LESSONS LEARNED FROM THE VIRGINIA REFLECTIVE CRACKING STUDY UNDER ACCELERATED PAVEMENT TESTING1

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ABSTRACT: Road administrators encounter situations where they must make decisions regarding the maintenance and rehabilitation of a road network without knowing the outcome of those decisions until years later. The Heavy Vehicle Simulator has been widely used as an accelerated testing tool to study pavement performance in a shorter period and under more controlled conditions than in the field. The Virginia Department of Transportation, in conjunction with the Virginia Tech Transportation Institute and the Virginia Transportation Research Council, has initiated a research project to study the behavior and performance of different pavement materials and structures under accelerated load through a Heavy Vehicle Simulator. Six pavement sections with different structures were built and instrumented with strain gauges, load cells, temperature gauges, and linear vertical displacement transducers. Two lanes were dedicated to study reflection cracking. They included a concrete pavement with joints 9.5 mm (3/8 inch) wide to reflect cracks in the surface. These lanes were covered with two 1.5-inch (38.1-mm) layers of a control SMA mix asphalt and a similar mix modified with a synthetic fiber. This article presents the results of this reflection cracking study. The article describes the characterization of the asphalt mixtures used, the pavement structure, the construction design, the Heavy Vehicle Simulator used and the installed instrumentation. The paper also presents some of the lessons learned, experimental changes, and study results in terms of cracking and rutting performance.

Keywords: accelerated pavement testing, heavy vehicle simulator, reflective cracking, synthetic fiber

LECCIONES APRENDIDAS DEL ESTUDIO EN VIRGINIA DE REFLEXIÓN DE GRIETAS POR MEDIO DE PRUEBAS ACELERADAS AL PAVIMENTO

RESUMEN: Los administradores de carreteras se encuentran con situaciones en las que deben tomar decisiones sobre el mantenimiento y la rehabilitación de la red sin conocer el resultado de esas decisiones hasta años después. El Simulador de Vehículos Pesados (HVS) ha sido ampliamente utilizado como una herramienta de prueba acelerada (APT) para estudiar el desempeño del pavimento en un periodo más corto y bajo condiciones más controladas que en el campo. El Departamento de Transportación de Virginia (VDOT), en conjunto con *Virginia Tech Transportation Institute (VTTI) y el Virginia Transportation Research Council* (VTRC) ha iniciado un proyecto de investigación para estudiar el comportamiento y desempeño de diferentes materiales y estructuras de pavimento bajo carga acelerada a través de un Simulador de Vehículos Pesados. Seis secciones de pavimento con diferentes estructuras fueron construidas e instrumentadas con medidor de deformación, celdas de carga, medidores de temperatura y transductores de desplazamiento vertical lineal. Se dedicaron dos carriles para estudiar el agrietamiento por reflexión. Incluían un pavimento de hormigón con juntas de 9.5 mm (3/8 de pulgada) de ancho para reflejar las grietas en la superficie. Estos carriles se cubrieron con dos capas de 38.1 mm (1.5 pulgadas) de una mezcla asfáltica (SMA) como control y una mezcla similar modificada con una fibra sintética. Este artículo presenta los resultados de este estudio de agrietamiento por reflexión. El artículo describe la caracterización de las mezclas asfálticas utilizadas, la estructura del pavimento, el diseño de la construcción, el Simulador de Vehículos Pesados utilizado y la instrumentación instalada. El documento también presenta algunas de las lecciones aprendidas, los cambios experimentales y los resultados del estudio en términos de rendimiento de agrietamiento y ahuellamiento.

Palabras clave: estudio acelerado del pavimento, fibra sintética, reflexión de grietas, simulador de vehículos pesados

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INTRODUCTION

Background

One of the primary problems faced by road administrators is finding appropriate and affordable preservation and renewal treatments given the limited funding available to maintain those roads. In many cases, treatments are delayed, and roads have to be rehabilitated instead. The Virginia Department of Transportation (VDOT) is looking for innovative approaches for the preservation and renewal of the road network. In many cases, VDOT does not have enough information on the performance of some of the treatments that can be applied. Since testing performance using an experimental in-service section takes too long, decisions often rely only on laboratory testing and/or engineering judgment. To be able to estimate the performance of new solutions in a shorter time, VDOT has explored the use of accelerated pavement testing (APT).

Objective

The objective of this paper is to describe the first reflective cracking study of hot-mix asphalt (HMA) overlays over jointed Portland cement concrete pavements (PCCP) conducted at the Virginia APT facility. The paper describes the characterization of the asphalt mixes, the pavement structure, construction layout, the Heavy Vehicle Simulator (HVS) used, and the instrumentation installed. The paper also presents some of the lessons learned, experimental changes, and the results of the study in terms of cracking and rutting performance.

Reflective Cracking

When an HMA overlay is placed over a jointed rigid pavement or severe cracks, distress known as reflective cracking may occur. Figure 1 shows the different reflective cracking mechanisms that can occur due to the traffic load and environmental causes. One of the causes of reflective cracking is related to horizontal movements due to the changes in temperature that are concentrated at joints and cracks in the existing PCCP. Another possible cause is the slab curling when the temperature decreases significantly, which will cause the HMA overlay to become stiffer. Lastly, reflective cracking can occur due to vertical deflection at the joints, or the existing cracks caused by the traffic loading (Lytton et al., 2010).

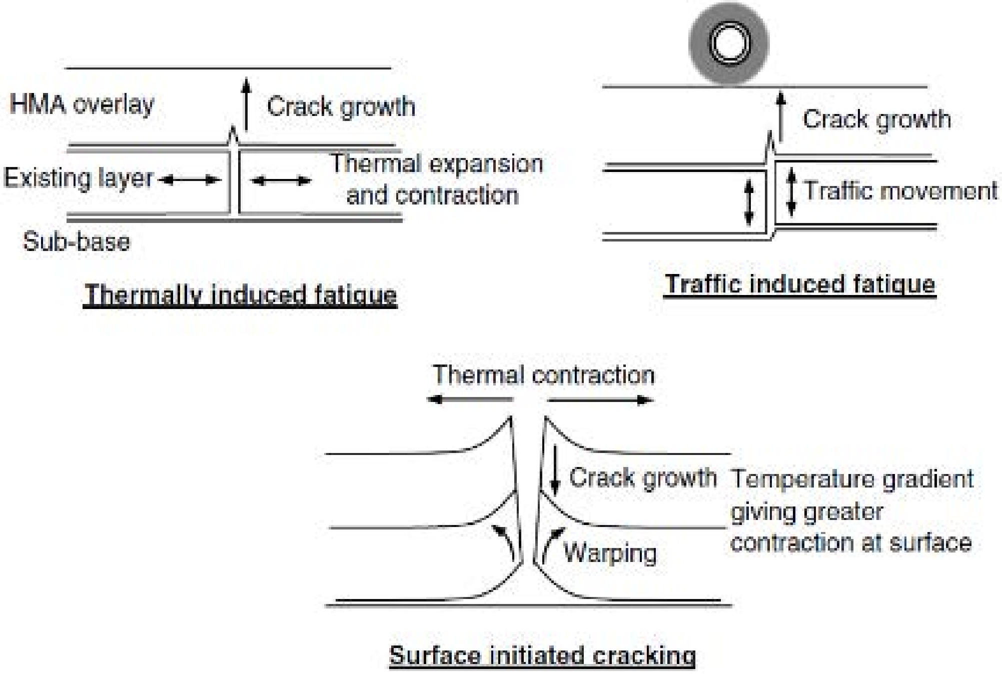


Figure 1: Reflective cracking mechanism (Lytton et al., 2010).

Von Quintus et al. (2009) studied techniques that can mitigate reflective cracking and concluded that methods such as pavement rubblization have the potential to delay the development of reflective cracking in overlays. They also found that it can be delayed through cold milling and placement of a new asphalt overlay or by increasing the thickness. Other strategies used to minimize or prevent reflective cracking are galvanized steel netting, geogrid, geonet, glass grid, paving fabric, geocomposite, stress-absorbing membrane interlayer (SAMI), rubblization, NovaChip, Strata®, saw and seal, different types of overlays or patches, leveling courses, heater scarification, and hot in-place recycling.

The Nevada Department of Transportation (DOT) monitored 33 projects in which they applied cold in-place recycling (CIR) overlays, reinforced fabric, stress-relief course, and mill/overlay. Results showed that CIR projects with roads subjected to an average annual daily traffic (AADT) of less than 6,000 developed reflective cracking as the main distress 1 to 2 years after construction. The reinforced fabric used on six roads with AADT between 1,000 and 10,000 had reflective cracking after being in service for 1 to 3 years. Results from the 1-inch stress-relief course used on five roads with an AADT between 1,900 and 40,000 showed that two projects presented reflective cracking 5 years after placing the stress-relief course. Lastly, mill and overlay used for roads with an AADT between 1,700 and 40,000 had reflective cracking 1 to 5 years after construction (Loria et al., 2008).

The Mississippi DOT evaluated the use of asphalt rubber interlayer systems for delaying the propagation of reflective cracking and found that the system in combination with an asphalt overlay of 38.1 mm (1.5-inches) can delay reflective cracking for 5 years (Amini, 2005).

A study conducted by Alabama DOT showed that asphalt rubber stress-absorbing interlayers delayed reflective cracking. The study used a 50.8 mm (2-inch) asphalt rubber layer placed below a 76.2 mm (3-inch) HMA overlay and monitored the section for 9 years to estimate the percentage of cracking on the surface. Results demonstrated the effect of asphalt rubber on cracking resistance. During the first 3 years there was no cracking on either pavement structure; however, after the third-year cracking started showing on both types of surfaces. After 9 years, 80% of the control section without the asphalt rubber had cracking and the experimental section with the asphalt rubber interlayer had cracking in 25% of the pavement section (Way, 1990).

Texas DOT (Chowdhury et al., 2009) evaluated the use of geosynthetics to delay reflective cracking. The researchers chose three locations in Texas with mild, moderate, and cool climates. The cool temperature section had a 50.8 mm (2-inch) overlay followed by the geosynthetic, 19.1 mm (0.75 inches) of leveling course, 63.5 mm (2.5 inches) of HMA, a 304.8 mm (12-inch) flexible base, and the subgrade. The moderate temperature section included a composite pavement with a jointed concrete base of 152.4 mm (6 inches) below a 44.5 mm to 50.8 mm (1.75- to 2-inch) HMA overlay and geosynthetic. The mild climate location had a 50.8 mm (2-inch) HMA surface with geosynthetic on a 355.6 mm (14-inch) flexible base 2% lime stabilized and a 304.8 mm (12-inch) subgrade 3% lime stabilized. The researchers monitored the sections over 5 to 6 years and found that at the end of the period the mild temperature sections had a maximum crack length of 381 mm (15 inches) versus 1.117 m (44 inches) for the control section without geogrid. The composite pavement located in the moderate temperature area developed a maximum crack length of 15.646 m (616 inches), versus 23.012 mm (906 inches) for the control section. Lastly, the cool temperature sections had a maximum crack length of 16.713 m (658 inches), versus 19.862 m (782 inches) for the section without a petrogrid. A common observation among the three areas of study was that cracks started showing up after 3 to 4 years depending on the thickness of the HMA overlay. Table 1 summarizes the results of the studies reviewed.

Table 1: Summary of Mitigation Techniques

ID	Location	Treatment	Performance (Reflective Cracking Delayed)
1	Nevada	Cold in Place Recycling Overlay	1–2 years
2		Reinforced Fabric	1–3 years
3		Stress-relief Course	5 years
4		Mill and Overlay	1–5 years
5	Mississippi	Asphalt Rubber Interlayer System + 38.1 mm (1.5-inch) Asphalt Overlay	5 years
6	Alabama	50.8 mm (2-inch) Stress-absorbing Interlayers (Rubber) + 38.1 mm (1.5-inch) Asphalt Overlay	3 years
7	Texas	Geosynthetics + HMA Overlay	3–4 years

Accelerated Pavement Testing

APT, in general terms, is defined as the controlled application of loading to a pavement structure using a wheel of known weight and pressure that is applied to the structure for a specific period. The loading simulates the traffic loading that the pavement will receive through its life, under controlled temperature, and sometimes moisture, conditions. The APT operation often involves measuring pavement response and testing conditions. Data such as load applications, subgrade and pavement material properties, temperature, drainage conditions, and/or the actual condition of the pavement structure help assess the pavement's performance under the APT and estimate its performance under real traffic.

PREVIOUS APT REFLECTIVE CRACKING STUDIES

A review of the literature showed that there have only been a few APT studies focus on reflective cracking on PCCP overlays. The main results of these studies are presented following.

National Center for Asphalt Technology

The National Center for Asphalt Technology (NCAT) began in 2015 a research study on its Test Track to validate asphalt mixes cracking tests by comparing performance results from the test track with the laboratory test. The sections included in the study were: (1) N1-control (20% RAP), (2) N2-control, higher density, (3) N5-control, low density, low asphalt content, (4) N8-control, 5% RAS, (5) S5-35% RAP, PG 58-28, (6) control, HiMA binder and (7) S13-gap graded, asphalt rubber. The surface layers of 1.5-inches were constructed over a HiMA layer with 17% RAP. Results showed that after 10 million ESALs cracking reached 21.5% of lane area in N1, 6.2% in section N2, 5.0% in N5, 16.9% in N8, and 0% in S5, S6, and S13.

Florida DOT

APT studies have improved throughout the years to target specific areas of pavement performance. Cracking has been one of the major concerns of the Florida DOT (Greene et al., 2012). The agency conducted a reflective cracking study to evaluate the effectiveness of SAMI. According to their report, SAMI is the primary reflective cracking mitigation technique used in the state. The tested section consisted of a 12.7 mm (0.5-inch) asphalt rubber membrane interlayer (ARMI) layer installed in one lane between a 228.6 mm (9-inch) slab with a joint spacing of 3.65 to 4.87 m (12 to 16 ft) and a 38.1 mm (1.5-inch) HMA overlay designed as a 12.5-mm (0.49-inch) Superpave mix with 5.1% of PG 76-22 asphalt binder. The second lane had a control section with the same pavement structure but without the ARMI layer. Within two weeks, reflection cracking appeared on all the joints of the section without ARMI, and approximately 25% of the joints had cracks in the section with ARMI. Analyzed cores showed that the cracks started from the surface, which according to the author, was due to excessive tensile stress caused by the curling of the concrete. Linear vertical displacement transducer (LVDT) measurements showed that the average maximum daily horizontal and vertical movements were 0.29 and 0.07 mm (0.01 and 0.002-inch), respectively.

French Institute of Science and Technology for Transport (IFSTTAR)

The French national institute IFSTTAR, previously known as Laboratoire Central des Ponts et Chaussées, conducted APT using their two facilities, "Fatigue des chaussées en Béton Armé Continu" (FABAC), applying a load of 14.5 kips with a twin wheel (Perez et al., 2007). Each FABAC had four twin wheels in a chain that applied a load on a circular 30.5 m (100-ft) long and 2.04 m (6.7-ft) wide test track. Testing was conducted on a composite pavement with 78.7 mm (3.1-inch) thick concrete slabs. Eight joints were included in the testing. A surface layer composed of 60.9 mm (2.4 inches) of standard HMA had four joints (test temperature: 12.2 °C [54 °F]). A surface layer made of a 20.3 mm (0.8-inch) sand bituminous mixed layer and a 38.1 mm (1.5-inch) regular HMA layer was placed over two joints (test temperature: 16.1 °C [61 °F]). Finally, 10.2 mm (0.4 inches) of a bituminous layer with a metallic grid and 50.8 mm (2 inches) of regular HMA layer was placed above the last two joints (test temperature: 7.2 °C [45 °F]). Reflective cracking started to appear after 450,000 cycles for every mix except the standard bituminous, which reached 500,000 cycles.

Summary of APT Reflective Cracking Studies

The results of the four studies discussed in the previous sections are summarized in Table 2.

Table 2: Summary of Reflective Cracking Testing with HVS

Location	Lanes	Surface Thickness (in)	PCC Thickness (in)	Load (Kips)	Cracking
NCAT	N1	1.5-control (20% RAP)	-	18	21.5% - 10M ESALs
	N2	1.5-control higher density	-	18	6.2% - 10M ESALs
	N3	1.5-control, low density, low AC	-	18	5.0% - 10M ESALs
	N8	1.5-control + 5% RAS	-	18	16.9% - 10M ESALs
	S5	1.5-35% RAP, PG 58-28	-	18	0% - 10M ESALs
	S6	1.5-control, HiMA binder	-	18	0% - 10M ESALs
	S13	1.5-gap graded, asphalt rubber	-	18	0% - 10M ESALs
Florida	1	1.5-HMA + 0.5-Interlayer	9	9	2 weeks 25% of the joints
	2	1.5-HMA	9	9	2 weeks on every joint
France	1	2.4-standard bituminous	3.1	14.5	450K cycles
	2	0.8-sand bituminous + 1.5-regular bituminous	3.1	14.5	No cracks
	3	0.4-bituminous + Metallic Grid + 2-regular bituminous	3.1	14.5	450K cycles

VIRGINIA APT PROGRAM

The first set of experiments at the Virginia APT program included three studies. The first study evaluated two sections with 127 mm (5-inches) of a cold central plant recycling base with different surface thicknesses. The second study compared asphalt mixes designed with different compacting energies; one of them was designed using a lower number of gyrations (50) than the typical level (65). The third study, which covered the last two sections, compared two different premium asphalt mixes on a jointed PCCP and measured the effectiveness of the overlay in delaying reflective cracking.

Equipment Used, Pavement Section Construction, and Instrumentation

Heavy Vehicle Simulator

The HVS used for the loading application was the model Mark VI designed and built by Dynatest Consulting, Inc. (Figure 2). The Mark VI has a standard test wheel speed of 20 ± 3.2 km/h (12.4 ± 2 mph) for loads that range from 30 kN (6.744 lb) to 100 kN (22,500 lb). It has the capability of testing bidirectionally, achieving 24,000 passes in 24 hours, or unidirectionally with 12,000 passes in 24 hours (Figure 3; Cooke, 2011).

Figure 2: HVS MK VI testing on Lane 4, Cell A.

Figure 3: Dual tire load application.

Construction Layout

The APT program included the construction of an 18.3 m by 91.4 m (60 ft. by 300 ft.) pavement test section located at VTTI’s facility. Figure 4 shows the sections included in the initial APT study and the HVS located on Lane 1, Section A. The pavement testbed was equally divided into six lanes with a width of 3.0 m (10 ft.) each. The third experiment of the first set focused on reflective cracking, was situated on Lanes 5 and 6.

Figure 4: Dimensions of pavement test sections.

Before lane construction, the area was excavated to provide a uniform foundation. The bottom of the excavation was covered with three layers of 152.4 mm (6-inch) Class I backfill material aggregate base 21-B with geogrids placed between each layer as shown in

Figure 5. These reinforced layers simulated a rigid foundation. The rest of the subgrade consisted of a soil with a California Bearing Ratio (CBR) of 7.5.

For the reflective cracking study, Lanes 5 and 6 were constructed with a base layer of 203.2 mm (8-inch) PCCP with an approximately 4,000-psi compressive strength at 28 days with 9.5 mm (3/8-inch) wide joints spaced at 3.0 m (10 ft) to create the cracks on the surface. Each lane was designed with the same 12.5 Nominal Maximum Aggregate Size (NMAS) stone matrix asphalt (SMA) mix, with the difference that one lane had a modified mix with synthetic fibers. There were two control sections built with two 38.1 mm (1.5-inch) layers of an SMA surface mix and two sections with two layers of the same SMA mix modified with 1 lb of the Forta-Fi synthetic fiber for each ton of asphalt mix. For the second phase of the study, one of the layers was milled, leaving a surface layer of 38.1 mm (1.5 inches).

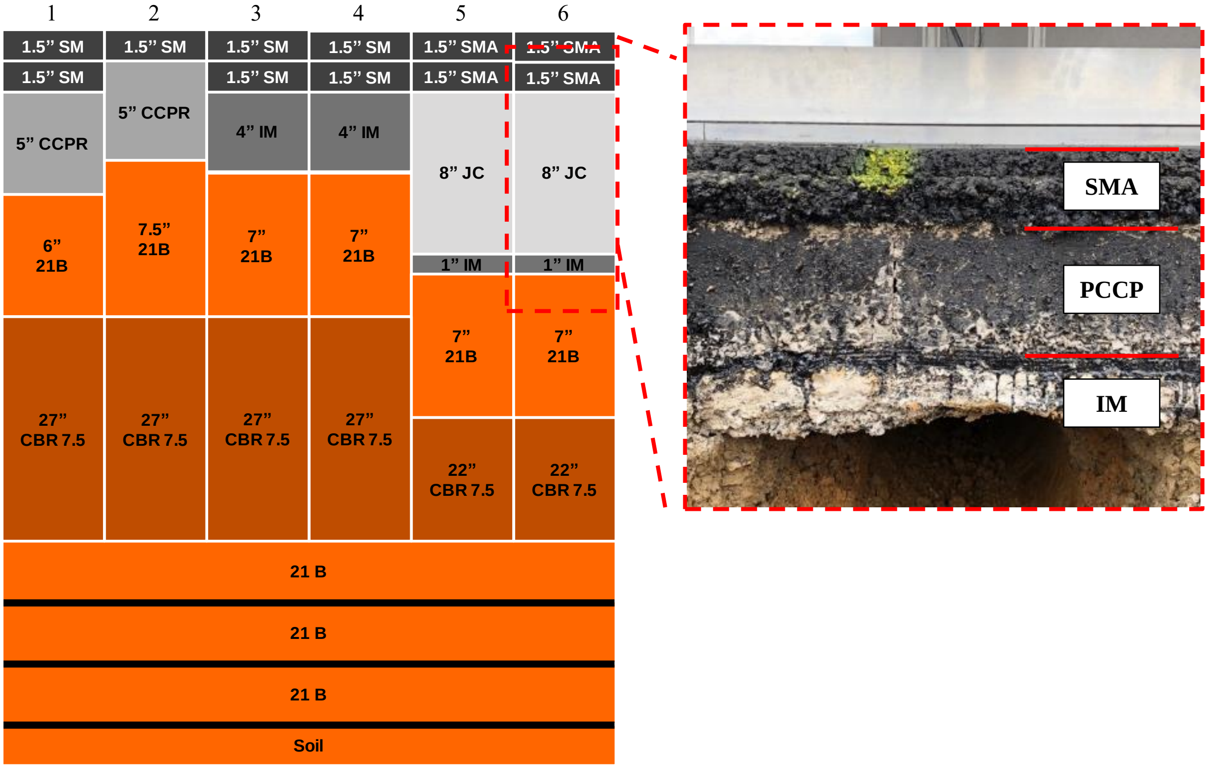


Figure 5: Pavement structure of tested sections (not to scale).

Instrumentation

Sensors were chosen from different manufacturers based on their reliability, accuracy, and compatibility.

Figure 6(a), (b), and (c) show the devices that were used for the test sections instrumented from subgrade to top layer with strain gauges, load cells, thermocouples, and LVDTs. The sensors were embedded under the wheel path to catch the critical responses from the pavement structure throughout its life cycle. Before the installation of the instruments, each one was calibrated and tested following the manufacturer's specifications.

(a) **(b)** **(c)**

Figure 6: (a) load cells, (b) strain gauge, (c) foil gauge.

A National Instruments PXIe-1075 data acquisition system was used in the experiment, along with the software LabVIEW, to collect signals from the embedded sensors. The cables of the sensors in the same pavement section were gathered and connected to the data acquisition system, which was accommodated in a conditioned stainless-steel cabinet.

Inside the HVS chamber, there is one camera to monitor the dual tire in case it stops working, if the load is not being applied correctly, or for times when maintenance is being conducted with a technician inside the chamber. Another camera monitored the initiation and propagation of the reflective cracking in Lanes 5 and 6.

Testing Conditions

Figure 7 shows a top view of the arrangement of the joints for the sections found in each lane. Although each section contains seven joints, only four were subjected to loading due to the length of the HVS, which does not cover the entire length of the section.

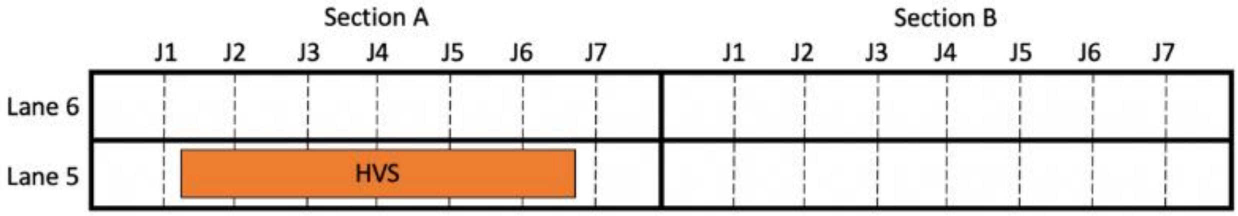


Figure 7: Arrangement of joints per section.

Each section had four samples to monitor the initiation and propagation of the cracks located at Joints 3, 4, 5, and 6. Each section was monitored and inspected daily to estimate the number of cycles needed for the crack to reach the surface. In addition to the visual inspection, the data acquired from the LVDTs were analyzed weekly to verify any changes in the measured vertical and horizontal movements of Joints 3 and 4.

All the tests were conducted at a constant speed of 4 mph. Due to the unknown response of the pavement sections for the reflective cracking study, during Phase I of the experiment, Lane 5, Section A started with a constant loading of 4.5 kips, which was incremented by 1.5 kips until reaching 15 kips.

Material Characterization

The study included a control SMA mix designed with an NMAS of 12.5 mm, of which 12% was composed of a limestone filler, 63% quartzite #7, 10% quartzite #8, and 15% recycled asphalt pavement (RAP). The mixes had 6.7% PG 64E-22 asphalt binder modified with 0.30% of the additive cellulose fiber and 0.50% of the antistripping Ad-here HP Plus. The experimental mix was a modified mix with synthetic fiber that had the same gradation and asphalt binder as the control mix with the difference that it was designed with 1 lb of Forta-Fi Fiber for each ton of asphalt.

These pavement sections tested with the HVS serve as a field study for comparison with the results obtained from a laboratory test by Salado et al. (2020), who evaluated the fracture resistance of asphalt mixes and determine the fracture resistance of these SMA mixes. They conducted the Indirect Tension Asphalt Cracking test to determine the Cracking Test Index, the Semi-Circular Bend test modified by the Louisiana Transportation Research Center to determine the critical strain energy release rate, the Semi-Circular Bend test modified by Illinois to estimate the Flexibility Index, and the Texas Overlay Test to estimate the crack propagation rate.

Phase I: Initial Experiment

The original plan included testing in the middle of each section using a typical wander pattern and increasing loading.

Wander

The load applied in the first phase used a normal distribution with higher application in the middle of the section and lesser on the sides, represented by the red bars in Figure 8. The red line with dashes represents the area where the unidirectional load was applied as a normal distribution. The green shaded area represents the coverage area of the HVS, which includes Joints 2 through 6, with Joints 3 through 6 being the samples under study.

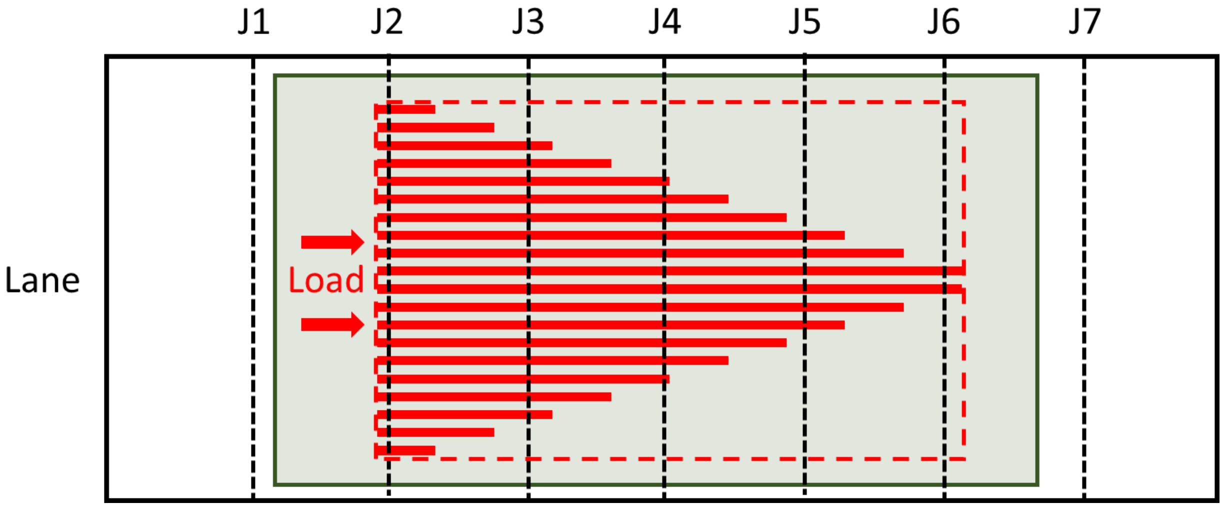


Figure 8: Distribution of load application.

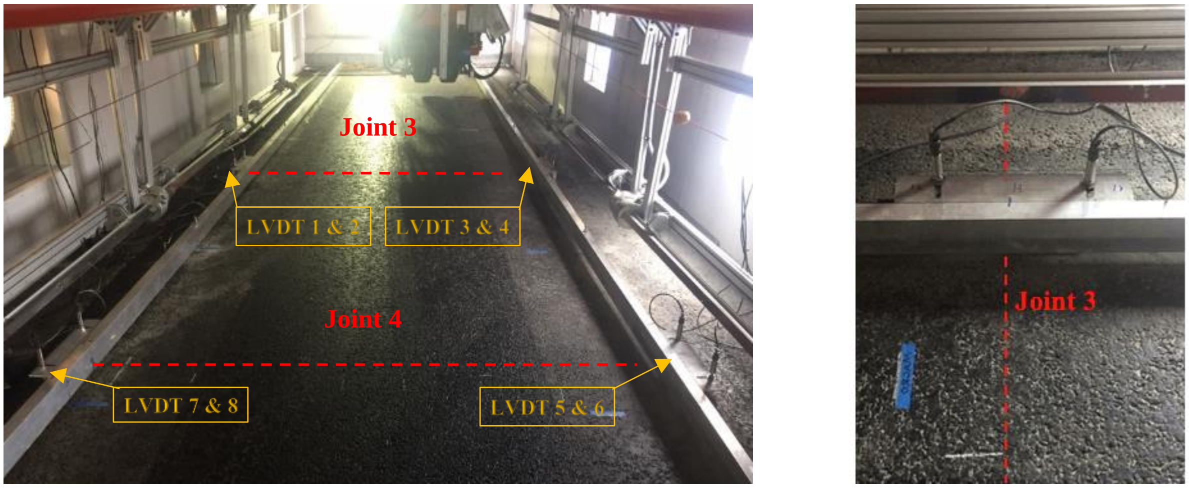
The load was applied starting at 4.5 kips and incremented by 1.5 kips until reaching 15 kips. The wander had a transversal coverage of 1.5 m (5 ft.) wide, as shown in Figure 8. The testing started on Lane 5, Section B for 8 months, then was relocated covering the edges of sections A on Lane 5 and 6.

Instrumentation

Instruments for the reflective cracking study in Lane 5 and 6 only included LVDTs and strain gauges located at the joints. Vertical LVDTs were used to register the lateral and vertical changes of the slabs due to the load application.

Figure 9(a) shows the location of the LVDTs installed on each side of Joints 3 and 4. The LVDTs were installed on the edge of each slab between the joint, as shown in

Figure 9(b).

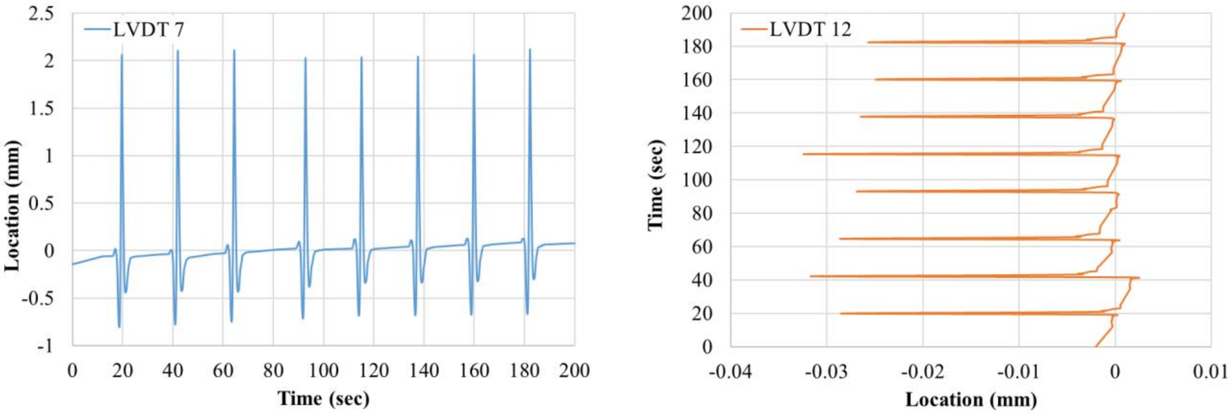


(a) **(b)**

Figure 9: (a) LVDTs located in Joints 3 and 4; (b) LVDT installed at Joint 3.

Figure 10(a) shows an example of the vertical displacement measured by the LVDT located in the slab of Joint 4. The plot presents the peak displacements of more than 2 mm for a period of 200 s measured every time the wheel passed on the joint at approximately every 20 s.

Figure 10(b) shows the horizontal displacement during the same period of 200 s with a maximum displacement of 0.032 mm (.001-inch).



(a) **(b)**

Figure 10: (a) Vertical and horizontal displacement measured by LVDT 7 and (b) LVDT 12.

Crack Recognition

Using the NI1778 camera, pictures were taken once a week to monitor the crack initiation and propagation on the surface at Joints 3, 4, 5, and 6. Figure 11 shows three images attached from Joint 5, taken from the top in December 2017 when the experiment started. The image has a coverage area of 1.4 m (4.5 ft.) wide and 0.5 m (1.8 ft.) in height.

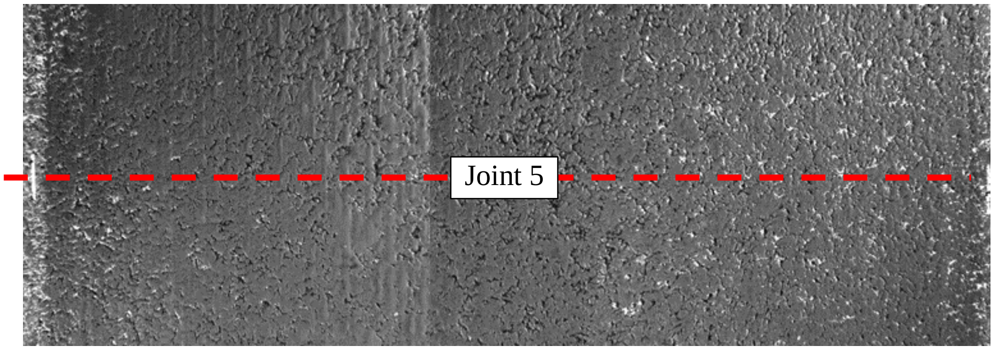


Figure 11: Top view image of SMA overlay at Joint 5.

Phase II: Experimental Changes

During the first 6 months of APT, there were no cracks reflected from the joints of the pavement section located in Lane 5 with the control SMA mix. Therefore, several modifications were made to the pavement structure and loading to increase the movement at the joints and allow the cracks to reach the surface faster. Table 3 shows the itinerary of major changes to the experiment. Due to the unknown response from the pavement, the study started in December 2017 with a small load of 4.5 kips. The load was increased by 1.5 kips every two weeks until March 2018 and was kept at 15 kips until the end of the experiment.

Table 3: Itinerary of Changes to HVS Experiment

	Dec 2017	Jan 2018	Feb 2018	Mar 2018	April 2018	May 2018	June 2018	July 2018	Aug 2018	Oct 2019
HVS Started (lane 5 cell B)	🟨									
Load increased		🟨	🟨	🟨						
Load Direction: Unidirectional to Bidirectional					🟨	🟨	🟨	🟨	🟨	
Subbase Drilling: Joints 4 and 5						🟨				
Cold Milling: 38.1 mm (1.5-inches)									🟨	
HVS Relocation: Edges of lanes 5 and 6									🟨	
Load Direction: Bidirectional									🟨	🟨
HVS Stopped										🟨

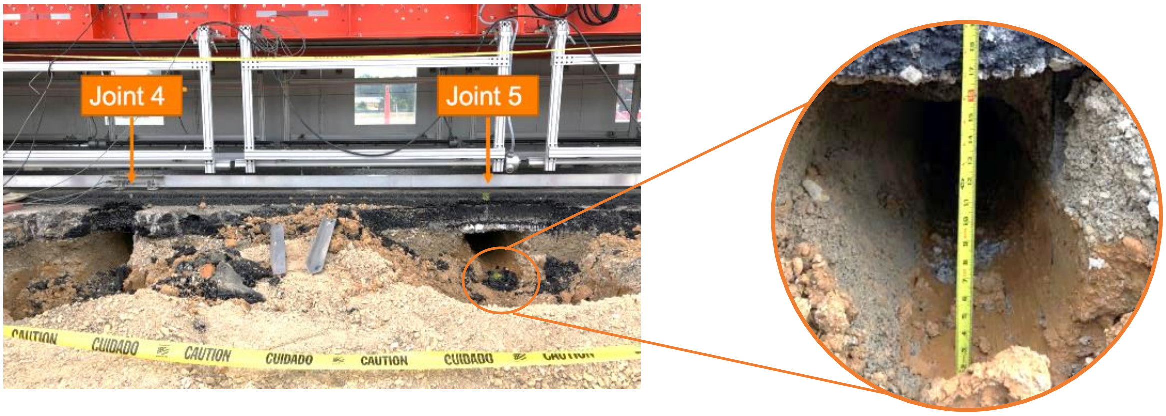
Load Direction

At the beginning of the pavement testing, loads were applied in only one direction. The first major modification to the experiment was to change the HVS from unidirectional to bidirectional travel. At 4 mph the daily number of passes increased from 3,500 to 6,500, which represented an increment of approximately 30,000 ESALs per day.

Subbase Drilling

It was decided to drill horizontally the subbase below Joints 4 and 5 to allow movement at the joints. Each hole had an approximate diameter of 406.4 mm (16-inches).

Figure 12 shows the change made to the pavement structure with the two holes drilled below Joints 4 and 5. After running for almost 16,200 passes (138,428 ESALs) there were no transversal cracks on the surface. However, the LVDT registered a maximum vertical movement of the slabs located at Joint 5 of almost 1 mm (0.04-inch).



(a) **(b)**

Figure 12: (a) Subbase drilling below Joints 4 and 5 with (b) an average diameter of 406.4 mm (16 inches).

Cold Milling

A third modification to the experiment was the cold milling of the surface. The original pavement section had two 38.1 mm (1.5-inch) layers, but it was decided to remove the top 38.1 mm (1.5-inch) layer.

HVS Relocation and Revised Wander

After the cold milling, the HVS was relocated between Lanes 5 (control) and 6 (synthetic fibers) to test both lanes at the same time. The wander was applied on the edge of both lanes, following a narrower normal distribution with a much smaller standard deviation, as shown in Figure 13.

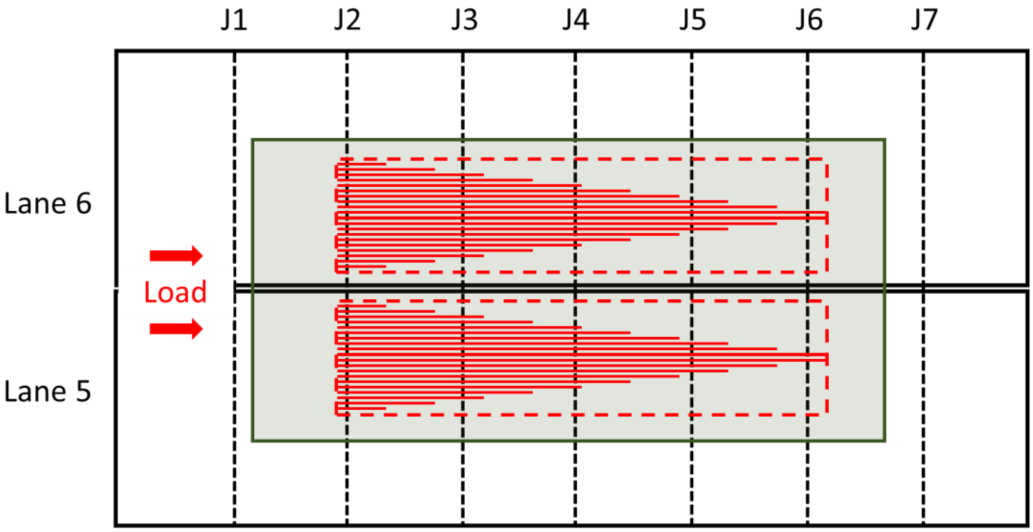


Figure 13: Load application distribution between Lanes 5 and 6.

PERFORMANCE RESULTS: SURFACE CRACKING AND RUTTING

Although the purpose of the research was to study cracking initiation and propagation from the joints to the surface, daily measurements of the surface profile were taken to estimate the permanent deformation or rut depth of the surface layer due to the load applied.

Reflective Cracking Propagation

After the HVS was relocated between Lanes 5 and 6, the experiment continued running until October 2019. During Phase I, the experiment in Lane 5 applied a load equal to 2,775,000 ESALs. A crack was first seen on Joint 5, during Phase II, after 291,716 passes (1,170,000 ESALS) during the inspection conducted on September 5, 2019.

Figure 14(a) shows a top view of Lane 5 (left side) and Lane 6 (right side) with the longitudinal joint that separates the lanes. The crack started from the left side of Lane 5, as shown in

Figure 14(b), and continued propagating to Lane 6.

Figure 14(c) shows the crack propagated on Lane 6, which was first seen during the inspection on October 16, 2019. Compared to the crack on Lane 5, it appeared on the surface of Lane 6 approximately after an additional 373,321 passes, which corresponds to an additional 697,000 ESALs, (cracking at 1,867,000 ESALs).

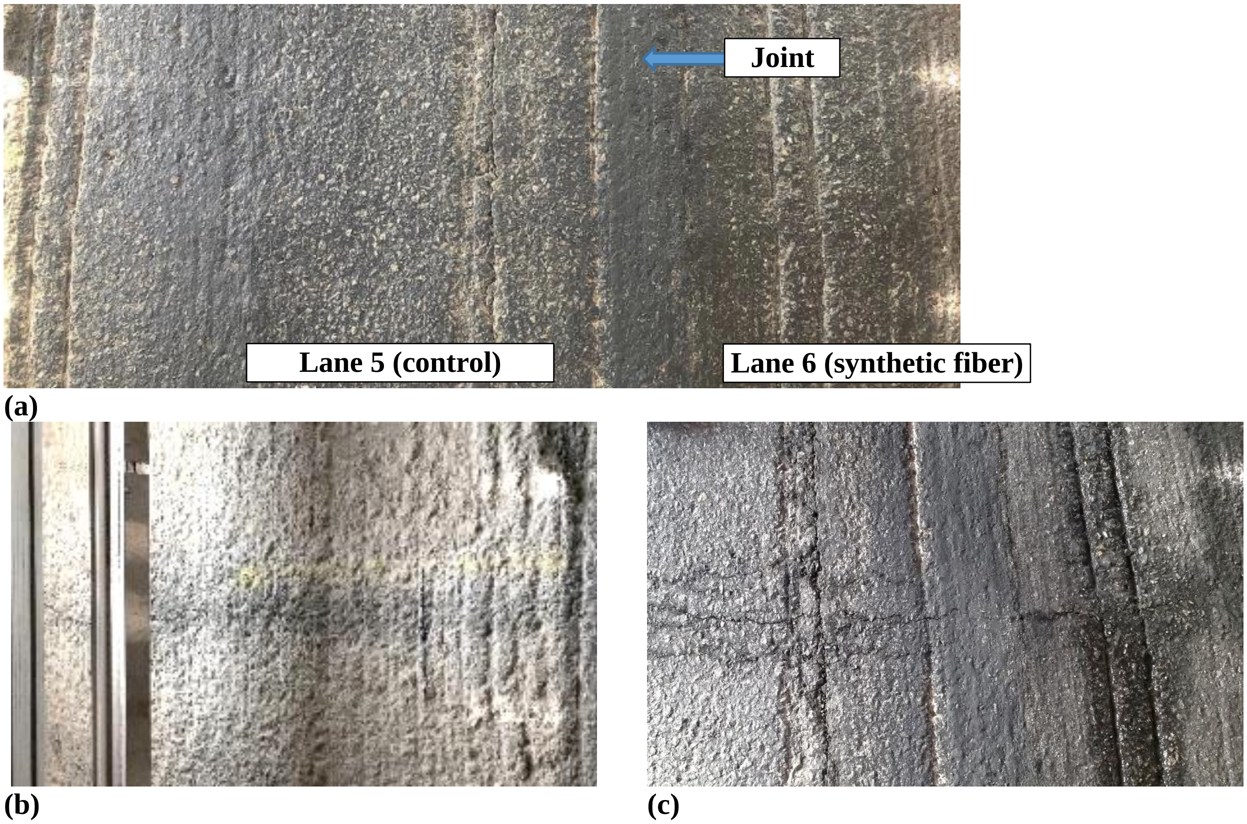


Figure 14: (a) Top view of Lane 5 and 6. (b) Crack on Lane 5. (c) Crack on Lane 6.

Surface Profile: Rutting

Daily measurements of the profile helped to monitor the rut depth of the pavement surface. Measured rut depth was compared to the measurements taken before the experiment started to determine the increment in depth.

Figure 15 shows the rut depth versus ESAL plot for the data acquired while the HVS was on call B of Lane 5 and after it was relocated between Lanes 5 and 6.

The first line, "Phase I: Lane 5," shows the results obtained during the first cycle of the study before it went through the experimental changes mentioned above (e.g., subbase drilling, load direction). The maximum rut depth measured by the sensors from the HVS was negligible, 0.2 mm.

During Phase II, in which the HVS was relocated between Lanes 5 and 6, maximum depths of 3.6 mm and 4.3 mm (0.14-inch and 0.16-inch) were measured for Lane 5 and 6, respectively. The nonuniform increasing trend reflects the accumulated rubber from the tire, asphalt binder, and uneven surface due to the cold milling performed and the accuracy of the method used to determine the rutting.

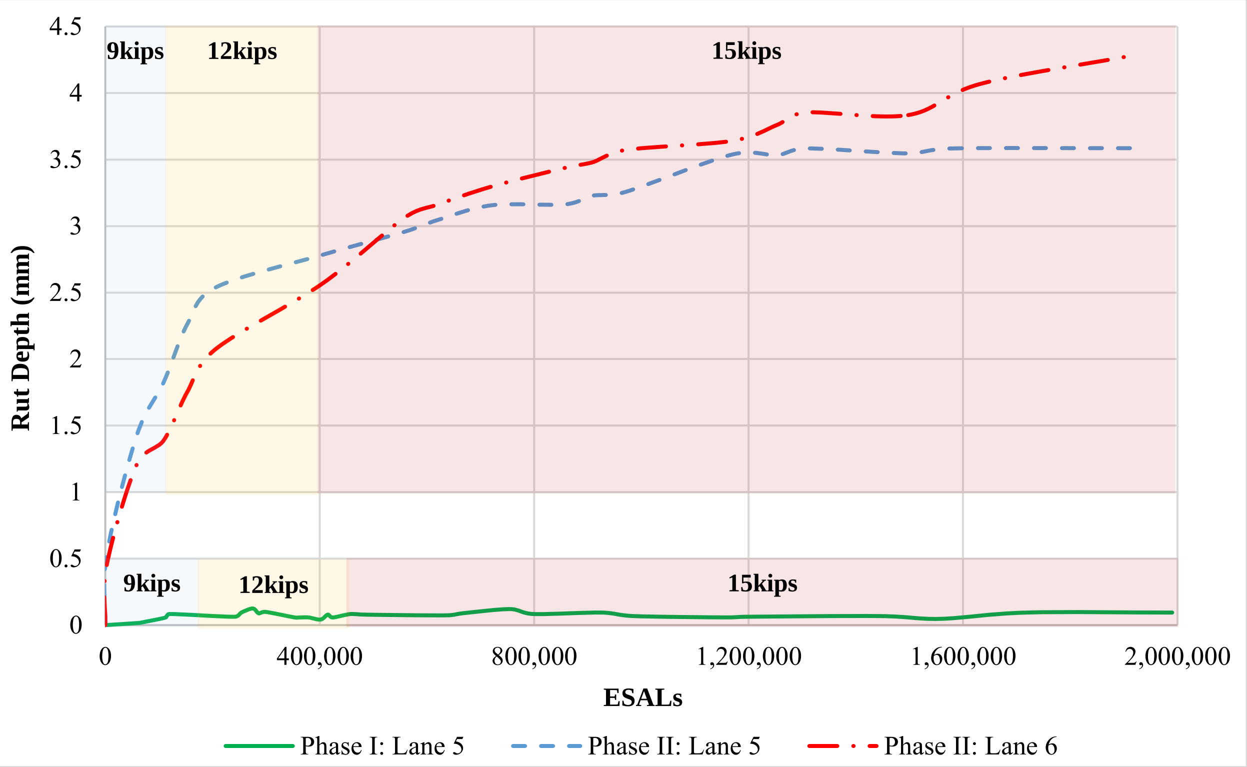


Figure 15: Rut depth vs. ESAL plot for Lane 5 during Phase I and Lanes 5-6 during Phase II.

LESSONS LEARNED

The following are some of the key lessons that were learned during the construction, instrumentation, and testing of the pavement sections:

- Numerical processing and analysis of the data collected by the HVS system should be supplemented by visual inspection of the pavement deterioration. The camera was not able to detect the initiation of the crack, probably due to the rubber deposit on the surface.
- Laboratory testing should be done to characterize the core samples taken at each tested section and/or plant mixed samples collected before placement and compaction.
- Profile readings should be taken every 24 hours to measure depth changes.

- After rainfall, the surface of the test section should be dried to avoid possible errors on the measured profile.
- The overall section was built too strong. Future tests should limit the overlay thickness to 38.1 to 50 mm (1.5 to 2-inch) and artificial voids should be built below some of the joints to simulate erosion due to pumping the generate movement at the joints.

CONCLUSIONS

Testing conducted using the HVS model Mark VI on the two SMA overlays showed that the modified mix with Forta-Fi synthetic fiber had better performance compared to the control mix. The crack started at approximately 1,170,000 and 1,867,000 ESALs on the control mix the mix modified with synthetic fibers, respectively. This suggests that the addition of fibers increased the time to develop the first crack by approximately 697,000 ESALs, which represents an increase of more than 50% with respect to the control mix. Rutting measurements were less than 5 mm on both sections suggesting good performance of both mixes.

The experiment also showed that it is hard to realistically replicate the conditions experienced by asphalt overlays over deteriorated concrete joints within the APT facility. The design of the original experiment did not allow enough movement at the joints to produce reflective cracking. It was necessary to create artificial voids below the surface, reduce the overlay thickness, and load the slabs close to the edge to produce the reflecting cracking over the joints

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