THREE-DIMENSIONAL FINITE ELEMENT MODELING TO EVALUATE BENEFITS OF INTERLAYER STRESS ABSORBING COMPOSITE FOR REFLECTIVE CRACK MITIGATION

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PRESENTED FOR THE 2002 FEDERAL AVIATION ADMINISTRATION AIRPORT TECHNOLOGY TRANSFER CONFERENCE

05/02

Abstract

An interlayer stress absorbing composite (ISAC) originally developed at the University of Illinois has been installed at a number of airports over the past five years in an effort to control reflective crack development in asphalt overlays. This three-ply composite combats reflective cracking via two mechanisms: reinforcement and base-isolation. While field data collected thus far indicates that ISAC significantly reduces reflective crack development relative to untreated control sections, there had been no modeling results published to quantitatively illustrate how interlayers such as ISAC reduce critical overlay responses that are related to reflective crack development.

This study presents the key results of extensive field, laboratory, and modeling efforts aimed at addressing this need. Field deflection testing, pavement instrumentation, fundamental laboratory testing, and three-dimensional nonlinear finite element modeling was performed in conjunction with the Rantoul National Aviation Center Demonstration project to better understand the key mechanisms of reflective cracking and to evaluate promising mitigation techniques. Modeling results indicate that ISAC nearly eliminates stress development in the bottom of the asphalt overlay due to joint opening and closing due to temperature cycling, and is particularly beneficial for thinner overlays. A viscoelastic constitutive model was used in ABAQUS and appeared to capture the relaxation tendencies of ISAC and the overlay itself during critical cooling events.

Keywords: Asphalt, Pavement, Rehabilitation, Overlay, Reflective, Reflection, Crack, Cracking, Interlayer, SUPERPAVE IDT, Instrumentation, 3-D Viscoelastic Finite Element Modeling

Introduction

Asphalt overlays used to rehabilitate deteriorated Portland cement concrete (PCC) pavements, while offering relatively low initial costs and benefits of rapid placement, often suffer from the rapid development of reflective cracking. Reflective cracking is simply the development of transverse or longitudinal cracks in an asphalt overlay, which are caused by and thus provide a reflective image of existing cracks and joints in the underlying pavement. Like many other distresses, reflective cracking is an unwanted presence on airfield pavements, as foreign object damage (FOD) to aircraft surfaces and engines can occur as a result of the debris associated with cracked and/or spalled pavement.

A demonstration project was developed at the Rantoul National Aviation Center in central Illinois to investigate several techniques for reflective crack mitigation and control at general aviation airports. The various methods used included: rubblization (fine, medium, and coarse breaking patterns); saw and seal; and the use of a composite paving fabric called ISAC (Interlayer Stress Absorbing Composite), which was developed at the University of Illinois in the early 1990s [Muhktar and Dempsey 1996]. The Rantoul demonstration project involved a comprehensive site investigation, materials testing, and the installation and monitoring of pavement sensors, including: thermocouples, joint movement sensors, and asphalt concrete strain gages. Additional details regarding the Rantoul demonstration project can be found in

Buttlar et al. (2001). One of the objectives of the RNAC demonstration project was to collect field data and to conduct preliminary modeling to support the development of a mechanistic design procedure for bituminous airfield overlays. The scope of the modeling included untreated sections and ISAC treated sections at the RNAC demonstration project. This paper is focused on the presentation of three-dimensional finite element modeling results associated with these two sections, with the goal of analytically examining the base isolation mechanisms associated with ISAC.

Objectives

The objectives of this paper are: 1) to present the results of a parametric study aimed at analyzing asphalt overlay responses under combined environmental and aircraft loading using a three-dimensional nonlinear finite element model developed in ABAQUS; 2) to quantify the effects of interlayer treatments used to protect the asphalt overlay via base isolation from stress concentrations caused by joints and cracks in the underlying PCC slabs, and; 3) to describe how field and laboratory measurements taken during the RNAC demonstration project have been utilized as inputs for the aforementioned model.

Scope

The analyses conducted herein were focused on the pavement structures, materials, and climatic conditions associated with the RNAC demonstration project. Furthermore, modeling complexity was focused on the surface materials, and involved: 1) three-dimensional meshing; 2) the use of a viscoelastic constitutive model for overlay mixtures and the ISAC sandwich layer, and; 3) a deformable contact algorithm allowing slab curling and frictional sliding. Due to the computational demands of the aforementioned modeling complexities, crack propagation (overlay fracture) was not pursued in the present study. However, the fundamental nature of the modeling conducted will allow this capability to be integrated in the future, in the analysis of RNAC and other overlay systems.

Interlayer Stress Absorbing Composite (ISAC)

Description of ISAC

ISAC is a three-ply composite interlayer (Figure 1), usually placed as a 0.91 meter (36 inch) wide strip-type treatment over joints and cracks. The bottom non-woven geotextile layer is provided mainly for manufacturing purposes and to facilitate bonding between ISAC and the existing pavement. The viscoelastic membrane layer is designed to provide base isolation benefits due to its low modulus and high ductility even at very low pavement temperatures. This layer consists of a highly-modified, elastomeric binder. The upper woven geotextile layer provides additional protection to the asphalt overlay, serving mainly as a reinforcing layer. The woven polyester used in this layer has a very high pull tensile strength (175.2 N/mm [1000 lbs/in]). The open weave of this layer promotes good bonding characteristics with the overlay. Before ISAC is laid down, a tack coat is applied to the surface of the existing pavement. The woven geotextile side of ISAC is covered with plastic to prevent pick-up during construction (Figure 2). The plastic is removed just before paving of the overlay.

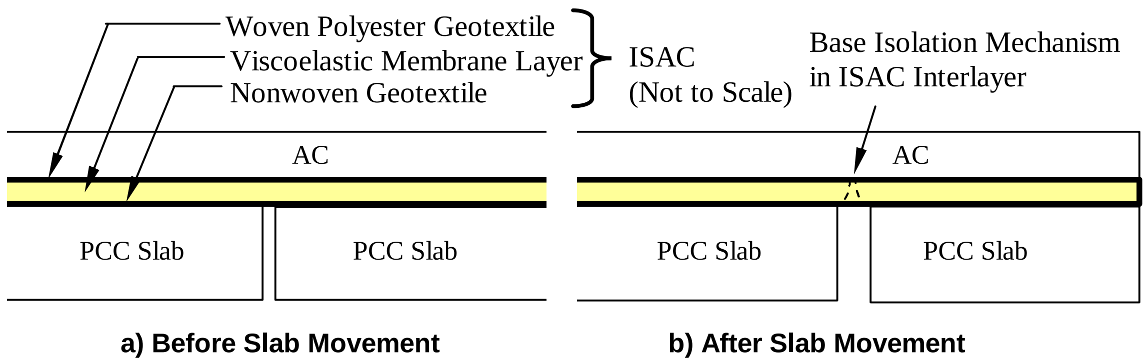


Figure 1. Base Isolation Provided by ISAC Material

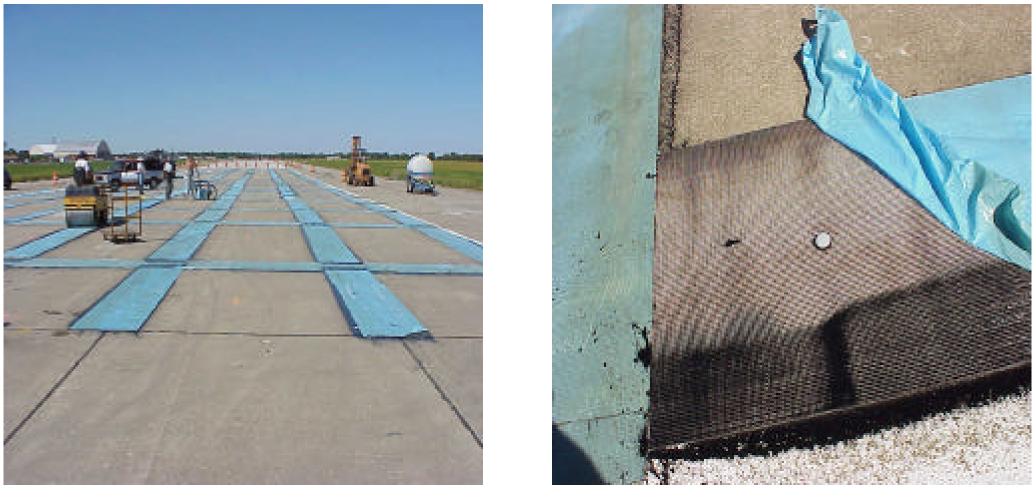
ISAC Field Performance

A recent paper by Dempsey (2002) summarizes the field performance of ISAC relative to control sections at three airport and three highway projects across Illinois, consisting of general aviation airports and low-to-medium volume state and city roads. Since ISAC is a relatively new product, the extent of performance data is relatively limited (one to seven years in the aforementioned projects). However, clear performance differences are already apparent. Field surveys have indicated that sections treated with ISAC have 85-90% fewer reflective cracks as compared to untreated control sections. Although further monitoring of these projects will be needed to completely assess the performance and life cycle economy of ISAC, it appears that ISAC has been effective in retarding initial reflective crack appearance.

Modeling to Support the RNAC Demonstration Project

Existing tools for the design of asphalt overlays over rigid and flexible bases are based upon empirical procedures with specific assumptions concerning the mechanisms that cause reflective cracking. Layered elastic design approaches, such as LEDFAA, do not consider the stress concentrations in the overlay in the vicinity of cracks and joints in the underlying structure, nor do they consider critical combined aircraft and environmental loadings. Furthermore, there is currently no means for considering the benefits of crack-resistant overlay materials (e.g., polymer-modified overlay mixtures) or crack-retarding interlayer materials and composites, such as ISAC.

In the past, it was not computationally feasible to handle such considerations, nor were the mechanisms of reflective crack development understood adequately to even develop a modeling scheme of this nature. However, in light of the rapidly increasing computational power available now for the designer, the move towards mechanistic overlay design methods can be envisioned in the near future. In the meanwhile, these advanced modeling tools and field demonstration projects can be used to gain a better understanding of the mechanisms of reflective cracking.



a) ISAC Placement at the RNAC Demonstration Project **b) Installed ISAC interlayer (plastic cover is partially removed)**

Figure 2. Installation of ISAC Interlayer Over Joints

Incorporation of Field and Laboratory Testing Results in the Response Model

FWD Testing

Falling-weight deflectometer (FWD) testing was conducted at RNAC before and after overlay construction. Prior to overlay construction, FWD testing was conducted in the interior of slabs to collect data for analytical backcalculation of effective subgrade modulus. FWD loads were applied at joints before and after overlay construction to measure load transfer efficiencies (LTEs). The FWD tests were conducted in May and September of 1999 (before overlay construction) and in June of 2000 (after overlay construction). The data collected during these tests provided valuable inputs for calibration of finite element models.

Current programs used for backcalculation of effective layer moduli are based upon static analysis methods; however, FWD testing involves measuring pavement response to dynamic loads. Therefore, three dimensional and axisymmetric dynamic analyses were used in this study to estimate subgrade modulus instead of using common backcalculation programs or elastic layer programs. A detailed presentation of this analysis are beyond the scope of this paper, but can be found in Bozkurt [2002]. The results of the dynamic finite element analysis (FEA) conducted to simulate the RNAC FWD tests were in general agreement to previous studies involving dynamic FEA [Mallela and George 1994 and Sebaaly et al. 1986]. The average deflections from static analysis were estimated to be 20 to 30 percent higher than those obtained from dynamic analysis. The axisymmetric dynamic analysis results were found to be in good agreement with those obtained from three-dimensional dynamic FEA. However, axisymmetric dynamic analysis can only be used as a simplified model of FWD testing conducted in the interior of slabs. When the load or geometry is unsymmetrical (such as loading at a joint), a three-dimensional model is needed. The average estimated subgrade modulus values from the dynamic analyses were found to be 68.90 MPa (10 ksi) for May 1999 and June 2000, and 75.79 MPa (11 ksi) for September 1999.

The LTEs from FWD testing were compared with the predictions from the model as shown in Table 1. The goal of the modeling was to match pavement response most closely in the post-overlay condition, since the primary modeling objective was to analyze responses in the overlay itself resulting from temperature and traffic loads. It was anticipated that the bridging effect of the overlay would lead to high LTE values (both measured and modeled), which was later verified with vertical relative joint movement sensors installed at RNAC. As a result, the initial approach was to model PCC slabs as unconnected to one another, except for the bridging action of the AC overlay, and to a lesser extent, the subgrade, which was modeled as a linear elastic half space. The predicted values showed good agreement with field measurements for the overlay model, so it was not necessary to model additional load transfer between slabs. This may be an indication that for overlay modeling, in general, the bridging effect of the overlay reduces relative deflections to very small values and leads to a consistent, high LTE value while the overlay is intact. It will be necessary to validate this hypothesis with additional field measurements.

It was difficult to assess the accuracy of the modeled LTE predictions before overlay placement, due to the high degree of variability present in field measurements across the RNAC test site. Measured LTE values ranged from 28% to 90%. However, it is interesting to note that when modeling unconnected PCC slabs, the presence of the continuous subgrade in the 3D FE model led to LTE predictions of about 40%. These values were considerably lower than the average measured LTE at RNAC (70%). However, after overlay placement, measured LTEs showed much better consistency, with values ranging from 68% to 80%. It would be incorrect to conclude that LTE, or more generally the condition of the joint, is an unimportant factor in overlay performance, since field observations support the contrary. However, from a modeling standpoint, the benefits of good LTE might only be apparent when reflective crack propagation is modeled, and overlay bridging effects are less dominant.

Temperature Measurements

To estimate thermally-induced stresses in the AC overlay accurately, realistic temperature distributions through the pavement thickness as a function of time were needed. While measured pavement temperatures were available for the RNAC project at various depths in the asphalt concrete overlay, future mechanistic designs will require estimated pavement temperature profiles. Furthermore, since temperatures were only measured on the top of PCC slabs at RNAC, there was also a need to use an analytical model to predict PCC temperatures with depth and time for the purposes of accurately modeling slab curling and contraction. The Integrated Climatic Model (ICM) developed by Dempsey et al. (1985) was used to estimate the required pavement temperature profiles. As shown in Figure 3, the ICM model, in general, yielded reasonable temperature predictions for the RNAC pavements. It is interesting to note that the presence of uncleared snow on runway 18-36 on December 20 and 30 created an insulating effect that resulted in larger discrepancies between measured and estimated pavement temperatures. The inputs for the ICM model are air temperature, wind speed, percent sunshine, and rainfall measurements. The ICM predicts the temperature distribution in the thickness for different times according to these inputs, as shown in Figure 4. When the inputs are not available, the ICM model allows the user to interpolate database measurements from nearby weather stations.

Table 1. LTE Comparisons for 3-D Modeling versus Field Measurements

Field Measurements		3-D Modeling	
Date/ Location	**LTE (%)**	**Model Type**	**LTE (%)**
June 15, 2000 South End of Runway 18-36 at RNAC (Taken Between Stations 0+00 and 9+50)	79.6 79.4 70.2 79.9 67.8	3D FEM, AC Overlay on Jointed PCC	80.0

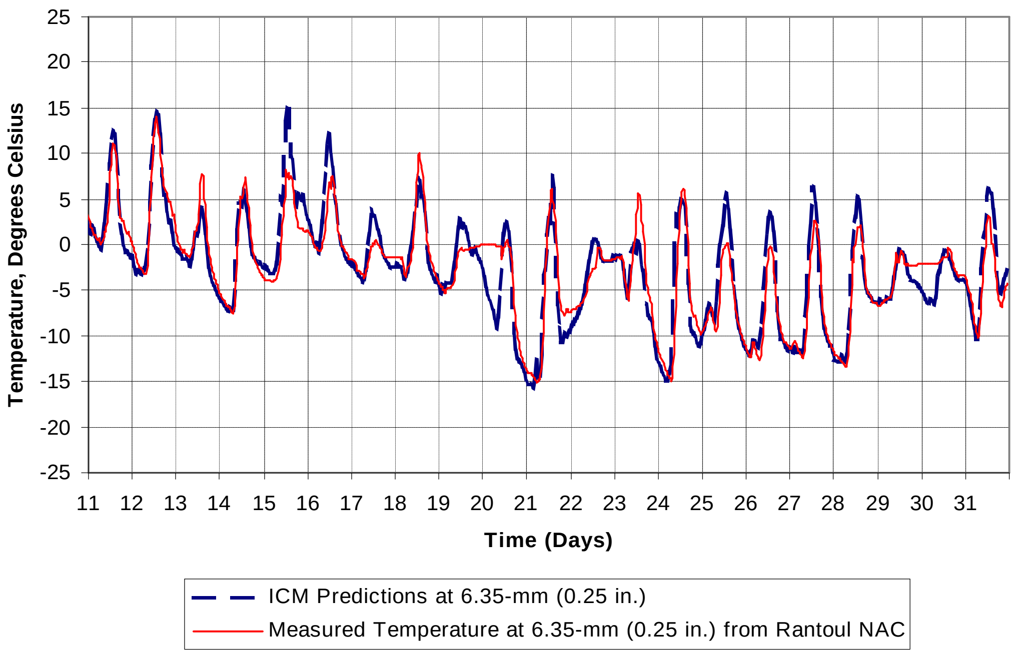


Figure 3. ICM Predictions versus Field Measurements at 6.35-mm Depth of AC Overlay for January 2000

Laboratory Measurements

Due to the importance of thermal stress development and relaxation characteristics of the overlay in overlay response modeling, it was necessary to obtain low-temperature viscoelastic properties of the RNAC overlay materials. Furthermore, the sandwich layer of ISAC required

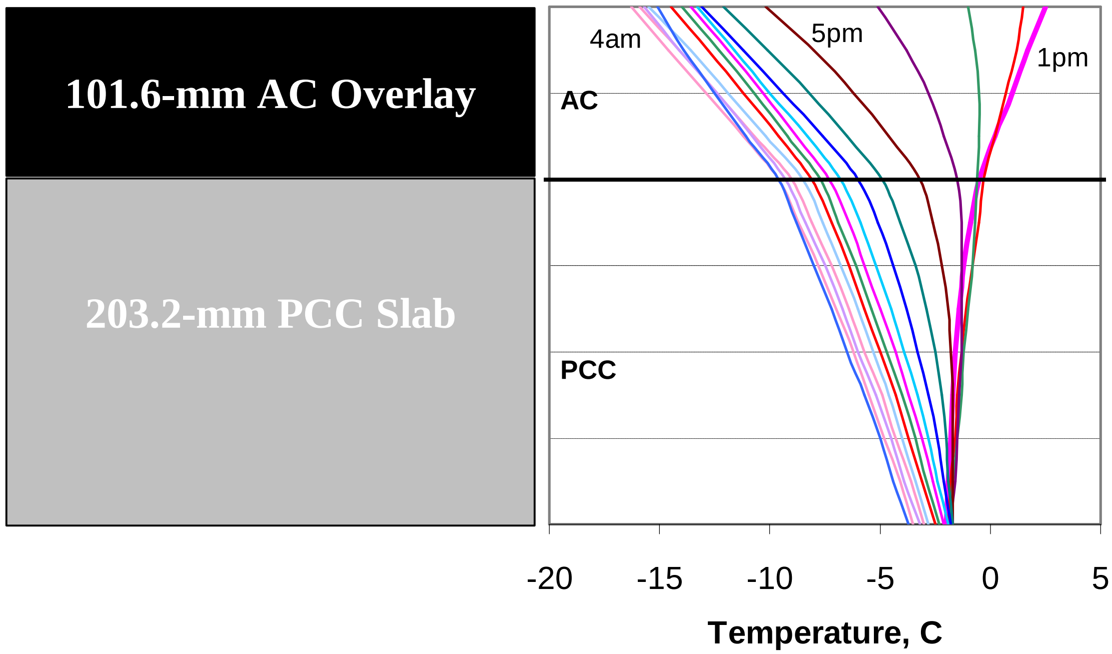


Figure 4. Temperature Distribution in RNAC Runway 18-36 During Critical Cooling Event of January 20-21, 2000

viscoelastic characterization and modeling. The Superpave (SUperior PERforming asphalt PAVEments) Indirect Tension Tester (IDT) was used to obtain low temperature viscoelastic properties for asphalt mixtures, while SUPERPAVE Bending Beam Rheometer was used to characterize the viscoelastic membrane layer of ISAC.

Mixture creep curves and tensile strength values were collected at –20°C, -10°C, and 0°C using the IDT. The creep compliance master curve and shift factors were also obtained from the program MASTER, as described by Buttlar et al. (1998). Then, the creep curve parameters were transformed to relaxation curve parameters using the Superpave TCMODEL program (Roque et al. 1995), which uses inverse Laplace transformation techniques to accomplish this inversion. Since the viscoelastic membrane layer of ISAC could not be tested with SUPERPAVE IDT (a test method for asphalt *concrete* mixes), the relaxation curve parameters for this layer were obtained from the BBR. ABAQUS, a general-purpose finite element code used for modeling in this study, uses a Prony series rheological model to characterize the relaxation master curve at a selected reference temperature (-20 C was used in this study), as described in equation 1. The Prony series rheological model consists of N-pairs of spring-dashpot assemblies, arranged in parallel.

$$E(x)=\sum_{i=1}^{N} E_i e^{-x/l_i} \quad \textbf{(1)}$$

where: $E(\xi)$ = relaxation modulus at reduced time ξ
E_i, λ_i = Prony series parameters for master relaxation modulus curve (spring constants or moduli and relaxation times for the Maxwell elements)

This function describes the relaxation modulus as a function of time at a single temperature, which is generally known as the reference temperature. The function defined at the reference temperature is called the master relaxation modulus curve. Relaxation moduli at other temperatures are determined by using the method of reduced variables (time-temperature superposition), which assumes that the mixture behaves as a thermorheologically simple material. Relaxation moduli at other temperatures are determined by replacing real time (i.e., time corresponding to the temperature of interest) with reduced time (i.e., time corresponding to the temperature at which the relaxation modulus is defined) according to the following equation:

$$x = \frac{t}{a_T} \qquad \textbf{(2)}$$

where:

ξ = reduced time
t = real time
a_T = temperature shift factor

The relaxation modulus function is obtained by transforming the following time-dependent creep compliance function, which is determined by performing creep tests at multiple temperatures. The creep compliance master curve was expressed in the form of a generalized Voight-Kelvin model:

$$D(x) = D(0) + \sum_{i=1}^{N-1} D_i\left(1 - e^{\frac{-x}{t_i}}\right) + \frac{x}{h_v} \qquad \textbf{(3)}$$

and:

$D(\xi)$ = creep compliance at reduced time ξ
ξ = reduced time $= t/a_T$
a_T = temperature shift factor
$D(0)$, D_i, τ_i, η_v = Generalized Voight-Kelvin model parameters

A user-defined subroutine was written for ABAQUS to perform a piecewise-linear interpolation of shift factors from the three test temperatures used in the IDT. The shift factors for the viscoelastic membrane layer in ISAC were manually determined using a simple spreadsheet program. Master relaxation curve parameters and shift factors for AC overlays and the rubber asphalt layer are summarized in Table 2.

The woven geotextile's load carrying capacity was also verified with the wide width tensile strength test (ASTM D4595-86 titled "Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method"). The loading capacity was measured to be very close to that reported by the manufacturer, or 175 N/mm (1000 lbs/in).

Table 2. Master Relaxation Curve Parameters for Asphalt Binder Included Layers

Prony Series Parameters					
Sample Type	***Spring Constants, MPa (ksi)***				
	E_1	E_2	E_3	E_4	E_5
PG 58-22 Overlay Mix	5498 (797.9)	1488 (215.9)	5139 (745.9)	5561 (807.1)	6589 (956.4)
PG 64-28 SBS Overlay Mix	5385 (781.5)	2574 (373.5)	1770 (256.8)	5118 (742.8)	4056 (588.7)
Rubber Asphalt Layer of ISAC	79 (11.4)	43 (6.2)	25 (3.7)	24 (3.5)	37 (5.4)
Sample Type	***Relaxation Times, sec***				
	λ_1	λ_2	λ_3	λ_4	λ_5
PG 58-22 Overlay Mix	8.1	101	826	6560	176087
PG 64-28 SBS Overlay Mix	3.8	22.3	126	346	5164
Rubber Asphalt Layer of ISAC	5.9	33.0	101	477	4263

Temperature Shift Factors, log ($1/a_T$), (Reference Temperature = -20°C)			
Temperature, °C	-20	-10	0
PG 58-22 Overlay Mix	0.00	2.20	3.10
PG 64-28 SBS Overlay Mix	0.00	0.75	1.60
Rubber Asphalt Layer of ISAC	0.00	0.885	1.77

3-D Modeling of Reflective Cracking Mechanism

Pavements have often been studied using 2-D plane strain models, which assume zero strain and a continuous strip load in the out-of-plane direction. However, these assumptions lead to overestimates of the pavement responses. In reality, pavements contract and expand in three dimensions, and traffic loading is applied through wheel contact area (not continuous in the third dimension as assumed in 2-D analyses). Therefore, a 3-D finite element modeling approach was undertaken using ABAQUS, which included the use of contact surfaces between PCC slabs and the underlying subgrade layer and viscoelastic constitutive material models for asphalt layers (Figure 5).

The domain extent was limited to the modeling of two adjacent slabs resting on a cohesive subgrade (Figure 5), due to the time-consuming nature of the model nonlinearities associated with contact surfaces and viscoelastic layers. The contact algorithm selected from the ABAQUS library allows frictional slip, opening between deformable surfaces, and exchange of contact pressure between two surfaces (when the contact surfaces are in compression). A similar approach was used by Kim [2000]. The curling of AC overlaid PCC slabs is important for overlay analysis, as this phenomenon contributes to the magnitude of bending stresses. There is also friction between slabs and the underlying subgrade during contraction of slabs due to movements caused temperature cycling. Therefore, frictional contact modeling should be considered a necessary complexity for modeling and evaluation of overlay response.

The thin, compliant, non-woven polypropylene layer of ISAC was not included in the modeling, as it was not expected to significantly affect overlay response. The membrane layer was modeled with 3-D solid elements with viscoelastic material properties. Because the woven geotextile layer is thin and has negligible stiffness out of plane, it was modeled with 2-D plane stress elements, which were connected to adjacent 3-D solid elements at nodes. The woven geotextile has a grid structure in reality. However, for simplicity, it was modeled as a uniform, thin layer having equivalent tensile properties per unit cross-section. The finite element model was constructed using a combination of continuum solid elements (8-noded brick elements for finite elements [C3D8] and infinite elements [CIN3D8], and 4-noded plane stress elements [CPS4] to simulate the woven geotextile layer). The model had approximately 47,500 nodes and 42,600 elements.

In the thermal analysis, the model was first subjected to nodal temperature loading for 15 hours of cooling, according to the data shown in Figure 4. Next, the model was subjected to a static single tire load of 40 kN (9 kip), to simulate general aviation aircraft loading present at RNAC. The traffic loading was also applied nodally, using a load discretization algorithm develop by Kim [2000]. The model inputs used in the thermal analyses are shown in Table 3. A daily cooling cycle with a very high cooling rate combined with a very low temperature at the end of cooling cycle represents a critical condition for the development of reflective cracking. After reviewing temperature data recorded at RNAC, the cooling cycle from January 20 to 21, 2000 was chosen to represent this critical condition. Models considering of two overlay mixtures, unmodified (AC-10) mixture and modified (PG 64-28) mixture, both with and without ISAC, are the focus of data presentation herein. First consider a frozen subgrade condition, where a frozen subgrade modulus of 206.7 MPa (30 ksi) was assumed. Figure 6 shows the stress distributions vertically through the thickness of the AC overlay along a line directly over the center of the joint and at the center of joint opening. At the end of the cooling cycle, the stress values at the bottom of the overlay with ISAC interlayer switched from –115 MPa (-17 kPa, compression before 40 kN (9 kip) load application) to 545 kPa (79 psi), tension after 40 kN (9 kip) load application). However, the overlay without ISAC treatment shows higher stresses values of 623 kPa (90 psi) and 1620 kPa (235 psi). These results show that an interlayer, which maintains a ductile characteristic under the cold temperatures, can significantly reduce the tensile stresses at the bottom of the asphalt overlay.

Additional analyses were also performed to evaluate subgrade modulus effects on critical overlay responses. In the early spring, a critical cooling event can occur in conjunction with a critical spring thaw condition in the subgrade. To simulate a highly critical condition, the same cooling cycle (January 20-21, 2000) was used with a critical subgrade modulus of 34.45 MPa (5 ksi). These analyses were run for both regular and modified mixes with ISAC and without ISAC as shown in Table 4.

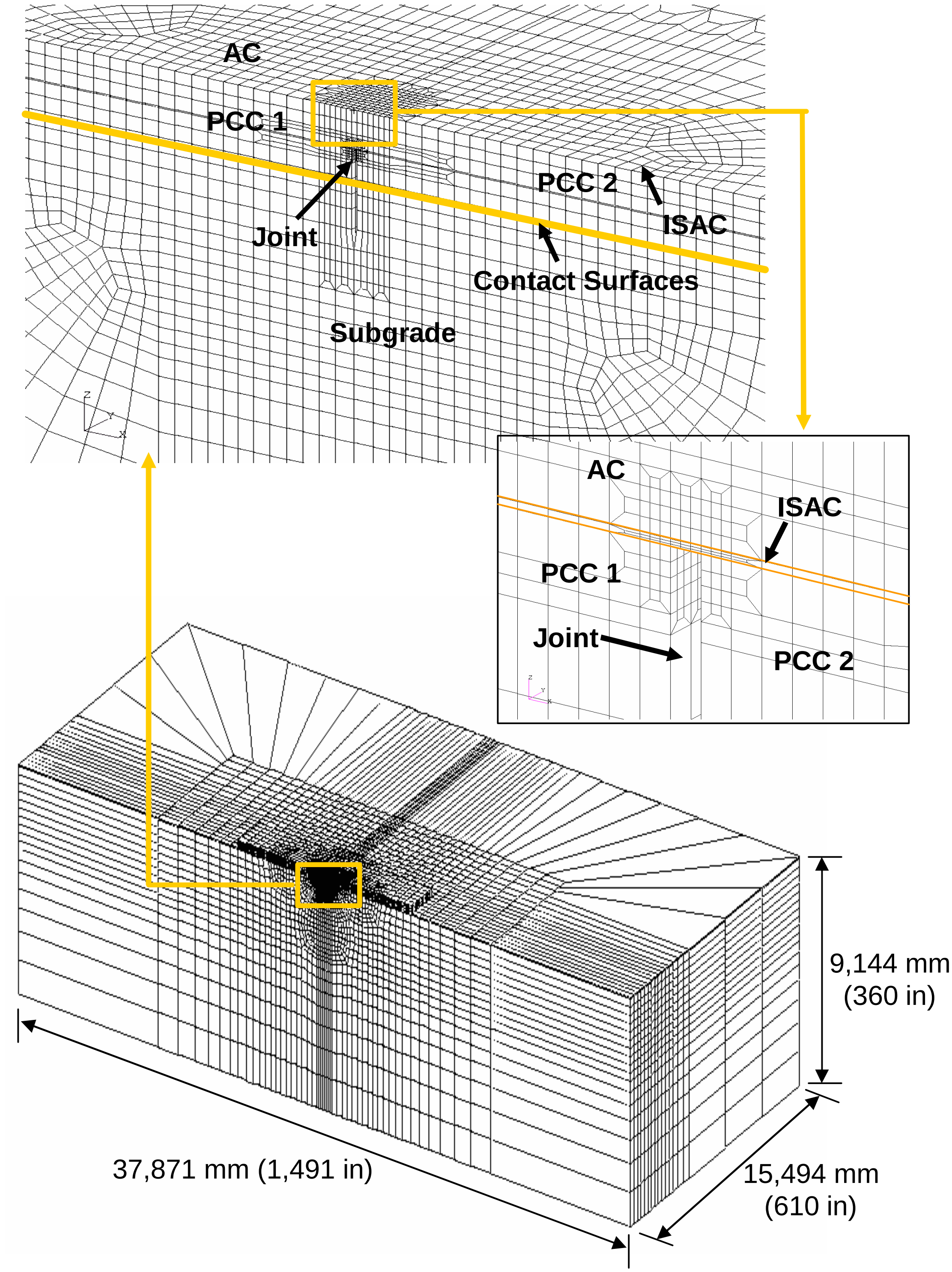


Figure 5. Model Used For Thermal and Traffic Loading Analyses (3-D FEA)

Table 3. Assumed Material Properties in Thermal and Traffic Loading Analyses

Layer	Young's Modulus MPa (psi)	Poisson's Ratio	Density N/m^3 (pcf)	Coefficient of Thermal Expansion (/°C)
Subgrade	34 (5,000) 207 (30,000)	0.45	18,858 (120)	-
PCC	27,560 (4,000,000)	0.15	23,573 (150)	$1.0*10^{-5}$
ISAC	*	0.35	21,215 (135)	$2.5*10^{-5}$
AC	*	0.30	22,787 (145)	$2.5*10^{-5}$

* Master relaxation curve parameters of ISAC and AC layers for viscoelastic modeling are presented in Table 2.

Table 4. Tensile Stresses in 101.6 mm (4 in) Thick AC Overlay

Computed Tensile Stresses, kPa (psi)					
At the end of cooling cycle		Regular Mix (PG 58-22)		Modified Mix (PG 64-28 SBS)	
Subgrade Modulus of 206.7 MPa (30 ksi) - **Frozen Subgrade**		With ISAC	Without ISAC	With ISAC	
Top of overlay	Thermal	1910 (277)	1522 (221)	201 (29)	N/A*
	Thermal + Traffic	-17 (-2)	-41(-6)	-1230 (-179)	
Bottom of overlay	Thermal	–115 (-17)	545 (79)	-1 (0)	
	Thermal + Traffic	623 (90)	1620 (235)	701 (102)	
Subgrade Modulus of 34.45 MPa (5 ksi) - **Weak Subgrade**		With ISAC	Without ISAC	With ISAC	Without ISAC
Top of overlay	Thermal	1901(276)	1924(279)	170 (25)	142 (21)
	Thermal + Traffic	437 (63)	-343 (-50)	-1368 (-199)	-1982 (-288)
Bottom of overlay	Thermal	-115 (-17)	734 (107)	3 (0.4)	760 (110)
	Thermal + Traffic	756 (110)	2192 (318)	829 (120)	2232 (324)

Note: Cooling cycle of January 20-21, 2000 and a static single tire load of 40 kN (9 kips) were used in calculations.
*Analysis was not conducted for this case.

As reported in Table 4, the weaker subgrade led to increased tensile stresses in the bottom of the asphalt overlay as a result of increased layer bending. However, the increment for overlays with ISAC treatment was not high. The overlays without ISAC treatment had very high tensile stresses at the bottom of the overlay in the combined load case. Finally, using modified asphalt mixtures can reduce tensile stresses at the top of overlay, but critical combined stresses (temperature plus load) in the overlay above the PCC joint were not significantly improved as a result of polymer modification (PG 64-28) based upon the analyses conducted in this study.

Conclusions and Recommendations for Future Study

Based upon the results presented herein, the following conclusions may be drawn:

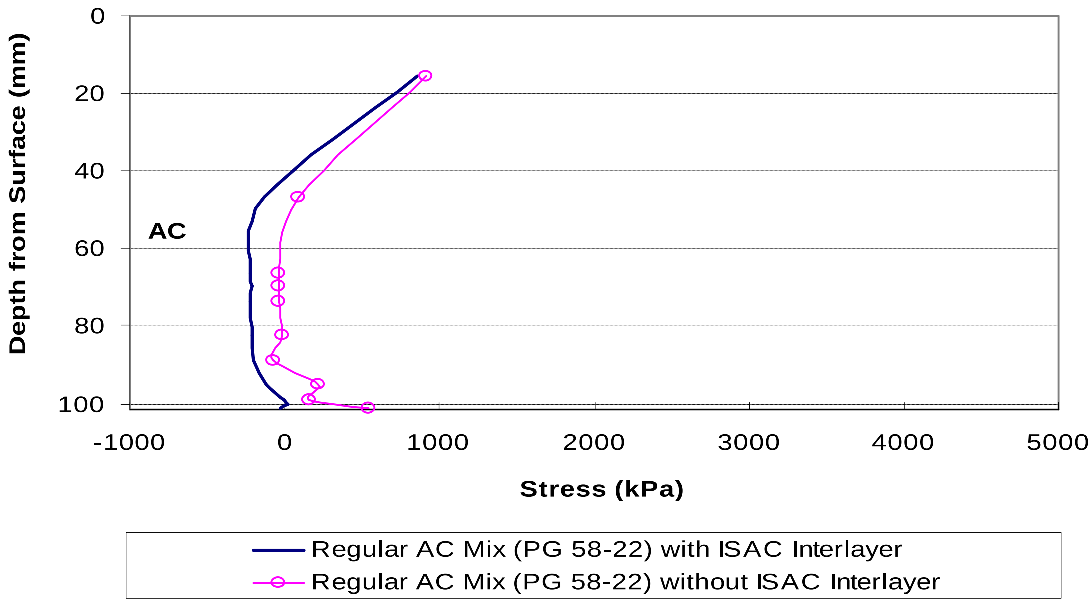
- The use of a base-isolating interlayer such as ISAC can significantly reduce temperature- and load-related stresses in the bottom of an AC overlay.

- Subgrade modulus had a very significant effect on critical overlay responses for the RNAC pavement structure (PCC on subgrade); therefore, careful estimates of subgrade modulus are required for prediction of overlay response.

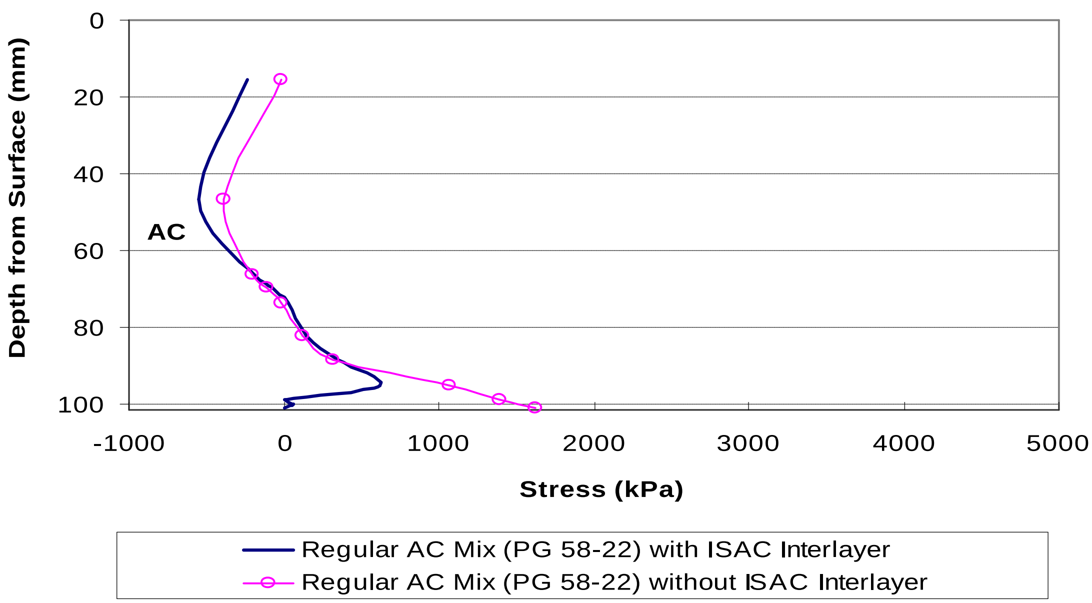
- Using modified asphalt mixtures can reduce tensile stresses at the top of overlay, but critical combined stresses (temperature plus load) in the overlay above the PCC joint were not significantly improved as a result of polymer modification (PG 64-28) based upon the analyses conducted in this study. However, benefits of polymer modification may be more apparent when fracture is incorporated into future models.

- For overlay response modeling, joint load transfer modeling did not appear to be an important modeling consideration. However, for models involving reflective crack simulation (fracture), joint load transfer may be a more important consideration.

The study presented here was limited to two slabs due to computational power and nonlinearities in the model. In the future, it is recommended that the domain size be increased to account for the boundary effects of additional adjacent slabs. Also, more mesh refinement around joints is strongly recommended to increase computational accuracy. On projects with heavier aircraft traffic and load levels, reflective cracking also will be strongly affected by shear stresses in the vicinity of joints and cracks. A more thorough analysis of shear stress responses at RNAC can be found in Bozkurt (2002). Finally, it is clear that untreated overlay systems and many treated overlay systems in cold climates will eventually develop reflective cracking. For a true mechanistic overlay design, the ability to consider crack propagation (e.g., fracture analysis) is desirable. The response modeling presented herein will provide a foundation for further study in this area.



a) End of Cooling Cycle, Thermally-Induced Stresses



b) End of Cooling Cycle, Stresses Under Combined Loading (Thermal + 40 kN [9 kip] Vertical Tire Load)

Figure 6. Tensile Stress Profile in PG 58-22 Overlay Under Critical Cooling Event, 206.7 MPa (30 ksi) Subgrade Modulus

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