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Utilization of Cold Central Plant Recycled Asphalt in Long-Life Flexible Pavements

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Abstract

Long-life flexible pavements are well documented and used widely across the U.S. Found in every climate zone and traffic classification, long-life pavements do not experience deep structural distresses such as bottom-up fatigue cracking or substructure rutting. Full-scale test sections, built in 2003 at the National Center for Asphalt Technology (NCAT) Test Track, provided the basis for an optimized design approach that utilizes strain distributions for long-life thickness design. These sections, containing only virgin materials, were subjected to 30 million standard axle loadings with excellent performance in terms of rutting, cracking, and roughness. In 2012, three new sections were built at the Test Track using cold central plant recycled asphalt materials as the base layer. These layers, made from nearly 100% reclaimed asphalt pavement (RAP), supported hot mix asphalt layers that also included RAP with one section featuring in-place stabilization of the existing aggregate base. This paper provides a direct comparison between the sets of sections to compare and contrast their performance histories and structural characterization, and consider their economic and environmental impacts. None of the recycled sections are exhibiting any surface deterioration, despite heavy trafficking, and the section with a stabilized base is exhibiting lower strains than established long-life pavement thresholds. The economic analysis suggested that the recycled sections can deliver similar performance at a lower average structure normalized section cost than the non-recycled sections. Furthermore, the section with the stabilized base and 76% recycled material is likely a long-life pavement and can potentially outperform the sections with no recycled content.

Long-life flexible pavements, also known as perpetual pavements, have gained wider recognition over the past 20 years through the awards program sponsored by the Asphalt Pavement Alliance (APA) and research studies aimed to improve the design, construction, and maintenance of these pavements (*1–9*). Since 2000, APA has identified over 150 sections from across the U.S. that are at least 35 years old, have not experienced deep structural problems (i.e., bottom-up fatigue cracking and deep structural rutting), have surface rehabilitation not more frequent than every 13 years, and have not increased the total asphalt concrete (AC) thickness by more than 4 in. during the pavement's life (*10*). Pavements that meet these criteria have been identified in wide-ranging climatic and traffic conditions. Though many of the existing perpetual pavements met the criteria through inherent conservatism built into older structural design systems (e.g., AASHTO 1993 Design Guide), more modern approaches aim to optimize the structure through careful selection of AC materials and thicknesses to meet, but not overly exceed, the criteria. This is sometimes accomplished through placing fatigue-resistant asphalt mixes at the bottom of the AC layers (*11–14*).

Perpetual pavement concepts have been a research focus area at the National Center for Asphalt Technology (NCAT) Pavement Test Track since the first set of full-scale structural test sections were built in 2003. Though expected to fail in the first test cycle with the application of 10 million equivalent single axle loads (ESALs), several exhibited excellent performance

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through three test cycles totaling 30 million ESALs and were judged to be perpetual since they did not experience any structural decay over time or traffic (*15*, *16*). The sections were part of a larger study that formed the basis for a new perpetual pavement design approach utilizing strain distributions, rather than stochastic endurance limits, to prevent bottom-up cracking. This approach was further validated with perpetual pavement award winners in a later investigation (*17*, *18*).

Most of the older real-world perpetual pavements feature dense-graded AC mixtures that predate the Superpave system. Newly designed and constructed perpetual pavements are beginning to take advantage of more modern mix design approaches like Superpave or may feature balanced mix design concepts, but are still largely conventional dense-graded AC mixtures. Recent emphasis on sustainable materials in pavement applications has identified the need for incorporating higher levels of reclaimed asphalt pavement (RAP) in new construction or reconstruction. This may be done through increasing RAP content in mixes, with most states finding 25%–30% RAP an acceptable level. Alternatively, using materials comprised of nearly 100% RAP as a base material is another, more aggressive, option and the potential for using 100% RAP in a perpetual pavement cross-section could improve their long-term economic and environmental impact.

Cold central plant recycling (CCPR) is one method of achieving nearly 100% RAP mixtures that can be used as bases in flexible pavement cross-sections. As described previously, CCPR uses existing RAP stockpiles or newly milled AC in combination with a recycling agent to create a paving material that can be placed with conventional asphalt paving equipment (*19*). The potential for significant cost and energy savings exist since the RAP particles are not heated during the CCPR production process. Mobile plants can be used, which can also reduce costs by limiting hauling activity. CCPR has been used as a base course for reconstruction, new construction, lane widening, shoulder strengthening, and other projects, but has historically been limited to lower-volume applications (*19*).

Having an abundance of RAP stockpiled in some areas of Virginia, Virginia Department of Transportation (VDOT) realized the potential of using CCPR in higher-volume applications to reduce costs and improve sustainability of higher-volume highway infrastructure, provided CCPR could withstand the heavier traffic demands. To test this potential, VDOT began an experiment in 2011 on a portion of Interstate-81 in western Virginia that carries more than 8,000 trucks per day, featuring, among other recycling technologies, a CCPR section (*20*). While I-81 was technically a high-volume setting, the need to evaluate CCPR under more rapidly applied traffic led VDOT to sponsor three sections at the NCAT Test Track built for the 2012 research cycle (*21*, *22*). The sections featured either 4 or 6 in. of AC over CCPR with one section also having a stabilized foundation achieved through a full-depth-reclamation (FDR) process (*21*, *22*). The sections also included embedded instrumentation to measure mechanistic responses (*21*, *22*).

According to AASHTO 1993 Design Guide predictions, the thinnest section without the stabilized base layer was expected to fail after only 3 million ESALs and the section with the stabilized base was expected to fail after 16 million ESALs (*19*). Despite these predictions, the sections performed well through two test cycles where 20 million ESALs were applied. As documented in this paper, no cracking was observed, rutting was below 0.3 in., and there was little change in the ride quality as of mid-July 2020, after applying nearly 28 million ESALs. Since the performance of the CCPR sections was so similar to the perpetual pavement sections built in 2003 described above, there was a desire to compare and contrast these very different cross-sections to determine if the CCPR sections should be considered perpetual. Determining the economic and environmental differences between the sets of sections was also important, since achieving the same performance through increased use of recycled materials would make perpetual pavements even more viable.

Objectives and Scope of Work

The main objective of this research was to directly compare the performance, mechanistic responses, and structural characteristics of the CCPR sections placed at the NCAT Test Track in 2012 with those of the confirmed perpetual pavements placed at the NCAT Test Track in 2003 in an effort to ascertain their perpetual status. A secondary objective was to quantify the potential economic and environmental savings achieved through incorporation of CCPR as a base layer. Extensive data sets collected over multiple research cycles were used to accomplish these objectives. Section performance was measured on a weekly basis for ride quality, rutting, and cracking. Embedded instrumentation in each section provided direct measurement of mechanistic responses in terms of stress and strain in addition to falling weight deflectometer (FWD) testing to measure in situ pavement responses. The economic analysis was conducted by comparing the expected materials costs of the 2012 CCPR sections and the 2003 dense-graded sections using VDOT data from recently awarded paving projects. The environmental comparison was completed by investigating the potential reduction in greenhouse gas emissions from the two design concepts.

Table 1. As-Built Layer Properties for 2012 Cold Central Plant Recycling (CCPR) Sections (*21*)

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 in. crushed granite aggregate base and 2 in. subgrade stabilized in-place with 4% Type II cement
Layer description	Subgrade—AASHTO A-4 soil		

Note: AC = asphalt concrete; NMAS = nominal maximum aggregate size; RAP = reclaimed asphalt pavement; SB = stabilized foundation base; SMA = stone matrix asphalt.

Test Facility and Sections

The NCAT Test Track is a 1.7 mi closed-loop full-scale asphalt pavement research facility that features 46 test sections. Located in east-central Alabama, the test site receives approximately 53 in. of rain per year with mid-depth pavement temperatures ranging from 40°F to 120°F (*19*). The Test Track operates on 3-year research cycles with the first year consisting of forensic analysis of the previous cycle and building the next set of test sections, followed by two years of trafficking. Traffic is applied with tractor triple-trailer trucks operating five days per week to apply 10 million ESALs in each trafficking cycle. The sections for this investigation are depicted in Figure 1 where the first three sections on the left were part of the 2012 research cycle for VDOT and featured CCPR while the last two sections on the right were part of the 2003 study. The total thickness of asphalt bound materials (including CCPR) was comparable between the sections, ranging from 8–10 in. over the foundation layers. The naming convention for the CCPR sections in Figure 1 indicate how much AC was placed over the CCPR (4 in. or 6 in.) and an additional label for the stabilized foundation base (SB) section (S12). The depth of CCPR in each section was 4–5 in. The older perpetual pavement sections are labeled according to their section number with the year they were built, 2003. They were designed to have 9 in. of AC with the as-built depths very close to that as shown in Figure 1. N3-2003 used a locally available PG 67-22 binder grade, while N4-2003 had an SBS modifier bringing the grade up to PG 76-22.

Each section was built on the same subgrade native to the Test Track which classifies as an A-4 soil. Except for section S12, the sections were also built on the same crushed granite aggregate base often used at the Test Track. More information on these materials has been extensively previously documented (*23*). Section S12, as part of the CCPR experiment, used the same crushed granite but was stabilized in place with 4% Type II cement using an FDR process. The in-place stabilization also included the top 2 in. of the Test Track subgrade. Tables 1 and 2 contain pertinent properties of the materials used in each layer for the 2012 CCPR sections and the 2003 dense-graded sections, respectively. Though the AC mixtures were designed under different specifications with 9 years between them, they arrived at similar binder contents and compacted densities. It should also be noted that the 2012 CCPR sections (Table 1) included RAP in the surfacing mixtures, while the 2003 dense-graded section surface mixtures (Table 2) did not. Since these sections were not meant to be part of the same experimental

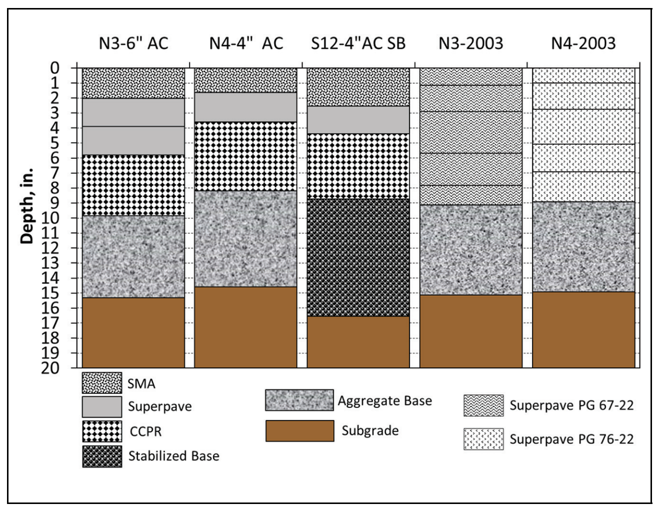

Figure 1. As-built pavement cross-sections.
Note: AC = asphalt concrete; CCPR = cold central plant recycling; SB = stabilized foundation base; SMA = stone matrix asphalt.

Table 2. As-Built Layer Properties for 2003 Perpetual Sections

Section	N3-2003 (PG 67-22)	N4-2003 (PG 76-22)
Layer description	Lift 1—9.5 mm NMAS Superpave	
Binder content, %	6.1	6.1
Air voids, %	5.7	5.5
Layer description	Lift 2—19 mm NMAS Superpave	
Binder content, %	4.3	4.3
Air voids, %	4.7	4.7
Layer description	Lift 3—19 mm NMAS Superpave	
Binder content, %	4.5	4.4
Air voids, %	3.1	3.3
Layer description	Lift 4—19 mm NMAS Superpave	
Binder content, %	4.3	4.7
Air voids, %	5.1	3.0
Layer description	Layer 5—19 mm NMAS Superpave	
Binder content, %	4.6	4.4
Air voids, %	4.0	4.5

Note: NMAS = nominal maximum aggregate size.

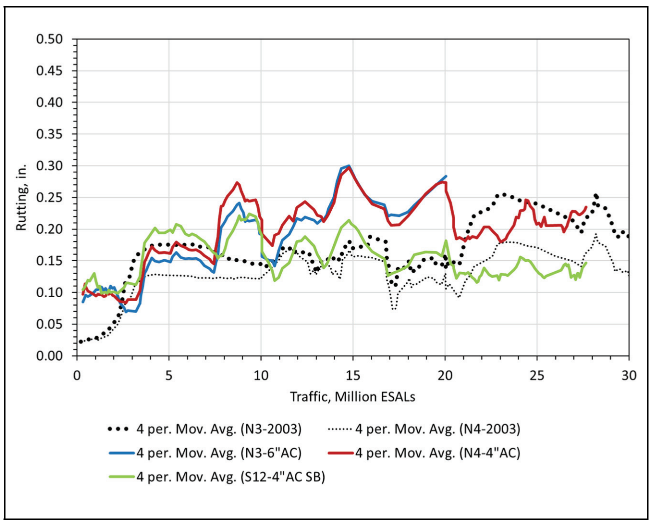

Figure 2. Rut depths versus traffic.
Note: ESAL = equivalent single axle load.

design, these differences are not unexpected but should be considered when comparing the two sets of sections.

Performance

The 2003 dense-graded sections were built during the summer of 2003 with trafficking beginning on October 21, 2003. The 2012 CCPR sections were built in the summer of 2012 with trafficking beginning on October 23, 2012. The 2003 dense-graded sections were subjected to three cycles of trafficking, totaling 30 million ESALs. Section N4 and S12 of the 2012 CCPR sections were also subjected to three test cycles, exceeding 27 million ESALs at the time of this paper while N3 was reassigned to another experiment after the first two cycles and was subjected to only 20 million ESALs. Each section was monitored on a weekly basis for cracking, rutting, and ride quality as described below.

Cracking

All sections were inspected on a weekly basis during trafficking for cracking. No cracks appeared in any of the 2012 CCPR sections. Some cracks were observed in the 2003 dense-graded sections near the completion of 30 million ESALs but were confirmed through forensic trenching to be top down (N4-2003) or related to the presence of instrumentation (N3-2003). None of the 2003 dense-graded sections experienced bottom-up fatigue cracking which would qualify them for perpetual status.

Rutting

Figure 2 shows the rutting performance of each section versus applied ESALs. The data was collected on a weekly basis, but 4-point (monthly) moving averages are plotted for better graphical representation and understanding of long-term trends. The 2003 dense-graded sections experienced an initial rutting increase during the first 4 million ESALs after which rutting generally stabilized and totaled less than 0.25 in. after 30 million ESALs. Given that rutting failure is often defined at 0.5 in., this was considered excellent performance. Similarly, the CCPR sections exhibited excellent performance with rutting essentially stable after the first 10 million ESALs and not exceeding 0.25 in. after more than 27 million ESALs (N4 and S12). N3, only subjected to 20 million ESALs, also ended its service at less than 0.25 in.

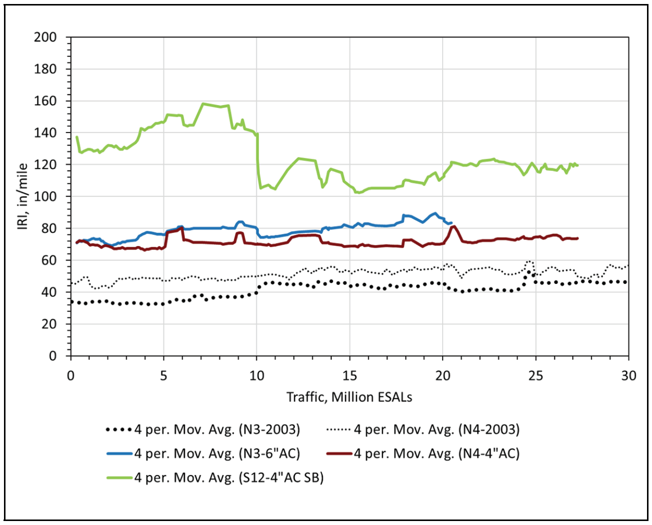

Figure 3. International roughness index (IRI) versus traffic.
Note: ESAL = equivalent single axle load.

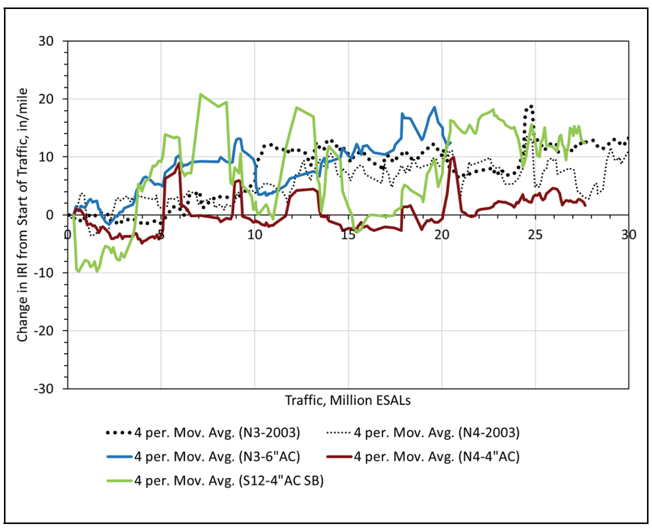

Figure 4. Change in international roughness index (IRI) versus traffic.
Note: ESAL = equivalent single axle load.

Ride Quality

Given that no bottom-up fatigue cracks formed in any of the 2003 dense-graded sections, and the excellent rutting performance for all sections, one would expect the ride quality data, obtained on a weekly basis, to also exhibit positive characteristics. Figure 3 contains 4-point (monthly) moving averages and shows that the 2003 dense-graded sections were built smooth and maintained low international roughness index (IRI) values through 30 million ESALs. The 2012 CCPR sections were built with higher initial IRI values but did not trend dramatically up or down with ESAL applications, with the exception of S12. As documented previously, this section had a localized area near the beginning of the section that had very high roughness (*22*). Despite the rough area, the section was left in place for the first 10 million ESALs, after which grinding was conducted to improve the roughness which explains the drop in IRI at 10 million ESALs. The following 20 million ESALs did not change the IRI appreciably.

To provide a more direct comparison between the sections' ride quality, the data in Figure 3 were normalized by subtracting the initial IRI data from the remaining measurements as depicted in Figure 4. It should be noted that the S12 data, after the first 10 million ESALs, was renormalized to account for the grinding that occurred between the first and second test cycles. Though the data shows fluctuation for each test section, it is notable that the net change at the end of traffic was less than a 15 in./mi increase, which was again considered excellent performance consistent with expectations of a perpetual pavement.

Structural Characterization

Though the surface performance characteristics described above support the sections being classified as perpetual, it is instructive to examine the measured pavement responses and in situ material properties in the context of perpetual design. The following subsections present the measured strain responses and in situ moduli determined through FWD testing and backcalculation.

Measured Strain Responses

Figure 5 depicts measured tensile strain responses in the longitudinal direction (i.e., with traffic) made at the bottom of the CCPR layer in each of the 2012 CCPR sections. The measurements were induced by 20,000 lb single axles traveling at 45 mph. Because of lack of extensive strain data, and differences in how strain were measured in the 2003 dense-graded sections, their strain data are not included in Figure 5.

Figure 5 clearly shows the impact of seasonal temperatures on the measured strain responses, with N3 and N4 behaving very similarly, while S12 appears to be much less affected by changing temperatures, likely because of the stabilized base layer. The strong influence of temperature was expected because of the viscoelastic nature of the asphalt-bound materials and has been often observed in other Test Track studies (*15*, *16*). Sections N3 and S12 do not appear to have appreciably changed over their test cycles, while N4 may have higher strain levels during the third cycle, which could be a precursor to pavement damage not yet observed at the surface.

To further examine the strain data, the values in Figure 5 were plotted in Figure 6 against the mid-depth

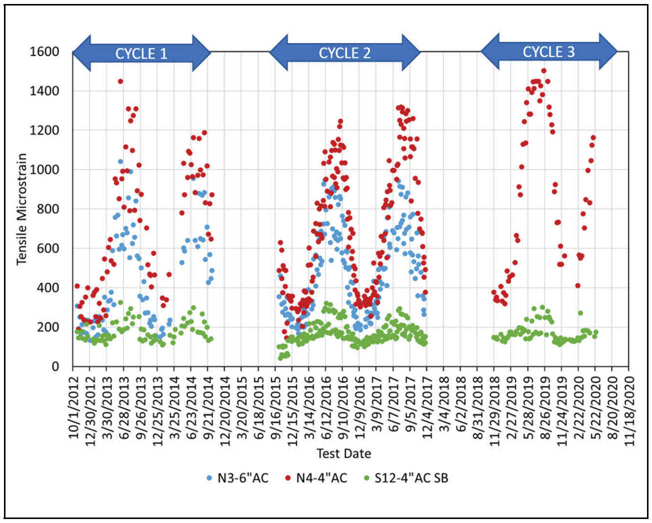

Figure 5. 2012 cold central plant recycling (CCPR) sections tensile strain versus test date.
Note: AC = asphalt concrete; SB = stabilized foundation base.

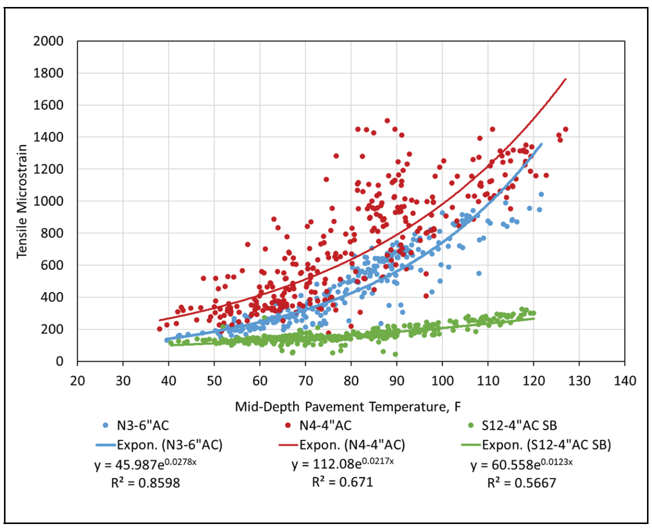

Figure 6. 2012 cold central plant recycling (CCPR) sections tensile strain versus temperature.
Note: AC = asphalt concrete; SB = stabilized foundation base.

pavement temperatures measured at the time of testing. Section S12 shows very little scatter in the data and is comparatively insensitive to temperature changes as indicated by the relatively flat exponential trendline. The other CCPR sections show much more scatter, with N4 having the most with significant deviations from the exponential trendline which was consistent with the seemingly higher strain levels in the third cycle for this section. The gap between the N3 and N4 trendlines was primarily a result of the 2 in. difference in total AC over the CCPR. However, that thickness difference does not

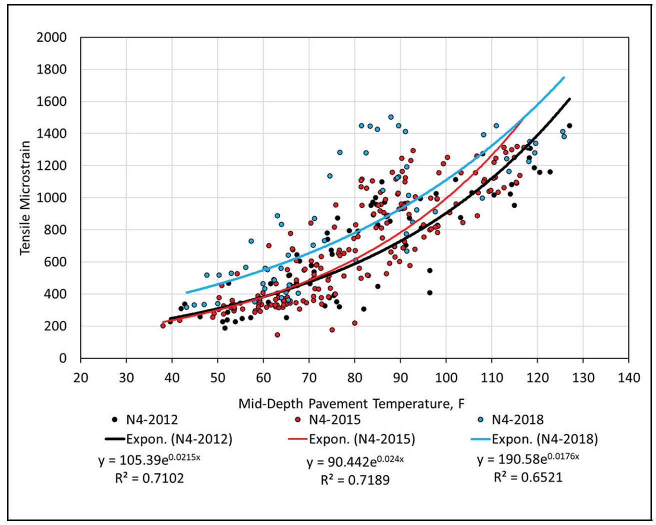

Figure 7. N4-4" asphalt concrete (AC) cold central plant recycling (CCPR) tensile strain versus temperature by test cycle.

explain the increased scatter in data, which could result from pavement damage not yet observed at the surface. To better understand the effect of time, the N4 data were divided according to test cycle as shown in Figure 7.

The data points and trendlines in Figure 7 show that tensile strain has generally increased with test cycle where the first and third cycle (2012, 2018) trendlines are nearly parallel but with an approximate 200 microstrain offset, while the second test cycle (2015) appears to split the difference between them. This could be an indication of pavement damage, though not yet observed at the surface, or merely artifacts of strain gauges wearing out over time. Analysis of the backcalculated FWD data will help determine which is more likely, as described in the next section.

A final strain comparison between the 2003 dense-graded and 2012 CCPR sections is depicted in Figure 8 where cumulative strain distributions are shown for the 2012 CCPR sections along with the so-called Willis Limit for perpetual pavement design (*15*, *16*). The Willis Limit was based on the 2003 dense-graded sections and expressed an upper bound for conventional flexible pavements to prevent bottom-up fatigue cracking. The limit was validated with perpetual pavement award winners from around the country and serves as a trial benchmark for the CCPR sections (*17*, *18*). Note that S12, with the stabilized foundation, is less than the limit (i.e., to the left) above the 40th percentile. Application of the criteria to this section indicates it should not experience bottom-up cracking. The other two CCPR sections, however, are well to the right of the limit and experience has shown from the Test Track that these *should* have exhibited bottom-up cracking with less than 20 million ESALs (*15*, *16*). That they have not indicates either prolonged fatigue life (i.e., they may crack in the future with more

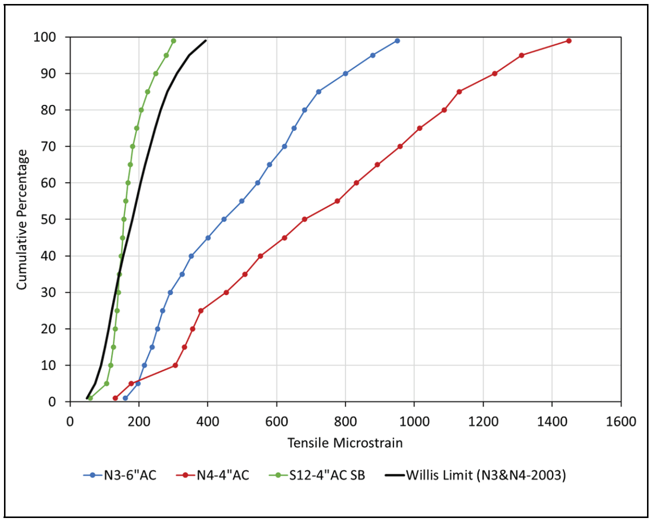

Figure 8. Cumulative strain distributions.

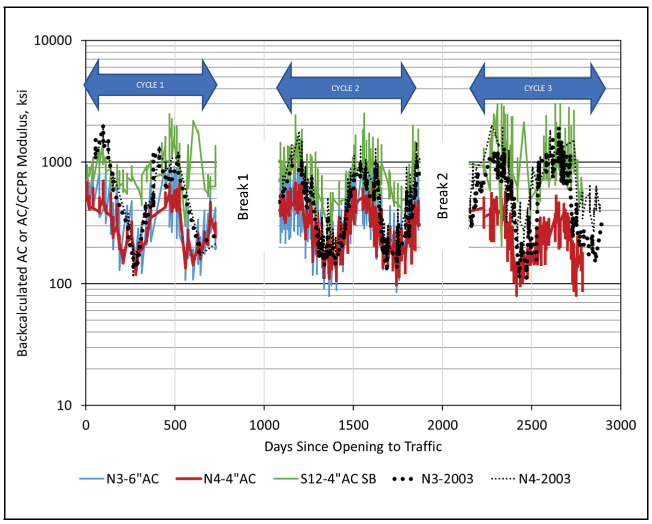

Figure 9. Backcalculated asphalt concrete (AC) or AC/cold central plant recycling (CCPR) modulus at all temperatures.
Note: SB = stabilized foundation base.

traffic applied) or that the use of CCPR requires a new limit to be determined, as the cracking behavior may be fundamentally different from conventional dense-graded materials. In either case, this study shows that the CCPR sections can perform as well as the older perpetual sections in excess of 27 million ESALs with significantly higher strain levels in the case of section N4-4" AC.

FWD Testing and Backcalculated Moduli

FWD testing was conducted frequently on each test section. The 2012 CCPR sections were tested several times per month during each cycle using a Dynatest 8000 Falling Weight Deflectometer with the standard 9-sensor arrangement. The same FWD device and testing frequency was used on the 2003 dense-graded sections in their second and third test cycles, but the testing during the first cycle was done on only a monthly basis using a 7-sensor arrangement. Testing was conducted at multiple longitudinal stations in each section representing 50 ft subsections, as well as in the middle of the instrumentation array. At each station, both wheelpaths and between wheelpaths were tested. Though multiple drop heights were used, only data pertaining to the 9,000 lb loading is included in this analysis. Mid-depth temperatures using embedded temperature probes were recorded at the time of testing. Backcalculation of the deflection basins was accomplished with EVERCALC 5.0, and a root mean square error limited to less than 3% was used to ensure reliable results. All analyzed sections were treated as three-layer structures for backcalculation purposes. For the 2003 sections, this meant combining all five lifts into the first layer, followed by the aggregate base, and then subgrade. For the CCPR sections, the AC and CCPR were combined into one layer. This decision was based on laboratory |E*| testing where a master curve was successfully developed for CCPR materials indicating it acts more like an AC material than an aggregate base (*21*, *24*). As a point of reference, the average unconfined dynamic modulus of the CCPR at 10 Hz and 70°F was 601,159 psi which is very comparable with dense-graded AC (*24*). The base and subgrade layers were the subsequent layers in the CCPR backcalculation models.

Figure 9 plots the backcalculated AC or AC/CCPR modulus in the outside wheelpath near the middle of the section (random location 2). The *x*-axis represents days since opening to traffic. Since the two experiments began trafficking within days of each other in late October in their respective construction years, the long-term seasonal trends resulting from temperature changes are remarkably aligned and obvious. The short-term cycling represents daily temperature fluctuations. The breaks between test cycles represent the forensic/reconstruction phases at the Test Track where no data was gathered.

It appears that each section in Figure 9, with the exception of CCPR N4-4" AC, experienced steady or even slightly increasing modulus over time. During the last test cycle, N4-4" AC appears to have declining modulus which could correspond to the higher strain levels depicted in Figures 5 and 7 and may indicate damage is occurring, though not yet observed at the surface.

To better understand the trend in the CCPR section N4-4" AC, the data from Figure 9 were plotted against their corresponding temperatures and subdivided according to test cycle in Figure 10. The first and second cycles were very similar, with a slight shift upward (stiffening) in the modulus versus temperature trend which could be expected as the material ages before

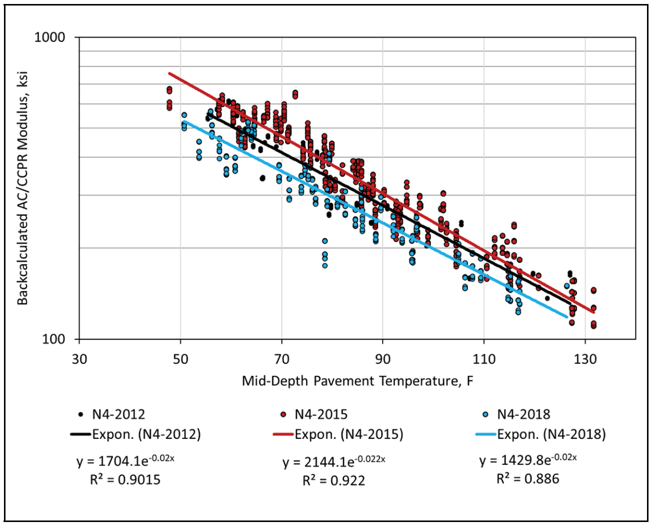

Figure 10. Backcalculated asphalt concrete (AC)/ cold central plant recycling (CCPR) modulus in N4 subdivided by test cycle.

distress develops. The third cycle (2018) exhibited a distinct shift downward (softening) which, again, supports the notion that the section could be experiencing some damage not yet observed at the surface. Though damage may be occurring, as discussed with the strain data investigation, the section has survived far longer than expected with excellent performance. The following section discusses the sections in terms of their economics and sustainability.

Economic and Environmental Impact

An economic analysis was conducted to compare the cost of the 2012 CCPR sections and the 2003 dense-graded sections as shown in Figure 1. The unit costs for each material are averages from recently awarded VDOT pavement rehabilitation projects and are shown in Table 3. Table 3 also shows the assumed density for each material required to convert from a weight-based unit cost ($/ton) to an area-based pavement section cost ($/SY).

Table 4 shows the results of the economic analysis. The upper part of Table 4 shows the as-constructed layer thickness for each of the test sections. Using this information and the unit costs and assumed density values from Table 3, the pavement section costs were calculated. The pavement section costs were found to range from approximately $37/SY to more than $56/SY. When comparing the 2012 CCPR sections to the 2003 dense-graded sections, the average cost of the CCPR and dense-graded sections was approximately $43/SY and $56/SY, respectively.

While the results of the structural monitoring show equivalent performance up through approximately 30 million ESALs, it is expected that the service life of

Table 3. Unit Costs and Densities for Economic Analysis

Material	Unit	Unit cost, $	Assumed density, lb/ft^3
Asphalt surface (SMA)	Tons	106	146
Dense-graded asphalt	Tons	95	146
CCPR	Tons	45	136
FDR	Square yard	8	
Aggregate base	Tons	20	152

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

Table 4. Economic Analysis Results

	CCPR N3	CCPR N4	CCPR S12	2003 N3	2003 N4
Layer thickness, inch					
Asphalt surface (SMA)	2.0	1.6	2.6		
Dense-graded asphalt	3.8	2.0	1.8	9.1	8.9
CCPR	4.0	4.6	4.3		
Agg base	5.5	5.2		6.0	6.0
FDR			7.8		
Pavement section cost, $/SY	$48.90	$37.04	$44.20	$56.52	$55.37
Structural number (SN)	4.62	3.80	5.40	4.74	4.64
Structure normalized pavement section cost, $/SY/SN	$10.57	$9.74	$8.18	$11.93	$11.93

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

certain sections (particularly S12) could be much longer. One way to account for this potential difference is to normalize the cost data by structural capacity. This was done by calculating the structural number (SN) for each pavement section using the design values specific to VDOT (*25*). When the pavement section costs were normalized with respect to SN, the average CCPR and dense-graded sections were approximately \$10/SY/SN and \$12/SY/SN, respectively. At the extreme end, the structure normalized cost for CCPR Section S12 was 31% less than the average cost of the 2003 dense-graded sections.

In addition to cost, the environmental implications of the pavement structure are important to consider. The percent recycled content for each of the recycled sections was calculated as a weighted average per inch of material. This analysis does account for the recycling or stabilizing agent and active filler in the CCPR and FDR mixes. Section N3-6" AC contained 54% recycled material when only considering the bound layers, and 34% recycled material when accounting for the aggregate base (the aggregate base was made using 100% virgin material). Section N4-4" AC contained 62% recycled material when only considering the bound layers, and 34% recycled material when accounting for the aggregate base. Section S12-4" AC SB contained 76% recycled material. The 2003 dense-graded sections contained no recycled material.

While a pavement life cycle assessment (LCA) is not within the scope of this paper, it is notable that the Federal Highway Administration released a case study of the Virginia Interestate-81 reconstruction project which used cold in-place recycling (CIR), CCPR, and FDR in similar combinations and the same RAP source as the 2012 CCPR sections. The authors calculated that materials and initial construction energy demand was reduced approximately 50%–70% and global warming potential (GWP) by 40%–70% compared with a "conventional" design (14 in. of asphalt above an 18 in. aggregate base) (*26*). While this provides a general estimate for the potential environmental benefits from an energy consumption and GWP perspective, an LCA should be conducted to capture the long-term benefits. The analysis should also capture the inherent sustainable nature of a long-life pavement, which is designed to be in place over 35 years without the need for any sort of deep rehabilitation or reconstruction.

Conclusions and Recommendations

This investigation featured five pavement sections built at the NCAT Test Track that were not originally part of a common experimental design but were instructive in exploring perpetual pavement concepts related to flexible pavements having no recycled materials versus those that contain much higher levels of recycled pavement. Based on the findings presented here, the following conclusions and recommendations are made:

1. All five sections exhibited excellent performance over their respective test cycles after applying 20 to 30 million ESALs. Final rut depths did not exceed 0.25 in., no bottom-up cracking was observed in any section, and ride quality did not change by more than 15 in./mi.
2. The strain data in two of the 2012 CCPR sections (N3-6" AC and S12-4" AC SB) were steady over their test cycles indicating good structural health with no signs of pavement distress. Conversely, section N4-4" AC had increased strain during the third test cycle which may indicate distress forming, but this was not yet evident at the surface.
3. Comparing cumulative strain distributions among the sections showed that the non-stabilized base CCPR sections far exceeded the limit derived from the 2003 sections which should correspond to eventual bottom-up cracking. This may occur in N4-4" AC with continued trafficking but was not yet evident. Since N3-6" AC was taken out of service after 20 million ESALs, it is impossible to conclude with 100% certainty whether it would experience cracking, but the data suggested good structural health. Since other NCAT Test Track sections experienced bottom-up cracking within 20 million ESALs with strain distributions less extreme than N3-6" AC and N4-4" AC, it is possible a new limiting strain distribution will be needed for perpetual design of pavements using CCPR.
4. The cumulative strain distribution for S12-4" AC SB fell below the limit for perpetual design and is expected to be perpetual given the low strain levels largely derived from the relatively stiff stabilized base layer.
5. Backcalculated AC and AC/CCPR moduli showed relative consistency over time for each test section, with the exception of the CCPR section, N4-4" AC, which supported the observations and conclusions made from the measured strain data. The apparent decline in AC/CCPR modulus for N4-4" AC during the last test cycle was consistent with the increase in strain and may be a precursor to observable pavement damage.
6. The economic analysis showed that the 2012 CCPR pavement sections had a lower average structure normalized section cost than the 2003 dense-graded sections. The CCPR section with the lowest cost, 2012 Section S12, had a structure

normalized cost that was 31% less than the average cost of the 2003 dense-graded sections.

7. Section S12-4" AC SB contains 76% recycled material and is an example of a perpetual pavement having a very high recycled content.
8. It is recommended that a pavement life cycle assessment be conducted on all sections presented here and account for the fact that S12-4" AC SB is a perpetual pavement.

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Author Contributions

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

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