

Evaluation of Formulae in PCA Design Approach for Ultra-Thin Whitetopping over Composite Pavement Section under Accelerated Loading

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Abstract

Ultra-thin whitetopping (UTW) is a popular pavement rehabilitation technique that involves the placement of a thin layer of portland cement concrete (PCC) over a distressed hot mixture asphalt (HMA) pavement. The new pavement is essentially a thin bonded concrete overlay. Thus, its composite performance depends on the stiffness of the underlying pavement layers. One objective of this project is to develop models that can be used for the mechanistic design of UTW pavements. Additionally, UTW performance models will be developed.

To accomplish this task, a UTW pavement test section was constructed in the Indiana Department of Transportation – Purdue University Accelerated Pavement Testing facility. The pavement section consisted of a UTW overlay of an existing composite pavement section (thin HMA layer over a PCC layer). The performance of the UTW overlay was monitored using destructive and non-destructive methods, including measurements of strain, strength, and pavement stiffness.

PCA design guidelines were investigated to assess their applicability to cases of UTW placed over composite pavements. Preliminary results indicate that the equations may be able to be used if the concept of an equivalent thickness is employed. Further, the effective radius of relative stiffness calculated from falling weight deflectometer testing of in-situ pavements may be able to be modified to account for the proposed UTW overlay and input into the design equations.

Introduction and Problem Statement

Ultra-thin whitetopping (UTW) is a pavement rehabilitation technique that involves the placement of a thin Portland Cement Concrete (PCC) overlay, 2 inches (50 mm) to 4 inches (100 mm) thick, over a distressed Hot Mixture Asphalt (HMA) pavement. Typically, the HMA pavement is milled and cleaned which helps to create a bond between the existing HMA pavement and the PCC overlay. The bond

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between the two layers promotes composite action of the pavement section. This composite action allows for the reduced thickness in the PCC layer. Additionally, a short joint spacing is typically used, which reduces the PCC flexural and curling stresses.

Traditionally UTW has been used to rehabilitate full depth HMA pavements. However, research has noted the need to consider the use of UTW over composite pavements (1). Additional research (2,3) indicates that performance of UTW may be different when used as a rehabilitation technique for existing composite pavements than when used over a full depth HMA pavement.

Mechanistic procedures have been developed to aid in the design of UTW overlays. In the procedure developed by the PCA, equations predicting critical stresses and strains were developed based on parametric analysis and validated with field data (4). Failure criteria were employed to consider PCC fatigue under corner loading, and asphalt fatigue under joint loading. The procedure also took into account temperature induced stresses and strains. The design procedure aids in the selection of overlay thickness and joint spacing. The procedure was developed for the UTW overlay of HMA pavements supported by a subgrade with a given modulus of subgrade reaction, k . As previously mentioned, this design method was validated using field data. However, the use of these guidelines to design a UTW overlay of a composite pavement has not been yet established. Traditionally, a composite section consists of a PCC layer constructed over a subbase or directly on top of the subgrade and overlaid with HMA. Therefore, investigation should be performed to allow for the incorporation of the composite action of the full pavement section in the current PCA design method.

This paper addresses the current PCA design guidelines in light of their use for design of UTW pavements over existing composite pavements (HMA overlay over PCC pavement) rather than their traditional use (HMA over base material). Two different approaches are employed: an equivalent thickness approach and a method using in-situ FWD testing.

Testing Facility

Testing was conducted at the Indiana Department of Transportation (INDOT) – Purdue University Accelerated Pavement Testing (APT) Facility located at the INDOT Research Division in West Lafayette, IN. The APT is housed in approximately 2,000 square feet (185 square meter) environmentally controlled building. The APT facility is composed of test pit, a loading mechanism and control and monitoring equipment.

The APT testing area consists of a 20 foot (6.1 m) wide by 20 foot (6.1 m) long by 6 foot (1.8 m) deep test pit. The pit allows the placement of full depth pavements

The operator control room houses both the software and hardware used to fully control the APT operation. The room is currently equipped with three personal computers networked together. The first computer is used to fully control and operate the APT, the second computer is used for data collection/reduction and the third computer is used for monitoring and diagnoses of the APT hardware.

The APT carriage, which can be equipped with either a full-size, dual-tire truck wheel or a super-single, half-axle assembly, is cable driven by a 30 hp motor and a 50 hp drive. This setup allows speeds up to 5 mph (8 kph). The APT loading mechanism uses a system of four air pistons that maintain a constant force up to 20,000 lbs (89 kN). This load can be programmed either in static or dynamic modes. These cylinders also allow the wheels to be raised and returned to the start-up position of the test pad in one direction type of testing.

Construction and Evaluation of UTW Test Sections

For the construction of the composite pavement, the APT test pit was completely emptied and cleaned. The test pit was filled with 46 inches (1.2 m) of pea gravel and an 8 inch (200 mm) layer of dense graded crushed limestone was placed over the pea gravel. Next a 6 inch (150 mm) thick plain PCC layer was placed over the crushed stone. The PCC layer was then overlaid by four HMA layers totaling 12.0 inches (300 mm). The HMA layers were Superpave intermediate and surface mixtures with PG 64-28 binder. 2.5 inches (63 mm) of the HMA layer were milled to allow the construction of the UTW layer. This left the HMA layer approximately 9.5 inches (237 mm) thick. Previous work (1) has suggested that UTW does not bond well to new HMA. However, sounding done after construction confirmed that bonding was achieved.

Pavement Instrumentation. In order to evaluate the strains throughout the depth of the pavement, strain gages were placed in the PCC, HMA, and UTW layers. Three different types of strain gages were used in this experiment. The first gage type, Texas Measurements embedment-type gages (PML-60-2L), was embedded in the UTW and PCC layers at a level of 0.5-inches (12 mm) below the surface and at 0.5-inches (12 mm) from the bottom of the layer. The second gage type, Texas Measurements surface-mount-type gages (WFLM-60-11-2LT), was glued to the surface of the milled HMA. The third type of gage was a CTL (ASG-152) HMA embedment gage that was placed at the bottom of the HMA layer. These gages were connected to a Vishay System 6000. This system has the ability to take individual strain readings at a very high sampling rate. The high frequency of data sampling enabled the recording of the dynamic strains as the wheel passed over the pavement. Dynamic strain data were collected after every 2500 load applications. The layout of the strain gages is presented in Figure 1. A previous study (2) compared the strain readings obtained by this system and using the Texas Measurements gages to the strains expected using finite element analysis. The study concluded that the measured strain readings and the finite element calculated strains were of similar magnitudes for both the asphalt and the concrete.

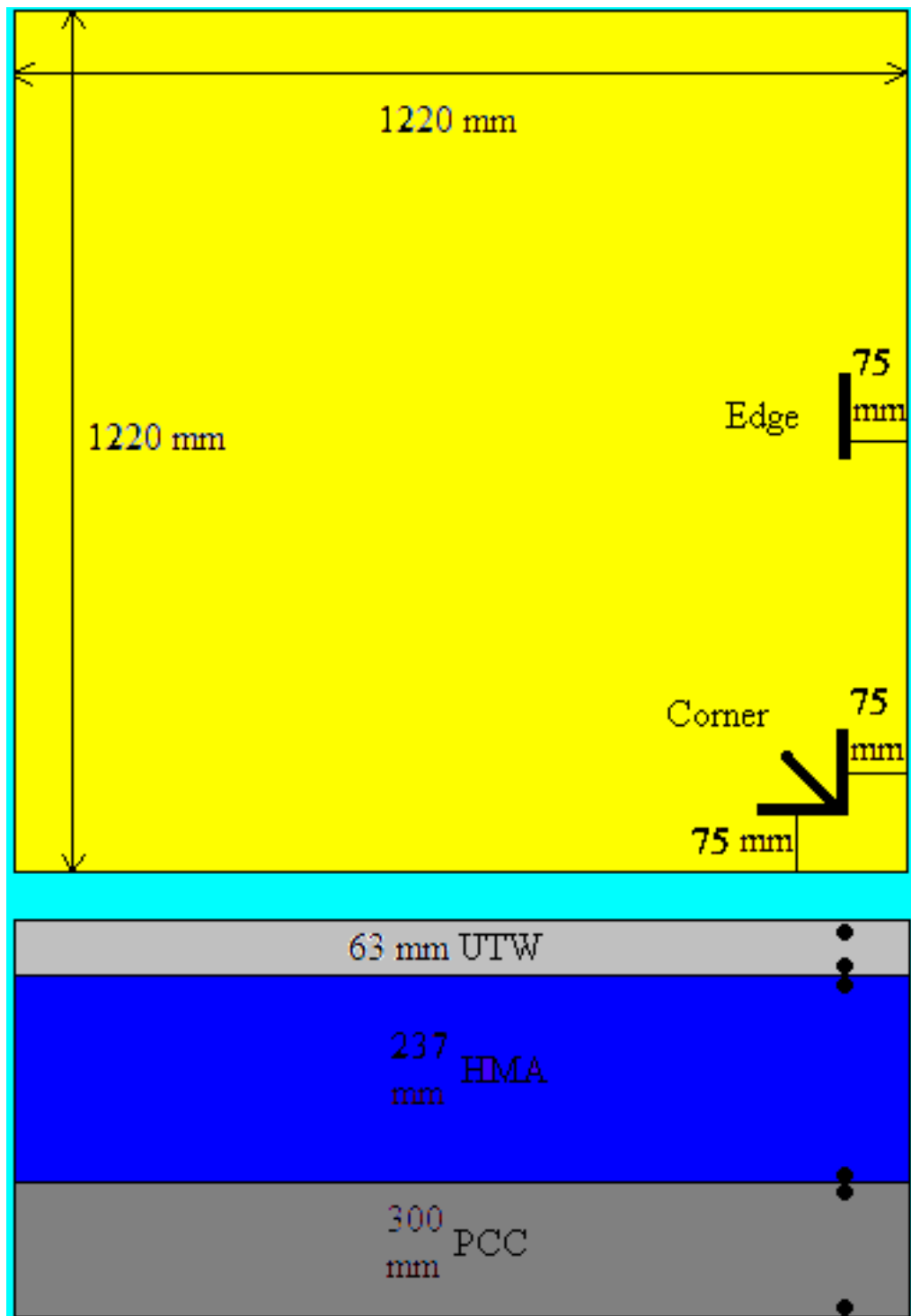


Figure 1. Instrumentation layout.

UTW Concrete Mixtures. Three different UTW concrete mixtures containing Class C fly ash, with a target water-cementitious material ratio of 0.36, were used for the UTW in this experiment. The UTW concrete mixture designs are presented in Table 1.

Table 1. UTW Concrete Mixture Designs.

Material	kg/m³
Cement (Type I)	375
Fly Ash	70
Coarse Aggregate	1000
Fine Aggregate	750
Water	160
HRWR	3-4 l/ m ³

(a) Mixture 1

Material	kg/m³
Cement (Type III)	375
Fly Ash	70
Coarse Aggregate	1000
Fine Aggregate	750
Water	160
HRWR	3-4 l/ m ³

(b) Mixture 2

Material	kg/m³
Cement (Type I)	375
Fly Ash	70
Coarse Aggregate	1000
Fine Aggregate	750
Water	160
HRWR	3-4 l/ m ³
Fibers	

(c) Mixture 3

Note: 1kg/m³ = 0.59 lbs/cyd

Test specimens were cast to evaluate the material properties of the UTW concrete. Specimens made included 4 inch (100 mm) by 8 inch (200 mm) cylinders for compressive strength and modulus of elasticity determination and 6 inch (150 mm) by 6 inch (150 mm) by 21 inch (525 mm) beams for modulus of rupture testing. Testing was done at 28 days. A summary of these material properties is presented in Table 2.

Table 2. Pavement Material Properties (28 Day).

Lane	1	2	3	4	5
UTW (28d)					
f'_c (MPa)	37.7	43.9	54.6	55.4	41.0
MR (MPa)	4.38	4.86	6.52	5.86	5.21
E (GPa)	30.6	33.4	38.4	38.9	37.3
HMA	2.07 (estimated)				
E (GPa)					
PCC (28d)					
f'_c (MPa)					
MR (MPa)					
E (GPa)					
Subgrade					
k (MPa/m)	12.1	7.9	4.94	7.79	16.6

Note: 1 MPa = 145 psi

Placement of UTW. Five different UTW test lanes were constructed. Figure 2 illustrates the lane configurations. In order to evaluate different bonding interfaces between the HMA and UTW, three different surface preparation techniques were employed. The surface of the milled HMA was swept and cleaned with a compressed air hose prior to UTW placement in Lanes 1, 2, and 3. In Lane 4, the milled HMA surface was not cleaned prior to placement of the UTW. A sheet of plastic was placed over the milled HMA layer in Lane 5. In all cases the UTW was placed at a width of 4 feet (1.2 m). Concrete Mixture 1 was used in Lanes 1, 4, and 5. Mixture 2 was used in Lane 2 and Mixture 3 was used in Lane 3. The UTW was placed and finished by hand. The UTW was covered with wet burlap and plastic and cured for 24 hours.

Collection of strain data by the System 6000 started immediately after placement of the UTW. After 24 hours the concrete joints were sawed at a spacing of 4 feet (1.2 m) by 4 feet (1.2 m) (Figure 2). The UTW was covered again with wet burlap and plastic and cured for an additional 2 days.

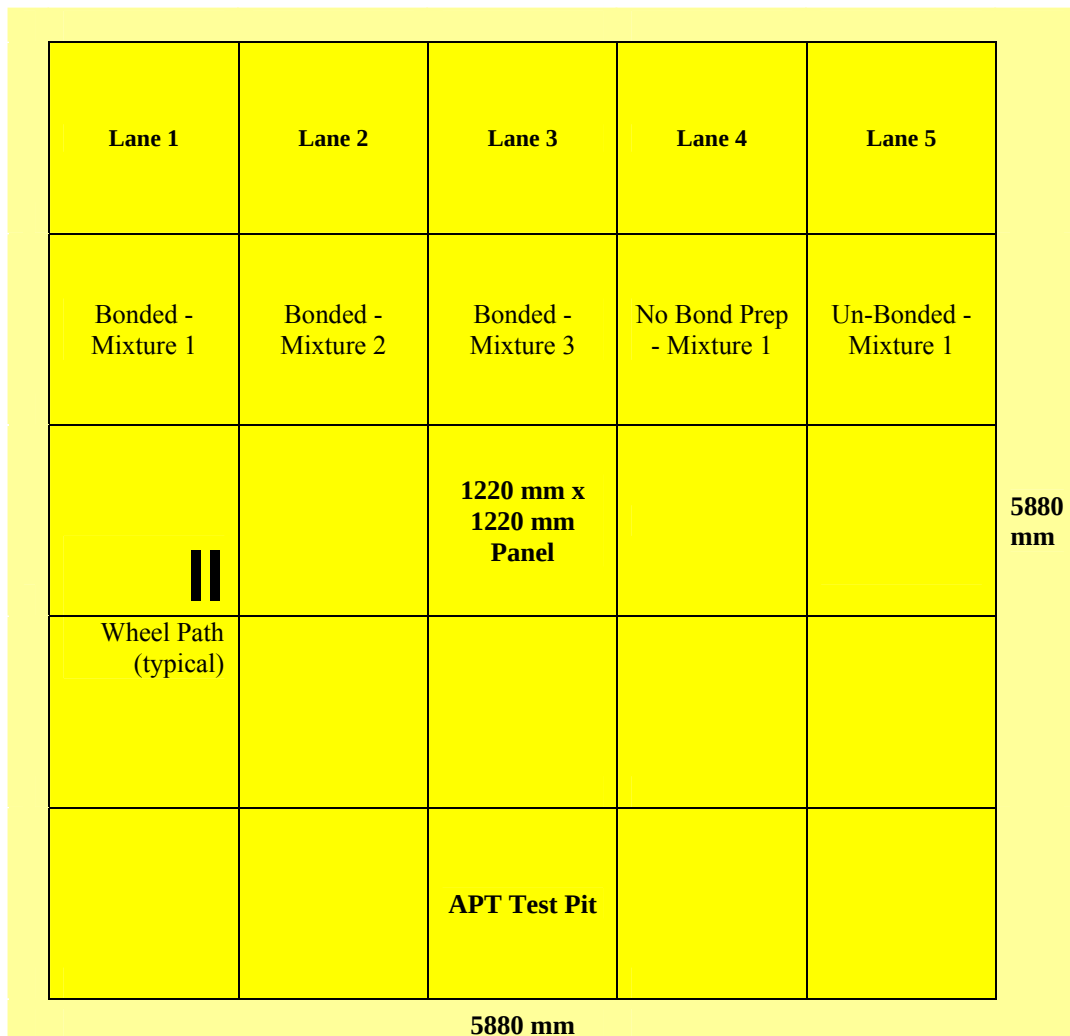


Figure 2. Layout of test area.

Accelerated Pavement Testing. The pavement was tested with a load of 15,000 lbs (67 kN) after the 3-day cure period. For all tests, a single-axle, dual-tire configuration was used and the tire was run bi-directionally over the pavement. Temperature in the APT facility was held relatively constant between 75 °F to 85 °F (24 °C to 29 °C) during testing. Approximately 300,000 load applications were applied to each lane except Lane 5 which only had 180,000 load applications prior to terminating the test.

Falling Weight Deflectometer Testing. Falling Weight Deflectometer (FWD) data were collected prior to milling of the HMA and before APT loading of the UTW. FWD tests were conducted on each of the five UTW lanes and at four different load levels: 7,000, 9000, 11,000, and 14,000 lbs (3200, 4100, 5000, and 6400 kg) using a Dynatest Falling Weight Deflectometer. Sensors were spaced at -12, 0, 8, 12, 24, 36, 48, 60, and 72 inches (-300, 0, 200, 300, 600, 900, 1200, 1500, and 1800 mm). Tests

were taken every 12 inches (300 mm) at nine different locations within a lane. Test data were averaged for each lane.

Assessment of Design Equations

The PCA UTW design method was developed for the overlay of a full depth HMA pavement. However, in some circumstances it may be necessary to design a UTW over an existing composite section. Previous work by the authors (5) indicated that two approaches hold promise for design of UTW overlays of composite sections. The test sections constructed in the APT were designed to investigate these approaches in light of the existing PCA design method.

Equivalent Thickness Approach. The PCA method requires the input of modulus of elasticity and layer thickness for calculating both the critical UTW stress and HMA strain. Critical values calculated in the PCA method are the UTW corner stress at the top of the slab and the HMA edge strain at the bottom of the layer. However, a composite pavement adds an additional layer, with significant stiffness, to the pavement section. In order to account for the additional layer in the existing composite pavement structure, use of an equivalent section is proposed. In this method, the underlying concrete layer was transformed into an equivalent HMA layer, using the Odemark transformation (6) [Equation 1].

$$t_e = t_3 \sqrt{\frac{E_1}{E_2}} \quad [1]$$

t_e = Equivalent Thickness

t = Slab Thickness with Modulus E_2

E_1 = Modulus of Layer Being Transformed

The equivalent section of the underlying HMA and PCC layers was developed, based on the moduli of the HMA layer ($E=300,000$ psi (2 GPa)) and underlying PCC layer ($E=5,000,000$ psi (34 GPa)). This resulted in an equivalent asphalt layer with a thickness of 15.33 inches with a modulus of 300,000 psi (2 GPa). These values were input into the PCA design equation for the radius of relative stiffness [Equation 2]. The value obtained for radius of relative stiffness was then input into Equations 3 and 4 to calculate the stresses in the UTW layer and the strains in the HMA layer. Stresses and strains were calculated for each test lane. Laboratory values determined for the relevant concrete properties (Table 2) in each lane at 28 days were utilized. The modulus of subgrade reaction used in the calculations was determined from FWD testing.

$$l_e = \{E_{utw} [t_{utw}^3/12 + t_{utw} (NA - t_{utw}/2)^2] / [k (1 - \mu_{utw}^2)] + E_{hma} [t_{hma}^3/12 + t_{hma} (t_{utw} - NA + t_{hma}/2)^2] / [k (1 - \mu_{hma}^2)]\}^{0.25} \quad [2]$$

$$\log \sigma_{COR} = 5.025 - 0.465 \cdot \log k + 0.686 \cdot \log \{12 \cdot [8 - 24 / (L/12 + 2)] / l_e\} - 1.291 \cdot \log l_e \quad [3]$$

$$\log \epsilon_{JT} = 5.267 - 0.927 \log k + 0.299 \log \{12 [8 - 24 / (L/12 + 2)] / l_e\} - 0.027 l_e \quad [4]$$

l_e = Effective Radius of Relative Stiffness (in)

E = Modulus of Elasticity (psi)

μ = Poisson's Ratio

t = Layer Thickness (in)

σ_{COR} = UTW corner stress (psi)

ϵ_{JT} = HMA edge strain

k = Modulus of Subgrade Reaction (psi/in)

L = Joint Spacing (in)

NA = Neutral Axis (in)

Note: Equations were developed for units noted.

In order to evaluate this methodology, the strain data recorded from each test section in the APT was obtained. Strains recorded from the edge location in the UTW and HMA layers were used. The UTW corner strains were recorded from gages placed in a rosette configuration and the maximum principal strain was calculated. The maximum load induced strains were calculated from the data by subtracting the minimum value recorded for the pass from the maximum value recorded for the pass. To minimize any anomalies, the average value from five recorded passes was used (passes 0, 5000, 10000, 15000, and 20000). To compare the calculated UTW stresses to the recorded strains, the calculated UTW stresses were converted to strains using a linear elastic assumption. These data were paired for each lane and plotted versus each other. Results are presented in Figure 3.

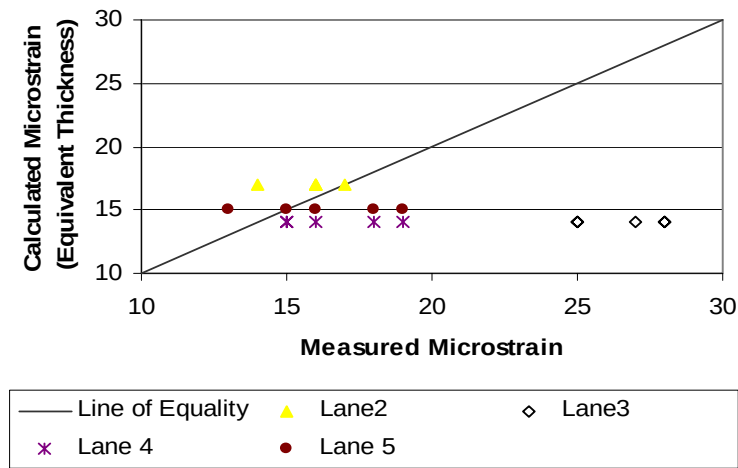
In general, the results indicate a good agreement between the calculated strains for the UTW layer and those measured in the APT (Figure 3a). The strain gage placed in Lane 1 did not provide useable results and thus comparisons for these lanes were not possible. However, calculated strain for Lane 1 was comparable to the values calculated for the other lanes. Thus, it is assumed that the result for this lane would be comparable to the other lanes.

Most of the values are close to the line of equality. One exception, however, is the value calculated for Lane 3. While this value is generally in line with the calculated values from the other lanes, the measured value from Lane 3 is significantly higher than the values from the other lanes. Thus, there may have been some reason that the gage for Lane 3 was reading higher. As this value comes from the rosette, it is possible that the rosette may have gotten bumped during construction of the UTW and alignment of the gages may have been affected. Another possible explanation is that a weaker bond between the UTW and HMA developed at the location of the gages thereby causing an increase in the strain.

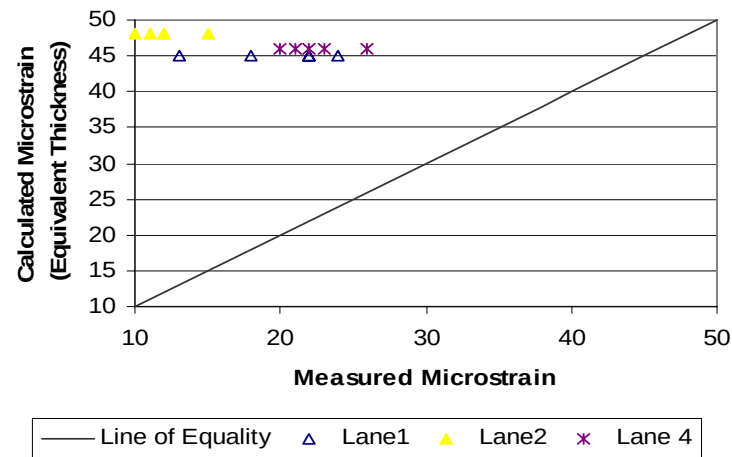
The strains calculated for the HMA layer were generally higher than those measured in the APT (Figure 3b). Strain gages placed in Lanes 3 and 5 did not provide useable results and thus comparisons for these lanes were not possible. However, calculated strains for Lanes 3 and 5 were in line with those in the other lanes. Again, it is assumed that the results for these lanes would be comparable to the other lanes.

One reason for the overestimation of the in-situ strains by the calculated strains is inherent to the methodology. The PCA equation for HMA strain calculates the strain at the bottom of the layer. When the equivalent thickness is used in the program it calculates the strain for the 15.33 inch (389 mm) transformed section. However, the actual HMA in the APT is only 9.5 inches (237 mm) thick. Thus, a correction must be made to adjust the strain calculated using the equivalent thickness.

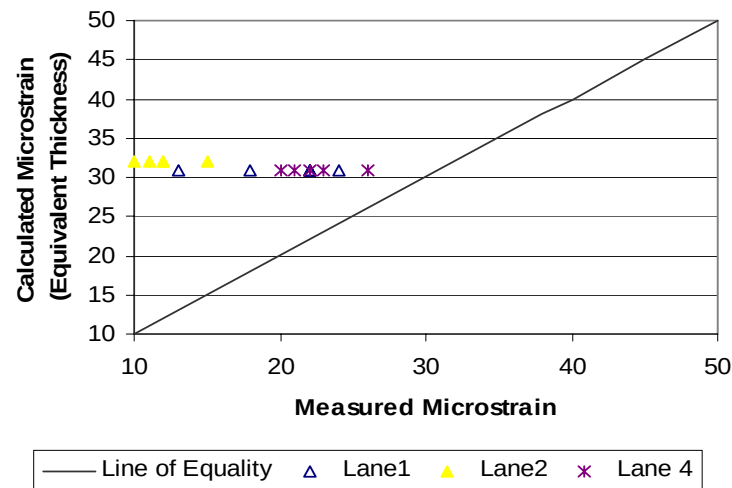
Such a correction was applied to these data. The strain was assumed to be linear from the neutral axis (calculated as an intermediate step in the PCA method) to the bottom the transformed section (Figure 4). This assumption enabled the strain to be estimated at the depth of the bottom of the HMA layer in the APT. The corrected HMA strains are presented in Figure 3c. As can be seen, the correction did bring the calculated values more in line with the measured readings as evidenced by a shift toward the line of equality. However, while the results are more reasonable, the agreement between the calculated and measured values for the HMA layer is still not as good as the agreement between the calculated and measured values for the UTW layer.



(a)



(b)



(c)

Figure 3. Comparisons of equivalent thickness calculated and actual strains: (a) UTW strains, (b) HMA strains, (c) adjusted HMA strains.

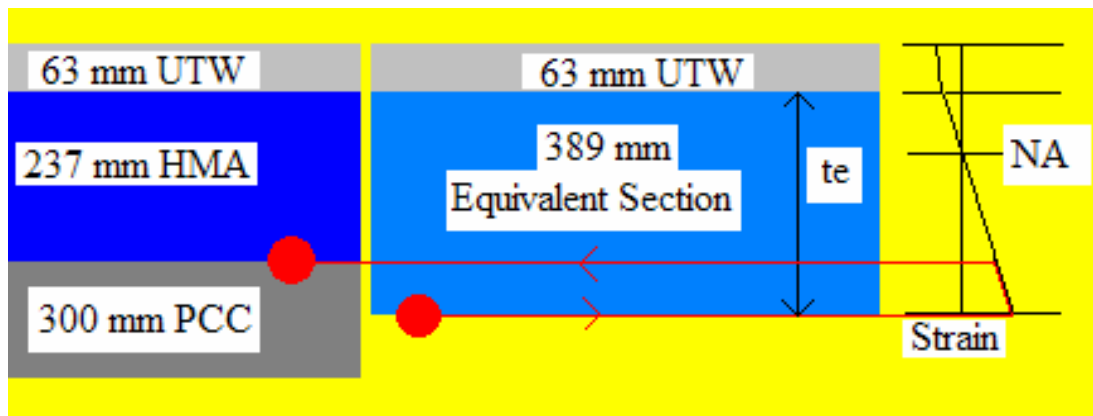
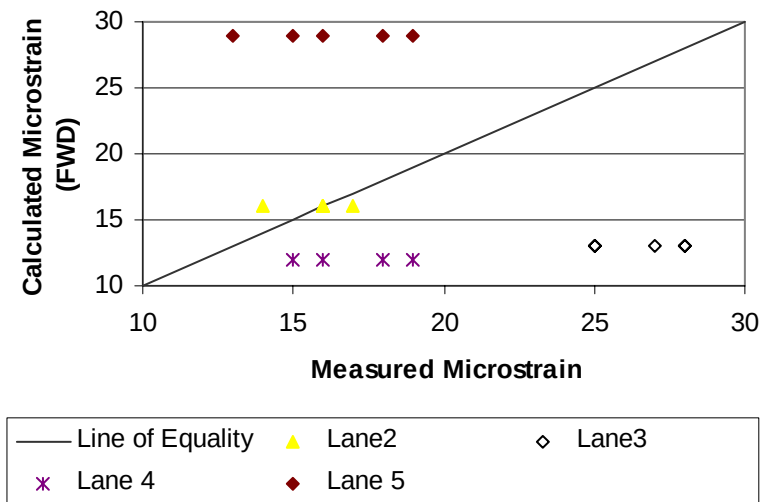


Figure 4. Comparison of equivalent and actual pavement sections.

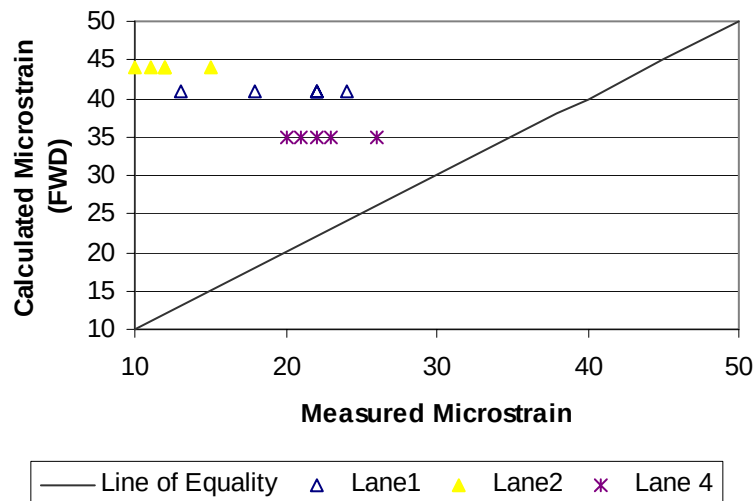
Falling Weight Deflectometer Approach. For mechanistic design applications, the effective radius of relative stiffness, l_e , can be estimated by in-situ falling weight deflectometer (FWD) testing (7). As can be seen in Equations 3 and 4 the stress and strain are a function of l_e . Thus, it is proposed that FWD data be used to calculate the l_e for the UTW section and use this value in the PCA equations for UTW stress and HMA strain.

As described above, FWD testing was conducted on the UTW lanes before milling the HMA and prior to testing in the APT facility. Values used were averages of four drops at 9 stations along the lane. The l_e values for each lane were calculated using the AREA5 parameter as outlined in the AASHTO guide (7). These data were input directly into the PCA equations for UTW stress and HMA strain. Values for UTW modulus of elasticity and subgrade modulus, k used were in-situ values presented in Table 2. To compare the calculated UTW stresses to the recorded strains, the calculated UTW stresses were converted to strains using a linear elastic assumption. Strains under loading in the APT were determined as described in the above section on the Equivalent Thickness Approach. These data were paired for each lane and plotted versus each other. Results are presented in Figure 5.

As can be seen from Figure 5a the UTW strain values determined from the FWD are reasonably comparable to those measured in the APT. Two of the data points are outliers however. The data for Lane 3 is skewed by the same gage reading as mentioned earlier. The calculated value from Lane 3 is generally in line with the calculated values from the other lanes however, the measured value from Lane 3 is significantly higher than the values from the other lanes. Thus, there may have been some reason that the gage for Lane 3 was reading higher. As proposed previously this discrepancy may have been due to a misaligned strain gage. The other outlier is from Lane 5. Lane 5 was the lane in which the UTW concrete was deliberately debonded. Thus, the strain value calculated from the FWD testing of Lane 5 rightly reflects the lack of bonding between the UTW and HMA layers.



(a)



(b)

Figure 5. Comparisons of falling weight deflectometer calculated and actual strains: (a) UTW strains, (b) HMA strains.

Similar to the Equivalent Thickness Approach, the strains calculated for the HMA layer using the FWD Approach were generally higher than those measured in the APT (Figure 5b). However, unlike the previous approach, the latter does not warrant the adjustment described above. As mentioned previously, strain gages placed in Lanes 3 and 5 did not provide useable results and thus comparisons for these lanes were not possible. Calculated strains for Lanes 3 and 5 were again in line with those in the other lanes, however. Thus, it is assumed that the results for these lanes would be comparable to the other lanes.

UTW Design Methodology Using the Falling Weight Deflectometer Approach. In order to implement a UTW design methodology using the FWD Approach, a way to estimate the UTW design radius of relative stiffness must be developed. In practice only in-situ FWD testing of the distressed HMA pavement will be conducted. The l_e of the in-situ pavement can be calculated from these data however, the l_e used in the PCA design equations is based on the final UTW pavement section. Thus, the in-situ l_e needs to be adjusted to account for the increase in structural capacity provided by the UTW layer.

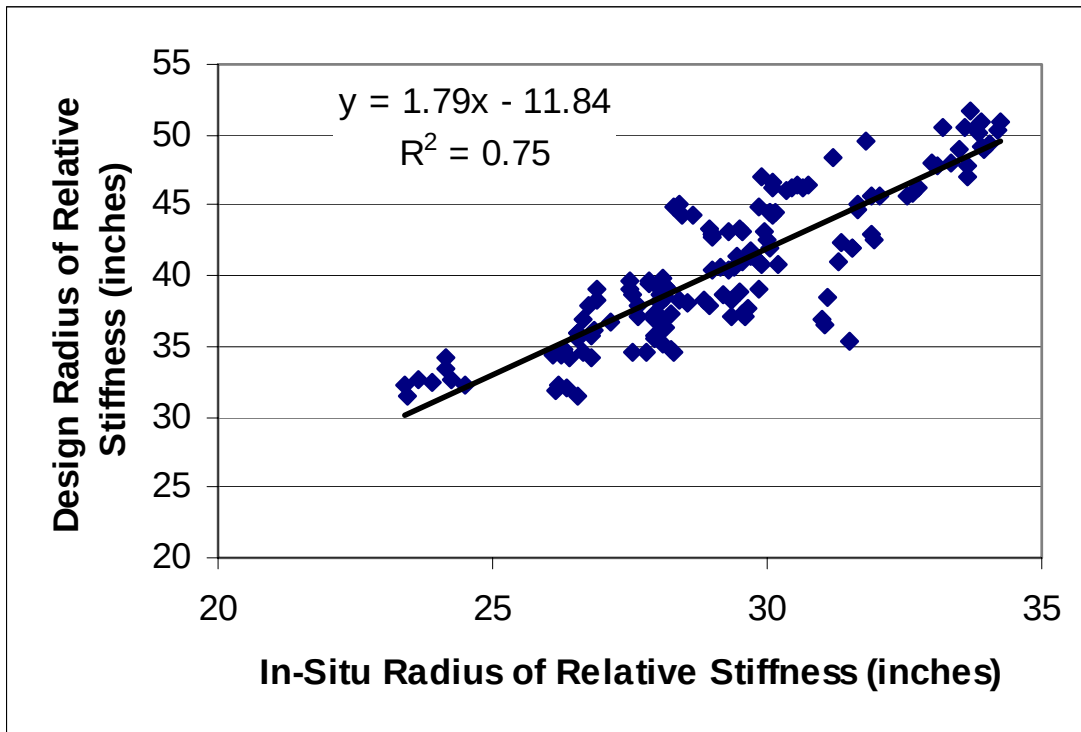


Figure 6. Relationship between in-situ and design radii of relative stiffness.

Using the FWD data that was recorded prior to milling the HMA surface (which represents an in-situ condition) and the FWD data collected prior to loading by the APT (reflecting the increased structural capacity provided by the UTW overlay) a linear regression analysis was performed. These data were plotted and are presented in Figure 6. Equation 5 presents the equation provided by the regression. Lane 5 data were not used since this lane was totally debonded and is not representative of an as-constructed condition encountered in practice.

$$L_{e,utw} = 1.79 \cdot l_{e,in-situ} - 11.84$$

[5]

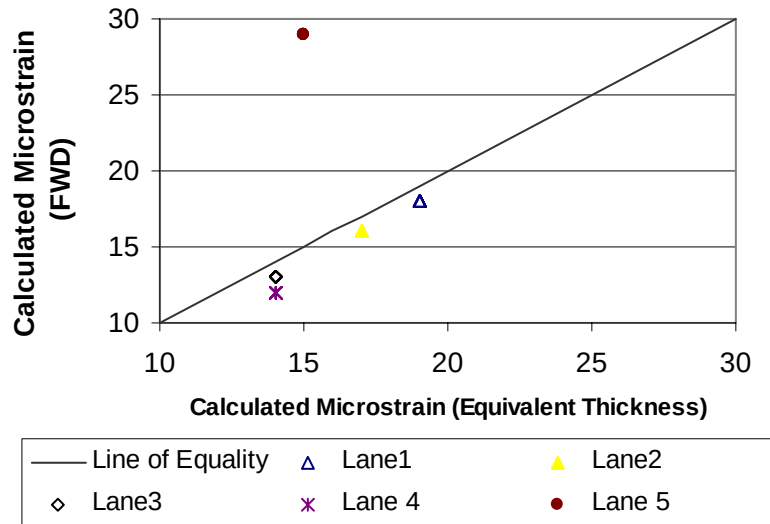
$l_{e,utw}$ = Design Radius of Relative Stiffness

$l_{e,in-situ}$ = In-situ Radius of Relative Stiffness from FWD Testing

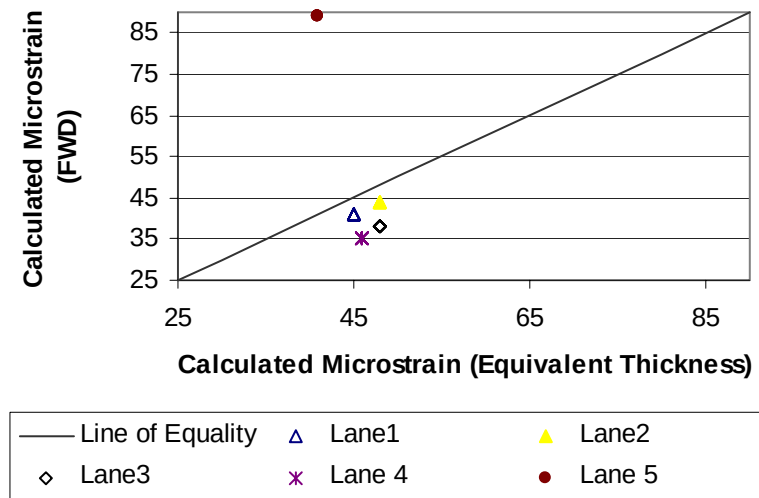
The R_{adj}^2 for this equation was 0.75 indicating that the relationship is reasonable. While this equation holds promise for use in UTW overlay design in the context of the FWD approach, its use may be limited. It was developed using only one UTW thickness (2.5 inches) and over a composite pavement section. Its applicability for use in designing UTW overlays thicknesses and/or over full depth HMA pavements is not known. However, if the equation is found not to be applicable under these conditions, a series of equations for different UTW overlay thicknesses and different existing pavement conditions can be developed. Future work scheduled in the APT will look into the use of this methodology for full depth HMA pavements.

Comparison of Approaches. To compare the two design approaches, equivalent thickness and falling weight deflectometer, the strains calculated by each approach were paired for each lane. These data were plotted and are presented in Figure 7. In general the two approaches produce similar results for the UTW strains as shown by their location in reference to the line of equality (Figure 7a). However, the UTW strains calculated from the Equivalent Thickness Approach are consistently higher than those calculated by the FWD Approach. The only exception to this statement is the data for Lane 5. The reason for this diversion is the debonded condition of the UTW in Lane 5. The FWD testing of Lane 5 reflected this condition while the equivalent thickness approach did not reflect the lack of bonding. This is because the PCA equation for the radius of relative stiffness, from which the strains were subsequently calculated using the Equivalent Thickness Approach, assumes a fully bonded condition.

The HMA strains calculated from the two approaches produce similar results in general (Figure 7b). However, the UTW strains calculated from the FWD Approach are consistently higher than those calculated by the Equivalent Thickness Approach. The data from the FWD testing of Lane 5 again produced much higher strains than those calculated using the equivalent thickness as a result of the debonding of the UTW in Lane 5.



(a)



(b)

Figure 7. Comparison of design approaches (a) UTW strains, (b) HMA strains.

Conclusions

The existing design methodology for UTW overlays do not have a mechanism to account for the existence of an in-situ composite pavement. Two different approaches to design UTW overlays of composite pavements were evaluated. The following conclusions can be made.

1. The equivalent thickness approach to model the existing composite pavement was evaluated and found to produce reasonable results. In general, the results

indicate a good agreement between the calculated strains for the UTW layer and those measured in the APT. The strains calculated for the HMA layer, after correction for the difference in depth between equivalent and actual HMA thicknesses, were generally in good agreement with the measured strains in the APT.

2. In-situ FWD testing can be effectively incorporated in a mechanistic UTW design procedure. FWD data analysis can be used to estimate the value of I_e for the in-situ pavement section. However, there is a need to adjust this value to account for the increased structural capacity provided by the UTW. An equation was developed to perform this conversion. Results indicate that this technique will work, however additional testing is needed to assess its applicability for use with full depth HMA pavements.

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