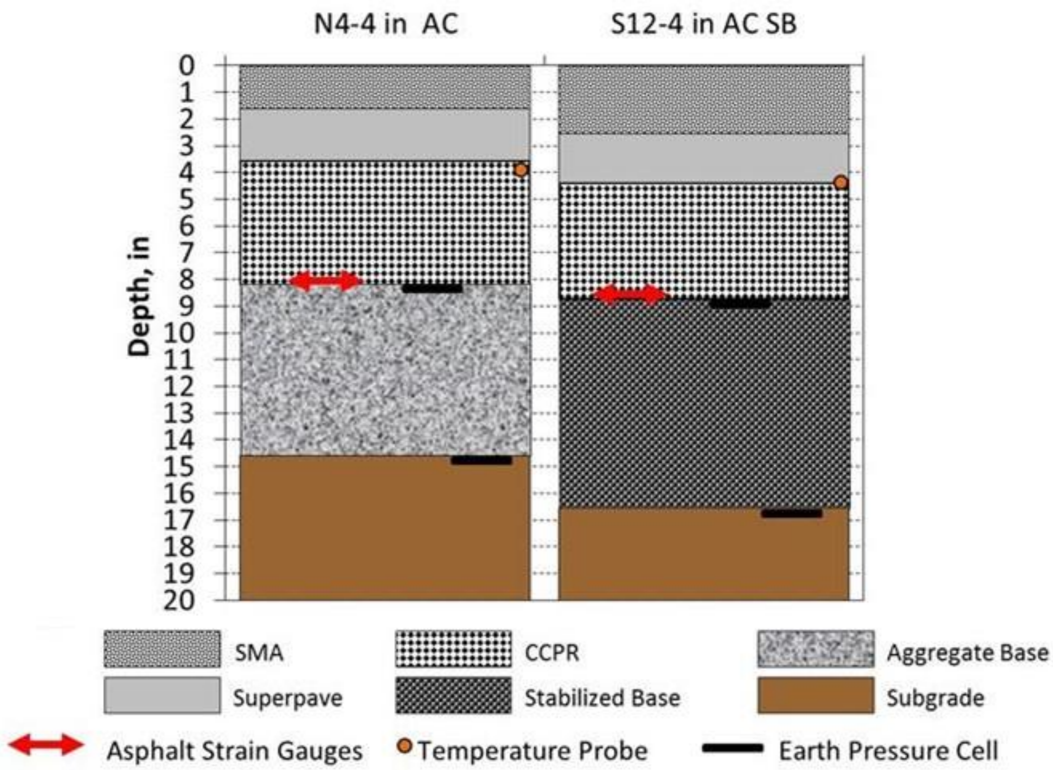

Figure 5. VDOT Sections at NCAT Test Track Showing Average As-Built Thicknesses and Depth of Instrumentation. VDOT = Virginia Department of Transportation; NCAT = National Center for Asphalt Technology; AC = asphalt concrete; SB = stabilized base; SMA = stone matrix asphalt; CCPR = cold central plant recycling.

Sections N4 and S12 can be used to determine the difference in performance between sections constructed with a 6-in-thick aggregate base vs. an 8-in-thick cement-stabilized base layer since both have the same 4-in asphalt overlay and 5-in CCPR layer.

Field Performance of NCAT Test Track Recycled Sections

Ride Quality and Rut Depth

Figure 6 shows the ride quality measured for the two test sections over the 30 million ESAL test period. The ride quality is expressed in terms of the IRI. From Figure 6 it is seen that the IRI increased with respect to loading, as expected. Linear trendlines were also fit to the measurements to indicate their change during the test period. Between the first two test cycles (at approximately 10 million ESALs), the pavement surface in Section S12 was corrected to address a spot of localized roughness at the beginning of the section. Therefore, two separate trendlines for Section S12 were calculated: one for the period 0-10 million ESALs and one for the period 10-30 million ESALs. Figure 6 also shows the regression equation of the line that could be used to describe the data from each section. There are two equations for Section S12: the upper one shown in Figure 6 represents data from 0-10 million ESALs, and the lower one shown in Figure 6 represents data from 10-30 million ESALs.

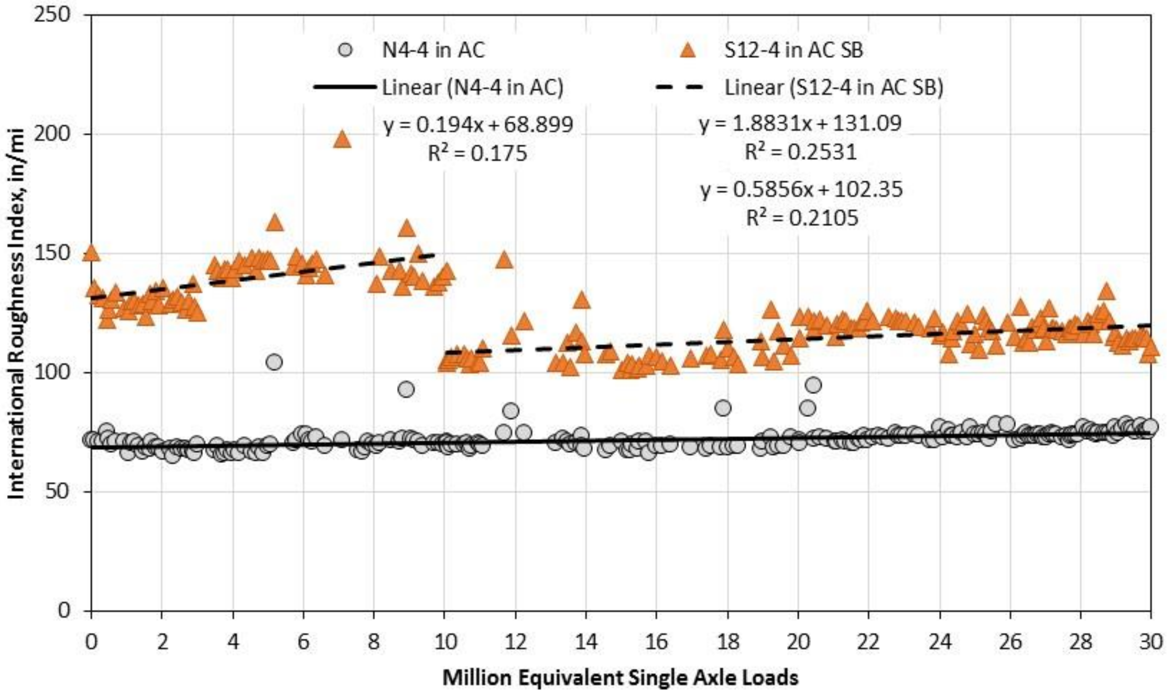

Figure 6. Ride Quality Results. AC = asphalt concrete; SB = stabilized base.

As seen, the IRI in Section S12 was greater than in Section N4. This was thought to be caused by difficulties in retrofitting the thick structure into the short length of the test section (200 ft). A similar, but thicker, cross section was built on the I-81 Pavement Recycling Project in Augusta County, Virginia, in 2011. The ride quality for the I-81 section was measured as 45 in/mi at nearly 3 years after construction (Diefenderfer et al., 2015). VDOT classifies an interstate or primary roadway segment having an IRI greater than 140 in/mi as having "poor" ride quality (VDOT, 2019b).

Figure 7 shows the rut depth measured for the two test sections over the 30 million ESAL test period. The figure shows that the rut depth increased from approximately 0.1 in soon after construction in both sections to approximately 0.3 and 0.25 in for Sections N4 and S12, respectively. Figure 7 also shows linear trendlines that were fit to the data to indicate the change during the test period. Similar to the ride quality data, two linear trendlines were fit to the data (one for the period 0-10 million ESALs, and one for the period 10-30 million ESALs) for Section S12 because of the local deficiency correction. Figure 7 also shows the regression equation of the line that could be used to describe the data from each section. There are two equations for Section S12: the upper equation shown in Figure 7 represents data from 0-10 million ESALs, and the lower equation shown in Figure 7 represents data from 10-30 million ESALs.

In general, the rut depth in Section N4 was greater than in Section S12 after the first approximately 8 million ESALs. Although it is difficult to estimate the cause for the increase in rutting, it is possibly linked to the thinner structure in Section N4. The values shown here can be compared to the VDOT threshold criterion of 0.26 in used in VDOT procedures for designing pavements with the AASHTOWare Pavement ME process.

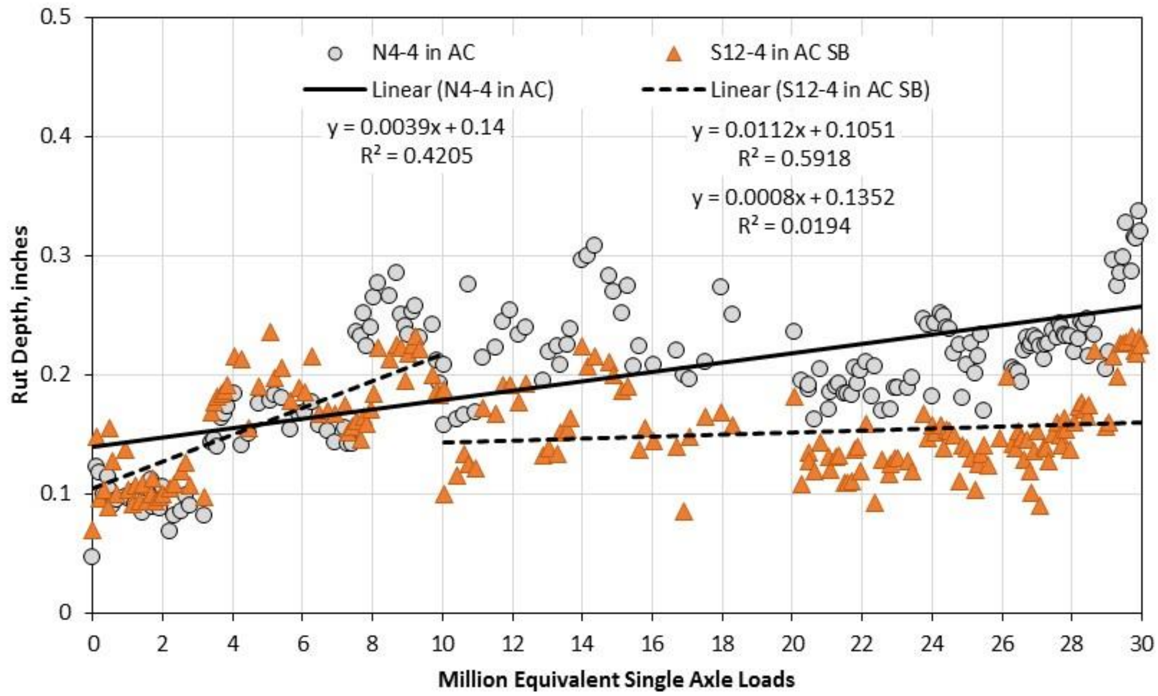

Figure 7. Rut Depth Results. AC = asphalt concrete; SB = stabilized base.

Elastic Modulus of Asphalt/CCPR Layers

Periodic testing with the FWD was used to assess the structural condition of the test sections over time. Within each test section, multiple measurements were conducted in three areas: the inside wheel path, the outside wheel path, and between the wheel paths. The data presented in this report represent the average response for each test date for those data collected from the outside wheel path, typically the worst case of the three locations.

The modulus values shown here are the result of a process known as *backcalculation*. Backcalculation is a computational process where the surface-measured deflections from a series of sensors are compared to the deflections from a pavement structural model composed of layers with thicknesses equal to the as-constructed condition and stiffness values that are allowed to vary over a known range. The stiffness values are modified in an iterative process until the error between the computed and measured deflections is minimized. The combination of stiffness values having the least error is generally taken as being representative of the pavement structure. For this study, all the asphalt layers (including the CCPR layer) were grouped together and treated as a single layer because of their similar viscoelastic behavior.

Figure 8 shows the backcalculated AC/CCPR modulus for Section N4 with respect to mid-depth temperature. The data are also presented with respect to the three track cycles: Cycle 1 represents the period 0-10 million ESALs; Cycle 2 represents the period 10-20 million ESALs; and Cycle 3 represents the period 20-30 million ESALs. As expected, the data show a strong influence of temperature on the calculated stiffness values. From Figure 8 it can be seen that the modulus values for Cycles 1 and 2 are similar at the same temperatures; however, the modulus values for Cycle 3 are lower and the difference increases with decreasing temperature.

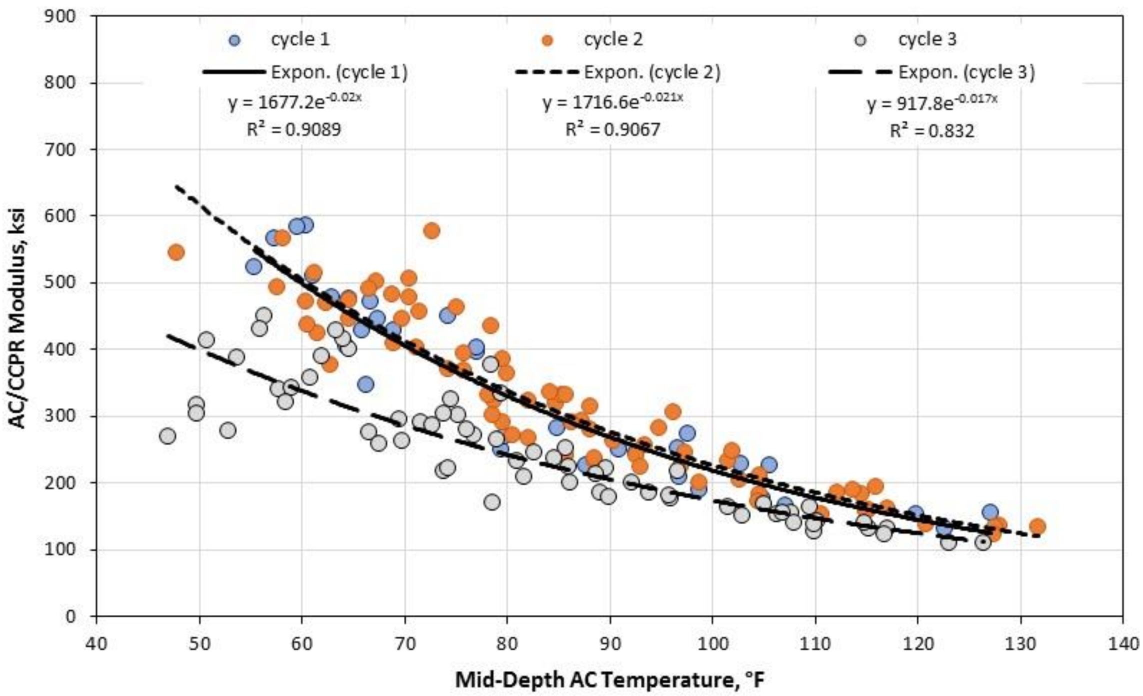

Figure 8. Section N4 AC/CCPR Modulus. AC = asphalt concrete; CCPR = cold central plant recycling; Expon. = exponential trendline.

This decrease for Cycle 3 is thought to be caused by deterioration within the pavement section because of trafficking. Also shown in Figure 8 are the exponential trendlines and regression equations that could be used to describe the data. It can be seen that the rate of decrease in modulus with an increase in temperature is the same for Cycles 1 and 2 whereas the rate of decrease was less for Cycle 3, indicating less sensitivity to changes in temperature. The researchers suggest that the decreased sensitivity to temperature is also caused by deterioration within the pavement section. At higher temperatures, the pavement system approaches a minimum stiffness value regardless of condition and thus the response with respect to pavement shifts for Cycle 3 but only at lower and intermediate temperatures.

To demonstrate further the changes in AC/CCPR modulus with respect to time, the data shown in Figure 8 were normalized with respect to a reference temperature. Equation 1 shows the general form of the exponential equation used to model the data as follows:

$$y = k1\left(e^{k2(x)}\right) \quad \text{[Eq. 1]}$$

where

y = strain
k1 and k2 = coefficients determined from an exponential trendline
x = temperature.

The temperature normalization process was completed using the exponent (k2) from Equation 1 in Equation 2. Equation 2 shows the general model used in the temperature normalization process as follows:

$$E_N = E\left(e^{k2(T_{ref}-T_{MD})}\right) \quad \text{[Eq. 2]}$$

where

E_N = temperature-normalized AC/CCPR modulus
E = AC/CCPR modulus
T_{ref} = reference temperature (68°F)
T_{MD} = mid-depth temperature.

Figure 9 shows the temperature-normalized AC/CCPR modulus by test cycle. Despite the normalization process, the influence of seasonal temperature fluctuations is seen in the results. From Figure 9 it can be seen that the temperature-normalized AC/CCPR modulus during Cycle 3 was less than for the other two cycles. This reduction in stiffness was attributed to internal deterioration within the pavement section. It is not known for certain if the reduction in stiffness occurred within the AC layers or the CCPR layer, but it could likely be determined by comparing the laboratory-measured stiffness of cored samples from each layer taken from between and within the outside wheel path during a future forensic investigation.

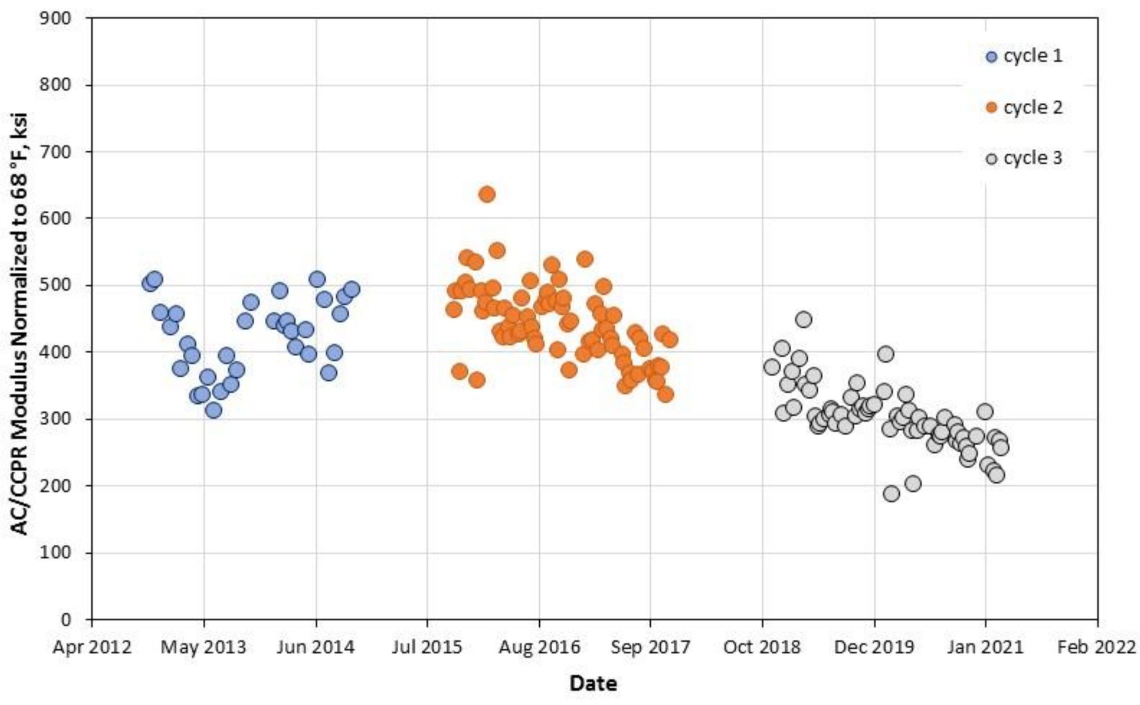

Figure 9. **Section N4 Temperature-Normalized AC/CCPR Modulus. AC = asphalt concrete; CCPR = cold central plant recycling.**

Figure 10 shows the backcalculated AC/CCPR modulus for Section S12 with respect to mid-depth temperature. The data in Figure 10 show the strong influence of the cement-stabilized base beneath the CCPR layer, as the stiffness values are much greater for Section S12. Since the AC and CCPR materials are the same for Sections N4 and S12 and were produced and placed at the same time for the two sections, the researchers do not expect significant differences in the material properties. It is possible that the FWD analysis attributed some of the stiffness of the cement-stabilized base to the asphalt materials in Section S12.

Figure 11 shows the temperature-normalized backcalculated AC/CCPR modulus for Section S12 with respect to time. Very high modulus values were noted for certain test dates in this dataset. Some of these high values were attributable to a reduced number of replicates included in the average modulus. Figure 11 also shows that the temperature-corrected AC/CCPR modulus appears, on average, to be similar in magnitude among the three test cycles. Thus, internal deterioration within the AC/CCPR layers is not expected. The lack of deterioration is thought to be caused by the support of the stiff underlying cement-stabilized base and suggests that the strong foundation used in Section S12 is increasing the service life of the AC/CCPR layers above.

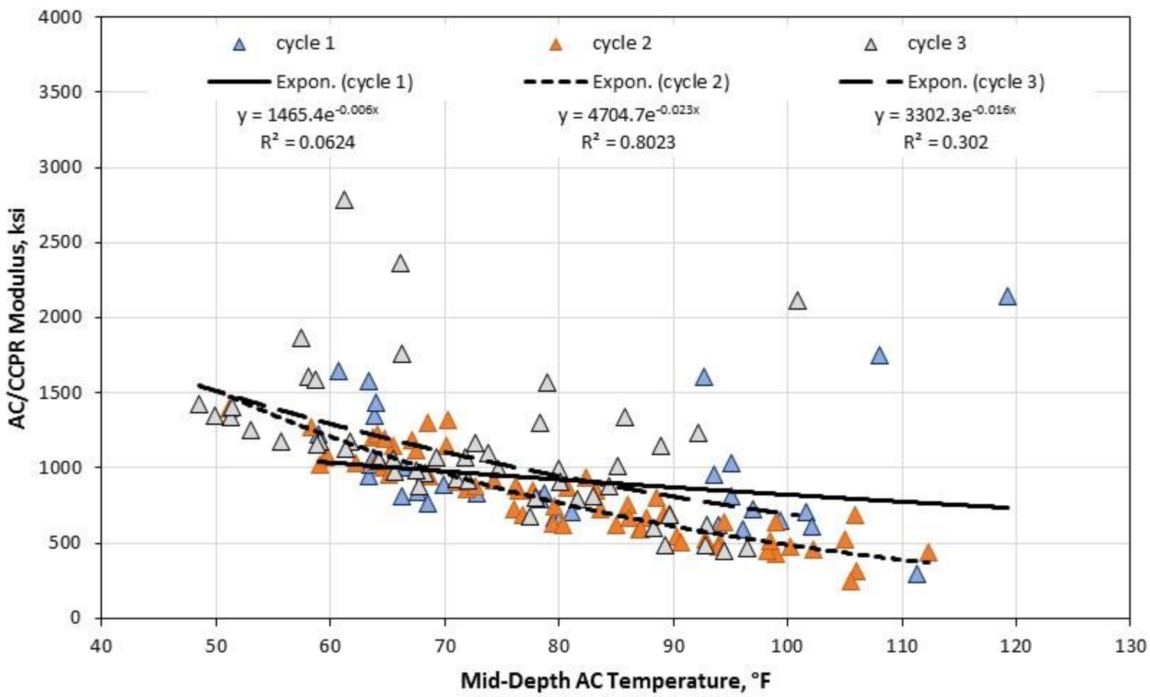

Figure 10. Section S12 AC/CCPR Modulus. AC = asphalt concrete; CCPR = cold central plant recycling; Expon. = exponential trendline.

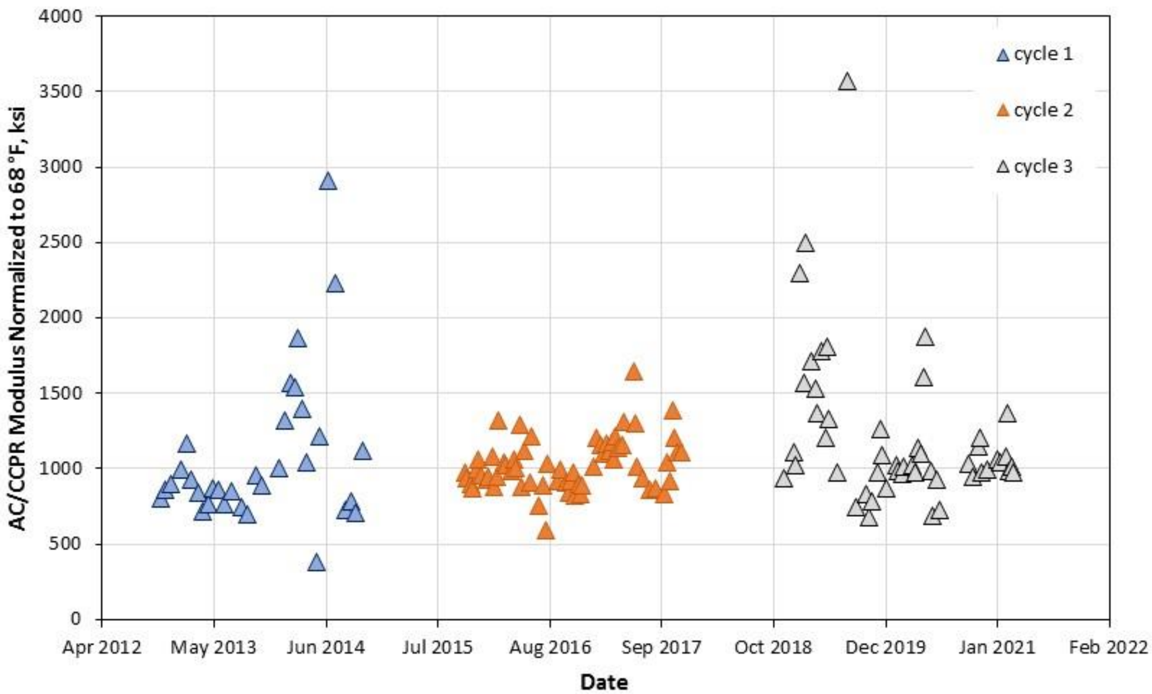

Figure 11. Section S12 Temperature-Normalized AC/CCPR Modulus. AC = asphalt concrete; CCPR = cold central plant recycling.

Instrumentation

Instruments were installed in the test sections during construction to monitor the pavement temperature in addition to the pressure and strain response from truck loading, as shown in Figure 5. These data are presented with respect to ESAL loading.

Vertical Base Pressure

Figure 12 shows the temperature-normalized vertical base pressure, normalized to 68°F. Also shown are the polynomial and logarithmic trendlines and associated regression equations for Sections N4 and S12, respectively. As expected, Section S12 (having the stabilized base) had a lower pressure than Section N4.

Following the trend of decreasing AC/CCPR stiffness in Section N4, shown in Figure 9, the vertical base pressure was found to increase with respect to accumulated truck loading and confirmed the expected impact on the pavement response from reduced stiffness values (caused by deterioration) in the overlying pavement structure.

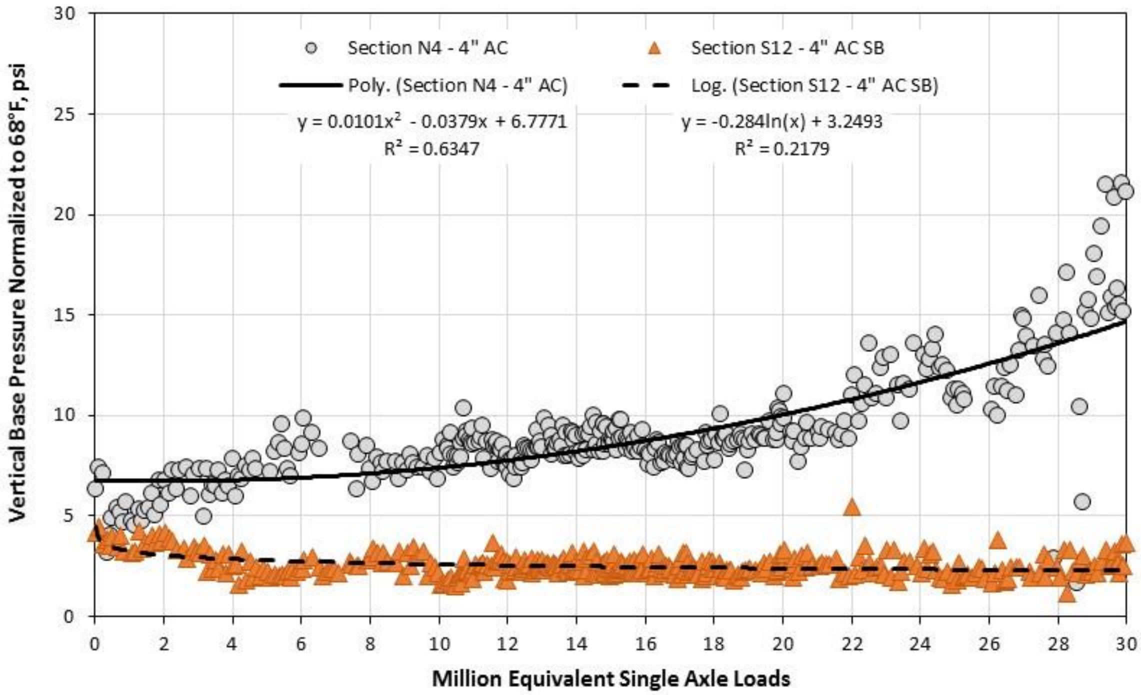

Figure 12. Vertical Base Pressure vs. Million Equivalent Single Axle Loads. AC = asphalt concrete; Poly. = polynomial trendline; SB = stabilized base; Log. = logarithmic trendline.

Vertical Subgrade Pressure

Figure 13 shows the temperature-normalized vertical subgrade pressure, normalized to 68°F. Also shown are the polynomial and logarithmic trendlines and associated regression equations for Sections N4 and S12, respectively.

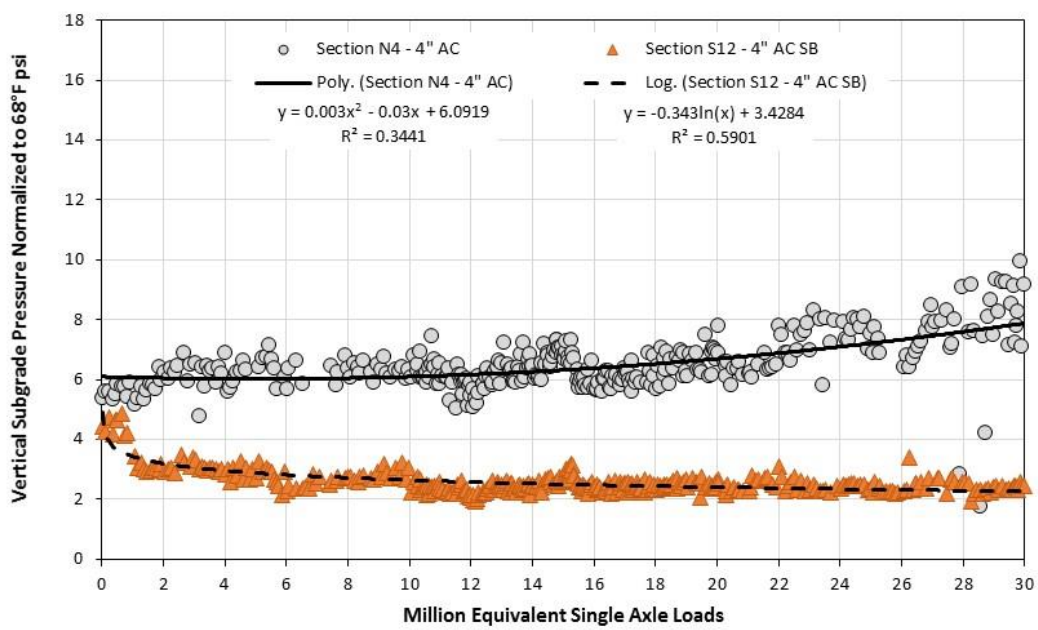

Figure 13. Vertical Subgrade Pressure vs. Million Equivalent Single Axle Loads. AC = asphalt concrete; Poly. = polynomial trendline; SB = stabilized base; Log. = logarithmic trendline.

Similar to the vertical base pressure, Figure 13 shows the vertical subgrade pressure to be greater in Section N4 than in Section S12. This was again expected because of the reduced stiffness of the overlying materials in Section N4 as compared to Section S12. Following the vertical base pressure trend, the vertical subgrade pressure was found to increase with accumulating truck loading likely caused by the reduced stiffness (caused by deterioration) in the overlying pavement structure.

Horizontal Strain

Figure 14 shows the temperature-normalized horizontal strain, normalized to 68°F, and the linear and polynomial trendlines and respective regression equations for Sections N4 and S12, respectively. For Section N4, Figure 14 shows that the strain values were not only increasing with respect to accumulated truck loading but also had a wider spread with respect to accumulated truck loading. It is thought that these two observations were the result of internal damage within the section. For Section S12, Figure 14 shows that the strain values continued to be both less and relatively stable. This is thought to be evidence of a very strong pavement section with little to no internal damage caused by trafficking.

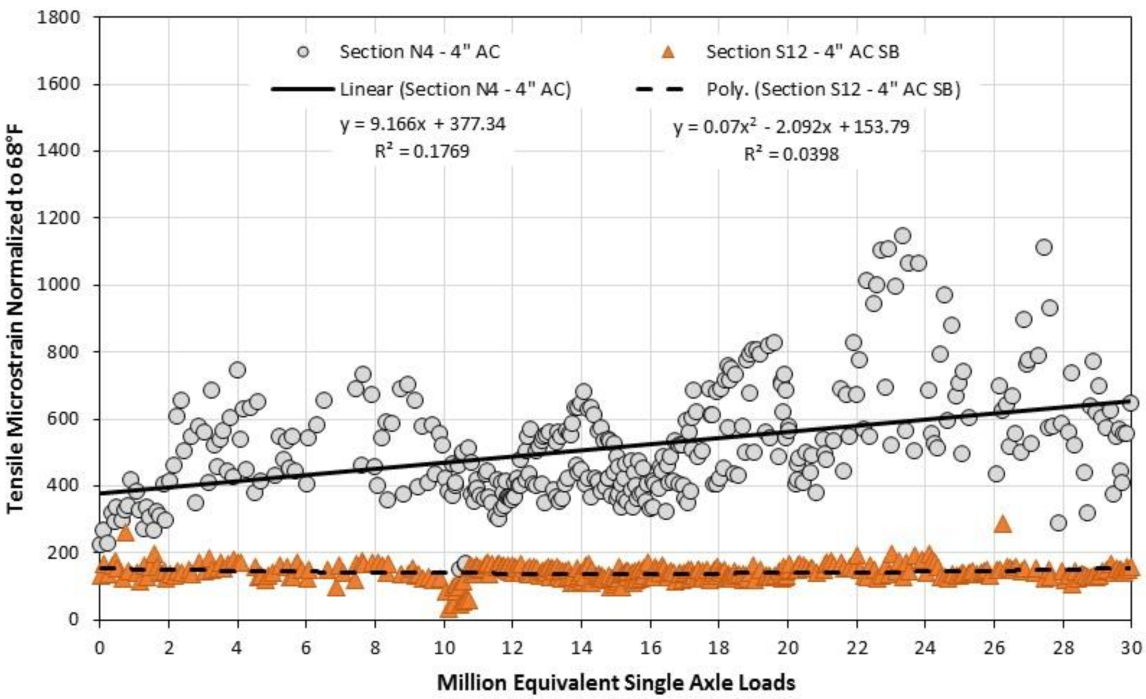

Figure 14. Horizontal Strain vs. Million Equivalent Single Axle Loads. AC = asphalt concrete; Poly. = polynomial trendline; SB = stabilized base.

Surface Distress

Near the end of the third test cycle (at approximately 29.6 million ESALs), cracking within the outside wheel path was observed at the surface of Section N4. The cracks were short, regularly spaced transverse cracks and were difficult to identify when the pavement was dry; they currently cover an area of less than 0.5% of the outside wheel path. It is suspected that these cracks might be the result of the higher strain values observed for Section N4 since the last test cycle. As of the writing of this report, no coring had been conducted to discern whether or not these cracks extended the full depth of the pavement structure. At the conclusion of this study, no deterioration was evident at the surface of Section S12.

Implications for Pavement Design

As described in this report, the test sections built using pavement recycling techniques have performed well under heavy truck traffic, especially Section S12, which has performed as a perpetual-type structure. However, the question still remains as to how to replicate these designs in other locations to have similar performance and to optimize the pavement structure to reduce costs. To create a cost-effective structural design using pavement recycling techniques, a designer must have an idea of the overall structural behavior, deterioration mechanisms, and expected service life of the pavement system. In the 1960s, these same topics were addressed by testing a series of concrete and asphalt pavements during the AASHO Road Test using non-recycled materials (Highway Research Board, 1962). Although the design manuals resulting from this testing have been refined over the years (AASHTO, 1993), the overall structural behavior, deterioration mechanisms, and expected service life of pavement systems built using pavement recycling techniques are still largely not well quantified. Thus, test sections similar to those described in this report are extremely important to realize better the potential performance benefits and life-cycle cost and environmental savings associated with using pavement recycling techniques (such as CCPR and FDR).

The literature suggests that pavements built using pavement recycling techniques (especially those containing CCPR) are likely to show behavior of the recycled layer similar to that of a granular material with improved cohesion (Jenkins et al., 2007) or a less-stiff asphalt-like material having properties that depend on the temperature and loading rate (Diefenderfer and Link, 2014; Schwartz et al., 2017). The actual behavior will likely fall between these two concepts. Pavement sections containing a stabilized base layer (like FDR) are expected to offer superior performance compared to a less-stiff aggregate base so long as the stiffness of the stabilized base layer is not so great that it becomes crack susceptible. It is also unknown if a pavement section built using a stabilized foundation is better modeled as a flexible or a semi-rigid system. For these reasons, it is important to continue monitoring the performance of existing field projects and test sections and to conduct forensic investigations at the end of their service lives to understand these concepts better as they relate to pavement recycling techniques.

CONCLUSIONS

- *The test sections evaluated are examples of new or reconstructed pavement structures that include CCPR or CCPR and a stabilized base layer (similar to FDR) that can achieve a long service life under heavy truck traffic.*

- *The use of the stabilized base layer in place of an aggregate base is credited for the superior performance of Section S12.*

- *Further trafficking of Section N4 is expected to provide additional information that might be used to determine a suitable design approach for pavement sections including CCPR and identify the deterioration mechanism(s) of the CCPR material.*

- *A forensic investigation of the test sections evaluated (to include trenching and laboratory testing of collected cores) when they are taken out of service would help to identify the specific layers in which any deterioration occurred.*

RECOMMENDATIONS

1. *The Virginia Transportation Research Council (VTRC) and VDOT's Materials Division should promote the design concept of including a stabilized base layer (similar to FDR) beneath a CCPR layer when CCPR is included on pavement sections having high traffic volumes.* Examples of future locations include potential widening of the I-64 corridor between Richmond and the Hampton Roads region; the addition of travel lanes on I-81 in western Virginia; and potential reconstruction of I-95.

2. *VTRC and VDOT's Materials Division should investigate if designing a pavement section consisting of both CCPR and a stabilized base layer (similar to FDR) is more appropriate using a flexible pavement or a semi-rigid approach.*

3. *VTRC should continue to sponsor trafficking of Section N4 for the 2021 NCAT Test Track cycle to understand better the behavior of the CCPR material in terms of its eventual deterioration.*

4. *VTRC and NCAT should conduct a forensic investigation of these test sections once they are taken out of service.* The forensic study will help identify the specific layers in which any deterioration occurred.

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, VTRC and VDOT's Materials Division should update VDOT's *Manual of Instructions* to recommend a stabilized base layer where CCPR is used for high volume / high priority locations where practicable. VTRC and VDOT's Materials Division will develop this update within Fiscal Year 2022.

With regard to Recommendation 2, VTRC and VDOT's Materials Division should consider a future study to investigate the predicted performance of a pavement section that includes CCPR and a stabilized base layer (similar to FDR) to determine if it should be designed as a flexible or a semi-rigid pavement structure within a mechanistic-empirical pavement design framework. VTRC and VDOT's Materials Division will draft and submit a research needs statement to the appropriate subcommittee of VTRC's Pavement Research Advisory Committee within Fiscal Year 2022.

With regard to Recommendation 3, VTRC should request implementation funding to sponsor the trafficking of Section N4, in its current configuration, for an additional test cycle. As the distresses evident in the test section continue to grow, the data generated from the test section should be used to understand better the behavior of the CCPR material in terms of its eventual deterioration. VTRC will draft and submit a research needs statement to the appropriate subcommittee of VTRC's Pavement Research Advisory Committee within Fiscal Year 2022.

With regard to Recommendation 4, VTRC should request implementation funding to conduct a forensic investigation of the test sections, following trafficking, to identify the specific layers in which any deterioration occurred. VTRC will draft and submit a research needs statement to the appropriate subcommittee of VTRC's Pavement Research Advisory Committee within Fiscal Year 2022 or 2023, depending on when testing is completed.

Benefits

The research reported herein describes a unique study investigating the performance of pavement sections constructed at the NCAT Test Track using CCPR and CCPR with a stabilized base layer (similar to FDR) that are instrumented and have undergone periodic performance measurements. In a review of the literature, the researchers did not find any other similar test sections. With regard to Recommendation 1, including a design recommendation in VDOT's *Manual of Instructions* regarding the use of CCPR and a stabilized base layer will assist VDOT with implementing a pavement structure built using pavement recycling techniques that has shown perpetual-type performance. Further, with regard to Recommendation 2, determining an appropriate design methodology for a pavement section that includes CCPR and a stabilized base layer (similar to FDR) within a mechanistic-empirical pavement design framework will assist VDOT with developing more cost-effective designs while gaining the benefits of using recycled materials. With regard to Recommendations 3 and 4, additional trafficking of Section N4 and a forensic study of both test sections after trafficking will benefit VDOT and the national pavement community by fostering a better understanding of the behavior of CCPR with respect to its eventual deterioration, leading to more cost-effective structural designs. Through the increased use of pavement recycling techniques (such as CCPR and FDR), VDOT and the national pavement community can gain significant cost and environmental savings, as documented in the literature.

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