

Response and Performance Of Thin Bonded Rigid Overlays Subjected To Accelerated Pavement Testing

Stefan Romanoschi¹, Cristian Dumitru² and Andrew Gisi³

ABSTRACT

The thirteenth full-scale Accelerated Pavement Test (APT) experiment at the Civil Infrastructure Laboratory (CISL) of Kansas State University aimed at determining the response and the failure mode of thin concrete overlays. Four pavement structures were built and tested in this experiment: two Thin Concrete Overlays (TCO) pavements, having 100 and 150 mm thick overlays constructed on top of a 125 mm thick PCCP and, two Thin Whitetopping (TWT) pavements, with 100 and 150 mm thick PCC overlays constructed on top of 125 mm hot-mix asphalt layer. The pavements were equipped with instrumentation to measure the strains at selected locations in each PCC overlay. Each of the four pavements was loaded with approximately two million passes of the CISL APT machine, under in-door ambient temperature conditions. No moisture was added to the pavements. Response measurements and performance evaluations were performed at about every 100,000 passes.

Due to the effect of wheel loading, the TCO pavements failed due to the loss of support underneath the concrete slab. No loss of bond between the PCC overlay and the supporting slab was observed. The 100 mm TWT exhibited a transverse fatigue crack at the middle of the slab, while the 150 mm TWT exhibited no cracks at the end of testing. The theoretical strains in the concrete overlays at the locations where instrumentation was installed were computed with the ANSYS Finite Element Method (FEM) software. It was found that the magnitude and shape of computed strains matched well those of the strains measured before any APT loads were applied. It was, therefore, concluded that the three-dimensional finite element model built and the assumption made (linear elastic materials, fully bonded overlays) can estimate accurately the response of TWT and TCO pavements under wheel loading and therefore, can be used for predicting the performance of thin concrete overlays.

Keywords: thin concrete overlays, pavement response, fatigue cracking

Conference Topic selected: Modeling and analysis of pavement systems

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Even after fifty years of experience accumulated with the construction of Portland Cement Concrete (PCC) overlays on existing distressed rigid and flexible pavements, the construction and design procedures for these overlays must be optimized. The two major PCC overlay types that are used to rehabilitate distressed PCC pavements are bonded and unbonded overlays. Unbonded overlays are effectively used to strengthen highly distressed Jointed Plain Concrete Pavement (JPCP) and Continuously Reinforced Concrete Pavements (CRCP). They are designed based on the assumption that no bond exists between the overlay and the underlying existing pavement. Bonded overlays are used when the underlying rigid pavement does not exhibit severe structural distresses and are designed on the assumption that the overlay and the underlying concrete slab are fully bonded and form a monolithic layer. Thus, bonded overlays are typically thinner than the unbonded overlays.

The technology of rehabilitating distressed hot-mix asphalt (HMA) pavements using a PCC overlay is called “whitotopping” in the United States. Conventional whitotopping has a thickness between 100 to 300 mm (4 to 12 inches) and has traditionally been designed based on the assumption that no bond exists between the PCC overlay and the distressed HMA layer (ACPA, 1998). The PCC overlay is designed as a new rigid pavement, with the HMA layer assumed to be a base layer with high stiffness underneath the concrete slab. The composite stiffness/support capacity of the existing pavement and the underlying subgrade is used to compute the design thickness of the PCC overlay. However, despite design assumption of no bond between the PCC overlay and the existing HMA layer, some partial bonding, which can contribute to the performance of the overlaid pavement, may occur (Smith et al., 2002)

A more recent but increasingly popular technology is the ultra-thin whitotopping (UTW), where the thickness of the PCC overlay is between 50 and 100 mm (2 and 4 inches). UTW is used on structurally sound asphalt pavements that exhibit mainly surface rutting. The overlay thickness is designed based on the assumption that the PCC overlay bonds well to the distressed HMA layer. Milling of the distressed HMA layer is normally done to ensure a good bond. The use of UTW is relatively new but has grown rapidly in the last decade, with over 200 projects built in 35 states since 1992 (Smith et al., 2002).

More recently, a new class of whitotopping, called thin whitotopping, has been used primarily on state highways. The thickness of this PCC overlay ranges from 100 -200 mm (4 and 8 inches). Joint spacing between 1.8 – 3.6 m (6 and 12 ft) is used. The overlay is designed assuming bonding between the existing HMA pavements and the new overlay (Tarr et al., 1998; Sheehan et al., 2004; Transtec, 2003). This assumption minimizes the need for additional thickness (Smith et al., 2002).

Kansas State University (KSU) has conducted a study to evaluate the performance of thin bonded PCC overlays on existing PCC and HMA pavements through accelerated pavement testing. The study was conducted at the Civil Infrastructure Systems Laboratory (CISL) in 2005. KSU, in cooperation with the Kansas Department of Transportation (KDOT), has developed the Accelerated Testing Laboratory (ATL) (Melhem, 1997), renamed CISL, in 2001. The facility allows full-scale accelerated tests on pavement structures using the APT machine as the loading device. The loading device is placed on a full-scale road structure constructed in a pit. A full-size truck axle passes over the pavement at about every five seconds, applying a total single or tandem axle load between 18,000 to 36,000 lbs (80 and 160 kN) depending upon axle used. Both single and dual tires, single and tandem axles can be accommodated in this system. About 100,000 passes are applied to the experimental pavement sections in a week, in bi-directional loading mode.

The advantage of using accelerated pavement test (APT) when compared to a field test is that the results of the comparative study can be obtained in the former in a few months. In a field test, the results are obtained after observing the behavior of the road test sections for a five-year period as a minimum. Also, in an APT test, some environmental factors and traffic loadings can be controlled. However, pavement performance evaluation using APT has three major limitations: a) the effect of the environment cannot be well simulated even though temperature can be controlled b) APT loading may differ from the vehicle loading provided by in-service traffic, in terms of speed and frequency (headway) of loading, lateral wheel wander and load spectra and, c) the effects of long term exposure

to water and extreme temperatures (e.g. freezing and thawing, water damage) and long term changes in material properties (e.g. ageing of asphalt binders) cannot be reproduced in an APT test.

CONSTRUCTION OF EXPERIMENTAL SECTIONS

To evaluate the performance of thin bonded PCC overlays on existing PCC and HMA pavements, four experimental pavement sections were constructed: two Thin White-Topping (TWT) sections and, two Thin Concrete Overlays (TCO) over PCCP sections. All pavements were 6 meters (20 ft) long and were constructed on the same clayey subgrade soil (AASHTO A-7-6).

To evaluate the TWT behavior, two pavement structures, having different thicknesses of concrete overlays, were constructed. The first experimental section was a 150 mm (6-inch) whitetopping placed on a 125 mm (5-inch) HMA pavement, and the second was a 100 mm (4-inch) whitetopping overlay on a 125 mm (5-inch) HMA pavement. The final pavement configuration is shown in Figure 1.

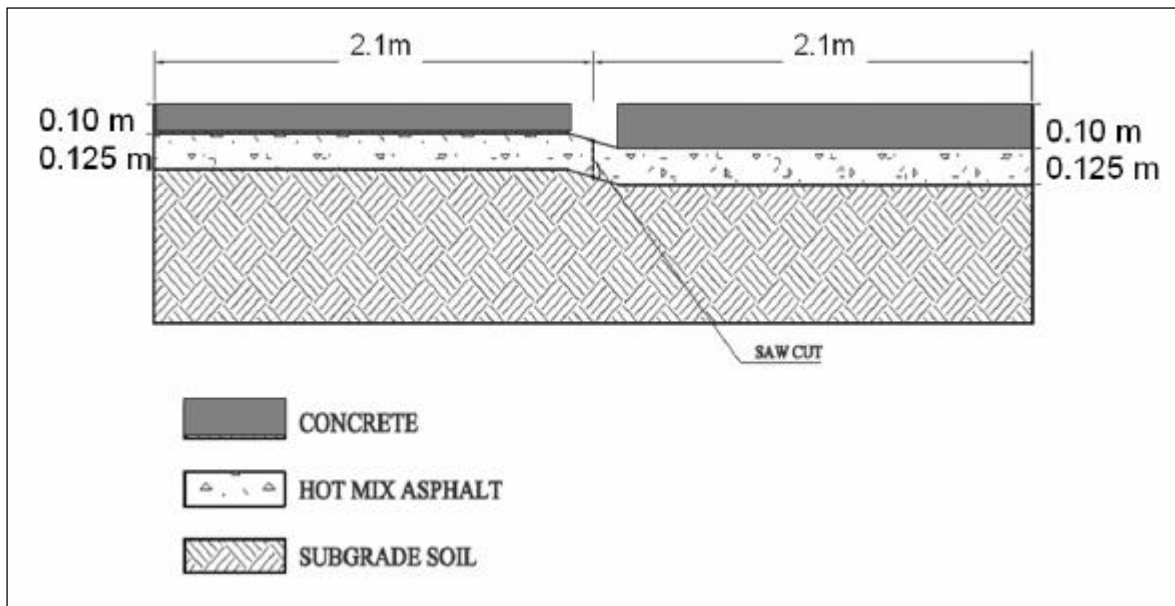


Figure 1 Schematic Configuration of the Thin White-Topping (TWT) Sections

The HMA layer was placed first on the compacted subgrade for both TWT lanes. Initially, the asphalt layer was constructed 1 inch thicker than the design thickness (125 mm). To avoid the influence between the two pavements, the asphalt layer was cut longitudinally before placement of the concrete layer, as shown in Figure 1.

To obtain an HMA layer that could represent a severely distressed layer, the asphalt layer was compacted at the lowest acceptable limit (92%). Also, full depth saw cuts were made in the asphalt layer as shown in Figure 3: a) two transverse cuts parallel to the concrete joints at a distance of 200 mm (8 in.); b) one longitudinal cut in the center of the wheelpath.

The performance of TWT is very sensitive to the bonding between the concrete and asphalt layer so the preparation of the interface was carefully performed. The HMA layer was milled 1 inch; then the surface was broomed and blown with compressed air. The macro-texture of the interface was achieved by milling, while the micro-texture was achieved by abrasive blasting (shot blasting). Before the concrete placement, the surface was again air blasted and wetted. Following the recommendations

found in previous studies and the common practices for whitetopping construction, no other preparation or treatment of the surface was performed.

The concrete layers were poured keeping a 100 mm (4 in.) gap between the lanes by placing vertical wood forms between the lanes. The concrete mix was designed for $4\pm 1\%$ entrained air and a 28 day compressive strength of 27.6 MPa (4,000 psi). The joints of concrete slabs on both lanes were sawn to one third of the depth, to obtain the final dimensions of the two slabs of 3 m x 2.1 m (10 ft x 7 ft) for the central slab, and 1.5 m x 2.1 m (5 ft x 7 ft) for the end slabs (Figure 3). No dowel bars were placed at the joints; their use is not recommended for PCC overlays thinner than 200 mm (8 in.) (Smith et al, 2002).

The TCO on PCC pavement sections were constructed in two stages: 1) 125 mm (5 in.) thick the concrete slabs with 25 mm (1 in.) diameter steel dowel bars at 0.3 m (1 ft) spacing were built over the compacted subgrade and were distressed at the joints with hydraulic thumpers; 2) the PCC overlay 100 or 150 mm (4 or 6 in.) thick was constructed on top of the distressed slabs (Figures 2 and 3).

To induce distresses in the concrete slabs, dynamic loads were applied at the joints using the steady state pulse equipment. The loading process was monitored by two programmable logic controllers, connected in closed loop with the hydraulic actuators, through a load cell and a servo-valve. The controllers monitored and maintained the magnitude and shape of the sine load. For all transverse joints, the dynamic loading caused transverse cracks in the two central slabs at about 0.6 m (2 ft.) away from the joints.

Before pouring the overlay, the concrete slabs were prepared by shot blasting to ensure a good texture and then air blasted to remove the dust. Based on common practices, the surface was wetted before the concrete overlay was poured. No dowel bars were placed at the joints; their use is not recommended for PCC overlays thinner than 200 mm (8 in.) (Smith et al, 2002).

The TCO overlays have the same dimensions as the initial concrete slabs. The concrete was vibrated with a small vibratory compactor, and finished with a vibratory screed. The final finishing was done manually, and then the pavements were textured by brooming. The joints in the overlays were cut to one third of the depth; the location of the cuts matched the joints of the initial slabs. Curing of concrete was done by water spraying and plastic sheeting.

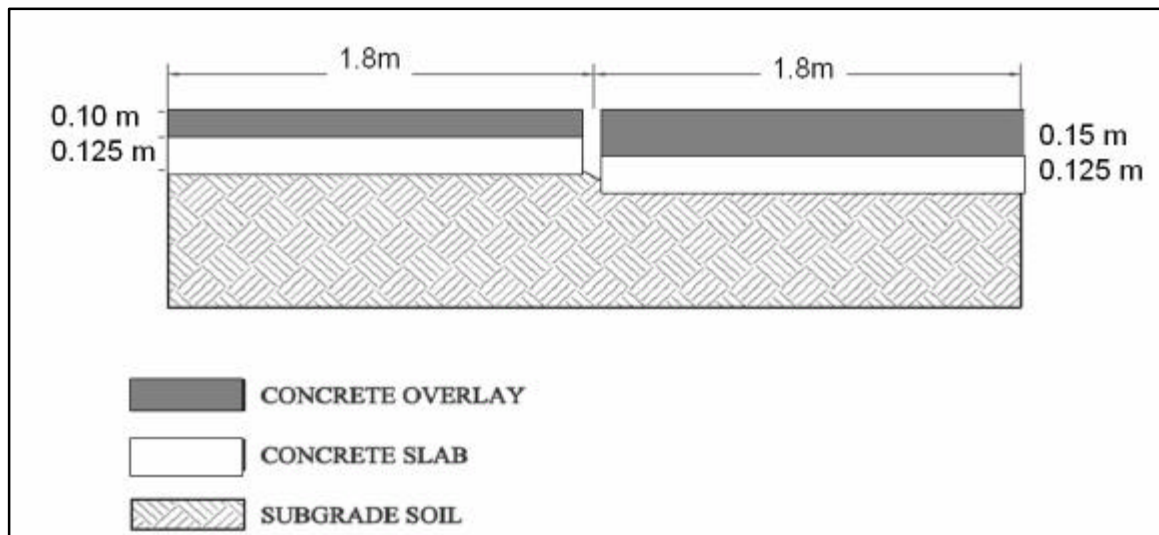


Figure 2 Schematic Configuration of the TCO Pavement Structures

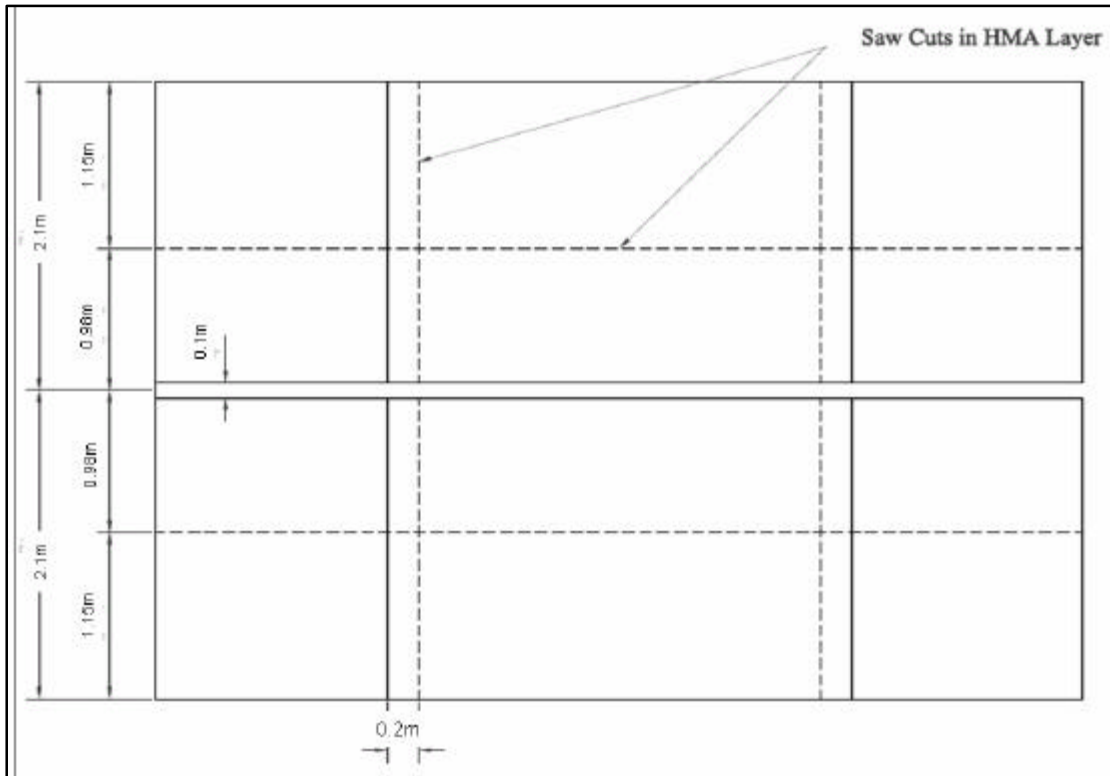


Figure 3. Top View of the TWT Pavement Sections

PAVEMENT RESPONSE INSTRUMENTATION AND ACCELERATED PAVEMENT TESTING

Strain gages and thermocouples were embedded in the PCC overlays pavement in the central slabs only to monitor the response of the pavement, as shown in Figure 4. The strain gages were installed in the same corresponding positions in both the TWT and TCO over PCC sections, at critical strain location: at the middle of the tied and untied joints, and at the corner of the slab (Figure 4). The placement of the strain gages was done before concrete paving; the strain gages were set in wire fixtures. Two gages were installed in each location: one gage at one inch from the top of the PCC slab, and one gage at one inch from the bottom of the concrete slab. Strain gages model Tokyo Sokkai PML-60-2L were used.

The APT testing was conducted under following conditions:

- The pavement sections were loaded in pairs with one wheel rolling over one of the two sections.
- The applied single axle load was approximately 115 kN (26 kips), equally distributed to the two pavements. The wheel load was monitored with load cells installed on each wheel;
- The lateral wander applied followed a truncated normal distribution, with the maximum lateral movement of 150 mm (6 in.).
- The testing was performed at ambient temperature. No water was added to the pavements during the APT loading of the two pavement structures
- A total of 2,000,000 passes were applied to each of the four pavement structures.

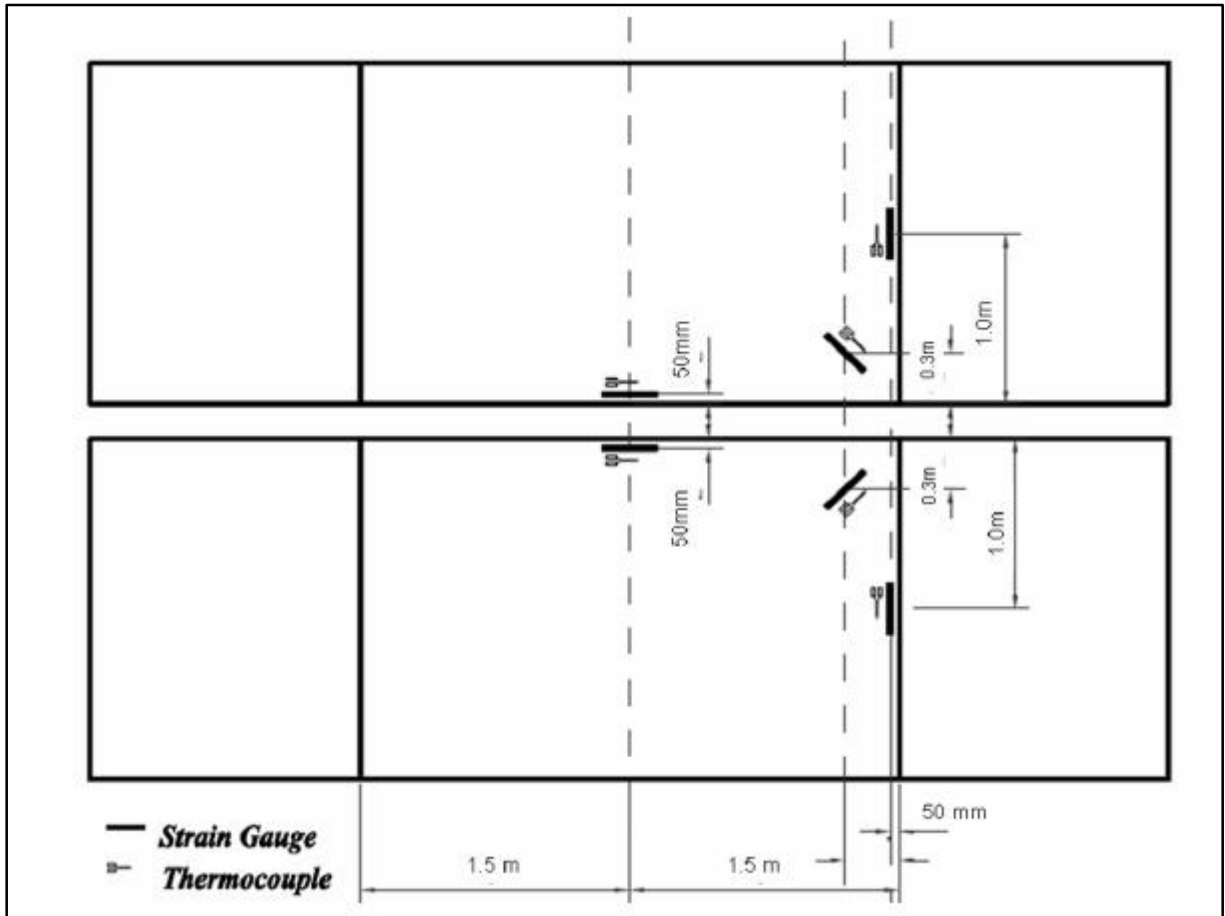


Figure 4 Instrumentation for the Experimental Pavement Structures

PERFORMANCE OF THE PCC OVERLAYS

The 100 mm TWT pavement section exhibited cracking. One transverse crack developed in the central slab, close to the middle of the slab, at about 400,000 passes of the APT machine. No significant joint faulting was recorded. At the end of loading (2.0 million passes), the 150 mm TWT pavement section exhibited no cracking or significant joint faulting. Due to budget and time constraints it was decided to stop loading on the TWT sections.

The TCO pavement sections exhibited cracking. One transverse crack developed in the central slabs of both pavement sections, at about 1/3 in length for the West joint, at 1.1 million passes of the APT machine in the 100 mm TCO pavement section and, at 1.7 million passes in the 150 mm TCO pavement section. Several other cracks developed after that only in the 100 mm TCO pavement section. No significant joint faulting was recorded (Figure 5).

At the end of the loading phase of the experiment (after 2,000,000 load cycles), 100 mm diameter cores were extracted from central slabs of TCO on PCCP pavements at several locations near the edges and the corners of the slabs. The examination of the cores showed no de-bonding between the concrete layers. It was thus assumed, and confirmed by the modeling of the pavement response, that the failure of these pavement sections was due to the loss of support underneath the transverse joints, that lead to transverse cracking.

PAVEMENT MODELING

The commercially available software program ANSYS was used to estimate the theoretical response of the four experimental sections. ANSYS has powerful capabilities of modeling structures. However, the version employed could only handle meshes with less than 32,000 nodes.

The 3 D FEM model was built for the each of the four sections separately. Each model was developed as a three layer pavement system, corresponding to the three layers: concrete overlay, existing pavement (asphalt or concrete slabs) and subgrade soil. Because the geometry and loading were symmetric, the model was developed for only one half of the structure in order to obtain a finer mesh. To model the joints in overlays and in the concrete layer an equivalent interlayer was used. The cracks in the asphalt layer were also taken in consideration in asphalt layer geometry.

The measurements on the TWT pavements showed that the strains at the top and the bottom of the concrete layer, measured above the saw cut in the asphalt layer, have the same absolute value. This indicates that the subgrade layer has no contribution to the horizontal equilibrium of this vertical section and that neither bonding nor friction developed between asphalt layer and subgrade soil. To reflect this finding, an orthotropic interlayer having no stiffness in horizontal directions and the same modulus of elasticity and Poisson's ratio for the vertical direction as those of the subgrade soil was used to model the ideal slip between the asphalt layer and the subgrade layer. The use of the contact elements instead of the interlayer for modeling of this interface was also considered, but computational problems were encountered.

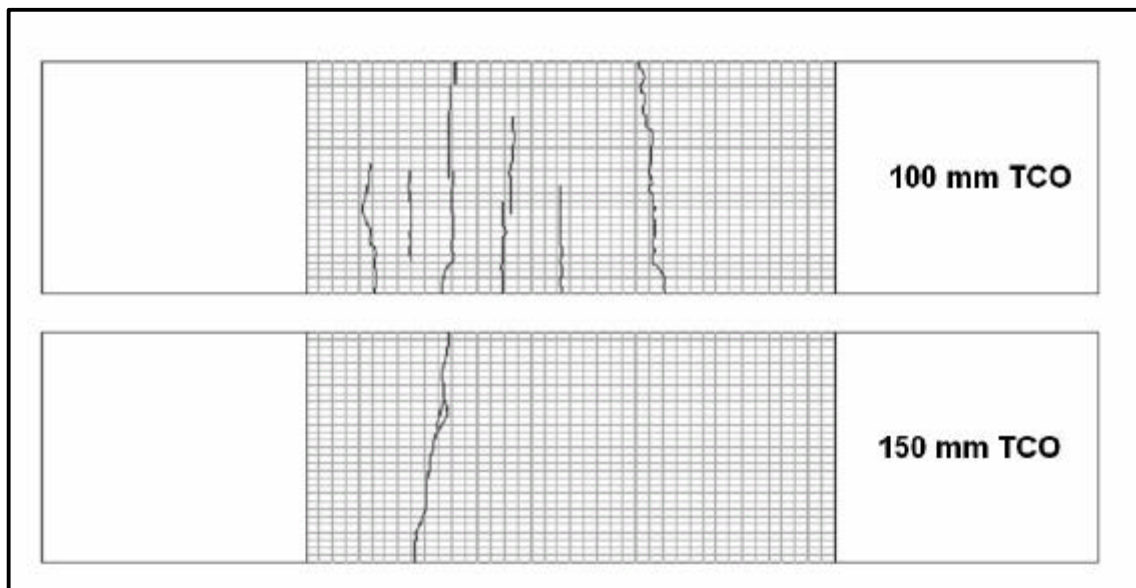


Figure 5 Crack Mapping on TCO Overlays after 2,000,000 passes

The concrete and the asphalt layers were meshed using a 20 nodes 3-D brick element with (SOLID186). The aspect ratio of 4:1 gives accurate results for this type of element. The mesh was refined around the discontinuities created by joints and close to the points where strains were measured. A coarser mesh with 8 nodes 3-D brick elements (SOLID45) were used for the soil layer.

The nodes on the bottom of the subgrade (the floor of the pit) were fixed in all directions. The nodes on the sides of the subgrade layer bordered by the pit were restrained in the direction of the pit walls. The nodes in the plane of symmetry were allowed to move only in vertical direction for a symmetrically loaded structure.

Two models were developed for each pavement section:

- One model for initial condition, considering the cracking in the initial concrete slab, and full support used as reference for damage estimation.

- One model considering the cracks in the concrete slab and different lengths of loss of support, in order to evaluate the loss of support.

All materials were considered as linear elastic. The modulus of the concrete in the existing slabs and overlays were assigned based on the results of the compressive strength measured at 28 days. The modulus of the asphalt concrete and subgrade soil were assigned based on the results of dynamic modulus test and triaxial resilient modulus test, respectively, performed in the laboratory. The modulus of PCC concrete was estimated based on the uniaxial compressive strength measured at 28 days (Romanoschi, 2007).

The loading was applied to the model at different positions along the wheel-path as a pressure on the upper faces of the elements at the surface of the PCC overlays. The longitudinal positions of the load were chosen according to the shape of the strain diagram; closer points were selected for locations that caused the peaks of the transverse and longitudinal strains. The modeled load was assumed to be rectangular, uniform over the applying surface, and equal to the tire inflation pressure.

The detailed description of the numerical simulation and comparison with measured values are given by Romanoschi (2007). Figure 6 shows the comparison of theoretical and measured strains corresponding to the strain gage measuring transverse strain at the top of the slab in the 100 mm TWT pavement. The data in the legend indicate the number of passes at which the strain measurements were recorded, in thousands. The maximum values of the measured transverse strain are close to the computed values (difference less than 8%), showing no significant influence of distresses on the strain occurred during the experiment. The peak values of the measured transverse strains remained stable during the accelerated loading.

Figure 7 shows the comparison between the theoretical longitudinal strain and measured longitudinal strain corresponding to the strain gage measuring transverse strain at the top of the slab in the 100 mm TWT pavement. The theoretical strain values are very close to the initially (0 load repetitions) measured strain values. The peak values of the measured longitudinal strain were increasing between 0 and 400,000 load repetitions, and then they drop significantly due to the cracking of the PCC overlay observed between 400,000 and 500,000 load repetitions.

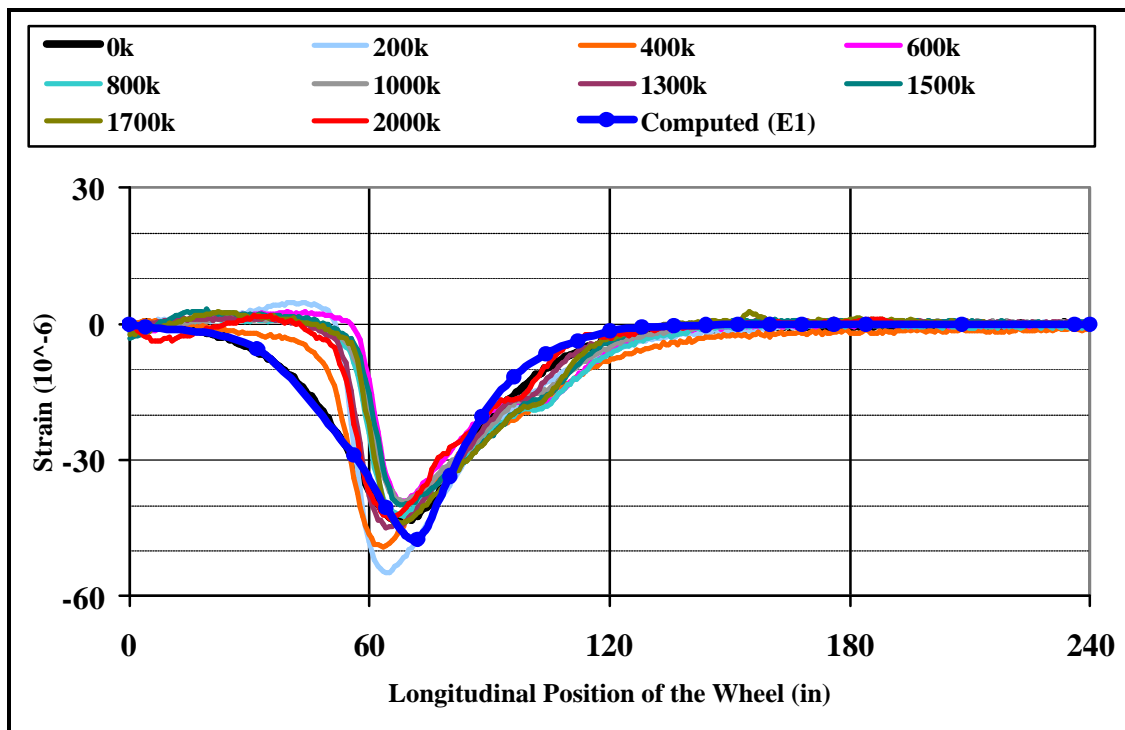


Figure 6 Measured vs. Computed Transverse Strains: 4in. TWT Pavement

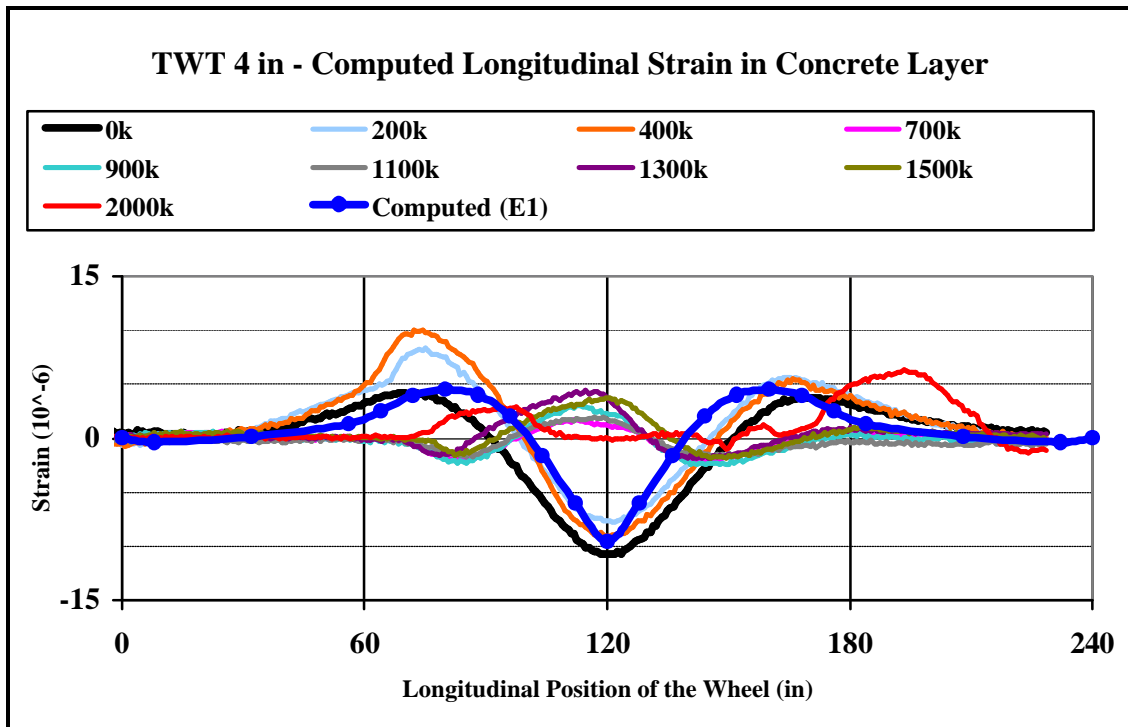


Figure 7 Measured vs. Computed Longitudinal Strains: 4in. TWT Pavement

The increase of the tensile peaks of the strain between 0 and 400,000 load repetitions was attributed to the loss of support under the joint since no de-bonding between PCC and HMA was observed at the end of loading. The FEM model was modified for different loss of support distances from the joint (0 to 1 meter) to compare the computed longitudinal strains with the measured strains by this gage. A regression equation relating the maximum tensile values of the longitudinal strain measured by this gage and the length of loss of support was then developed. The regression equation was used to back-estimate the loss of support distance was for the period between 0 and 400,000 load repetitions. It was found that the length of the loss of support increased between 0 and 200,000 load repetitions, and then stabilized to a distance of 580 mm at one transverse joint and at 360 mm at the other transverse joint.

The procedure for estimation of the length of loss of support was applied to the 150 mm TWT. The evolution of the estimated length for the loss-of-support is plotted in Figure 8 for each joint. The figure shows that the length of the loss-of support of the 150 mm TWT pavement increased in the first 400,000 passes of the APT machine, same as to that of the 100 mm TWT section, and then it remained unchanged until the end of loading.

The modeling of the transverse cracks in the concrete slab below the 150 mm TCO overlay allowed the estimation of the evolution of the length of loss-of-support. Figure 8 shows that the length of loss-of-support increased faster under the TCO pavement than under the TWT pavements. This was expected, since the subgrade underneath the PCC slabs was softened when the pulsating loading was applied to damage the slabs.

The FEM model was modified and run again for the length of loss of support estimated for 1,200,000 load repetitions. It was found that the maximum computed longitudinal strain at the upper fiber and the edge of the slab was very close to the measured strain at that location. When the longitudinal strain at the top of the overlay on the wheelpath was computed for the load positioned at the joint (critical location), it was also found that the maximum longitudinal strain caused by critical

load developed where the transverse crack occurred in the 150 mm TCO overlay (Figure 9). This suggests that the assumption made in the development of the finite element model were correct.

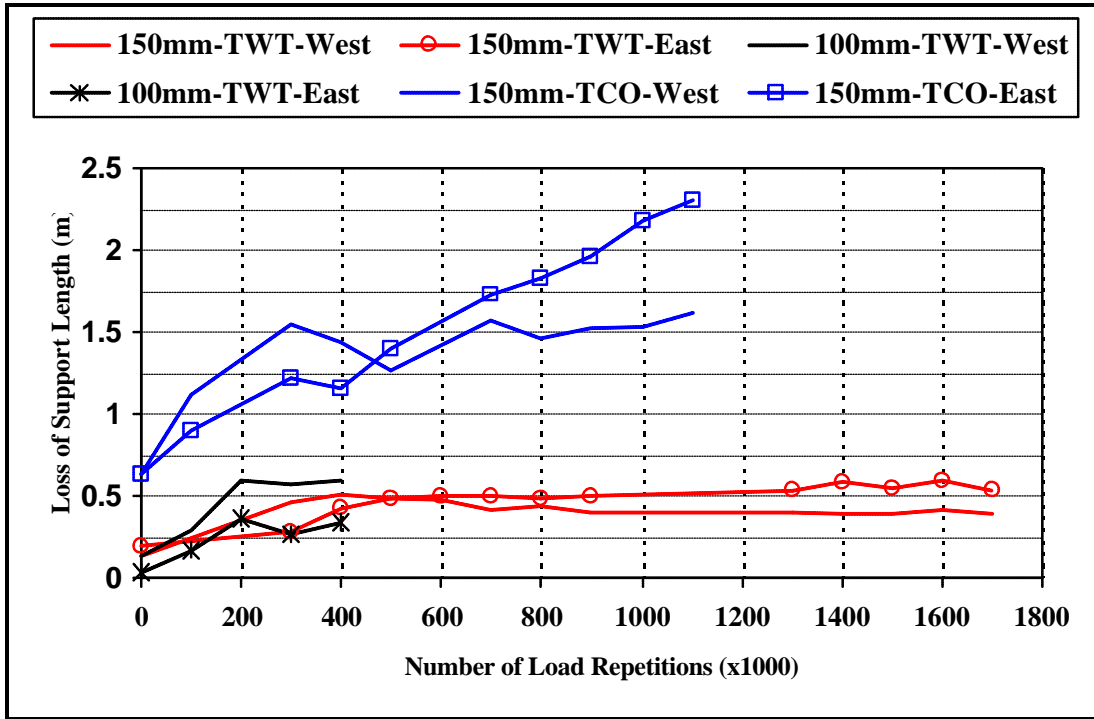


Figure 8 Back-estimated Length of the Loss of Support

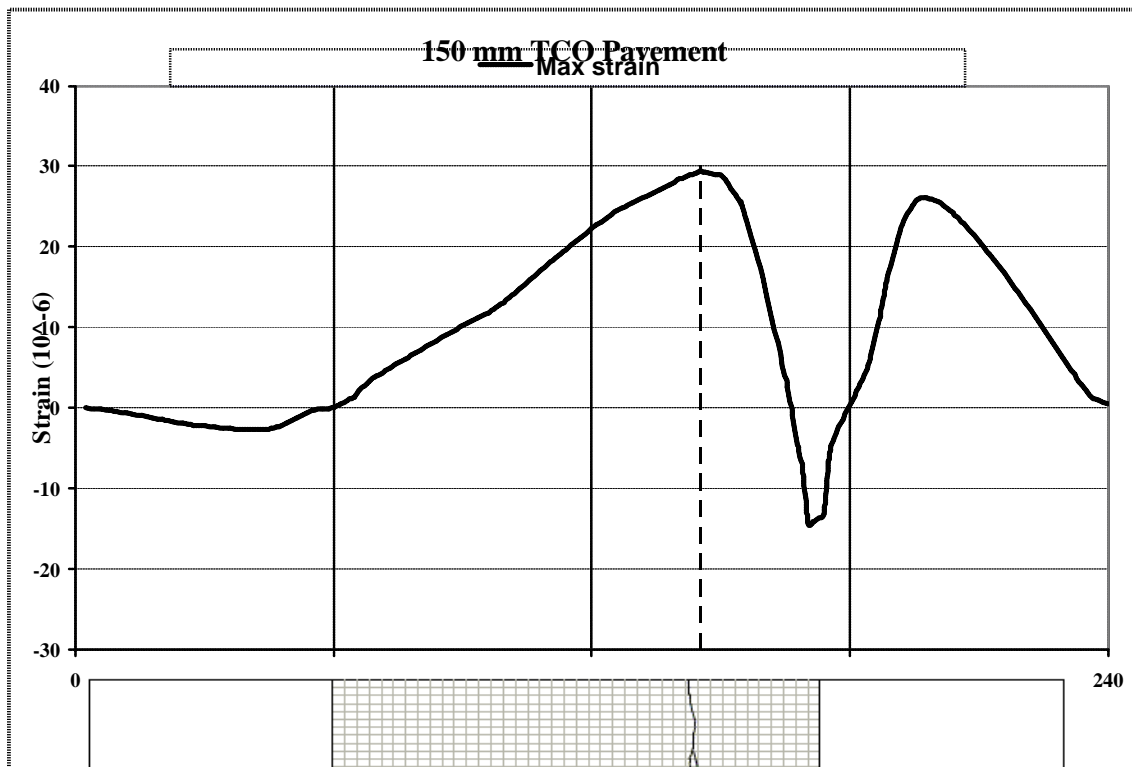


Figure 9 Location of the Maximum Tensile Strain and of the Transverse Crack

CONCLUSIONS AND RECOMMENDATIONS

This research study aimed at evaluating the performance of thin bonded PCC overlays on existing PCC and HMA pavements through accelerated pavement testing (APT) and to determine the failure modes of these pavement structures. The study was conducted at the Civil Infrastructure Systems Laboratory (CISL) of Kansas State University. Four pavement sections tested in the thirteenth experiment carried out at CISL:

- Two Thin Concrete Overlay (TCO) pavements, having 100 and 150 mm (4 and 6 in.) thick overlays, were constructed on top of a 125 mm (5 in.) thick PCCP pavement built without a subbase layer and with distress at the joints from cyclic loading applied by a thumper system.
- Two Thin Whitetopping (TWT) pavements, having 100 and 150 mm (4 and 6 in.) thick overlays, were constructed on top of a 125 mm (5 in.) hot-mix asphalt (HMA) layer built directly on the clayey subgrade. Longitudinal and transverse full-depth cuts were made in the HMA layer before placing the PCC overlay to simulate longitudinal and transverse cracking that would be present in a distressed flexible pavement.

Appropriate construction methods were applied during construction to ensure optimum bond between the overlays and the supporting layers. The pavements were equipped with instrumentation to measure the strains in selected locations in each PCC overlay and the parameters that affect the mechanical characteristics of the material (moisture in subgrade soil and temperature in the asphalt layer). Each of the four pavements was loaded with two million passes of the CISL APT machine. Response measurements and performance evaluations were performed at about every 100,000 passes of the CISL machine.

Three of the four pavements had a good performance during the APT test; the 100 mm (4 in.) TCO on PCCP pavement developed a transverse crack after 1,100,000 load repetitions; the 150 mm (6 in.) TCO on PCCP pavement developed a transverse crack after 1,700,000 load repetitions; the 150 mm (6 in.) TWT pavement experienced no cracking after 2,000,000 load cycles. The 100 mm (4 in.) TWT pavement exhibited the first crack after 400,000 load cycles. No significant joint faulting was recorded. Cores taken at several locations in the TCO pavements showed that no loss of bond developed between the two PCC layers.

Theoretical values for the strains developed at the locations where the strain gages had been placed were computed using a finite element model developed using the ANSYS general purpose finite element software. The FEM considered all materials linear elastic and a perfect bond between the overlays and the supporting layers.

The transverse joints between the slabs were modeled using orthotropic elements. The steel dowel bars were modeled using 3-D brick elements; one half of each bar was allowed to slip from the surrounding concrete. No temperature or moisture gradients were modeled since the APT experiment was conducted without temperature and moisture changes. The position of the wheel load was changed along the slab to determine the changes in the values of the strain at the gage location when the wheel traveled along the pavements.

The comparison between the measured and the computed strains was done by looking at the signal of the measured strains and the curve obtained from the strain values estimated under the moving wheel load. The corresponding magnitude of the maximum strains and strain signal shapes were compared. It was found that the magnitude and shape of computed strains matched well the magnitude and shape of strain signals measured by the installed strain gages before any APT loading was applied. This indicated that the FEM analysis and the assumptions made modeled the undamaged composite pavement structures well.

The FEM model was then modified to include loss of support under the joint. Then the strains at the top fiber at the mid-span of the slabs were computed for several length of the loss of support area, which was considered to be the same along the transverse joint. The length of the loss of support area was estimated by interpolation from the obtained computed strains and the values of the

corresponding strains measured during the APT loading. The evolution of the length of loss of support underneath the joints with the number of applied passes of the CISL machine was thus estimated.

The major findings of this study are:

- The 3D finite element model built and the assumption made (linear elastic materials, fully bonded overlays) can predict very well the response of TWT and TCO pavements under wheel loading. This suggests that the calculation of pavement response using 3D finite element can be used effectively to estimate the effect of wheel loading on the performance of thin concrete overlays.
- Under the wheel loading applied by the APT machine, all pavements experienced loss of support under the joints which caused the increase of the maximum longitudinal strains at the mid-span of the slabs. This suggests that the loss of bonding between the PCC overlays and the existing pavement may be attributed to environmental factors (high daily or seasonal temperature gradients, presence of water at the interface, etc.).
- The length of the loss of support can be successfully back-estimated from the values of the strains computed with the FEM model. The length of loss of support increased continuously up to a certain value after which it remained constant. At this point the flexural stiffness of the slabs prevented a further consolidation of the subgrade soil underneath the joints.

The following recommendations can be made from this research:

- The FE model with the assumption of linear elastic materials should be used for the effective estimation of the response of TCO and TWT pavement structures under wheel loading.
- The thin PCC overlays should be modeled as fully bonded to the under laying layer; TCO and TWT pavement structures should be modeled as monolithic structures.
- In the modeling of the deterioration of TCO and TWT pavements, it should be assumed that the length of loss-of-support increases with the applied traffic loading and then remains constant. Field studies on full-scale overlaid sections should be embedded with strain gages to measure the evolution of strain with the applied traffic. Finite element models should be used to estimate the evolution of the length of the loss of support from the measured strain data. The effect of material type and magnitude of the vertical stresses at the top of the subbase layer on the evolution of the length of loss of support should be studied.
- Further studies should be conducted to better understand the behavior of these structures. The effect of the environment, subbase material type and thickness of the existing distressed pavement on the performance of thin PCC overlays should be further investigated.

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