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Cold Central Plant Recycled Asphalt Pavements in High Traffic Applications

David H. Timm[1], Brian K. Diefenderfer[2], and Benjamin F. Bowers[2]

Abstract

Cold central plant recycling (CCPR) is gaining wider use in the U.S. for rehabilitating existing asphalt pavements or for new construction. Although it is used widely in lower traffic volume situations, CCPR use in high volume pavements remains an open question when considering its structural capacity and expected performance. A project completed in 2011 on I-81 in Virginia indicated CCPR may be suitable for high-volume traffic applications and was further evaluated with the construction of three CCPR test sections at the National Center for Asphalt Technology Test Track in 2012. These sections are now approaching 20 million equivalent single axle load applications and this paper documents their structural and surface performance thus far. The structural characterization indicates healthy pavements with no significant increases in measured pavement response or decreases in backcalculated moduli over time. Performance has been excellent with no cracking observed on any section, rut depths less than 0.3 inches and ride quality that has remained almost unchanged. Perpetual pavement analyses were also conducted and found that the section with a cement-stabilized base layer supporting the CCPR layer met the criteria and is likely perpetual. The other two sections, without the cement-stabilized base, did not meet the criteria and may develop bottom-up cracking. Data from the I-81 and Test Track sections enabled the Virginia Department of Transport (VDOT) to proceed with a design-build project on I-64 that will feature CCPR with a cement-stabilized base and full-depth reclamation (FDR). It is estimated that nearly 170,000 tons of reclaimed asphalt pavement will be used with over $10 million in savings.

Pavement recycling is a series of processes that includes cold in-place recycling (CIR), cold central-plant recycling (CCPR), and full-depth reclamation (FDR). Pavement recycling is effective at rehabilitating existing pavements or constructing new pavements while reducing the construction costs, environmental impacts, and construction time (*1–3*). Although the use of pavement recycling is becoming more common in several US states, its use is not consistent or widespread throughout the country. Several reasons for this exist and include the absence of defined materials characterization inputs for engineered structural design, a lack of rapidly applied quality control and/or assurance procedures, and a shortage of long-term performance data in the literature that documents the structural performance of existing sections. Studies related to the first two of these reasons are either underway or recently completed as part of work sponsored by the National Cooperative Highway Research Program (*4–5*); this paper addresses the third reason by describing research using CCPR and FDR conducted by the Virginia Department of Transportation (VDOT) and the National Center for Asphalt Technology (NCAT).

CCPR is a process in which newly milled or existing stockpiled reclaimed asphalt pavement (RAP) is combined with a recycling agent (and chemical additives, if used) to create a paving material that can be placed with conventional asphalt paving equipment. Great cost and energy savings are realized because the RAP particles are not reheated. These processes occur at a mobile plant which can be located at or near the paving project or RAP source stockpile. Also, because CCPR is not performed in-place the underlying foundational materials can be stabilized (using a process such as FDR), if needed, before placement of the CCPR material. Additionally, the CCPR process can be used to place multiple lifts for thicker applications. It is through this process that CCPR can be used to produce a recycled base course for reconstruction, new construction, lane widening, shoulder strengthening, and other projects.

[1]Auburn University, Auburn, AL
[2]Virginia Transportation Research Council, Charlottesville, VA

Corresponding Author:
Address correspondence to David H. Timm: timmdav@auburn.edu

Typical layer thicknesses for CCPR range from 2 to 6 inches (*6*) but multiple lifts may be used to increase the total thickness of the recycled layer.

VDOT has completed construction and is conducting research projects subjecting recycled pavements to high truck volumes to study their long-term structural performance, including CCPR. In 2011, VDOT completed construction on a portion of Interstate-81 in western Virginia that carries more than 6,000 trucks per day. CCPR and FDR were used in combination to reconstruct the right lane on this 3.7 mile-long project. Along with using CIR in the left lane, this project was the first time these three processes were used together on the interstate system in the US (*7*). In 2012, VDOT sponsored three test sections at the NCAT Pavement Test Track to further study CCPR pavements under high truck traffic conditions and included embedded instrumentation in the sections (*8*). The sections performed well through the first research cycle subjecting them to 10 million equivalent single axle loads (ESALs) of trafficking and were left in place for a second research cycle that would apply an additional 10 million ESALs.

As CCPR pavements have rarely been subjected to such high traffic levels, it is critical to provide updates on their condition and overall performance as agencies look to using CCPR more frequently in high traffic conditions. Additionally, the pavements showed signs that they may be perpetual (i.e., no deep structural distress development) and therefore an analysis was warranted to determine if they are predicted to be perpetual based on modern design criteria. Finally, the results of the research on the I-81 project and the test sections at the NCAT Test Track have given VDOT the confidence to use pavement recycling on other high profile projects (*9*). Providing discussion of this particular example may help other agencies begin using CCPR more routinely in high-volume applications.

Objectives

Given the needs described above, the objectives of this paper include the following:

1. Document the performance and structural condition of the VDOT sections at the NCAT Test Track through two test cycles approaching 20 million ESALs.
2. Evaluate the VDOT Test Track sections under perpetual pavement criteria.
3. Discuss real-world implementation, including cost comparisons, of CCPR pavements in high truck traffic volume situations.

Scope of Work

To accomplish the objectives, data collected from the three VDOT sections at the NCAT Test Track were compiled over two test cycles. The data included routine surface performance measurements (i.e., rutting, cracking, and roughness) in addition to structural evaluation through frequent falling weight deflectometer (FWD) testing and backcalculation. Frequent measurements using embedded instrumentation were also used for structural characterization. The strain measurements were used as part of a perpetual pavement analysis in addition to simulations conducted using the design software, PerRoad. Real world implementation was demonstrated through the I-64 reconstruction and widening project near Williamsburg, VA. Cost analyses, using data from VDOT, were also conducted that compared the recycled versus conventional approaches.

Full-Scale Testing and Evaluation

NCAT Test Track Facility

As described previously, the NCAT Test Track is a 1.7 mile closed-loop full-scale flexible pavement test facility located in Opelika, AL (*8*). Operating on two-year test cycles, the 46 test sections are loaded with approximately ten million ESALs per cycle. During this time, pavement response, deflection and performance measurements were made on a routine basis. Precise climate records and traffic data, applied by a fleet of triple-trailer trucks, were also kept during the test cycle. On average, the test site receives approximately 53 inches of rain per year with mid-depth pavement temperatures ranging from 40 °F to 120 °F. The CCPR materials were subjected to typical testing for recycled materials during mixture design that included an assessment of the retained indirect tensile strength. The materials used in this study passed the requirements of 70% retained indirect tensile strength (ITS) and a dry ITS of 45 psi. The sections in this experiment were constructed during the summer of 2012 and trafficking began in October 2012. Ten million ESALs were applied between October 2012 and October 2014. A second test cycle applying another ten million ESALs began in October 2015.

Test Track Cross Sections

The pavement cross-sections in this study are shown in Figure 1. Each section featured a stone-matrix asphalt (SMA) surface and Superpave dense-graded asphalt concrete (AC) layers above the CCPR layer. Sections N3 and N4 were constructed on top of a crushed granite aggregate base layer and S12 was built on a cement-stabilized base layer simulating FDR. The FDR layer is

Table 1. As-Built Layer Properties (*8*)

Section	N3-6"AC	N4-4"AC	S12-4"AC SB
Layer description	Lift 1-19 mm NMAS SMA with 12.5% RAP and PG 76-22 binder		
Binder content, %	6.1	6.0	6.1
Air voids, %	4.3	4.7	4.2
Layer description	Lift 2-19 mm NMAS Superpave with 30% RAP and PG 67-22 binder		
Binder content, %	4.6	4.6	4.7
Air voids, %	7.1	7.4	6.7
Layer description	Lift 3-19 mm NMAS Superpave with 30% RAP and PG 67-22 binder		
Binder content, %	4.4	NA	NA
Air voids, %	6.4	NA	NA
Layer description	CCPR-100% RAP with 2% foamed 67-22 and 1% type II cement		
Layer description	Crushed granite aggregate base		6" Crushed granite aggregate base and 2" subgrade stabilized in-place with 4% Type II cement
Layer description	Subgrade – AASHTO A-4 Soil		

Note: AC = Superpave dense-graded asphalt concrete; NMAS = nominal maximum aggregate size; CCPR = cold central plant recycling; RAP = reclaimed asphalt pavement: SMA = stone-matrix asphalt; AASHTO = American Association of State Highway and Transportation Officials; SB = stabilized base.

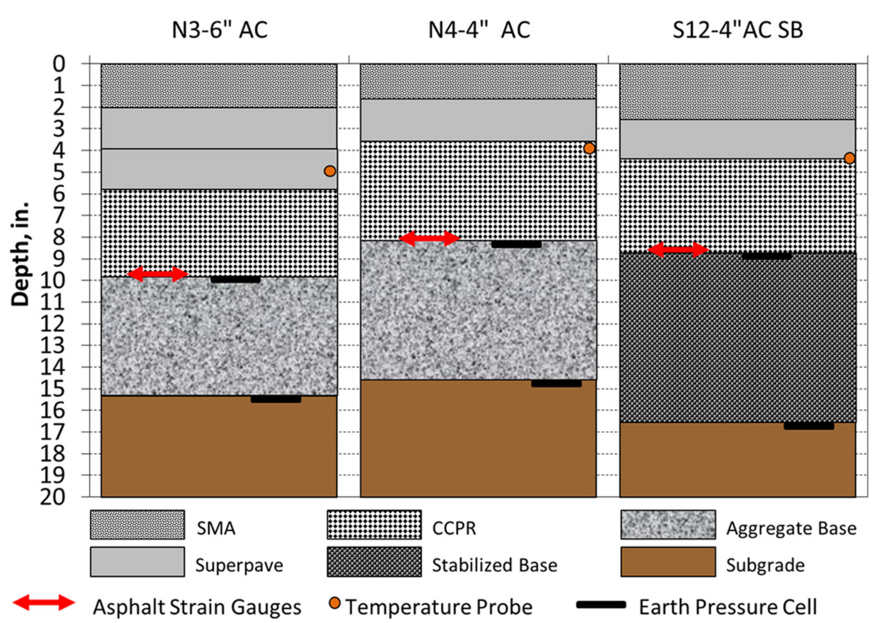


Figure 1. Average test track as-built thicknesses and depth of instrumentation (*8*).

described as simulated because, although traditional FDR construction techniques and equipment were used, no bound materials were included in the FDR process. All three sections were constructed on the same subgrade native to the Test Track and classified as an A-4 soil (*10*). Sections N3 and N4 were designed to evaluate the difference in performance between 4 inches and 6 inches of AC over 5 inches of CCPR. Sections N4 and S12 were designed to determine the performance differences between the aggregate base (6 inches) and the stabilized base (SB) layers (8 inches). Table 1 contains the as-built layer properties and further details of the mix design and construction were previously documented (*8*), but it is important to point out that the CCPR layers were placed as a single lift.

Figure 1 also shows the types and depths of instrumentation used in the sections. Asphalt strain gauges were installed to measure bending at the bottom of the

CCPR. Earth pressure cells (EPCs) were installed at the bottom of the CCPR and the top of the subgrade to measure vertical stress distributions through the pavement. Finally, temperature probes were installed at approximately mid-depth of the AC/CCPR layer to capture environmental effects on the pavement.

The three recycled sections on the Test Track were designed to mimic the cross section of a project placed in Virginia on Interstate 81 in 2011 (*7*, *11*). It is possible to determine the expected service lives of the three Test Track sections by following procedures in the American Association of State Highway and Transportation Officials (AASHTO) 1993 Pavement Design Guide (*12*) and using VDOT's typical design parameters for asphalt pavements (*13*, *14*). Structural numbers for Sections N3, N4, and S12 were calculated as 5.1, 4.2, and 5.5, respectively. Using these structural numbers and inputs for designing an interstate-style pavement, the ESALs that could be carried assuming a soil support of 9400 psi (about 1/3 of the FWD measured values, [*10*]) yields ESAL values ranging from about 3 to 16 million.

Test Track Traffic

Trafficking of the sections began on October 22, 2012 and was applied with five triple-trailer trucks each having a steer axle (11,000 lb), a drive tandem axle (40,000 lb), and five single axles (20,750 lb/axle). This truck configuration corresponded to approximately 10 ESALs per truck pass. During the first two year study (2012–2014), approximately 10 million ESALs were applied. The second test cycle (2015–2017) was to apply an additional 10 million ESALs. There was approximately a one-year break, during Test Track forensic and reconstruction activities, during which no traffic was applied to the sections. At the time of writing this paper (mid-October, 2017), the total traffic for the two cycles was approximately 19 million ESALs.

Test Track Performance Characterization

During each two-year cycle, the sections were manually inspected weekly for signs of cracking in addition to manual rut depth and ride-quality measurements made with an automated road profiling vehicle. These measurements and observations were conducted at different intervals, so the data sets are current through slightly different dates and ESAL totals. For 19 million ESALs, no cracking was observed in any of the three CCPR test sections. This excellent cracking performance was further evaluated according to perpetual pavement criteria as described later in this paper.

Figure 2 shows the rutting performance through to the August 7, 2017 (18.3 million ESALs). Sections N3 and N4 (without the SB) were nearly indistinguishable with maximum rutting of approximately 0.3 inches. S12 (SB) had maximum rut depths of approximately 0.25 inches. As the measured rutting in all three sections

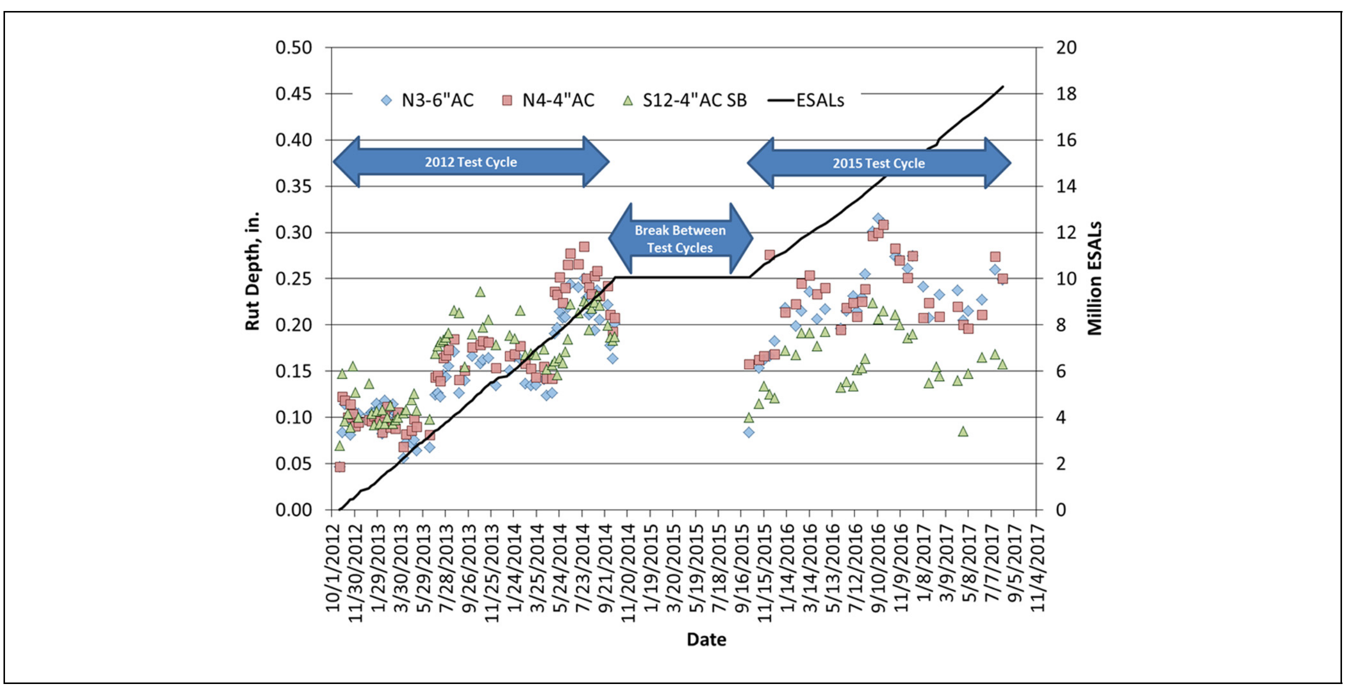


Figure 2. Test track sections—rutting performance.

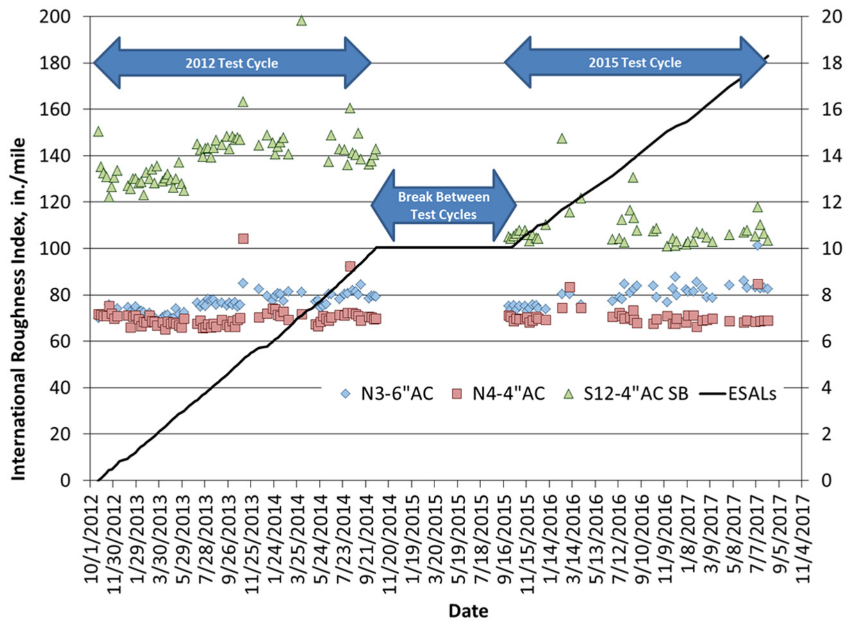


Figure 3. Test track sections—ride quality.

was well below the failure threshold of 0.5 inches, they each exhibited excellent rutting performance with the SB section showing a slight advantage.

Figure 3 plots pavement smoothness, expressed as the International Roughness Index (IRI), versus time through 18.3 million ESALs (August 7, 2017). As noted previously, Section S12 (SB) had an initial roughness of nearly double that of the other sections (*8*). This section had a localized low spot approximately 40 to 60 feet into the section that was identified immediately after construction which produced relatively high IRI values. In addition, the transition from the previous section (S11) into S12 was notably rough at the start of the 2012 research cycle. Between the 2012 and 2015 test cycles, the transition zone was milled and inlaid which appreciably improved the ride quality data. Overall, it is important to note that the IRI of S12 has not changed significantly over time.

Test Track Structural Characterization

As described previously (*8*), FWD testing was conducted on each section multiple times per month during each research cycle. Each round of data consisted of deflections collected at twelve locations corresponding to between, inside and outside wheelpaths at four longitudinal locations in each section. Although four drop-heights were used, with three replicates at each height, only data from the 9-kip load-level are presented here. Following previously-documented procedures that utilized EVERCALC 5.0 for backcalculation (*8*), the data shown in Figure 4 shows the backcalculated AC moduli normalized to 68 °F for both test cycles, through to July 10, 2017 (17.9 million ESALs). It is important to note that the AC and CCPR layers were combined into a single layer for the purposes of backcalculation, as was previously documented (*8*).

Visual inspection of Figure 4 does not indicate appreciable changes in the modulus over time. If there were significant aging or damage occurring over the two test cycles, one would expect to see increases or decreases in temperature-normalized moduli, respectively. Trendlines were fit to each series in Figure 4, but were not included as they all resulted in R^2 values below 0.03, meaning there was no appreciable change attributable to time or traffic application. In other words, the sections appear to be structurally healthy and have not experienced significant aging detectable through backcalculation. Additionally, the apparent increase in modulus for S12 may be partly owing to the presence of the SB layer which may artificially increase the AC modulus during backcalculation. The slight increase over time in the S12 AC modulus may also be attributed to curing of the SB.

Test Track Pavement Response Measurements

Asphalt strain gauges and earth pressure cells installed at the time of construction were routinely monitored throughout the two research cycles to track changes in pavement response over time. Previous documentation

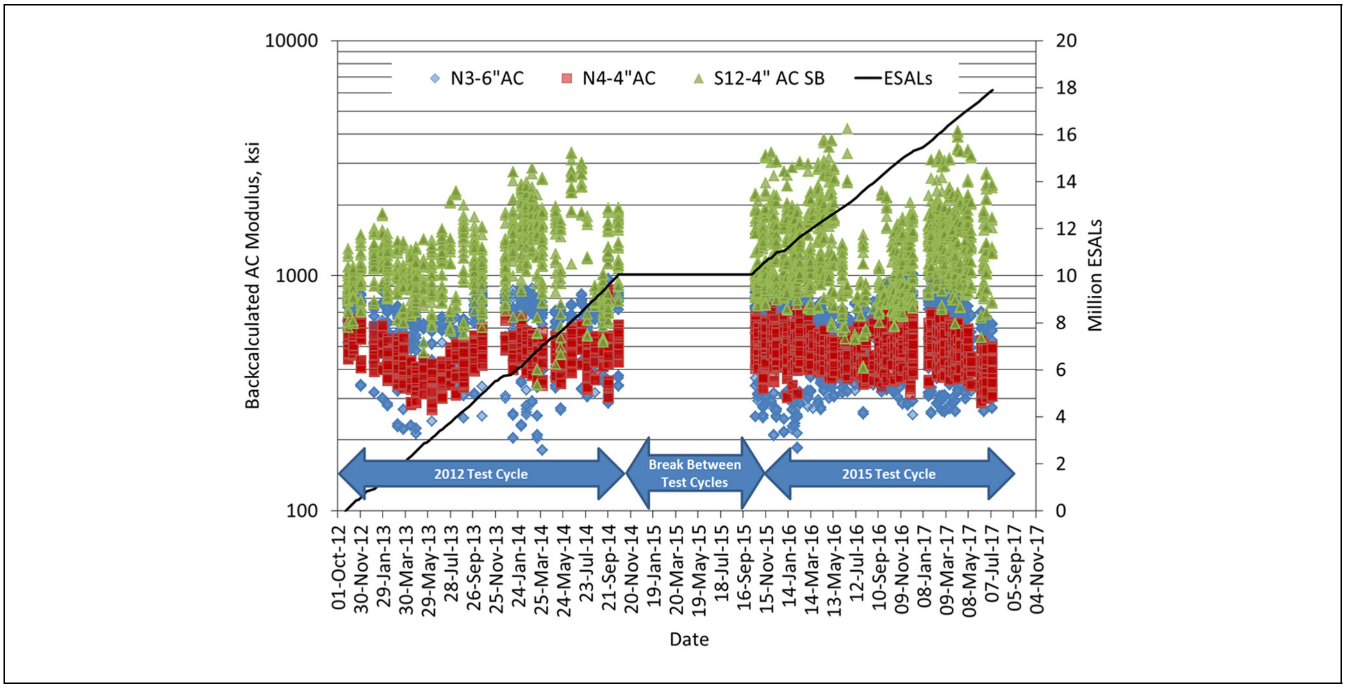


Figure 4. Back calculated AC/CCPR modulus normalized to 68 °F vs. date.

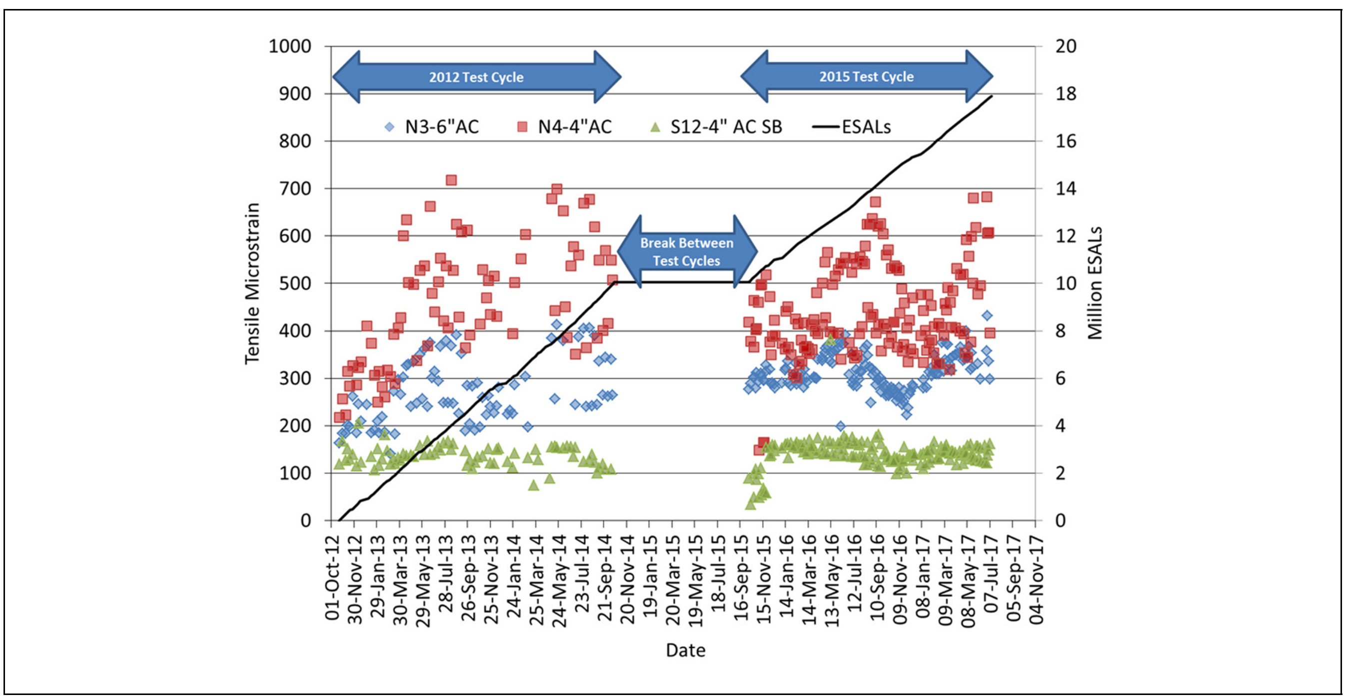


Figure 5. Tensile microstrain normalized to 68 °F vs. date.

described the data collection and reduction processes from these gauges in great detail (*8*). Of particular interest are the strain measurements made at the bottom of the CCPR layer as they are indicative of fatigue cracking performance. Figure 5 plots strain measurements, normalized to 68 °F, made over the two research cycles following the aforementioned procedures (*8*). The data are current through to July 7, 2017 (17.9 million ESALs).

Figure 5 supports the conclusions from Figure 4 that the sections all appear to be structurally healthy with no

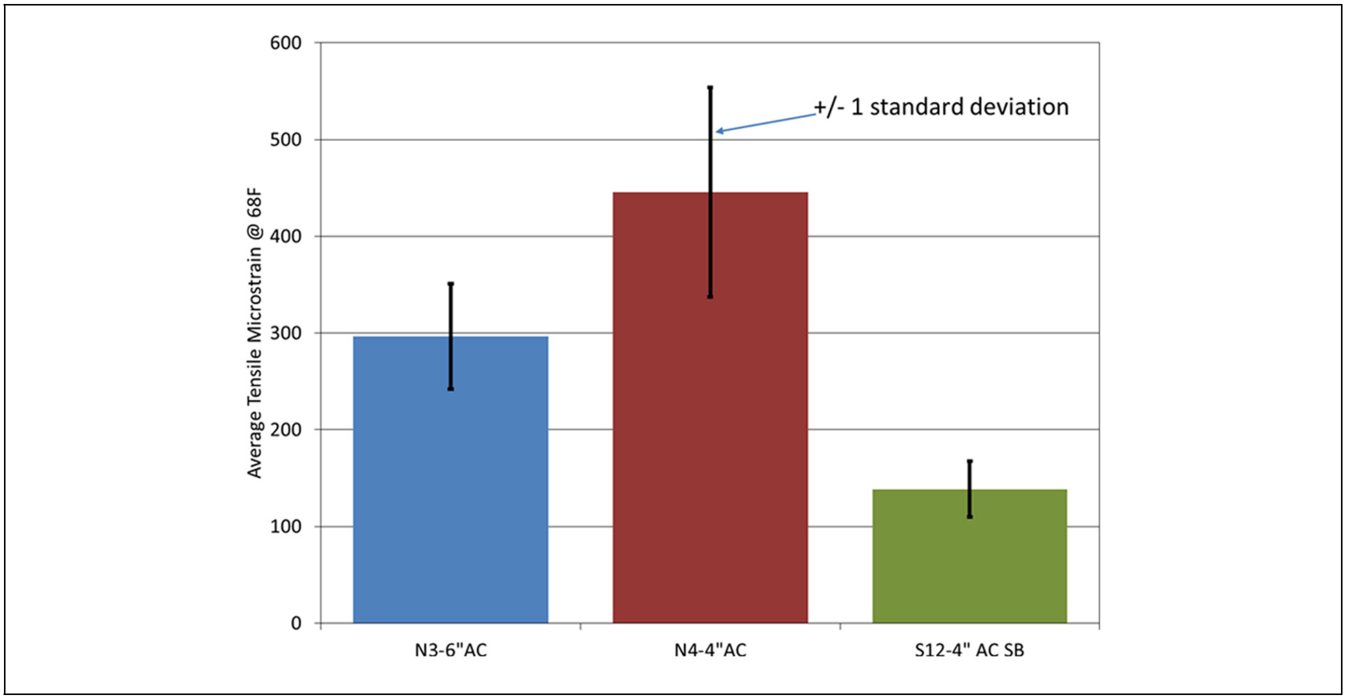


Figure 6. Average tensile microstrain and standard deviation normalized to 68 °F.

appreciable changes in strain response over the two test cycles. Interestingly, there does appear to be an initial increase in strain response for section N4 at the very beginning of the experiment in 2012, but it quickly leveled off and no upward or downward trends have been observed since then. Trendlines were also fit to the series in Figure 5 but were not included as the R^2 were again very low (<0.2). This indicates, as observed in the backcalculated moduli data above, that there has been no appreciable change attributable to time or traffic application.

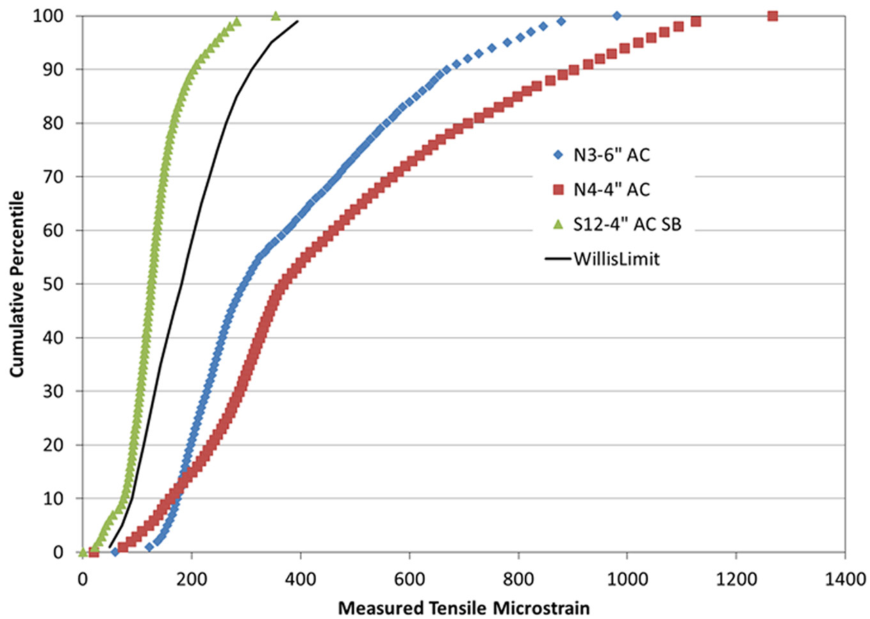
Differences in strain magnitude are evident between the sections, as expected, owing to differences in AC thickness and the presence of the SB layer. The average strain values and standard deviation, computed from Figure 5, are plotted in Figure 6. Tukey–Kramer analysis ($\alpha = 0.05$) showed that the difference in all mean values was statistically significant so the observed 33% decrease in strain from N4 to N3 and the 69% decrease from N4 to S12 are both practically and statistically significant.

Perpetual Pavement Analysis

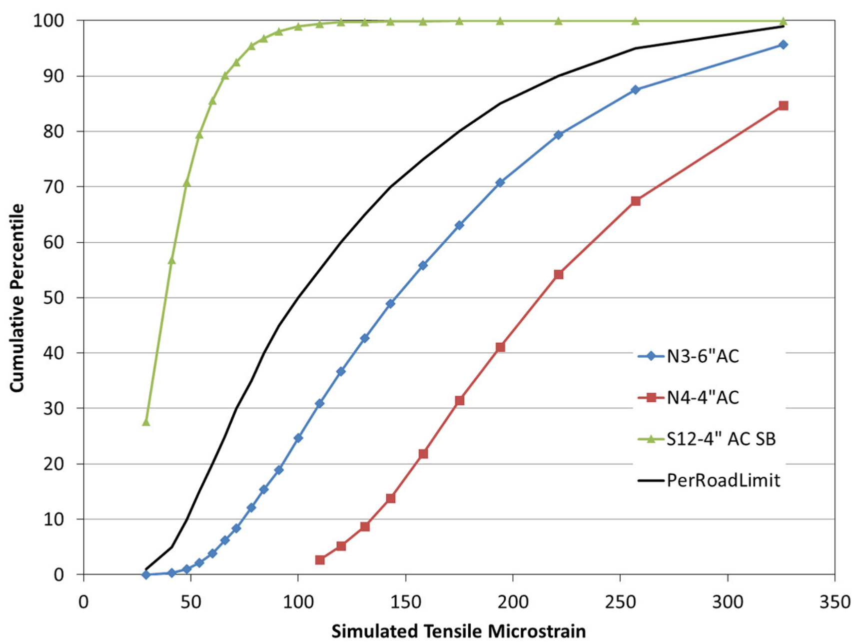
AS the CCPR sections at the Test Track exhibited excellent performance through two research cycles, analyses were conducted to evaluate whether these sections may be considered as perpetual pavements with respect to bottom-up fatigue cracking. Studying the fatigue performance of a pavement section subjected to high truck traffic volumes is a common practice for traditionally-constructed asphalt pavements. However, it is not yet known if the CCPR materials used in this study are expected to ultimately fail by fatigue or some other mechanism.

The Test Track sections were evaluated with respect to recently-developed criteria that utilize control strain distributions in the evaluation process. The first, a measured strain distribution, was developed from Test Track data using measured strain data from several sections that either did or did not experience bottom-up fatigue cracking (*15*, *16*). This control distribution serves as an upper limit to the strain response above which cracking may be expected and below which perpetual performance is expected. The second, a simulated strain distribution, was also developed from NCAT Test Track data, but relied on simulated strain levels in the design software, PerRoad, and was further validated with field-documented perpetual pavements (*17–19*). It is important to emphasize that these criteria were not developed from CCPR or cement-stabilized base pavement sections so it is currently unclear whether they are truly applicable. However, they do serve as a checkpoint against conventional flexible pavements and further trafficking and monitoring of the sections will help to further validate whether they may be applied, or new criteria are needed.

To evaluate the sections against the measured strain distribution criteria, a cumulative strain distribution was generated from measured data for each section and plotted with the control distribution as shown in



(a)



(b)

Figure 7. Perpetual pavement analysis cumulative strain distributions (*a*) measured strains; and (*b*) PerRoad simulated strain.

Figure 7*a*. Simulated strain distributions were generated through the PerRoad software by entering relevant input parameters (i.e., layer moduli, layer thicknesses, and traffic conditions) and utilizing the Monte Carlo features in PerRoad to produce cumulative distributions as illustrated in Figure 7*b*. Both analyses resulted in the same conclusion that section S12 – with the cement-stabilized base layer – is expected to be perpetual as its strain distribution is less than the control distribution. The other two sections both exceed the control distribution, and according to the criteria, are expected to experience bottom-up cracking at some point. Furthermore, both analyses show the benefit of the additional 2 inches of AC resulting in lower strain levels for N3 relative to N4.

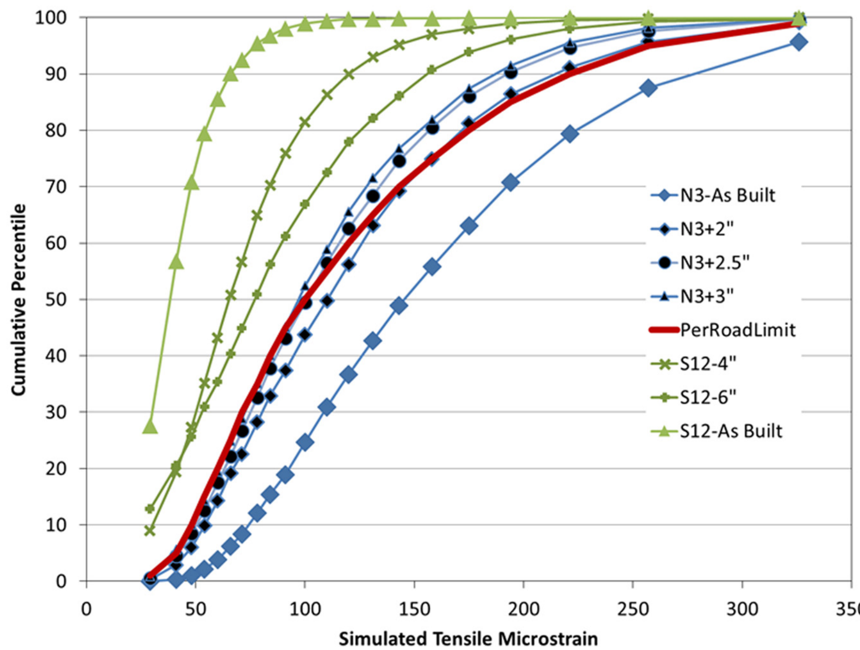


Figure 8. Additional perpetual strain analyses.

At this point, it is unknown whether the sections exceeding the strain limits will truly develop bottom-up cracking as the criteria were not developed from CCPR sections. Likewise, cracking could develop in S12, perhaps from cracking of the cement-stabilized layer reflecting through the CCPR and AC layers. However, application of the current perpetual criteria indicate that S12 is likely perpetual while the others are not.

Further perpetual analyses were conducted with PerRoad to evaluate sections N3 and S12 to quantify the changes in thickness needed to bring them closer to the perpetual design limit (i.e., optimized perpetual design). In section N3, this required additional thickness while S12 required thickness reductions. Figure 8 summarizes the results of the analyses in which the as-built cross-sections were first analyzed followed by incrementally increasing (N3) or decreasing (S12) the AC thickness. For example, the N3 + 2" series represents the simulation in which an additional 2 inches were added to the as-built AC/CCPR layer thickness. The figure shows that an additional 2.5 to 3 inches of AC/CCPR, bringing the total AC/CCPR depth to 11.75 to 12.25 inches, will move N3 into the non-cracking side of the perpetual limit.

Figure 8 also shows that a dramatic decrease in the AC/CCPR thickness (up to 6 inches) still leaves the strain distribution well to the left of the perpetual limit. An obvious concern with this cross section, which focuses only on controlling strain at the bottom of the AC/CCPR layer, is that covering the SB layer with only three or less inches of AC/CCPR would potentially lead to cracking of the SB layer. Additional mechanistic simulations were conducted with the layered elastic program, WESLEA for Windows, to examine the horizontal strain levels through the depth of varying S12 cross-sections. These simulations, discussed in depth below, used the average modulus values from the PerRoad analysis and a single wheel load of 9,000 lb with 100 psi of contact pressure.

Figure 9 summarizes the results for the three simulated S12 cross-sections. In each case, the neutral axis (point of zero strain) of the cross-section lies within the AC/CCPR layer with the bottom of the CCPR and SB layers both in tension. The as-built cross-section has nearly equivalent strain levels at the bottom of both layers, but the SB layer experiences significantly higher strain levels as the AC/CCPR thickness is reduced. Changing from as-built to 6-inch results in a 40% increase in the tensile strain at the bottom of the CCPR layer, but the SB tensile strain increases by almost a factor of three. The strain (or stress) tolerance of the SB layer is not currently known, but this analysis highlights the potential risk of placing too little AC/CCPR over the SB layer in which it would be forced to carry significantly greater tensile loadings. Measurement of the fatigue tolerance of the SB should be studied in the future.

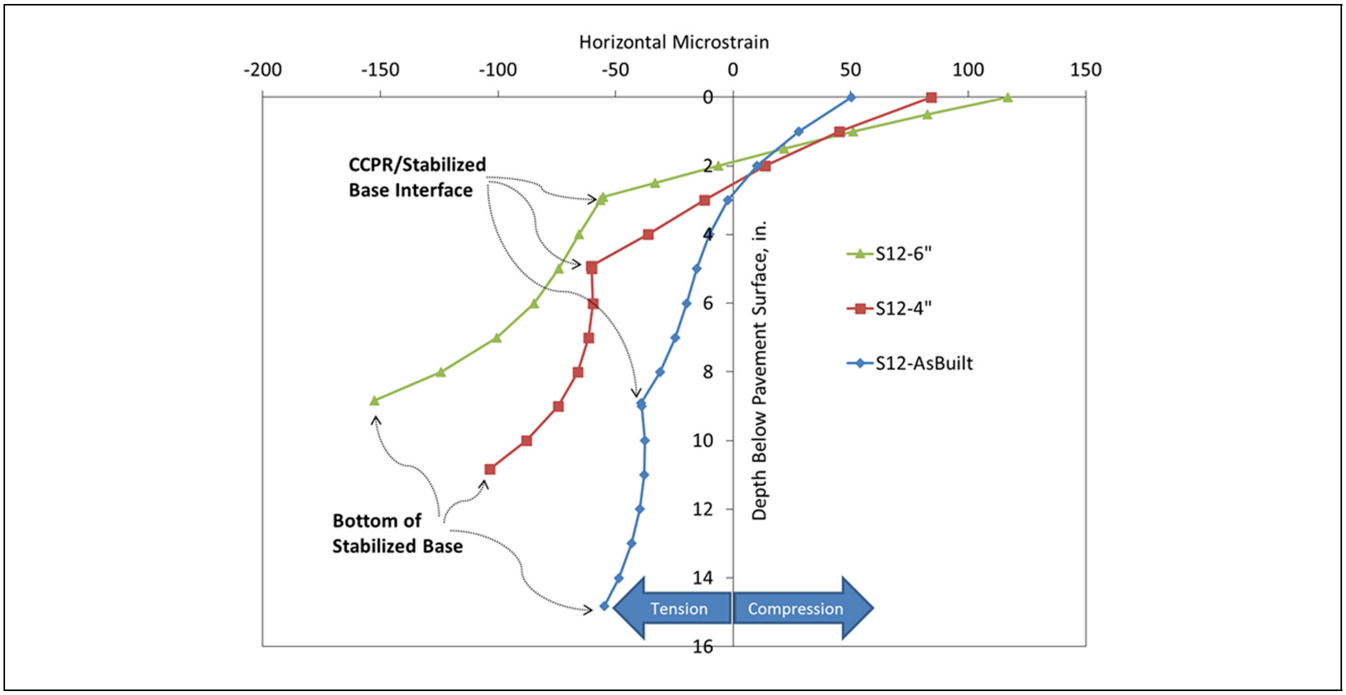


Figure 9. S12 Horizontal strain versus depth simulations.

Application of Results

In 2016, VDOT awarded a design-build contract to reconstruct and widen a portion of Interstate 64 near Williamsburg, VA using FDR and CCPR as major components of the new pavement sections. The first phase of the project will consist of building a new travel lane and full-width shoulder to the inside of the existing roadway in both directions. These new lanes will be an asphalt pavement having a 6-inch-thick CCPR base placed on top of 12 inches of cement treated base produced from crushed concrete. The second phase of the project will consist of replacing the existing two lanes and outside shoulder of the jointed concrete pavement with an asphalt pavement having a 6-inch CCPR base on top of a 12-inch-thick FDR foundation. The project length is 7.08 miles and this section of I-64 carries approximately 37,500 vehicles per day (in each direction) with about 8.5% trucks. Considering typical RAP contents for the surface asphalt layers and the CCPR layer, it is estimated that nearly 200,000 tons of RAP will be used on the project.

VDOT gained the confidence to move forward with this innovative pavement solution from the excellent performance results observed at the NCAT Test Track sections in conjunction with the performance of Virginia's Interstate 81 pavement recycling project (*7*, *11*). Given the current ESAL counts for the NCAT sections (approaching 20 million ESALs), it would take approximately 22 years on the I-64 project to reach the same ESAL values.

Cost Analysis of Recycled Versus Conventional Designs

Figure 10 shows the pavement cross-sections for the original and recycled designs. The two designs are structurally equivalent and use the VDOT typical layer coefficients (*13*, *14*). The calculated structural numbers are 7.08 and 7.06 for the original and recycled designs, respectively. A significant cost savings using the recycling design was identified by comparing local material prices (shown in Table 2) for the original design to the as-bid prices for the recycled design. The costs for the original and recycled sections were calculated as $88 per square yard and $42 per square yard, respectively. For this project, the cost savings using the recycled design is greater than $10 million.

Conclusions and Recommendations

The following conclusions and recommendations are drawn from this study:

- The three recycled pavement test sections at the NCAT Test Track are examples of new or reconstructed pavement structures built with high percentages of recycled materials. The results of this

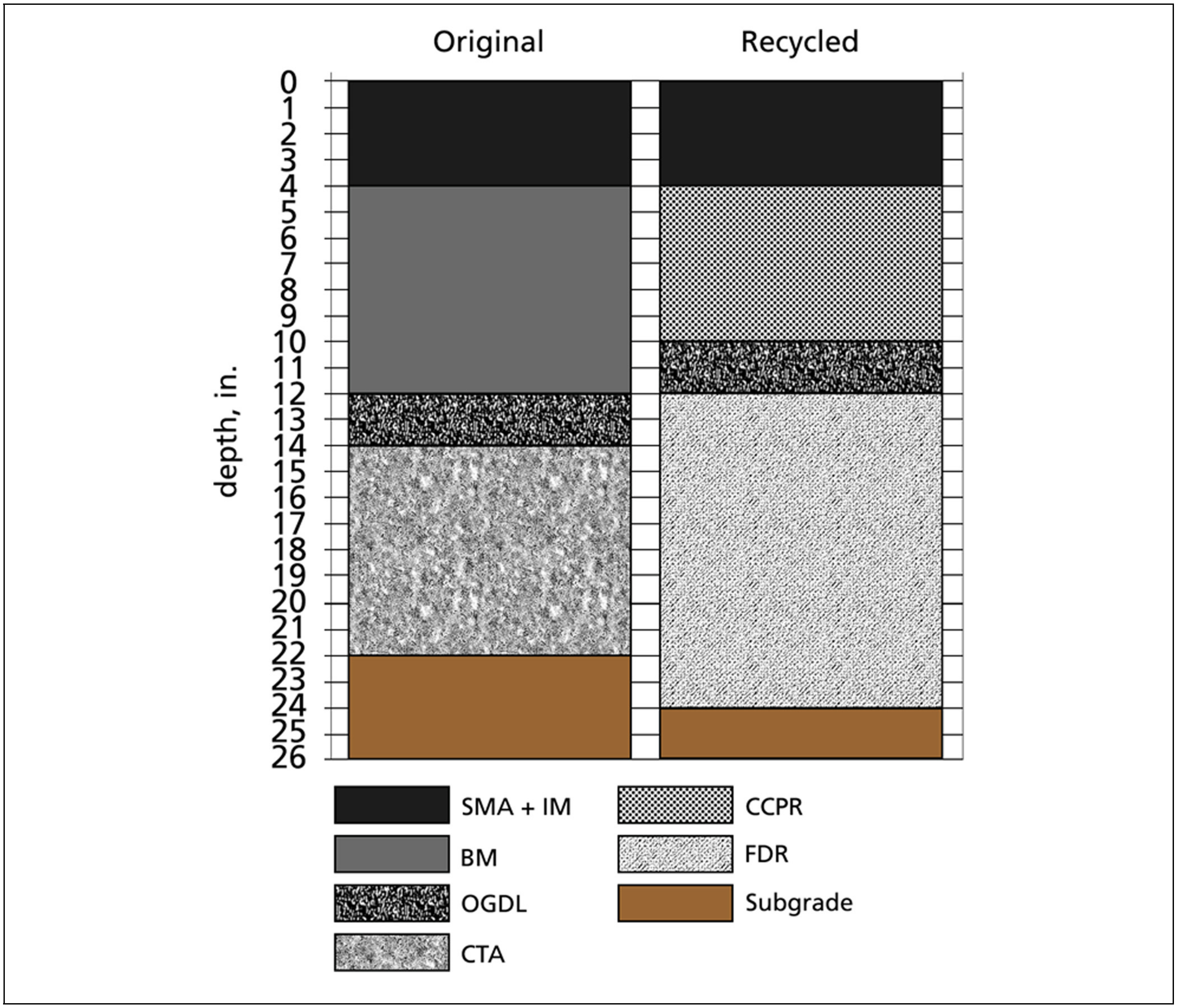


Figure 10. Original and recycled designs for I-64 project.

Table 2. Local Material Prices Used in Cost Analysis

Material	Unit	Unit Cost ($)
Asphalt surface (SMA)	Tons	106
Asphalt intermediate (SMA)	Tons	93
Asphalt base	Tons	82
Cement treated aggregate	Tons	44
CCPR	Tons	45
FDR	Square yard	12

Note: SMA = stone-matrix asphalt; CCPR = cold central plant recycling; FDR = full-depth reclamation.

study show that they have outperformed their designed service lives based on the current traffic level of 19 million ESALs and probably much longer based on performance and structural characterizations.

- CCPR layers may be treated like conventional asphalt concrete materials in pavement design and modeling as supported by the measured and simulated strain data presented in the perpetual pavement analysis in addition to the backcalculated layer properties using layered elastic analysis. This is consistent with other studies of similar materials

that found that CCPR materials could be modeled in the same way as asphalt concrete materials (*20*, *21*).
- Additional AC thickness was more effective at reducing AC strain than the cement stabilized layer. Although the cement-stabilized base produced a greater overall strain reduction (69% reduction) than additional AC thickness (33% reduction), when the thickness of the respective layers is considered the additional AC reduced the strain by 14.9% per inch of AC, while the SB was 8.8% per inch of base.
- Based on perpetual strain analysis, section S12 – with the cement-stabilized base layer – is expected to be perpetual as its strain distribution is less than the control distribution. This assumes that the previously-developed criteria may be applied to CCPR pavements with a cement-stabilized layer. Section S12 should be left in place for the next cycle of trafficking to validate this assumption and expectation.
- Based on perpetual strain analysis, sections N3 and N4 exceed the control strain distribution, and are expected to experience bottom-up cracking at some point. Again, it is currently unknown whether the criteria apply to CCPR pavements, and this warrants further trafficking and monitoring in the next test cycle.
- By using the information learned from the NCAT Test Track, a recycled design for a new or reconstructed pavement can be constructed with significant cost savings compared to the original design.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Timm, Diefenderfer, and Bowers; data collection: Timm, Diefenderfer, and Bowers; analysis and interpretation of results: Timm, Diefenderfer, and Bowers; draft manuscript preparation: Timm, Diefenderfer, and Bowers. All authors reviewed the results and approved the final version of the manuscript.

References

1. Bemanian, S., P. Polish, and G. Maurer. Cold In-Place Recycling and Full-Depth Reclamation Projects by Nevada Department of Transportation: State of the Practice. *Transportation Research Record: Journal of the Transportation Research Board*, 2006. 1949: 54–71.
2. Thenoux, G., A. Gonzalez, and R. Dowling. Energy Consumption Comparison for Different Asphalt Pavements Rehabilitation Techniques Used in Chile. *Resources, Conservation and Recycling*, Vol. 49, 2007, pp. 325–339.
3. Stroup-Gardiner, M. *NCHRP Synthesis 421: Recycling and Reclamation of Asphalt Pavements Using In-Place Methods*. Transportation Research Board of the National Academies, Washington, D.C., 2011.
4. *NCHRP Project 09-51: Material Properties of Cold In-Place Recycled and Full-Depth Reclamation Asphalt Concrete for Pavement Design*. Transportation Research Board of the National Academies, Washington, D.C., 2017.
5. *NCHRP Project 09-62: Rapid Tests and Specifications for Construction of Asphalt-Treated Cold Recycled Pavements*. Transportation Research Board of the National Academies, Washington, D.C., 2017.
6. Asphalt Recycling and Reclaiming Association. *Basic Asphalt Recycling Manual*. Publication No. FHWA-HIF-14-001. Asphalt Recycling and Reclaiming Association, Annapolis, MD, 2014.
7. Diefenderfer, B. K., A. K. Apeagyei, A. A. Gallo, L. E. Dougald, and C. B. Weaver. In-Place Pavement Recycling on I-81 in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, 2012. 2306: 21–27.
8. Timm, D. H., M. Diaz-Sanchez, and B. Diefenderfer. Field Performance and Structural Characterization of Full-Scale CCPR Pavements. Presented at the 94th Annual Meeting of the Transportation Research Board, Washington, D.C., 2015.
9. Virginia Department of Transportation. *Interstate 64 Widening – Segment II*. http://www.i64widening.org/learn_more/segment_2.asp. Accessed July 24, 2017.
10. Taylor, A. J., and D. H. Timm. *Mechanistic Characterization of Resilient Moduli for Unbound Pavement Layer Materials*. Report No. 09-06. National Center for Asphalt Technology, Auburn University, Auburn, AR, 2009.
11. Diefenderfer, B. K., B. F. Bowers, and A. K. Apeagyei. Initial Performance of Virginia's Interstate 81 In-Place Pavement Recycling Project. *Transportation Research Record: Journal of the Transportation Research Board*, 2015. 2524: 152–159.
12. American Association of State Highway and Transportation Officials. *Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, D.C., 1993.

13. Virginia Department of Transportation. *Notice of Revision to Materials Division's Manual of Instructions Chapter VI*. Memorandum 386-15. Virginia Department of Transportation, Richmond, VA, 2015.
14. Virginia Department of Transportation, Materials Division. *Guidelines for 1993 AASHTO Pavement Design*. Virginia Department of Transportation, Richmond, VA, 2000.
15. Willis, J. R., and D. H. Timm. Development of Stochastic Perpetual Pavement Design Criteria. *Journal of the Association of Asphalt Paving Technologists*, Vol. 79, 2010, pp. 561–596.
16. Willis, J. R., and D. H. Timm. *Field-Based Strain Thresholds for Flexible Perpetual Pavement Design*. Report No. 09-09. National Center for Asphalt Technology, Auburn University, Auburn, AR, 2009.
17. Castro, A. J., N. Tran, M. M. Robbins, D. H. Timm, and C. Wagner. Further Evaluation of Limiting Strain Criteria for Perpetual Asphalt Pavement Design. *Transportation Research Record: Journal of the Transportation Research Board*, 2017. 2640: 41–48.
18. Robbins, M. M., N. Tran, D. H. Timm, and J. R. Willis. Adaptation and Validation of Stochastic Limiting Strain Distribution and Fatigue Ratio Concepts for Perpetual Pavement Design. *Journal of the Association of Asphalt Paving Technologists*, Vol. 84, 2015, pp. 181–217.
19. Tran, N., M. M. Robbins, D. H. Timm, J. R. Willis, and C. Rodezno. *Refined Limiting Strain Criteria and Approximate Ranges of Maximum Thicknesses for Designing Long-Life Asphalt Pavements*. Report No. 15-05. National Center for Asphalt Technology, Auburn University, Auburn, AR, 2015.
20. Diefenderfer, B. K., B. F. Bowers, C. W. Schwartz, A. Farzaneh, and Z. Zhang. Dynamic Modulus of Recycled Pavement Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, 2016. 2575: 19–26.
21. Schwartz, C. W., B. K. Diefenderfer, and B. F. Bowers. *NCHRP Research Report 863: Material Properties of Cold In-Place Recycled and Full-Depth Reclamation Asphalt Concrete*. Transportation Research Board of the National Academies, Washington, D.C., 2017.

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