DEFLECTIONS MEASURED ON EXPERIMENTAL ULTRA-THIN WHITETOPPING PAVEMENTS

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ABSTRACT

In the spring of 1998, the Federal Highway Administration (FHWA) and the American Concrete Pavement Association (ACPA) jointly constructed eight full-scale lanes of ultra-thin whitetopping (UTW) over existing hot mix asphalt (HMA) pavements. These sections were placed at the FHWA's Pavement Test Facility, located at the Turner-Fairbank Highway Research Center in McLean, Virginia. The experiment employed various combinations of thickness, joint spacing, fiber reinforcement of the Portland cement concrete overlay and HMA base type.

FHWA began testing the UTW pavements in May 1998 with one of its two Accelerated Loading Facility (ALF) machines. The second ALF machine was incorporated into the UTW program in November 1998. The full-scale pavement tests, which included the collection of data on UTW performance and response, were completed in November 1999. This paper presents results of one part of the response data collected, the pavement deflections monitored during the testing, and a preliminary analysis. The deflections from all lanes were found to increase with load applications and the rate of change in deflections correlated well with UTW performance in terms of percent slabs cracked. The HMA layer stiffness was identified as the most important factor affecting the deflection response for all lanes in the experiment. Static and dynamic deflections were also compared for some UTW sections.

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INTRODUCTION

Ultra-thin whitetopping is a relatively new rehabilitation technology applying a 50 to 100 mm (2- to 4-in) thick concrete overlay on top of existing asphalt pavement. Since the first experimental section of UTW was installed in 1991 on an access road to a landfill in Louisville, Kentucky, more than 170 UTW projects have been constructed across the United States [1]. The prediction of UTW overlay load-carrying performance is somewhat uncertain, however, because of its nature as a composite system. In order to help state highway agencies and contractors better design and apply the UTW, well-controlled pavement response and performance data is needed to improve and refine the existing UTW design procedures. As part of this research effort, in the spring of 1998, FHWA and ACPA entered into a cooperative agreement to conduct Accelerated Load Facility (ALF) tests of ultra-thin whitetopping. Eight full-scale lanes of UTW were placed over existing HMA pavements that were in various stages of rutting distress after extensive testing with the ALFs for a Superpave validation study [2]. The asphalt pavements had been built with seven different HMA mixtures which displayed a broad range of stiffness. The experiment employed various combinations of thickness, joint spacing, and fiber reinforcement, and HMA base type.

Full-scale loading of the UTW sections began in May 1998 and was completed in November 1999. Pavement response and performance data were collected during the testing period. One type of response data was the pavement deflections, monitored during the testing. This paper presents the deflection results and their impact on the UTW performance.

EXPERIMENTAL DESIGN

The eight UTW test lanes were built with various design features. The experimental design included two levels of UTW thickness, 64 mm (2.5 in.) and 89 mm (3.5 in.), overlaying 140 mm (5.5 in.) and 115 mm (4.5 in.) of HMA, respectively. The HMA was originally 200-mm (8-in.) thick, but had been milled to leave the thinner layers after having been rutted in earlier ALF testing. Two Portland cement concrete (PCC) mixtures were used, one containing fibrillated polypropylene fibers at a rate of 1.78 kg/m^3 (3.0 lb/yd^3), and one without fibers. Joint spacing in the concrete overlay was also an experimental factor. Specific experimental factors for the eight test lanes are shown in Table 1.

Table 1 UTW Experimental Factors and Lane Assignments

UTW Thickness (mm)	HMA Thickness (mm)	Joint space (m)	Fiber Concrete	Plain Concrete
64	140	1.22	**Lane 5**	**Lane 6**
		0.91	**Lane 7**	**Lane 8**
89	114	1.83	**Lane 9**	**Lane 10**
		1.22	**Lane 11**	**Lane 12**

1 mm = 0.04 in.
1 m = 3.28 ft

The lane numbers, shown in Table 1, were kept consistent with the previously tested HMA lane designations. Before being overlaid with UTW, the HMA pavements were in various stages of rutting distress with at least 10 percent compressive strain in the HMA after testing with the ALF machines at temperatures ranging from 42 to 76 ^{o}C (108 to169 ^{o}F) during the previous three years. Existing rut depths, based on the conventional definition under a 1.22 m (4 ft) straight edge, range from 20 to 50 mm, shown in Table 2. The pavement sections had been built with seven different HMA mixtures, as part of an experiment to validate the Superpave performance grading asphalt binder system. The HMA layer had originally been placed over a 450-mm (18-in.) crushed stone base course atop recompacted subgrade soil.

MATERIAL PROPERTIES

The measured, as-built properties for the PCC and the HMA in the test lanes are shown in Table 2. The asphalt mixture moduli were obtained with the Superpave Shear Tester (SST) at 40^{o}C (102 ^{o}F) while the concrete flexural strength and modulus were obtained following ASTM standard testing procedures. Thickness information was obtained from pavement cores, removed after the tests.

INSTRUMENTATION

Strain gauges were installed at the top of the milled HMA surface prior to placement of the UTW. Typically, 18 strain gauges were installed in each UTW test section during construction. Two linear variable deformation transducers (LVDT) were placed on the surface of

Table 2. Measured As-Built PCC and HMA Properties

Test Lane Number	HMA Thickness (mm)	PCC Thickness (mm)	HMA Modulus (psi)	Flexural Strength (kPa)	Modulus of Elasticity (mPa)	HMA Rutting Distress before Overlay	
						Loads (ESALs)	Rut Depth (mm)
5	104	70	8580	5,640	33,100	5,810	34
6	107	82	13070	6,700	38,000	-	-
7	112	83	34260	5,300	28,800	293,000	32
8	117	79	22930	6,230	38,600	305,000	29
9	81	109	5630	5,400	31,300	2,930	41
10	86	124	13070	6,960	38,700	14,600	35
11	89	118	16910	5,780	32,600	35,900	34
12	86	107	33260	6,821	37,900	293,000	31

1 mm = 0.04 in.

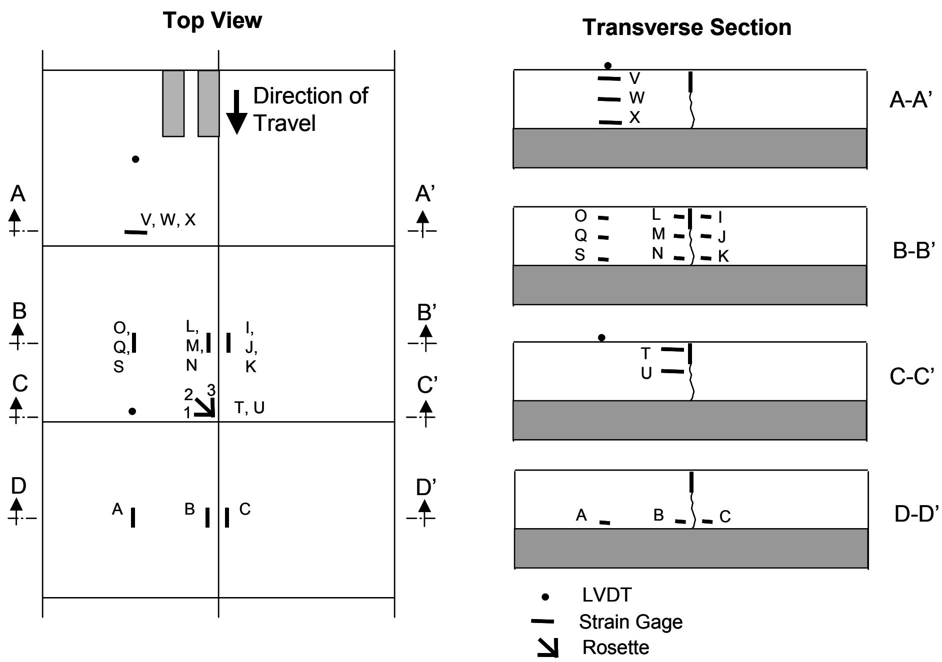
1 kPa = 0.145 lb/in^2

each UTW section during the load testing to monitor the pavement deflection. One LVDT was located at the mid of slab while the other was located at the transverse joint with a 0.69 m (27 in.) distance from the loaded longitudinal joint. Figure 1 shows the layout of strain gages and LVDT positions in a typical test section.

ALF TESTING AND DATA COLLECTION

The UTW sections were tested with the ALF full-scale load machines. The ALFs are 29-m (95-ft) long frames with rails to direct rolling wheel loads. In this experiment, the ALF applied a 54-kN (12 kip) load to the test pavements on a half axle pair of dual tires. ALF loading is in one direction only; in this particular study, loading was applied without wander at a constant speed of 17 km/hr (10.5 mph.). A radiant heat system under the ALF frame was used to maintain the pavement temperature at 27 ^{o}C (80 ^{o}F). The ALF machines operate 24 hours a day, except for breaks at 3-day interval for maintenance.

Both performance and response data were collected during the ALF loading. Performance data included: (1) Visual surveys to record cracks. (2) Faulting measurement on certain sections with a Georgia fault meter. (3) Pavement profile measurement using a “dipstick”



Note: Gages A, B, and C were only installed in lane 5.

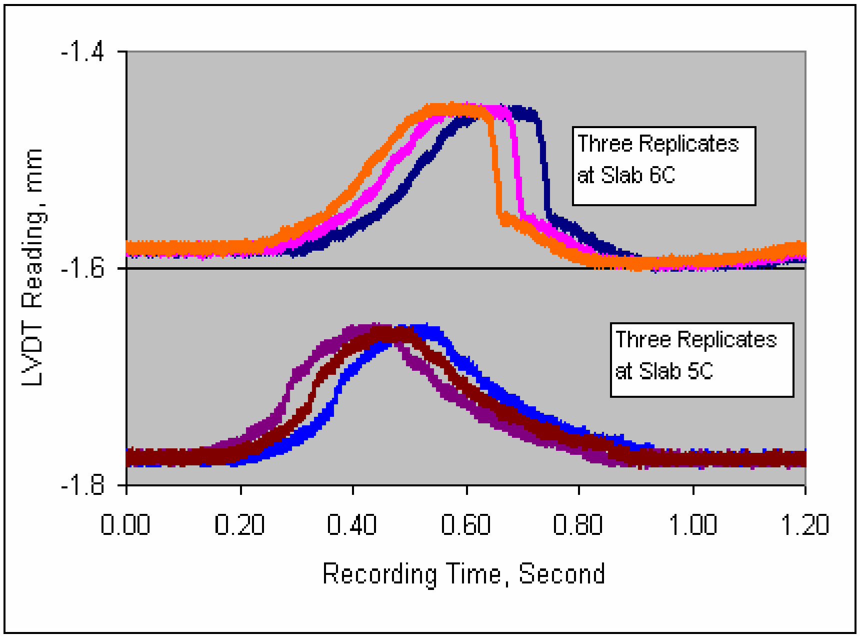
Figure 1 Layout of Strain Gages and LVDT Locations in Typical Test Section

at the start and end of testing. Response data consisted primarily of strain readings from the 18 sensors in each section and pavement deflection measurements at the mid slab and transverse joint. These response values were typically recorded at twice each loading day.

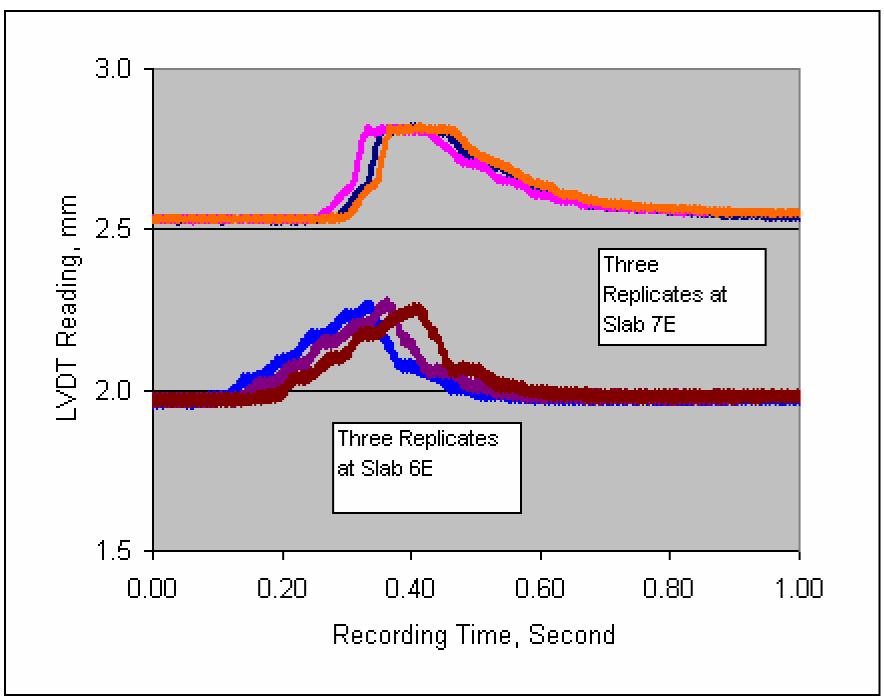
RESULTS AND ANALYSIS

Typical Deflection Response

The pavement deflections under the rolling wheel loads were monitored by two LVDT's, which were connected to a data acquisition system. Figure 2 shows typical deflection response time histories: Figure 2(a) shows the deflection at mid slab while Figure 2(b) shows the deflection at the transverse joint. Three replicate measurements were taken at each data collection time. The repeatability among the three replicates is excellent. To check the deflection variation between slabs, measurements of deflection were taken from two adjacent slabs at both mid slab and the transverse joint for certain load applications. Figure 2 shows the results from two adjacent slabs. The peak deflections, i.e., the difference between the maximum and unloaded LVDT readings, from two adjacent slabs were very close.



(a) Deflection at Mid Slab after 49,300 Wheel Passes



(b) Deflection at Transverse Joint after 50,300 Wheel Passes

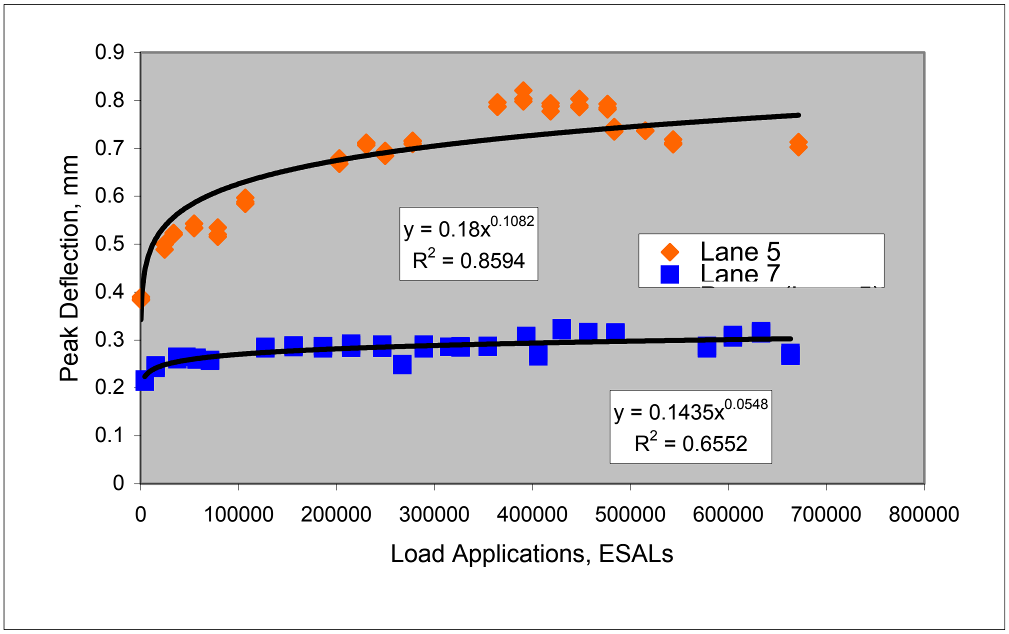
Figure 2 Typical Deflection Curves Measured from Lane 12

Peak Deflection versus Load Applications

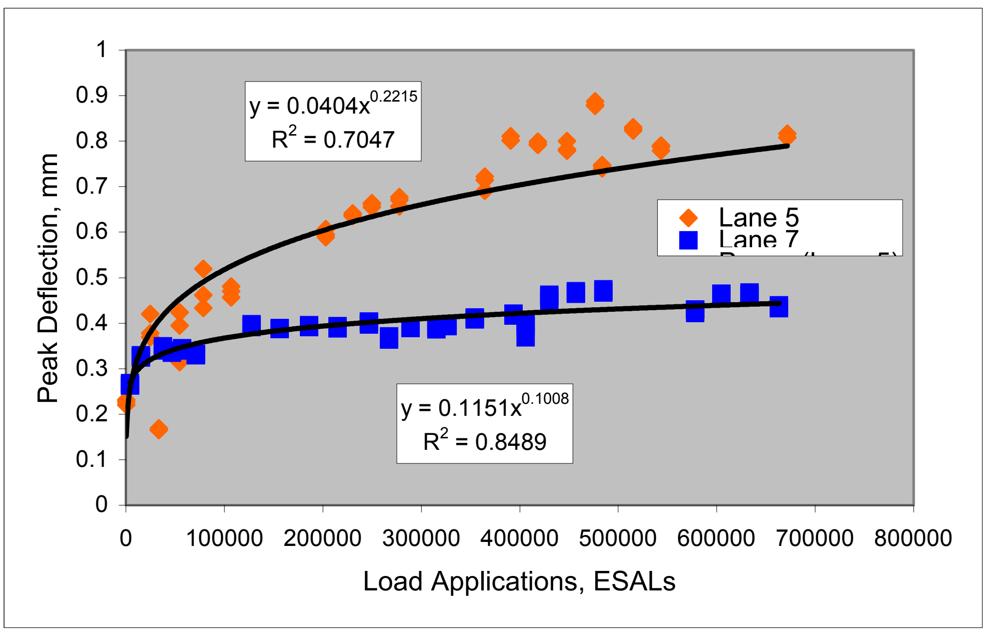
Peak deflections were calculated for each individual measurement. Typical peak deflections as a function of load applications are shown in Figure 3. The fluctuation in peak deflection can be observed from the measured data points. A power model, $y = a\,x^{b}$, was selected to fit the deflection curve to eliminate scatter and avoid any interpolation for analyses. Figure 4 shows the power model curves for all lanes. In general the deflections at both mid slab and the transverse joint were increased with load applications. However, the rate of change varies for different lanes. Obviously, Lanes 5 and 9 changed much more than other lanes in deflection at mid slab. Note in Table 2, lanes 5 and 9 have the lowest HMA modulus of the eight lanes. For deflections at the transverse joint, Lanes 6, 8, and 10 join lanes 5 and 9 as those with the highest rates of change.

Correlation between UTW Performance and Deflection

In order to evaluate the correlation between UTW performance and deflection, deflections need to be compared at specific numbers of load applications. Since the measured deflection data are only available from 1,000 to 678,000 ESALs for some lanes, deflections were calculated at these two values for use in correlation evaluations. Table 3 shows the deflection model parameters, “a” and “b”, the calculated deflections from the models at 1,000 and 678,000 ESALs; and the field measured slab cracking data at 678,000 ESALs for the eight sections. Figures 5(a) and 5(b) show the correlations between percent slabs cracked and deflections at 1,000 and 678,000 ESALs, respectively. As indicated by the squared correlation coefficient, R^2, the deflection at 678,000 ESALs shows better correlation with the percent cracked than does the deflection at 1,000 ESALs. The correlation between percent slabs cracked and the model exponential parameter, “b”, is also included as Figure 5(c). It should be noted that the model coefficient “b” has a physical meaning, which is the rate of change in deflection in log-log domain. From Figure 5(c) it can be seen that a better correlation exists between pavement performance (% slabs cracked) and the rate of change in pavement deflection at mid slabs. During the accelerated load testing, slab rocking was observed in some of the UTW lanes. This could have significant impact on the deflection measurement at the transverse joints and needs to be evaluated before any further analysis is conducted. The correlation analysis was not performed on the deflection data from the transverse joints because of this observation. Note that foundation support was excluded as a variable because water content is unknown.

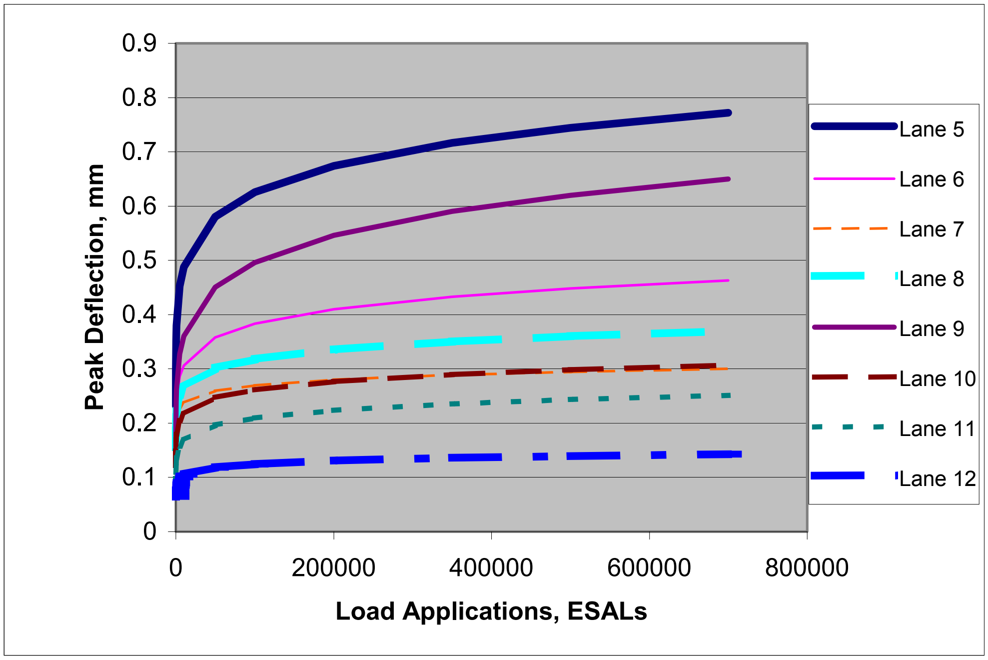


(a) Measured at Mid Slab

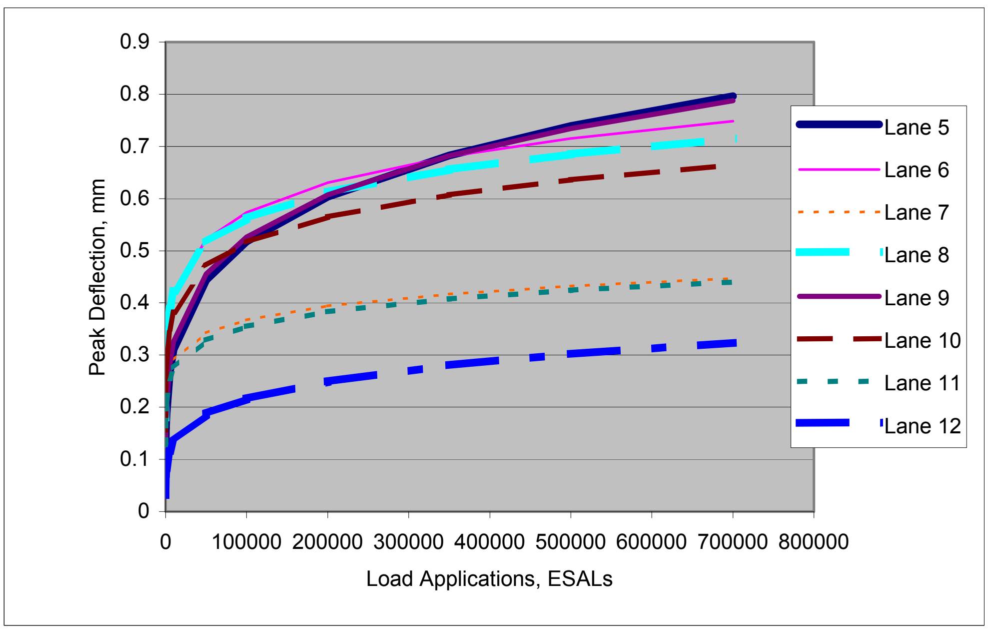


(b) Measured at Transverse Joint

Figure 3 Typical Peak Deflections vs. Load Applications



(a) Deflection at Mid Slab

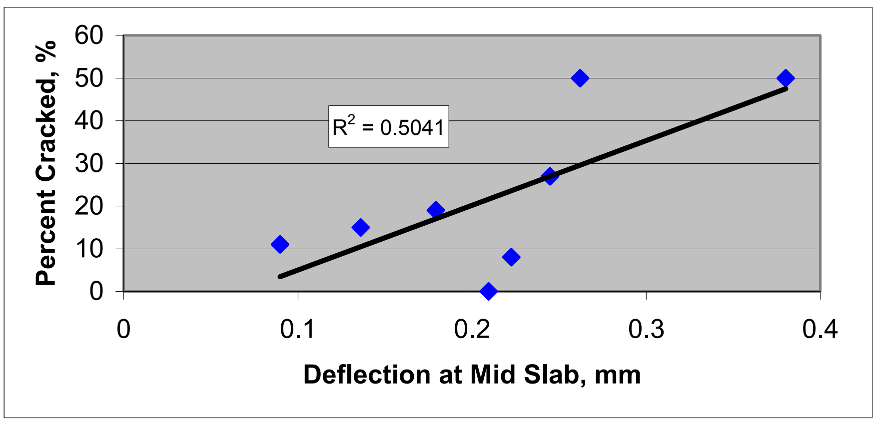


(b) Deflection at Transverse Joint

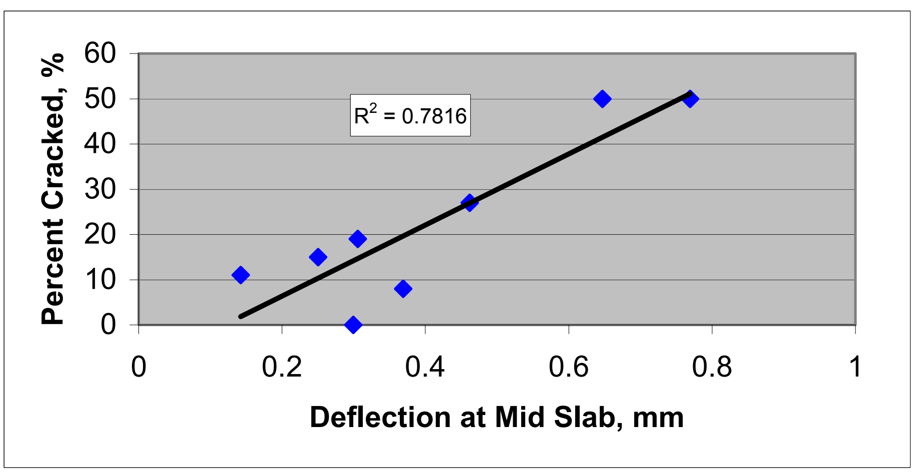
Figure 4 Peak Deflection Calculated from Models for All Lanes

Table 3 Summary of Regression Parameter, Deflection and Cracking Data

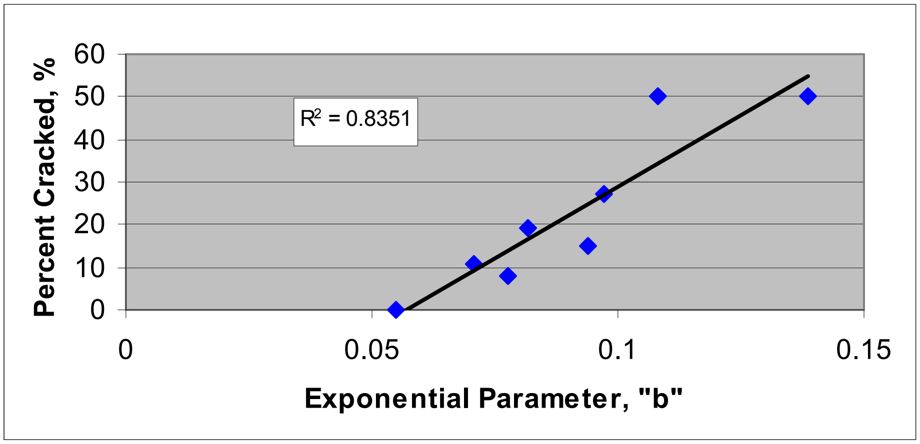
Lane No.	Parameter "a"		Parameter "b"		Deflection @ 1000		Deflection @ 678000		Cracking
	Slab Center	Slab Edge	Slab Center	Slab Edge	Slab Center	Slab Edge	Slab Center	Slab Edge	(%)
5	0.1800	0.0404	0.1082	0.2215	0.3801	0.1866	0.7695	0.7907	50
6	0.1250	0.1186	0.0973	0.1369	0.2448	0.3053	0.4616	0.7454	27
7	0.1435	0.1151	0.0548	0.1008	0.2095	0.2309	0.2995	0.4455	0
8	0.1302	0.1359	0.0776	0.1233	0.2225	0.3185	0.3691	0.7116	8
9	0.1006	0.0483	0.1386	0.2074	0.2621	0.2024	0.6469	0.7822	50
10	0.1018	0.1158	0.0819	0.1298	0.1792	0.2839	0.3057	0.6616	19
11	0.0712	0.0992	0.0937	0.1107	0.1360	0.2131	0.2505	0.4386	15
12	0.0550	0.0198	0.0709	0.2076	0.0898	0.0831	0.1425	0.3215	11



(a) Percent Slabs Cracked vs. Deflection after 1000 ESALs



(b) Percent Slabs Cracked vs. Deflection after 678,000 ESALs



(c) Percent Slabs Cracked vs. Model Exponential Parameter "b"

Figure 5 Correlations between Percent Slabs Cracked and Deflection at Mid Slab

Factors Significantly Affecting Deflection

Stepwise Regression was utilized to develop a prediction equation relating a dependent variable (deflection) to predictor variables (UTW design features). Although it is a type of multiple regression analysis, stepwise regression differs from the commonly used multiple regression technique in that it introduces predictor variables sequentially based on partial-F statistics; thus, stepwise regression analysis yields prediction equations from which one must be selected as the "best" model by only including the most significant variables without reducing the accuracy of prediction significantly [3].

The correlation matrix, which was based on the data from the eight UTW lanes, is shown in Table 4. The first column lists the variables included in the analysis and their symbols. The matrix is characterized by high inter correlations and moderate predictor-dependent correlations. The high inter correlations suggest that stepwise regression can reduce the number of predictors without a significant loss of prediction accuracy. The matrix also shows that the correlation of deflection versus HMA modulus (x_5-y) stands out among the predictor-dependent correlations. The predictor X_5 enter the model first since it has the largest partial-F among the initial F values calculated in step 1. Table 5 summarizes all the steps for the stepwise regression. Using the classic approach to model selection, partial F statistics were evaluated for each step, using a 5 percent level of significance. If $F > F\alpha$, the variable entered is statistically significant, and the variable should be included in the equation. If $F < F\alpha$, the variable is insignificant, and the

Table 4 Correlation Matrix for the Deflection Data

	X1	X2	X3	X4	X5	X6	Y
X1: UTW Thickness (mm)	1.000	-.853	-.079	.670	-.090	.293	-.475
X2: HMA Thickness (mm)		1.000	-.097	-.805	.305	-.160	.106
X3: Fiber Content (%)			1.000	.000	-.210	-.925	.437
X4: Joint Spacing (ft)				1.000	-.646	.182	.248
X5: HMA Modulus (psi)					1.000	.095	-.754
X6: UTW Flexural Strength (psi)						1.000	-.459
Y: Deflection at 678000 ESALs (mm)							1.000

Table 5 Stepwise Regression Summary for Deflection Data

Step		1	2	3	4	5	6
Variable Entered		X5	X1	X2	X6	X4	X3
|R|		1.00	.9919	.2172	.1916	.0294	.0020
R		.75	.93	.96	.98	.99	.99
R^2		.57	.87	.93	.97	.99	.99
ΔR^2		.57	.30	.06	.04	.02	.00
Se		.1493	.0911	.0750	.0573	.0305	.0431
Se/Sy		.7097	.4332	.3565	.2724	.1452	.2048
Partial F		7.896	11.109	3.380	3.852	8.562	0.005
Critical Fα		5.99	6.61	7.71	10.13	18.00	161.00
F vs. Fα		F > Fα	F > Fα	F < Fα	F < Fα	F < Fα	F < Fα
Partial Regression Coefficient	B0	0.6775	1.243	2.429	2.635	2.1141	2.0544
	B1	-	-0.005675	-0.010241	-0.009043	-0.009868	-0.009876
	B2	-	-	-0.008073	-0.007153	-0.004196	-0.004069
	B3	-	-	-	-	-	0.002760
	B4	-	-	-	-	0.074024	0.075154
	B5	-0.000015	-0.000016	-0.000013	-0.000013	-0.000009	-0.000009
	B6	-	-	-	-0.000068	-0.000081	-0.000074

equation from the previous iteration is the final model. By examining the partial F and critical Fα in Table 5, only Steps 1 and 2 are necessary, so the model with X_5 and X_2 should be selected.

Examining other statistical criteria such as ΔR^2, Se and Se/Sy, would provide the same model as identified using the partial F criterion. Therefore, through the model selection using the stepwise regression, HMA modulus was identified as the most significant variable relating to deflection, UTW thickness followed and all other variables are not significantly related to the deflection based upon the data measured at the mid slabs.

Loading Speed Effect

For some UTW sections, different loading speeds were used to evaluate that variable's effect on pavement deflection at the beginning of tests. Figure 6 shows the plot of deflection at mid slab versus wheel loading speed. Zero speed represents the static loading. Deflection clearly decreases with increases in loading speed. To closely exam the speed effect, the ratio of deflection at 10.5 mph to static load was calculated. The ratio ranges from 80% to 90% for these sections.

CONCLUSIONS

Based upon the results from the field measured deflection and the preliminary analysis, the following conclusions can be drawn:

1. Peak deflections increased with load applications for all UTW lanes, especially for lanes 5 and 9 with the softest binder in the HMA, i.e., the lowest stiffness layers.
2. Deflections at both 1000 and 678,000 ESALs were correlated to the UTW performance in terms of percent slabs cracked.
3. The rate of change in deflection was better correlated to the pavement performance.
4. Stepwise regression analysis showed that the HMA layer stiffness was the most important factor affecting the deflection response, followed by UTW thickness. Other factors such as HMA layer thickness, addition of fiber, joint spacing and PCC flexural strength were statistically insignificant.
5. Deflections decreased as the wheel loading speeds increased.

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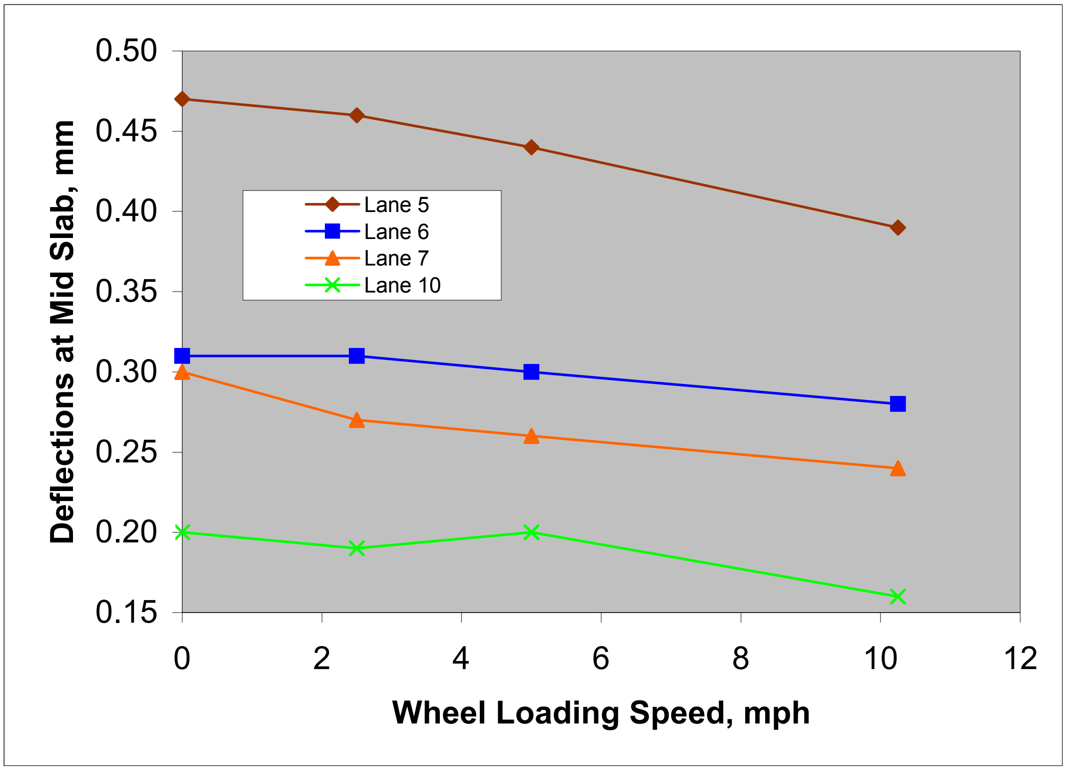

Figure 6 Deflection vs. Wheel Loading Speed