FULL-SCALE TEST OF THERMALLY-INDUCED REFLECTIVE CRACKING: LESSONS LEARNED FROM 5-YEAR RESEARCH AT FAA NAPTF

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INTRODUCTION

For a moderately deteriorated portland cement concrete (PCC) pavement where jet blast and fuel spillage are not a major concern, resurfacing the existing pavement with a relatively thin (less than 4 in) hot mix asphalt (HMA) layer provides an economic means of restoring or improving pavement life. The new asphalt concrete (AC) overlay unfortunately often fails before reaching its design life due to the occurrence of reflective cracking. In the early stages of development, reflection cracks may barely be visible and are not considered to be a structural problem. However, when they propagate through the pavement, infiltration of water can weaken the foundation and fine material may be pumped to the surface, resulting in the creation of voids beneath the concrete. Field experiences indicate that reflection cracks usually propagate into the overlay at a rate of approximately 1 inch per year and appear at the surface, in most cases, within 3 years or less (1).

Thermally-induce reflective cracking is probably the most commonly accepted mechanism of reflection cracks. Temperature variations cause horizontal movements of the underlying PCC pavement joints. As a result, tensile stresses are induced in the overlay immediately above the joint/crack whenever contraction occurs. AC can relax under slow-moving conditions; therefore, considerable daily temperature changes have a far more instrumental role in the performance of HMA overlay than gradual seasonal temperature cycles. For instance, a number of reflection cracks were observed on the 18-month-old, 4-in.-thick AC overlaid PCC runway (1L-19R) at the Kansas City International Airport (KCI). Since the Southwest Boeing 737 was identified as the predominant aircraft loading at KCI, these reflection cracks appeared to be the result of fairly large local temperature swings.

FULL-SCALE TEST NEEDS

The LEDFAA overlay design model incorporated an estimate of reflection crack growth (1 inch per year), but this was believed unsatisfactory or illogical and therefore removed from FAARFIELD. The FAA Advisory Circular currently does not explicitly consider this important distress mode (2). To incorporate HMA overlays as an alternative to increasing initial slab thickness, a reliable performance prediction model based on reflection crack growth is essential. The performance model is expected to relate the required thickness of HMA overlay to several input variables, including aircraft loads, climatic effects, and the condition of the existing pavement. One key element of developing such a sophisticated model is to acquire full-scale test data, particularly, crack propagation rates, under controlled loading conditions to mimic the temperature cycles occurring in nature. Failure in this case is considered to be the appearance of bottom-up cracks on the overlay surface that initiate from underlying concrete joints.

PROJECT OVERVIEW

This section first presents the preliminary study and then introduces the Temperature Effect Simulation System (TESS). This is followed by a brief summary of each phase of full-scale test conducted at the FAA National Airport Pavement Test Facility (NAPTF).

Preliminary Study

Prior to full-scale tests, a theoretical study was first carried out to predict the pavement temperature using Enhanced Integrated Climate Model (EICM) and calculate the joint opening using Finite Element Analysis (FEA). An experimental study was then performed to characterize the viscoelastic properties of HMA, asphalt concrete (AC) – portland cement concrete (PCC) interface bond strength, fracture resistance, and fatigue performance of AC at low temperatures. Findings from both theoretical and experimental studies lead to the development of Temperature Effect Simulation System (TESS).

Temperature Effect Simulation System (TESS)

Temperature Effect Simulation System (TESS) was designed, built and installed at the NAPTF. The TESS consists of hydraulic and temperature units, as shown in Figure 1a. The function of the hydraulic unit (HU) is to generate forces that create precise and repeatable horizontal displacement to simulate joint opening and closing induced by temperature changes. The main components of the HU are two cylinders that can generate a maximum total joint opening/closing force of 700,000 lb, as shown in Figure 1b. The force is fully adjustable via the motion controller for monitoring the overlay stress relaxation. The cylinders are closed loop position control (resolution of 0.001 in) with dynamic synchronization from side to side. The temperature unit (TU) is designed to maintain the test temperature with a variation no more than ±1.0oF. The TU consists of a 40-ton chiller and refrigeration grids. As shown in Figure 1c, flexible crosslinked polyethylene (PEX) tubes are placed at three depths within PCC slabs to ensure a uniform temperature. Furthermore, the TESS is equipped with a state-of-the-art data collection system, which can accurately capture crack initiation and propagation.

Full-scale Tests and Technical Findings

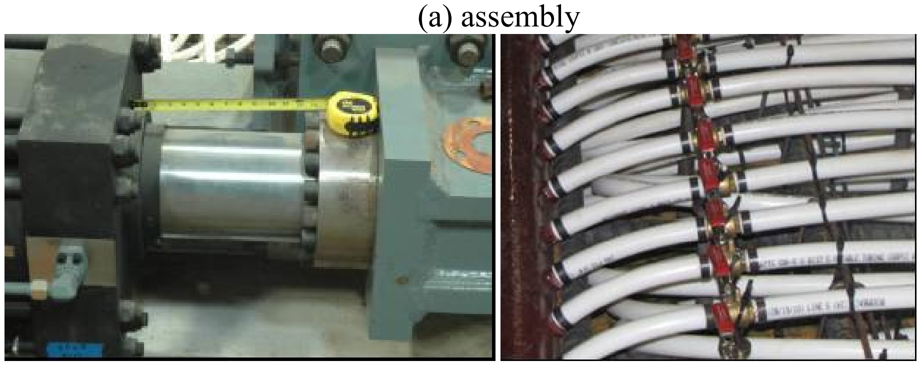
The primary objectives of Phase I test were to examine the feasibility of substituting temperature load mechanically and understand the mechanism of thermally-induced reflective cracking. Phase II test pavement was designed to asses if bottom-up reflection cracks propagate roughly 1 inch per year. In the third phase, the research focus was placed on identifying an applicable mitigation technique and evaluating its effectiveness to retard thermally-induced reflection cracks.

<u>Phase I Test</u>

Phase I test pavement consisted of two 12-in thick, 15- by 15-ft heavy broom finished concrete slabs; one was stationary and the other was movable. A thin tack coat of straight PG 64-22 asphalt was applied before HMA placement. The HMA layer was constructed with two 2.5-in. lifts. Standard FAA materials were used, P-401 (PG 64-22) for AC and P-501 for PCC. The complete test pavement is shown in Figure 2. In May 2012, the test began with a sinusoidal displacement waveform with a 0.015-in. joint opening. Two loading rates, one cycle per 600 and 300 sec, were used, respectively. Later on, a ramp loading with a displacement rate of 0.10 mil/sec was applied to propagate the crack through the top 0.5-in. overlay. The key findings from Phase I test included (3):

- The nonuniform AC-PCC interface conditions from the slab finish and tack coat application resulted in different hydraulic forces from the TESS.
- Fracture Mode I controlled thermally-induced reflection cracks.
- Since the testing protocol did not include rest period during cyclic loading tests, a significant joint closing force was generated and accumulated at the overlay bottom and consequently interfered with further crack development.
- Although the higher loading rate did not result in higher strain level, the loading rate had a substantial influence on the crack propagation, especially when the crack reached the upper portion of the overlay.

(a) assembly



(b) hydraulic cylinder (c) PEX tubing

Figure 1. Temperature Effect Simulation System (TESS).

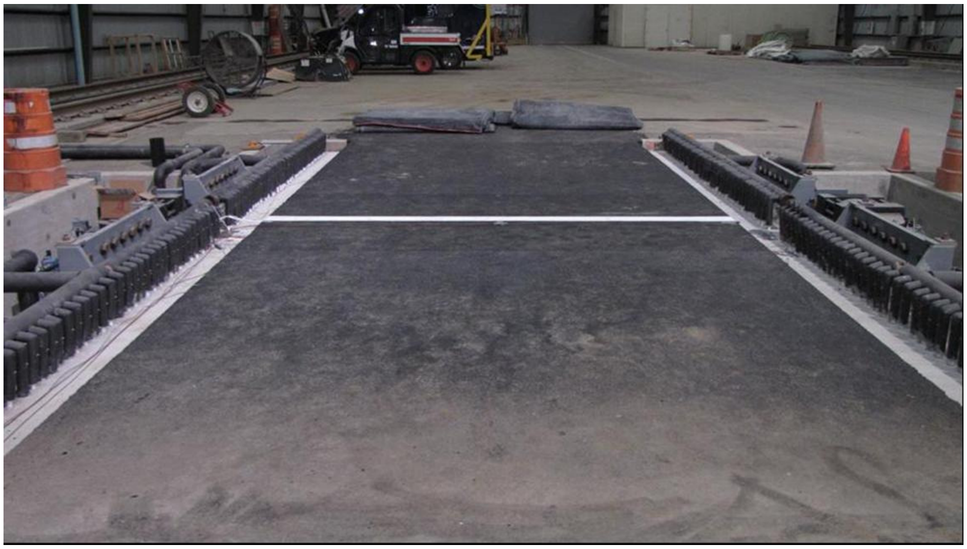


Figure 2. Phase I Test Pavement.

Phase II Test

The construction of Phase II test pavement took place in 2012. To prevent unintentionally damage caused by the differential hydraulic forces and generate maximum amount of data from one round of full-scale test, a wood form was set prior to paving to divide the overlay into two 5.5-ft-wide strips with a 1-ft gap, as shown in Figures 3. The overlay was paved with two 2.5-in. lifts of standard FAA P-401 materials (PG 64-22). The full-scale test began on January 24, 2013. A maximum horizontal displacement (joint opening) of 0.012 in., a loading time of 150 sec, and a rest period of 600 sec were used. After 4869 cycles, the test concluded on March 8, 2013. The major conclusions from Phase II test were (4):

- "1 inch per year" was quite conservative for thermally-induced reflective cracking.
- Two overlay strips exhibited almost identical performance.
- Inclusion of a rest period at the end of each loading cycle allowed sufficient time for the overlay to relax.
- Once bottom-up reflection cracks reached a critical length, the crack evolution became very aggressive. For that reason, it is logical to sandwich a strain relieving HMA interlayer between the PCC slabs and the new overlay to minimize overlay stresses and to tolerate horizontal movements at the joint.

Figure 3. Phase II Test Pavement.

Phase III Test

To facilitate paving process, the overlay of Phase III test pavement consisted of two 5-ft wide strips: north strip and south strip. The north strip was designated as the control section and constructed with 5-in thick control HMA mixture (FAA P-401, PG 64-22). The south strip represented a reflective cracking mitigation treatment for a PCC pavement. In this case a 1-in thick asphalt-rich, highly polymer modified asphalt (PG 76-22) and fine aggregate HMA was placed over the existing PCC slabs first. The purpose of this strain relieving interlayer was to isolate relative displacements between the overlay and existing pavement such that the longitudinal horizontal tensile stresses in the overlay caused by thermal cycling can be significantly reduced. A 4-in HMA overlay was placed atop the strain relieving interlayer. The standard HMA mixture which was used in the control section was also used as the overlay material on the south strip. A picture of Phase III test pavement is given in Figure 4. Phase III test is currently under way.

LESSONS LEARNED

Many things were developed and learned at the full-scale reflective cracking tests. Some for the first time, others were reinforcements of existing practice and concepts. This section discusses lessons learned from four components of full-scale test: advanced computational mechanics, instrumentation, material characterization, and construction.

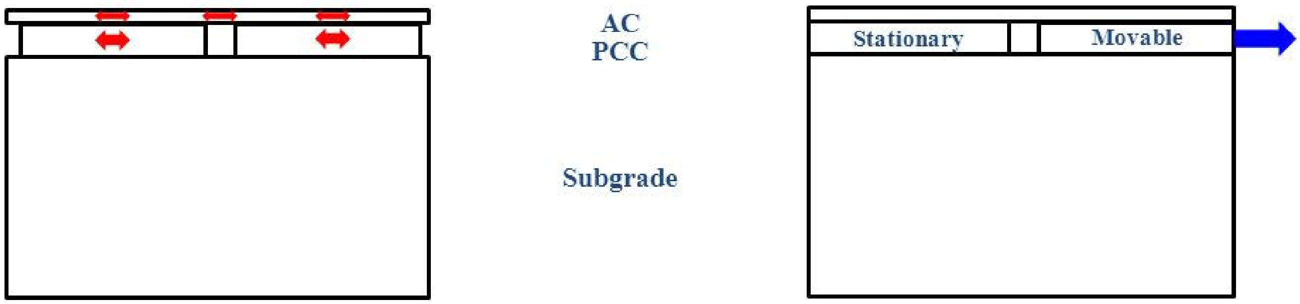
Figure 4. Phase III Test Pavement.

Benefits of Advanced Computational Mechanics

Temperature induced reflection cracks develop in the overlay above a discontinuity, such as the PCC joints. Unlike a continuous HMA layer, excessive movement occurs at PCC joints due to thermal expansion and contraction, as shown in Figure 5a. In this study, a three-dimensional (3-D) finite element (FE) pavement model was developed to perform stress analysis using a general purpose finite element software ABAQUS (5).

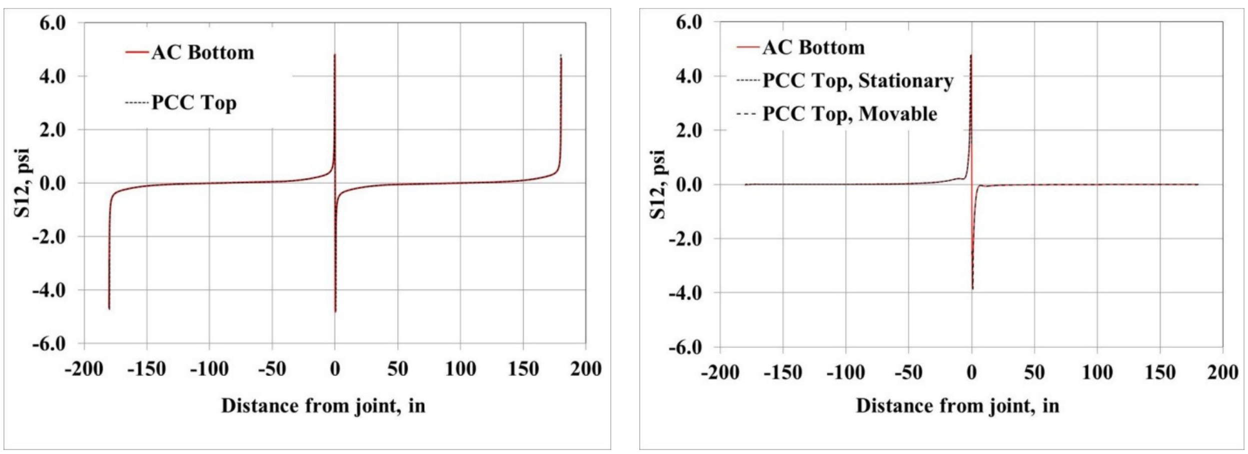
Feasibility Evaluation

Simulating realistic temperature variations in any full-scale test can be extremely challenging, as shown in Figure 5a. It was proposed to apply a mechanical force to one slab while keeping the other slab stationary and a constant temperature in both slabs, as shown in Figure 5b. The joint opening was first calculated by applying temperature changes at each node. Then, the temperature load was replaced by the mechanical load and the load magnitude was iteratively varied until the joint opening matched the temperature induced value. For the same amount of joint opening, it was found that mechanical and temperature load resulted in almost identical maximum tensile stresses at the overlay bottom. The shear stresses induced by any differential movement must be effectively transferred across the AC and PCC interface. A joint opening of 15 mil was selected herein for demonstration purpose. The calculated shear stress distributions at the AC-PCC interface are presented in Figures 6a and 6b. As no separation in normal direction was allowed between layers, the shear stresses lied on top of each other. Under both temperature and mechanical loads, the shear stress sharply declined from its peak value directly above the joint towards the middle of slab. The maximum shear stress was only about 5 psi. Since the stationary and movable slabs were subjected to asymmetric mechanical loading conditions, the shear stress was to some extent asymmetric across the joint. Overall, it was concluded that mechanical load would be suitable to simulate the joint opening due to temperature changes.



(a) Temperature load (b) Mechanical load

Figure 5. Comparison of Load Conditions.

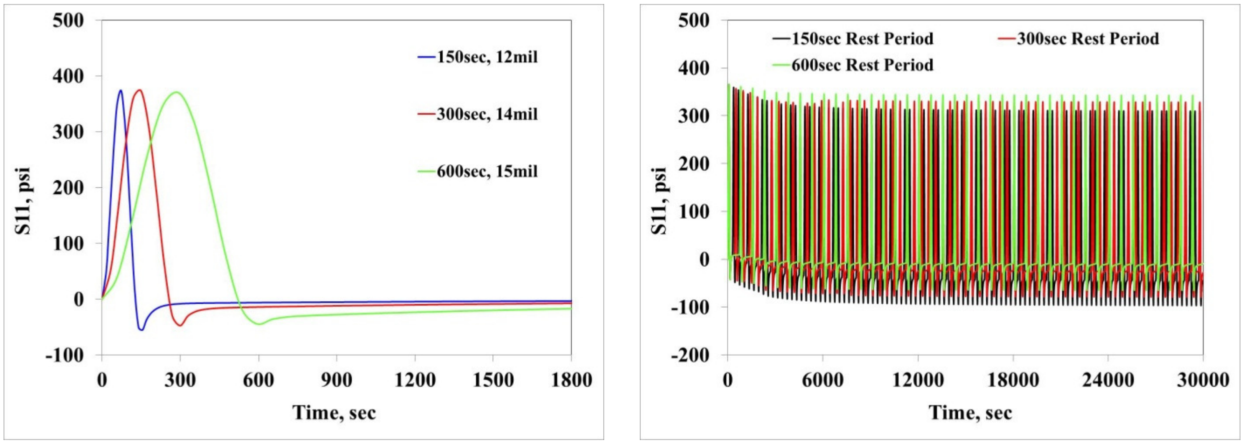


(a) Temperature load (b) Mechanical load

Figure 6. Comparison of Shear Stress Distribution at AC-PCC Interface.

Optimization of Test Parameters

Two key parameters to be considered in full-scale tests are joint opening and cycle time (displacement rate). To approximate the daily temperature variations, a haversine function describing the relationship between the joint opening and cycle time was adopted. It can be seen from Figure 7a that three arbitrarily selected sets of joint opening and cycle time resulted in similar maximum tensile stress at the bottom of overlay during one loading cycle. Because the deformation cannot be fully recovered under displacement-controlled conditions, the stresses at the end of the cycle appeared to be compressive. The haversine function was, therefore, modified with an inclusion of a rest (nonloading) period at the end of each cycle. The predicted maximum tensile stresses at the overlay bottom for a joint opening of 12 mil, loading time of 150 sec, and different lengths of a rest period are plotted in Figure 7b. Including a rest period effectively preserved the tensile stress while reducing the compressive stress. For a rest period of 600 sec, the compressive stress was completely eliminated after 40 cycles, and the tensile stress only dropped 7.8%.

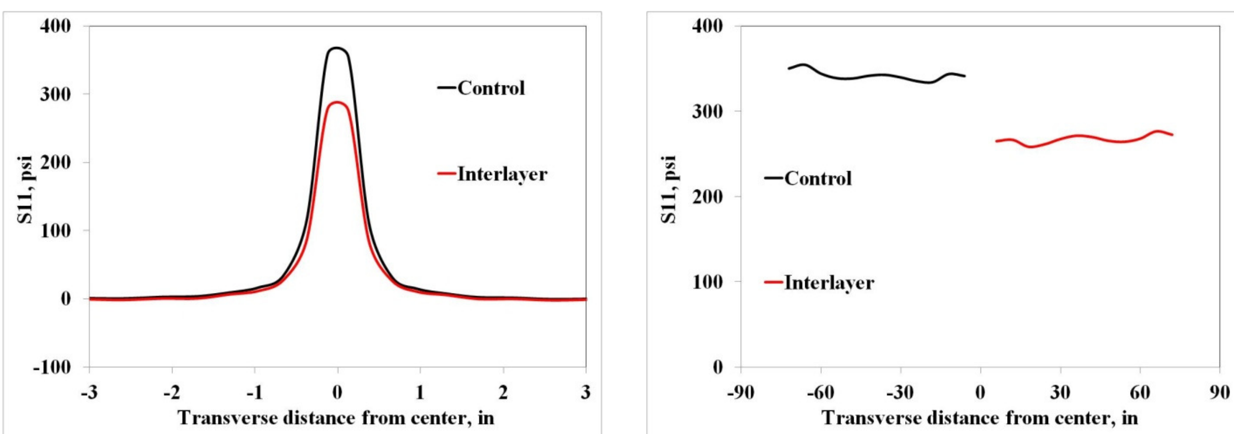


(a) Single cycle (b) Multiple cycles

Figure 7. Stress Analysis Results.

<u>Facilitation of Instrumentation</u>

To understand the mechanism of thermally-induced reflective cracking, the crack initiation and propagation need to be accurately captured. Figure 8a illustrates the tensile stress distributions in the longitudinal direction. The tensile stresses concentrated within 1 in from the joint. The tensile stress sharply declined from its peak value atop the joint towards the middle of slab. For the control section, the maximum tensile stress was 355 psi. With an inclusion of interlayer, the stress magnitude was considerably reduced to 277 psi. The tensile stress distributions in transverse direction are given in Figure 8b. The tensile stresses reached peak values at 6 in from the outer and inner edges for both strips. Consequently, instrumentation devices were placed at these critical locations.



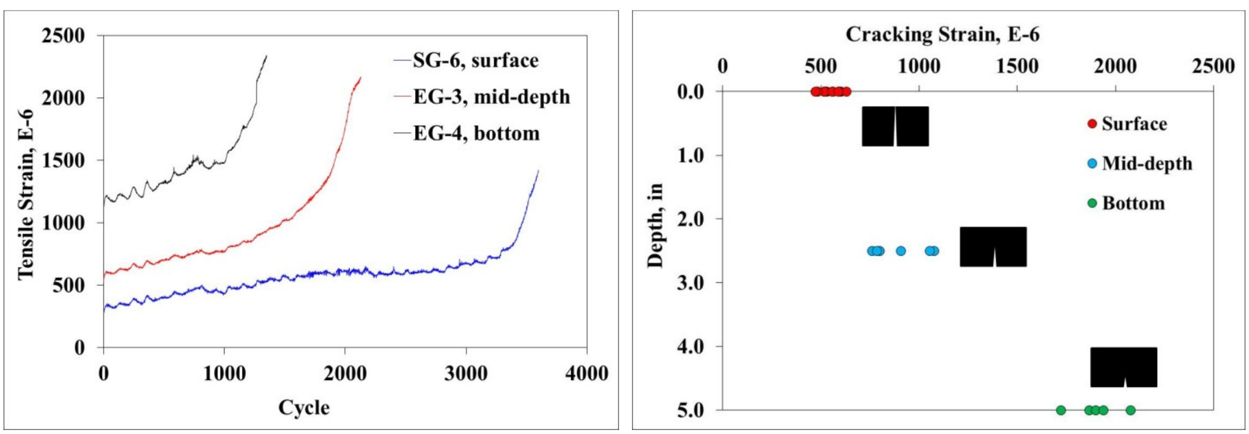
(a) Tensile stress in longitudinal direction (b) Tensile stress in transverse direction

Figure 8. Tensile Stress Distributions.

Instrumentation Highlights

Thermally-induced reflection cracks may start as microcracks that later coalesce to form macrocracks that propagate due to tensile, shear stress, or combinations of both. These cracks grow in a discontinuous manner under cyclic loading conditions. Monitoring crack-progression is extremely been challenging. Specifically, the fracture process zone ahead of the crack tip has complex phenomena where aggregates can slide along and bridge the crack face. Several types of sensors were successfully utilized in Phase I to III tests. These sensors included surface strain gage (SG), crack detector (CD), H-type strain gage (EG), fiber optic strain gage (FG), and LVDT displacement transducer (DT). For instance, Figure 9a shows the signals from strain gages during the course of Phase I test. In general, the tensile strain continuously grew at a slow rate until a sudden rise occurred. The strain at the slope change indicated the formation of an invisible damaged area/zone. At the gage location, the repeated loading-associated cracking strains varied. As shown in Figure 8b, the embedded strain gages at the overlay bottom recorded an average cracking strain of 1900 microstrains. When a bottom-up crack reached the middle of the overlay, the cracking strain ranged from 758 to 1075 microstrains. The cracking strain on the pavement surface further reduced to approximately 550 microstrains. It can be concluded from Phase II test that, as part of the upward crack propagation process, a substantial amount of energy was dissipated.

A further lesson learned was to cover the embedded sensors with material close to the lift thickness (i.e., 1-in) and then use the screed of the paver to strike off the excessive HMA to the proper depth and grade. As a result, instrumentation damage could be reduced to the minimum.



(a) Strain gage responses, Phase I test

(b) Cracking strains, Phase II test

Figure 9. Instrumentation data

Material Characterization

<u>Support of Construction</u>

Redistribution of stresses and strains at the pavement layer interface due to an inadequate bond can be a cause of premature pavement failure. Spreading an asphaltic tack coat over an existing concrete pavement before placing an AC overlay is a common field practice for ensuring the bond between layers. As a part of the preliminary study, a 15- by 15-ft P-501 concrete slab was built and finished with heavy broom and steel rake. To avoid tears during the finish process, both techniques were performed after the concrete had hardened sufficiently (about 1 hour). Two weeks later, two types of tack coat, straight PG 64-22 asphalt and emulsified PG 76-22 asphalt, were applied at an application rate of 0.04-0.06 and 0.06-0.08 gal/yd2, respectively. Finally, a 5-in. layer of P-401 material (PG 64-22) was laid down in two lifts. Field cylindrical cores with 4-in. diameters were taken from the overlay and conditioned at 32°F for 24 hours. A displacement rate of 0.05 mil/sec was selected for the bond strength test using the FAA Bond Shear Strength Tester (BSST). The combination of straight asphalt and heavy broom finish provided the strongest bond strength, 60 psi.

Assistance to Test Protocol

There are few records of operational and reliable test equipment that can characterize the mechanical behavior of reflection cracks. Although the Texas Overlay Tester is essentially a fatigue-type test, it currently represents the best laboratory method to truly simulate horizontal joint movements in the joint/crack vicinity of PCC pavements. The Texas Overlay Tester is generally run in a controlled displacement mode at a specific loading rate with a fixed maximum opening displacement. The growth of the crack, as observed on the sides or top of the sample, is manually recorded at the end of each load cycle. For this study, the overlay test was conducted at a temperature of 32°F and with a horizontal displacement of 15 mil. The loading rates were set at one cycle per 30, 60, and 120 seconds. The number of cycles to failure ranged from single digits to over 200. Regression analysis found that the full-scale test may take thousands of cycles to fail at slower loading rates (i.e., 1150 cycles at 0.10 mil/sec, 5250 cycles at 0.05 mil/sec).

Selection of Interlayer Mix

The goal of Phase III test was to assess if a strain relieving HMA interlayer can successfully mitigate thermally-induced reflective cracking. A strain relieving interlayer is a soft layer that is usually placed at the bottom of an HMA overlay to absorb a large portion of the energy, which would otherwise be part of the crack propagation process. A strain relieving interlayer typically consists of a fine graded, polymer modified binder (PMA), asphalt-rich mixture. The PMA gives the elasticity to withstand and partially absorb the tension, shear and bending exerted on the pavement. For this study, two interlayer HMA (PG 76-22) mixes were developed. Key volumetric properties and gradation of these mixes are summarized in Table 1.

The Disk-shaped Compact Tension, DC(T), tests were performed to evaluate the fracture resistance of both interlayer mixes. A constant crack mouth opening displacement (CMOD) rate of 0.039 in/min was used. Fracture energy of the specimens was determined by calculating the normalized area under the Load-CMOD curve. Testing temperature was set at 10oF. Based upon the results from 5 replicate specimens, the average fracture energy for Mix A and B were 2.90 and 3.51 in.-il/in2, respectively. Therefore, interlayer Mix B was selected due to its favorable fracture performance.

Table 1.
Volumetrics and Gradation of Interlayer HMA Mixes.

Sieve Size	Percent Passing	
	Interlayer Mix A	Interlayer Mix B
No. 4 (4.75 mm)	92.0	92.3
No. 8 (2.36 mm)	46.8	55.9
No. 16 (1.18 mm)	25.3	34.7
No. 30 (0.600 mm)	16.7	23.7
No. 50 (0.300 mm)	12.4	16.8
No. 100 (0.150 mm)	8.3	11.8
No. 200 (0.075 mm)	4.6	8.2
Volumetrics	Interlayer Mix A	Interlayer Mix B
Air voids, %	1.6	3.7
VMA (%)	16.2	18.1
Asphalt Content, %	8.4	8.2

Construction Challenges

The following summarizes critical lessons learned from Phase I, II, and III pavement construction:

- For thin HMA lift, segregation should be carefully detected and eliminated so that design volumetrics can be acquired;

- Between HMA lifts, time that required to allow application of tack coat, installation of instrumentation sensors, and maintain mix temperature to achieve desirable density has to be cautiously balanced;

- Controlling and maintaining an adequate mix temperature are critical for interlayer HMA. There were unexplained spikes and dips in the temperature ranges that might have contributed to the tearing appearance in the surface of interlayer. However, after compaction the interlayer was smooth and stable;

- After a pavement has been milled, the surface should be cleaned by sweeping or washing before any overlay is placed, otherwise the dirt and dust will decrease the bond between the new overlay and the existing pavement;

- Drainage via a V-shape ditch and pipe should be considered to minimize water on pavement surface from condensation.

SUMMARY

Typical airport pavement rehabilitations include restoration, recycling, resurfacing, and reconstruction. For a moderately deteriorated Portland cement concrete (PCC) pavement, resurfacing existing pavement with a relatively thin hot-mix asphalt (HMA) layer, known as an

HMA overlay, is regarded as an efficient method. However, due to the combination of load and temperature induced movements, complex stresses and strains develop at the vicinity of slab joints and cracks in PCC. Consequently, the new asphalt overlay often fails before reaching its design life due to the occurrence of reflective cracking. This paper presents an on-going project on thermally-induced reflective cracking. In the past five years, three full-scale pavements were constructed, instrumented, and tested at the FAA National Airport Pavement Test Facility (NAPTF). This paper reviews the progress and primary findings from the experiments, including efforts under way to evaluate the effectiveness of strain relieving HMA interlayer to battle reflection cracks. Reflections on the lessons learned from full-scale tests are presented. It is expected that future tests, along with ongoing field investigation, will serve as the basis for the next generation of the Federal Aviation Administration (FAA) Advisory Circular for AC overlaid rigid pavements.

ACKNOWLEDGEMENT

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