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Analysis of Load-Induced Strains in a Hot Mix Asphalt Perpetual Pavement

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Analysis of Load-Induced Strains in a Hot Mix Asphalt Perpetual Pavement

Final Report

Wisconsin Department of Transportation Technical Services

April 2009

FINAL REPORT

For the

ANALYSIS OF LOAD-INDUCED STRAINS IN A HOT MIX ASPHALT PERPETUAL PAVEMENT

WisDOT Report FEP 01-09

Wisconsin Research Study # FEP-02-02
"EVALUATION OF AN ASPHALTIC CONCRETE PERPETUAL PAVEMENT"
(Kenosha Safety & Weigh Station Facility)

Presented To:
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Submitted By:

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16. Abstract

This report presents the findings of a research study conducted to investigate the structural performance of a 275 mm hot mix asphalt perpetual pavement constructed as part of the WIM bypass lane at the Kenosha Safety & Weigh Station Facility. Two separate test sections were constructed using variable binder types and in-place air voids. Asphalt strain sensors were fabricated at Marquette University and installed during the construction of the HMA pavement. Sensors were positioned within the outer wheel path and located at the bottom of the 275 mm HMA pavement and at the interface between the lower layers at a depth of approximately 175mm from the surface. Strain sensors were oriented in both the transverse and longitudinal directions. A total of 16 strain sensors were installed during construction. Of these, only three survived to provide strain data under traffic loadings.

Deflection data obtained from FWD testing was used as comparative measures to strain measurements obtained during testing and to estimate the combined dynamic HMA layer moduli at the time of testing and to develop monthly trends of dynamic HMA layer moduli as a function of the expected mean monthly mid-depth pavement temperature. A comparative analysis of measured strains to those predicted from FWD measurements provided generally good agreement. A mechanistic appraisal of the constructed test sections was completed using the outputs of the EVERSTRESS pavement analysis program. This analysis computed the expected monthly damage induced by the application of 521,000 monthly ESAL loadings. The results of the mechanistic appraisal indicate the expected service life to 50% bottom-up fatigue cracking is in excess of 90 years for sections with air voids of 4% within the lower layers. If the air void content increases to 5% - 6% in the lower layers, the expected fatigue life may be significantly reduced to between 13 – 32 years.

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INTRODUCTION

This report presents the analysis of the HMA perpetual pavement constructed at the Kenosha Safety and Weigh Station Facility in early August, 2003. This pavement is the second HMA perpetual pavement designed and built in the State of Wisconsin, and represents the current trends in building pavements with longer service lives.

The HMA perpetual pavement at the Kenosha facility is located on the northbound return ramp to I-94. The pavement was designed for 75 – 125 million equivalent single axle loadings (ESALs) and is composed of 275 mm (11 inches) HMA, Type E-30X, 100 mm (4 inches) crushed aggregate base course, open graded No. 2, 425 mm (17 inches) crushed aggregate base course, dense graded, over lean clay soils (CL, A-4).

Two separate test sections were constructed using variable binder types and in-place air voids. The specifics of each test section are as follows:

Test Section 1 – Station 3002 to 3620
Surface Layer: 50 mm HMA, 12.5 mm NMAS, PG 76-28 binder, 6% Air Voids
Middle Layer: 114 mm HMA, 25 mm NMAS, PG 70-22 binder, 6% Air Voids
Lower Layer: 114 mm HMA, 25 mm NMAS, PG 64-22 binder, 4% Air Voids

Test Section 2 – Station 3620 to 3958
Surface Layer: 50 mm HMA, 12.5 mm NMAS, PG 70-28 binder, 6% Air Voids
Middle Layer: 114 mm HMA, 25 mm NMAS, PG 70-22 binder, 6% Air Voids
Lower Layer: 114 mm HMA, 25 mm NMAS, PG 64-22 binder, 6% Air Voids

The 12.5 mm E-30X mixture was designed using crushed limestone coarse aggregates, manufactured sand, and a target binder content of 5.4%. The 25 mm E-30X mixture was designed using crushed limestone coarse aggregates, manufactured sand, and a target binder content of 4.8%.

PAVEMENT INSTRUMENTATION

Marquette University was contracted to design, build and install asphalt strain sensors to record load-induced strains within the HMA perpetual pavement system. A total of 16 H-Type strain sensors were fabricated and installed in the outer wheel path at stations 3037 and 3600. Eight sensors were installed at the bottom of the lower HMA layer and the remaining eight sensors were installed at the interface of the lower and middle HMA layers. Figure 1 provides a schematic illustration of the sensor arrangement used at each placement/depth location. As shown, there is a redundant set of longitudinal and transverse oriented strain sensors at each instrumented location.

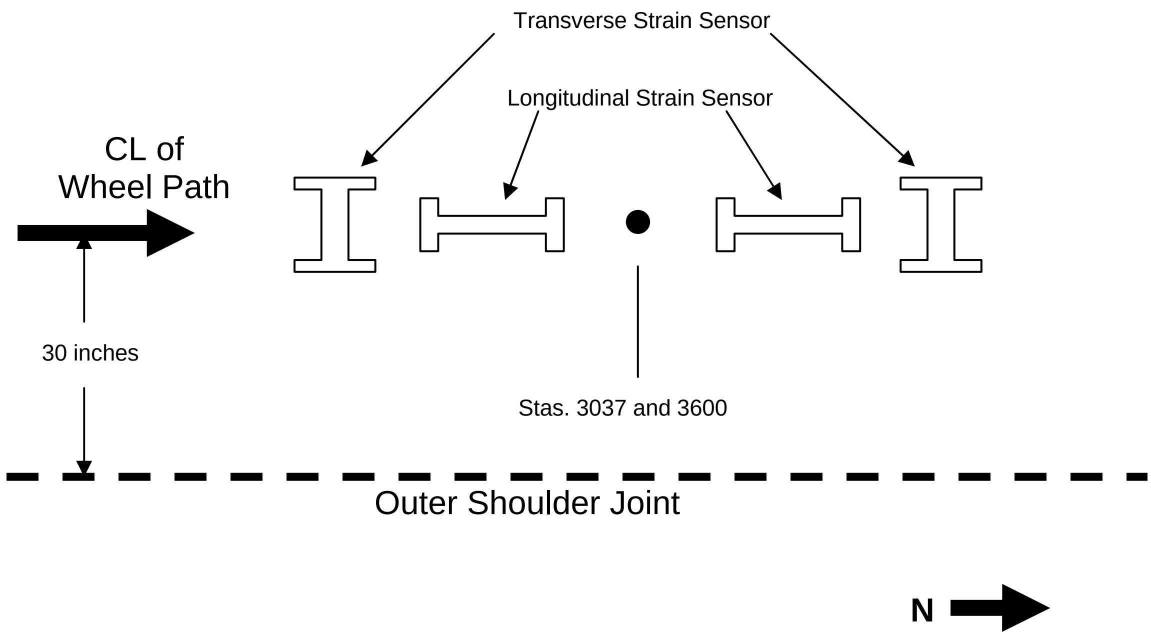

Figure 1: Schematic Illustration of Strain Sensor Configurations

The strain senor locations were selected prior to construction to include one set of sensors within each test section. However, the section limits were modified during construction and it was not possible to relocate the sensors from Station 3600. Of the sixteen strain sensors installed during pavement construction, only three survived to provide strain data under traffic loadings. The exact cause(s) of failure for the 13 non-surviving sensors is unknown, but most likely is a result of:

a) inadequate strain relief in the sensor wires,
b) insufficient shielding of the sensor wires, and/or
c) excessive strains during construction operations.

DEFLECTION TESTING RESULTS

Falling Weight Deflectometer (FWD) tests were conducted in September, 2003 in conjunction with strain measurements to provide data for analysis and comparative purposes. The pavement surface temperature during testing varied from 93 ^{o}F to 102 ^{o}F. Initial tests were conducted in the outer wheel path at approximately 30 m (100 ft) intervals using applied loads of approximately 5,000, 9,000 and 12,000 lbs. This data was used to backcalculate the subgrade breakpoint resilient modulus, Eri, and the HMA layer modulus, E_{AC} (all HMA layers combined). Figures 2 and 3 provide profile plots of the backcalculated Eri and E_{AC} values, respectively.

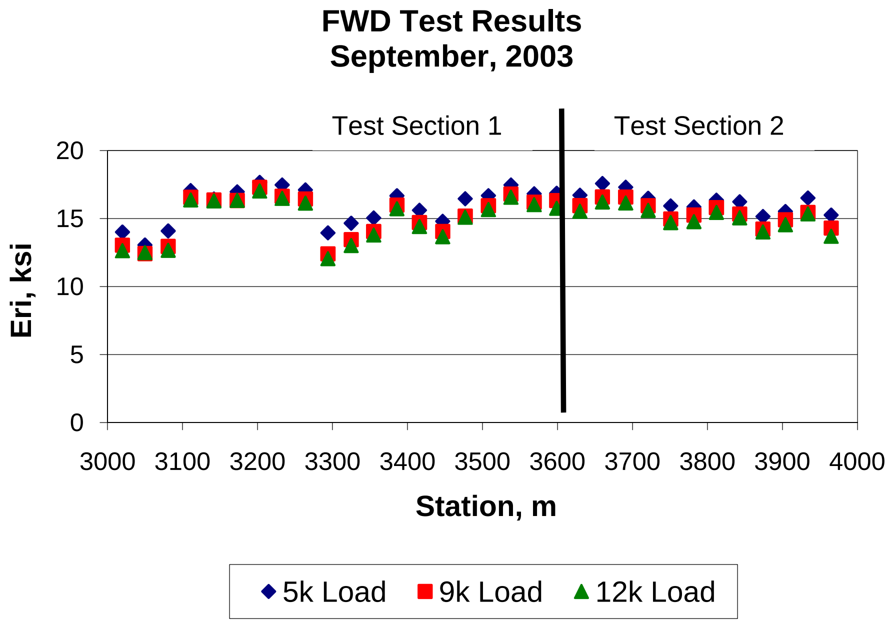

Figure 2: Backcalculated Subgrade Eri Profile, Sept. 2003

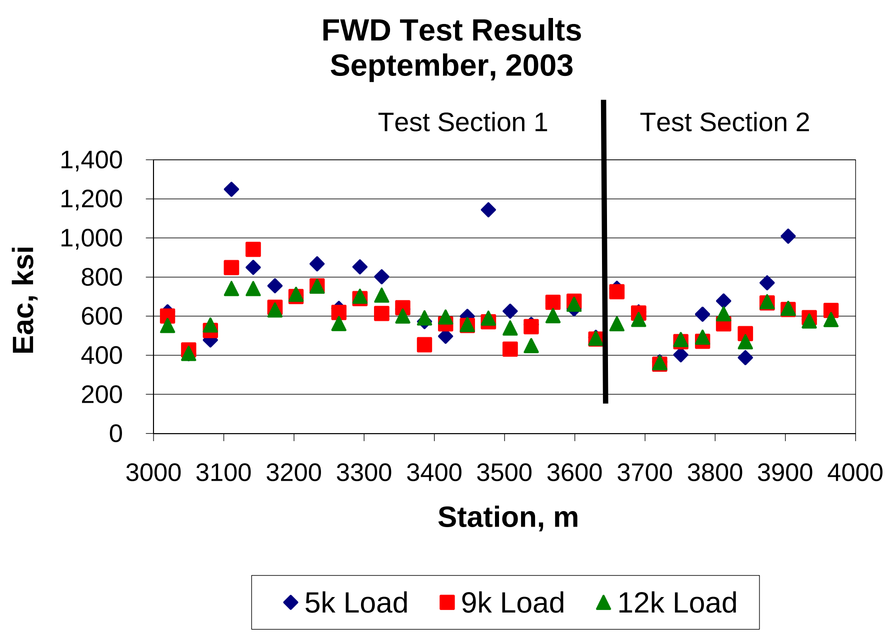

Figure 3: Backcalculated HMA Modulus Profile, Sept. 2003

Subgrade Eri values were backcalculated from FWD data using the following equation:

$$Eri = 22.04 - 3.645\ D_{36} + 0.158\ D_{36}^2 \qquad \text{Eq. 1}$$

Where: Eri = subgrade breakpoint resilient modulus, ksi
D_{36} = normalized surface deflection at 36 inches from the load center, mils
$D_{36} = 9{,}000\ (\delta_{36})\ /\ Load$
δ_{36} = measured surface deflection, mils
Load = actual applied load, lbs

Note: Eq. 1 is valid for normalized D_{36} deflections less than 11.5 mils

As shown in Figure 2, the backcalculated subgrade Eri values are relatively consistent within Test Section 2 and more variable in Test Section 1. Furthermore, the deflection results indicate a slight stress sensitivity in the lean clay soils, whereby there is a minor reduction in the backcalculated Eri values with increasing FWD load levels. This trend of stress-softening is typical for fine grained, cohesive soil materials. Summary statistics for the backcalculated subgrade Eri values are provided in Table 1.

The combined HMA layer moduli values, E_{AC}, were backcalculated using the following equations:

$$SCI = D_0 - D_{12} \qquad \text{Eq. 2}$$

$$E_{AC}T_{AC}^3 = 1{,}821{,}789\ SCI^{-1.594359} \qquad \text{Eq. 3}$$

Where: SCI = surface curvature index, mils
D_0 = normalized surface deflection at 0 inches from the load center, mils
D_{12} = normalized surface deflection at 12 inches from the load center, mils
$D_i = 9{,}000\ (\delta_i)\ /\ Load$
δ_i = measured surface deflection at i inches from the load center, mils
Load = actual applied load, lbs
E_{AC} = combined HMA layer modulus, ksi
T_{AC} = combined HMA layer thickness, inch (= 11.0 inches)

The backcalculated E_{AC} values illustrated in Figure 3 and provided in Table 2 indicate relative consistency within each test section; however, there is more variability compared to the backcalculated Eri values (i.e., higher COV values). Also, the overall average E_{AC} values are increased within Test Section 1 as would be expected due to the reduced air voids in the lower HMA layer.

Table 1: Summary Statistics for Backcalculated Subgrade Eri Values, Sept. 2003

		FWD Load Level		
		5 kips	9 kips	12 kips
Test Section 1 3020 – 3560	Ave Eri, ksi	15.9	14.9	14.9
	Std. Dev., ksi	1.4	2.0	1.6
	Coef of Var, %	8.9	13.4	11.0
	No. of Values	20	20	20
Test Section 2 3560 - 3960	Ave Eri, ksi	16.2	15.4	15.1
	Std. Dev., ksi	0.8	0.8	0.8
	Coef of Var, %	4.6	5.0	5.2
	No. of Values	12	12	12

Table 2: Summary Statistics for Backcalculated HMA E_{AC} Values, Sept. 2003

		FWD Load Level		
		5 kips(1)	9 kips	12 kips
Test Section 1 3020 – 3560	Ave E_{AC}, ksi	654	624	612
	Std. Dev., ksi	132	129	95
	Coef of Var, %	20.2	20.7	15.4
	No. of Values	18	20	20
Test Section 2 3560 - 3960	Ave E_{AC}, ksi	570	559	543
	Std. Dev., ksi	140	104	87
	Coef of Var, %	24.6	18.7	16.1
	No. of Values	11	12	12

Note (1): Summary statistics exclude outliers in each test section at the 5k load level.

STRAIN MEASUREMENTS DURING FWD TESTING

Strain measurements were made in conjunction with deflection testing to provide comparative measures to values backcalculated from FWD data. At the time of deflection testing, strain readings were only available from one of the interface strain sensors at Station 3037 and from one of the bottom strain sensors at Station 3600. Using FWD data collected with the load plate positioned directly over the active strain sensors, the FWD-induced strain at the bottom of the HMA layer was estimated as:

$$\varepsilon_{ac\text{-}bottom} = 10^{(1.0 + 0.9 \text{ Log AUPP})} \qquad \text{Eq. 4}$$

$$AUPP = ½ (5D_0 – 2 D_{12} – 2D_{24} – D_{36}) \qquad \text{Eq. 5}$$

Where: $\varepsilon_{ac\text{-}bottom}$ = FWD induced strain at the bottom of HMA layer, x 10^{-6}
AUPP = Area Under the Pavement Profile
D_i = deflection at i inches from the load center, mils

For the purpose of comparing measured and FWD estimated strain values for Station 3037, the estimated FWD-induced strain at the bottom of the HMA (Eq. 4) was adjusted based on the assumption of linear strain variation below the neutral axis of the HMA layer using the equation:

$$\varepsilon_{ac\text{-}interface} = (d/5.5)\ \varepsilon_{ac\text{-}bottom} \qquad \text{Eq. 6}$$

Where: $\varepsilon_{ac\text{-}interface}$ = FWD-induced strain at the lower HMA interface, x 10^{-6}
$\varepsilon_{ac\text{-}bottom}$ = FWD-induced strain at the bottom of HMA layer, x 10^{-6}
d = depth of interface below neutral axis, inches (= 2.0 inches)

The depth of the layer interface was set to 2.0 inches, which represents a lower HMA layer thickness of 3.5 inches. This lower layer thickness is less than the design thickness of 4.5 inches (114 mm), but corresponds to observations during paving between stations 3020 and 3050 (i.e., the initial truckload of HMA).

Table 3 provides comparative strain data collected during the September 2003 FWD testing. Also shown are the backcalculated E_{AC} values for each specific test location, based on data from the 9,000 lb load level (HMA temperature = 110 ^{o}F). As indicated, the FWD estimates are within 10% of the actual strain measurements, indicating an excellent agreement between estimated and measured values.

Table 3: Comparative Strain Data – Sept. 2003

Test Station	FWD Test Load kips	Actual Strain Reading x10^{-6}	Strain Sensor Position	Estimated FWD-Induced Strain x10^{-6}
Station 3037 E_{AC} = 427 ksi	5	15.8	Interface HMA Layer 2-3	16 *
	9	25.0		29 *
	12	36.9		39 *
Station 3600 E_{AC} = 676 ksi	5	30.0	Bottom HMA Layer 3	34 **
	9	59.9		66 **
	12	84.7		89 **

* Estimated using Eqs. 4, 5 and 6 ** Estimated using Eqs. 4 and 5

Falling Weight Deflectometer (FWD) tests were again conducted in October, 2003 in conjunction with strain measurements to provide additional data for analysis and comparative purposes. FWD tests were only conducted at locations of active strain sensors (Stations 3037 and 3600). During this round of FWD testing, the HMA interface sensor at Station 3600 provided data. The lack of data from the sensor during the September tests was most likely due to an improper connection between the sensor and the data acquisition system. Applied loads of approximately 5,000, 9,000 and 12,000 lbs were used with pavement surface temperature varying from 48 ^{o}F to 57 ^{o}F during testing. The collected FWD data was used to backcalculate the effective combined HMA layer modulus, E_{AC}, and to estimate the FWD-induced strain values (Eqs. 4 – 6).

Table 4 provides comparative strain data collected during the October 2003 FWD testing. As indicated, the estimated FWD-Induced Layer 2-3 Interface strains are under-predicted at Station 3037 and in close agreement at Station 3600. Also, the estimated FWD-induced Bottom HMA strains are over-predicted at Station 3600. Also note that the backcalculated E_{AC} values for each specific test location, based on the 9,000 lb loading, are significantly higher than the values backcalculated from the September 2003 data, which is to be expected due to the reduced HMA temperatures measured during FWD testing.

Table 4: Comparative Strain Data – Oct. 2003

Test Station	FWD Test Load kips	Actual Strain Reading $x10^{-6}$	Strain Sensor Position	Estimate FWD-Induced Strain $x10^{-6}$
Station 3037 E_{AC} = 3,135 ksi	5	9	Interface HMA Layer 2-3	6 *
	9	15		9 *
	12	20		14 *
Station 3600 E_{AC} = 3,609 ksi	5	5	Interface HMA Layer 2-3	5 *
	9	9		8 *
	12	11		11 *
	5	13	Bottom HMA Layer 3	18 **
	9	21		28 **
	12	29		39 **

* Estimated using Eqs. 4, 5 and 6 ** Estimated using Eqs. 4 and 5

STRAIN MEASUREMENTS DURING TRUCL LOADINGS

Strain measurements were made in conjunction with moving truck loadings to establish trends of strain data as a function of speed, load magnitude and position. On June 24, 2004 a series of strain measurements were obtained in Test Section 2 (Station 3600) under the action of FHWA Class 9 trucks (WisDOT Designation 3S-2). Strain measurements were captured at the bottom of the HMA layer for four separate trucks traveling between 37 – 42 mph. Axle loadings were obtained from the weigh station records and ranged from 10,480 – 12,740 lb on the steering axle and from 10,240 – 34,680 lb on the dual-tandem axle. Figures 4 – 7 illustrate the maximum strain readings obtained under each axle of the four truck loadings. As shown, the peak strain values (tension is negative) produced by the single axle loads (SAL) and tandem axle loads (TAL) are well correlated to the magnitude of the axle loadings and all strain reading are below 50 mirostrain.

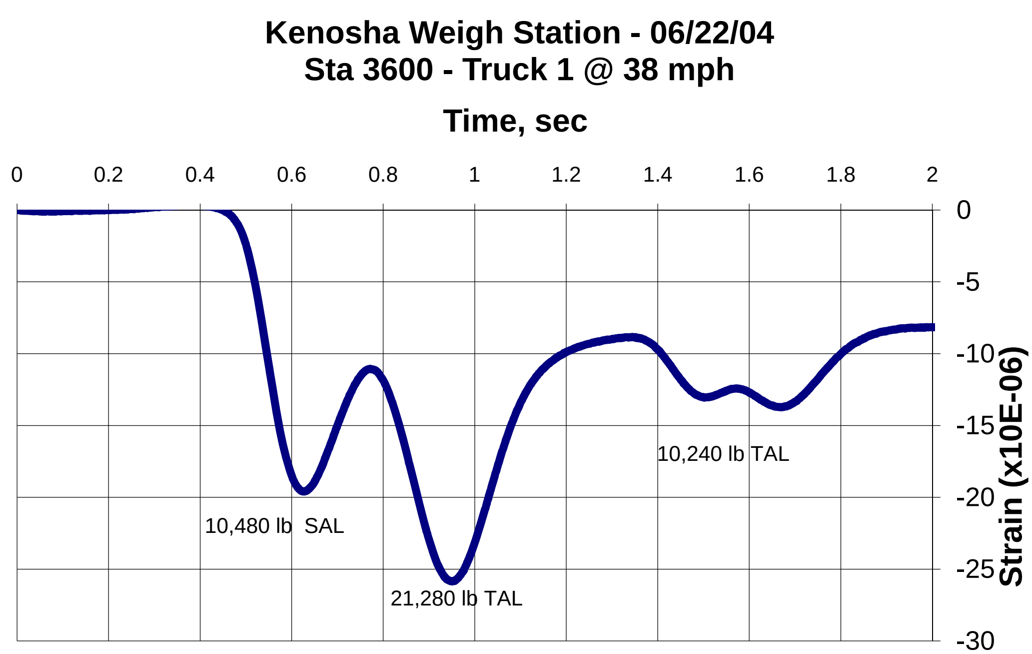

Figure 4: Strain Measurement from Truck 1 – June 2004

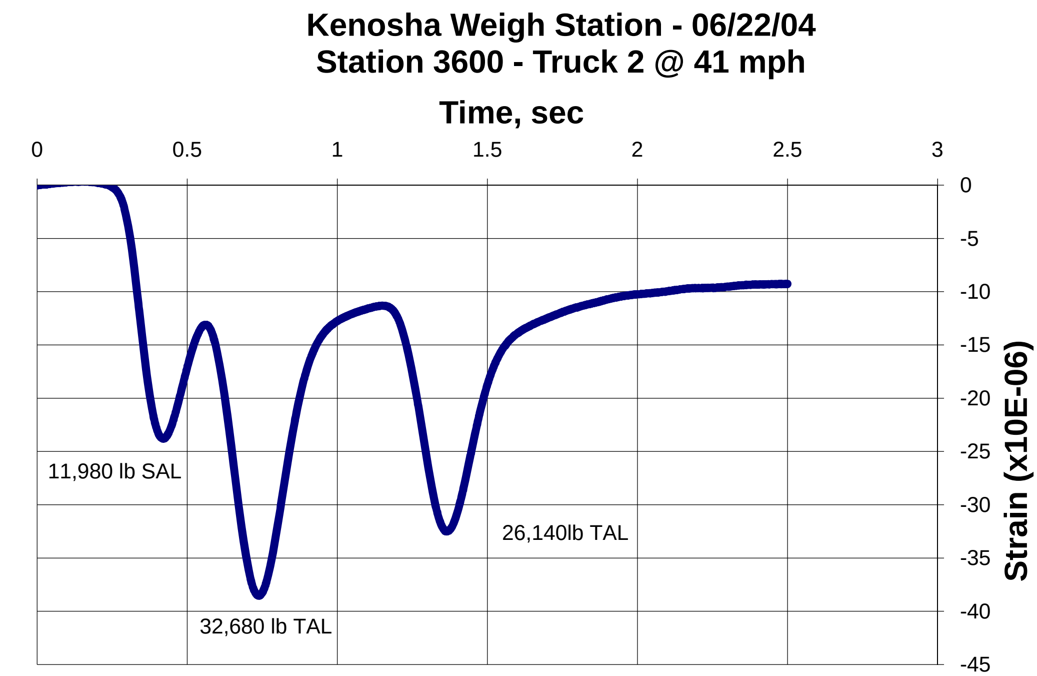

Figure 5: Strain Measurement from Truck 2 – June 2004

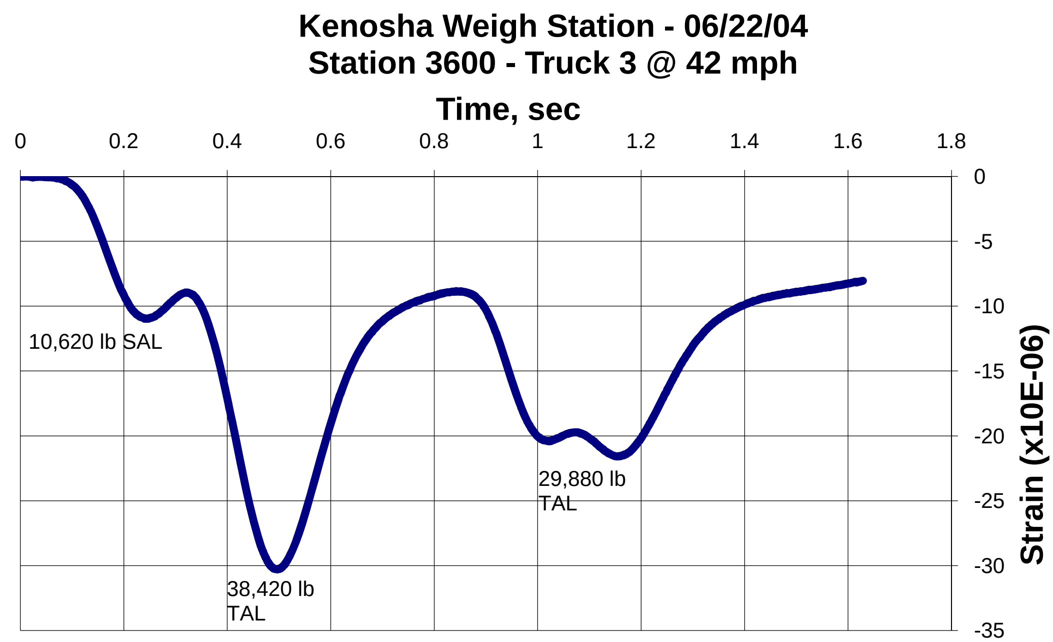

Figure 6: Strain Measurement from Truck 3 – June 2004

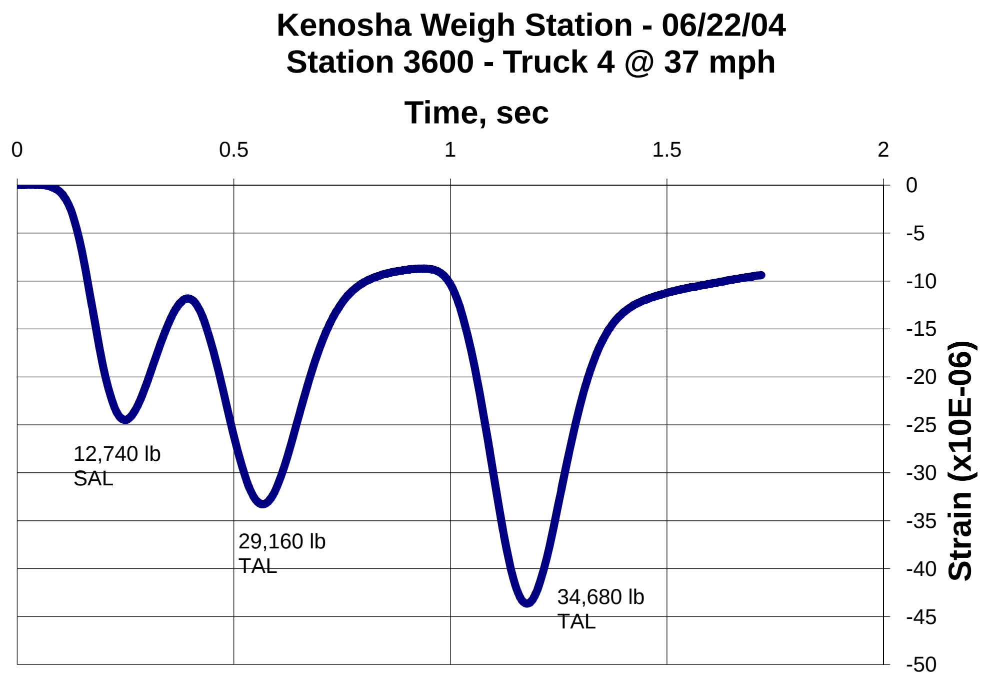

Figure 7: Strain Measurement from Truck 4 – June 2004

A second series of truck measurements were made on April 18, 2005 using a loaded quad-axle dump truck with a total gross vehicle weight of approximately 72,700 lb. Strain measurements were obtained from the bottom and interface sensors at Station 3600. Pavement surface temperatures ranged from 80.2 to 90.8 ^{o}F during testing. Two truck runs were recorded with the pusher wheels up, which results in a steering axle loading of approximately 25,400 lb and a rear dual-tandem axle loading of approximately 47,300 lb. An additional truck run was recorded with the pusher axles down, resulting in a steering axle loading of approximately 19,000 lb, a rear dual-tandem axle loading of approximately 38,600 lb and a pusher axle loading of approximately 15,000 lb. Figures 8 - 10 illustrate the results of these truck tests. As shown, the bottom strain readings are significantly higher than the interface values, as expected. Furthermore, all strain readings are below 25 microstrain.

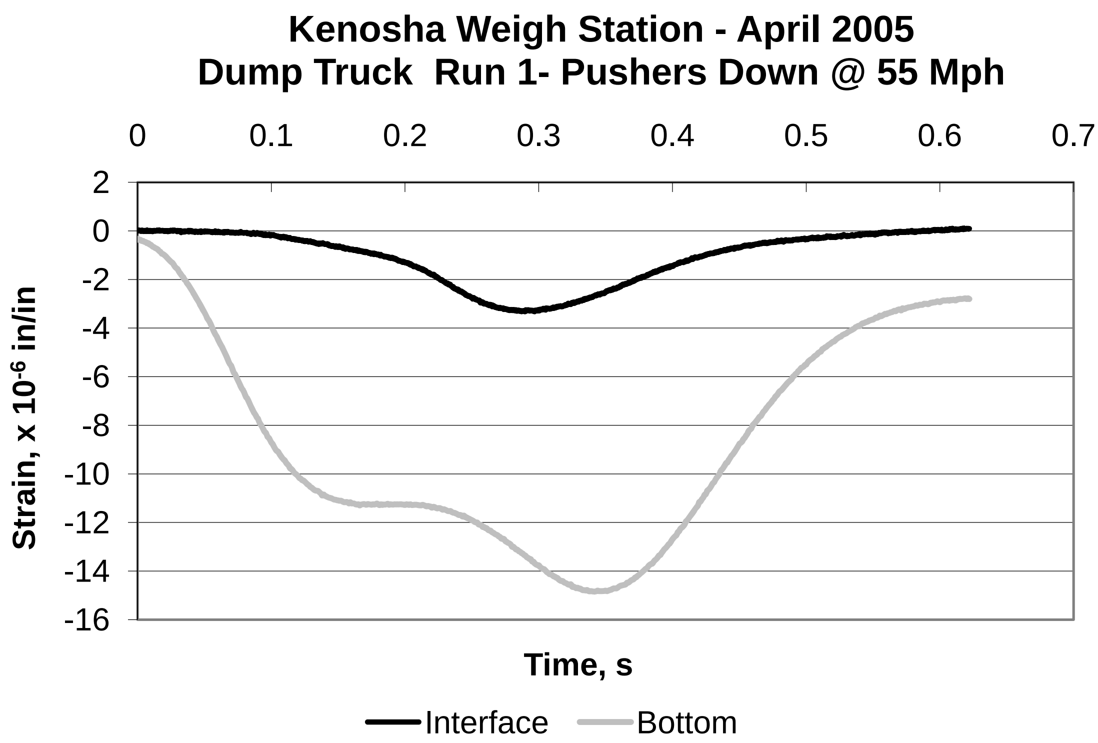

Figure 8: Strain Measurement from Truck Run 1 – April 2005

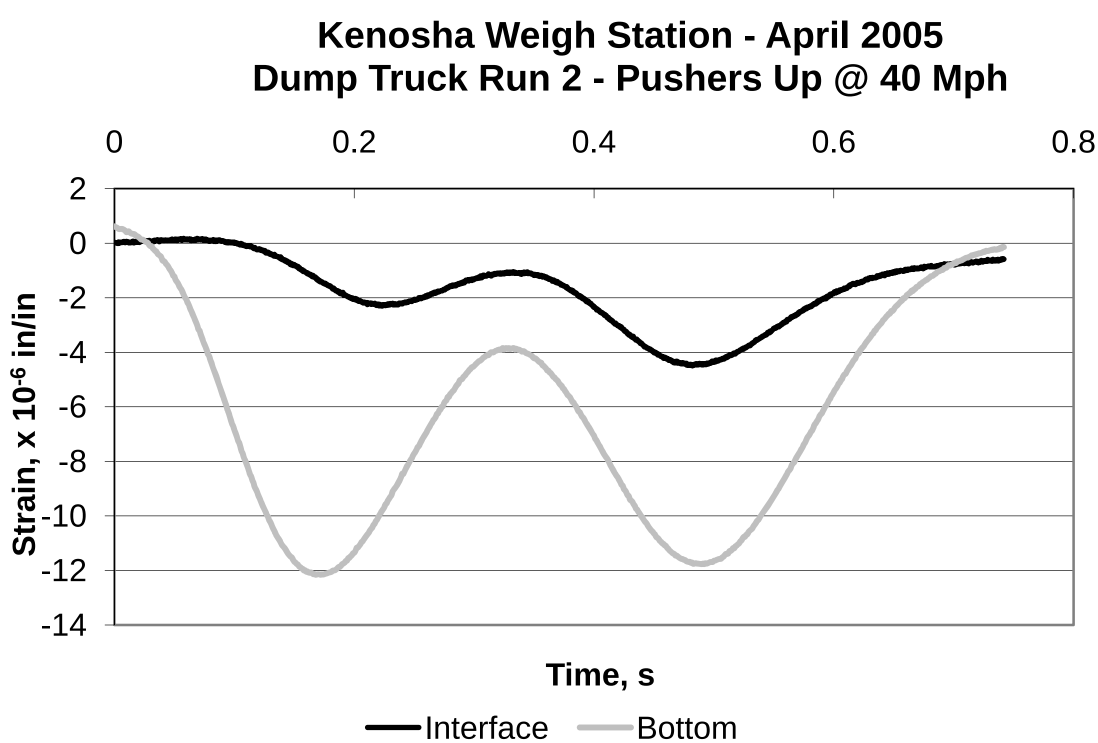

Figure 9: Strain Measurement from Truck Run 2 – April 2005

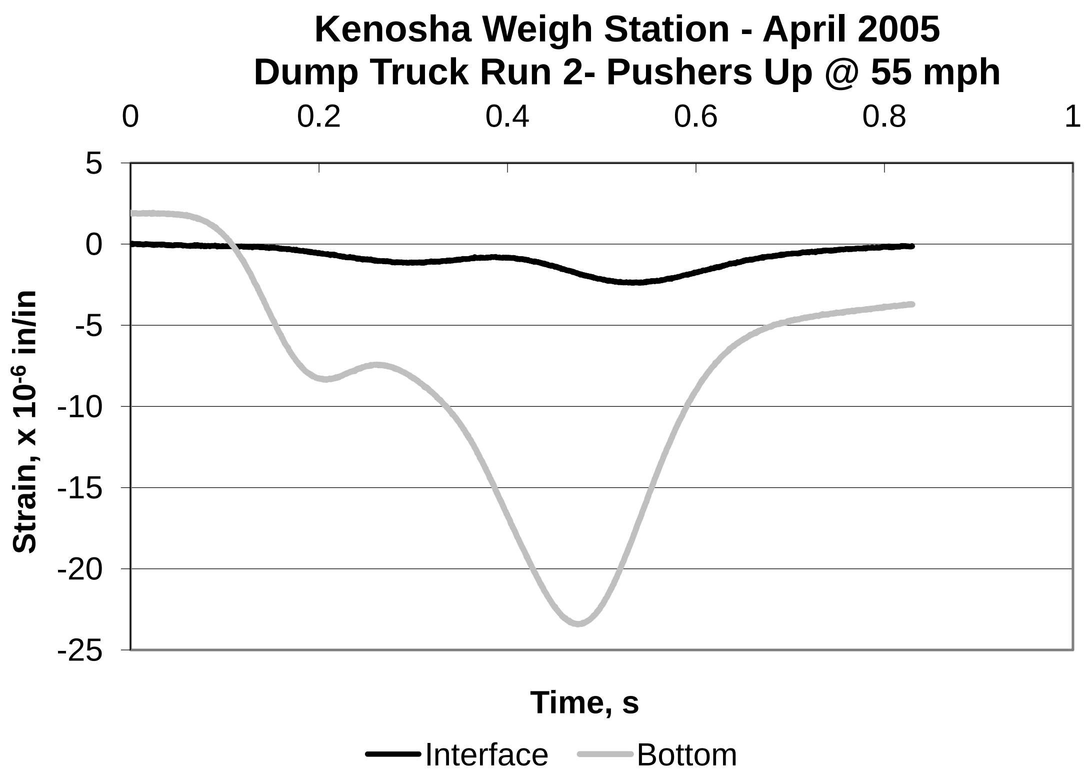

Figure 10: Strain Measurement from Truck Run 3 – April 2005

A final series of truck measurements were conducted on July 26, 2005. Strain measurements were obtained from the bottom and interface sensors at Station 3600. These measurements were again made under the action of the loaded quad-axle dump truck with a total gross vehicle weight of approximately 72,700 lb. Pavement surface temperatures ranged from 90 to 103 ^{o}F during testing. Four truck runs were recorded with the pusher wheels down (19,000 lb SAL, 38,600 lb TAL, 15,000 lb PAL). Four additional truck runs were recorded with the pusher axles up (25,400 lb SAL and 47,300 lb TAL). During each run, the position of the right front steering wheel was recorded in reference to the centerline of the right wheel path. Figures 11 - 18 illustrate the results of these truck tests. As shown, the strains recorded during this testing are substantially higher than during the previous test series in April 2005, likely due to the higher pavement temperatures and slower truck speeds. In particular, the effects of speed on strain development can be seen by comparing Figures 12 and 13, which clearly demonstrate the increase in strains resulting from reduced truck speeds (equal offset values). When the pusher axles were lowered (legal loadings) all strain readings were below 70 microstrain. With the pusher axles raised, slower truck speeds produced bottom layer strains in excess of 100 microstrain under the heavily loaded single axle (steering axle).

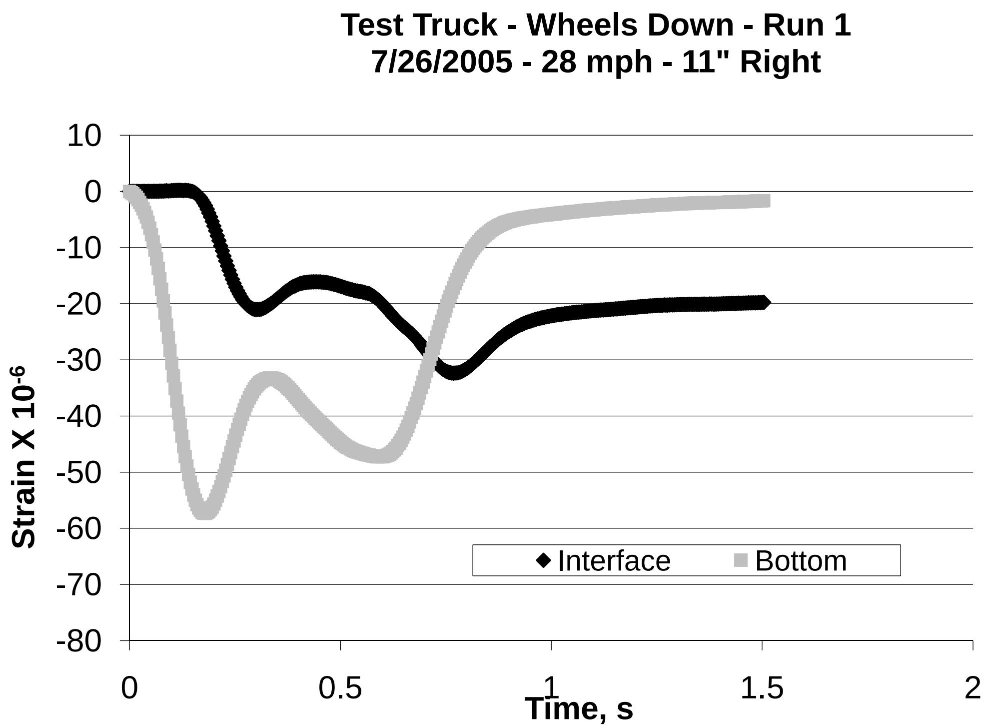

Figure 11: Strain Measurement from Truck Run 1 – July 2005

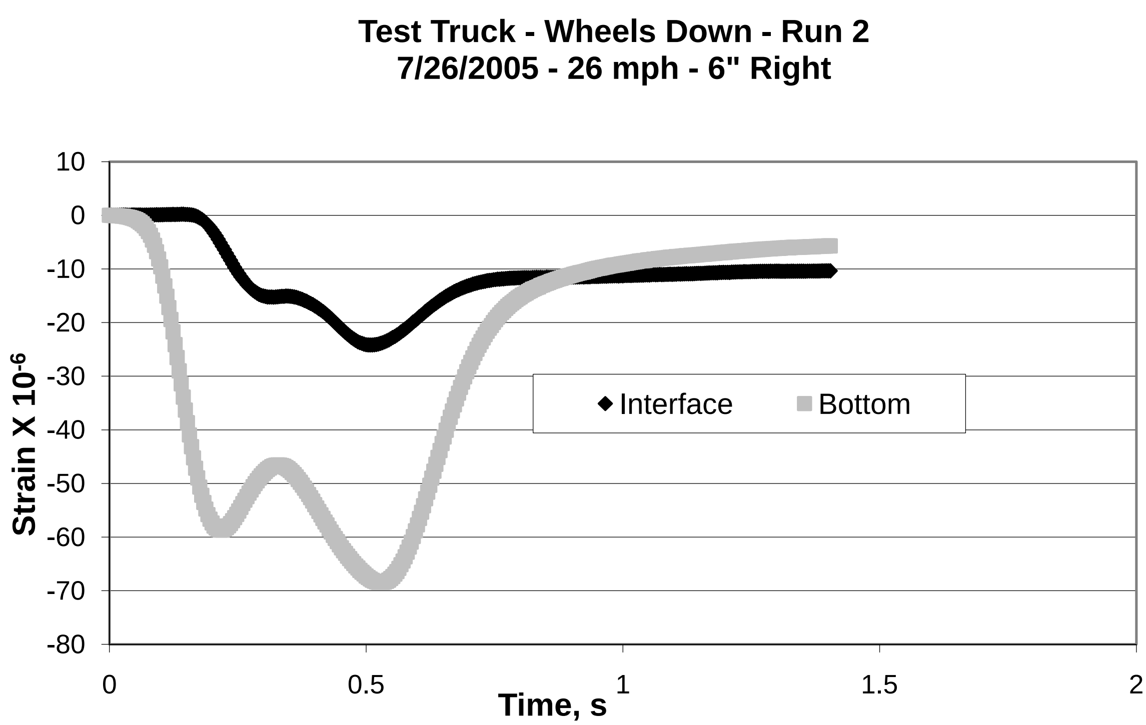

Figure 12: Strain Measurement from Truck Run 2 – July 2005

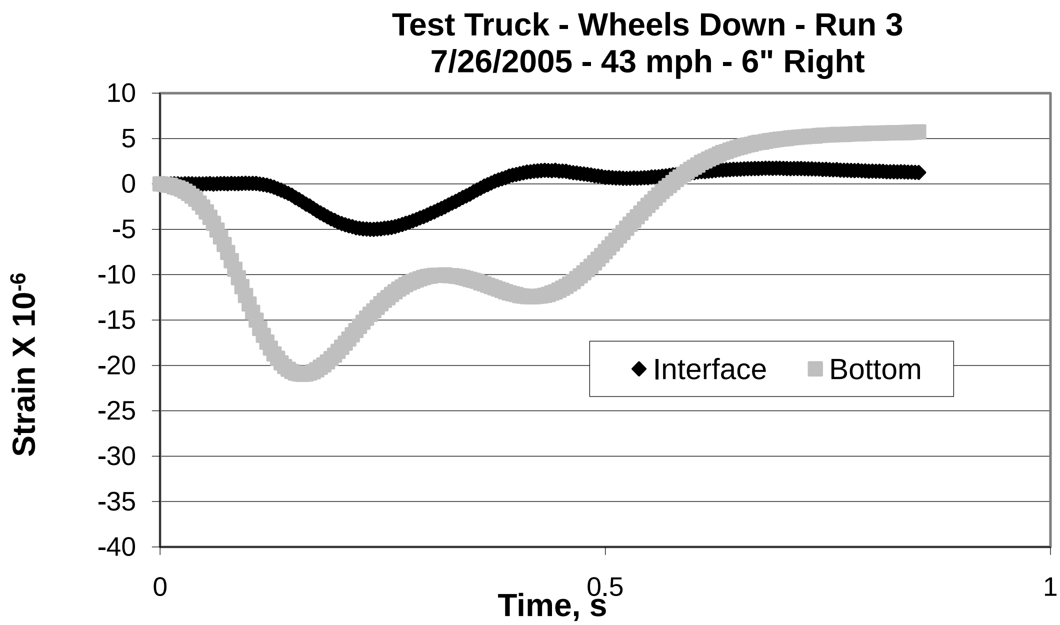

Figure 13: Strain Measurement from Truck Run 3 – July 2005

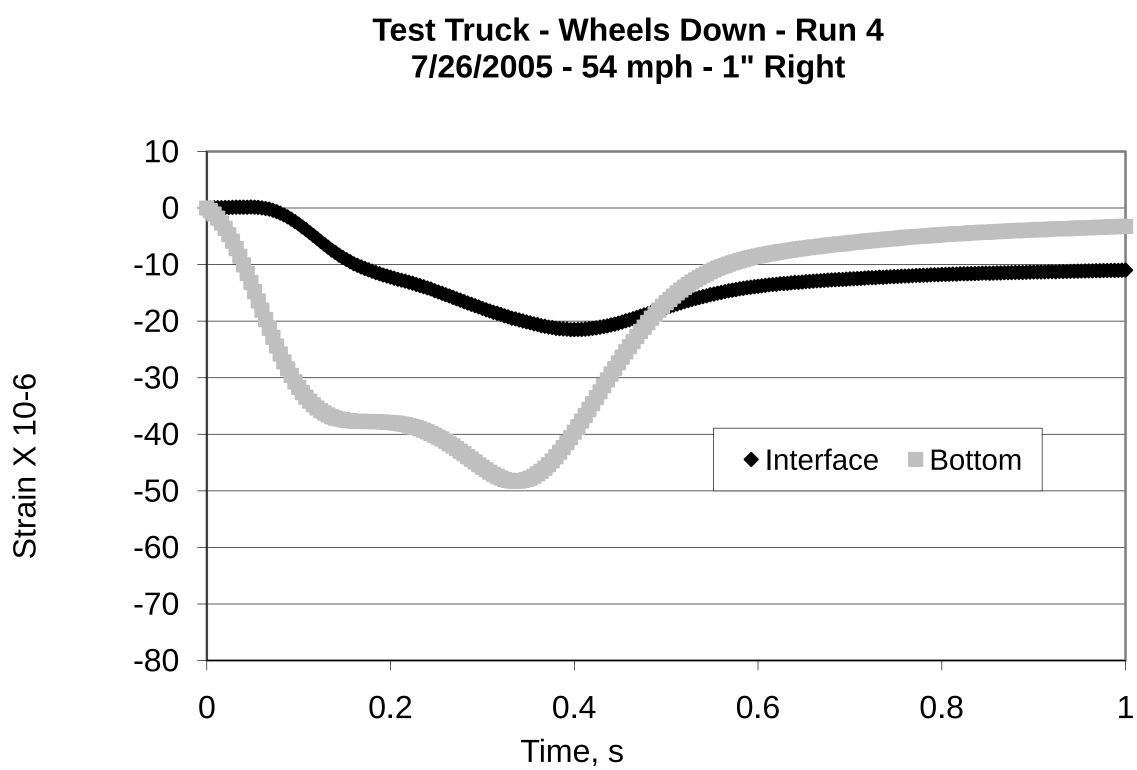

Figure 14: Strain Measurement from Truck Run 4 – July 2005

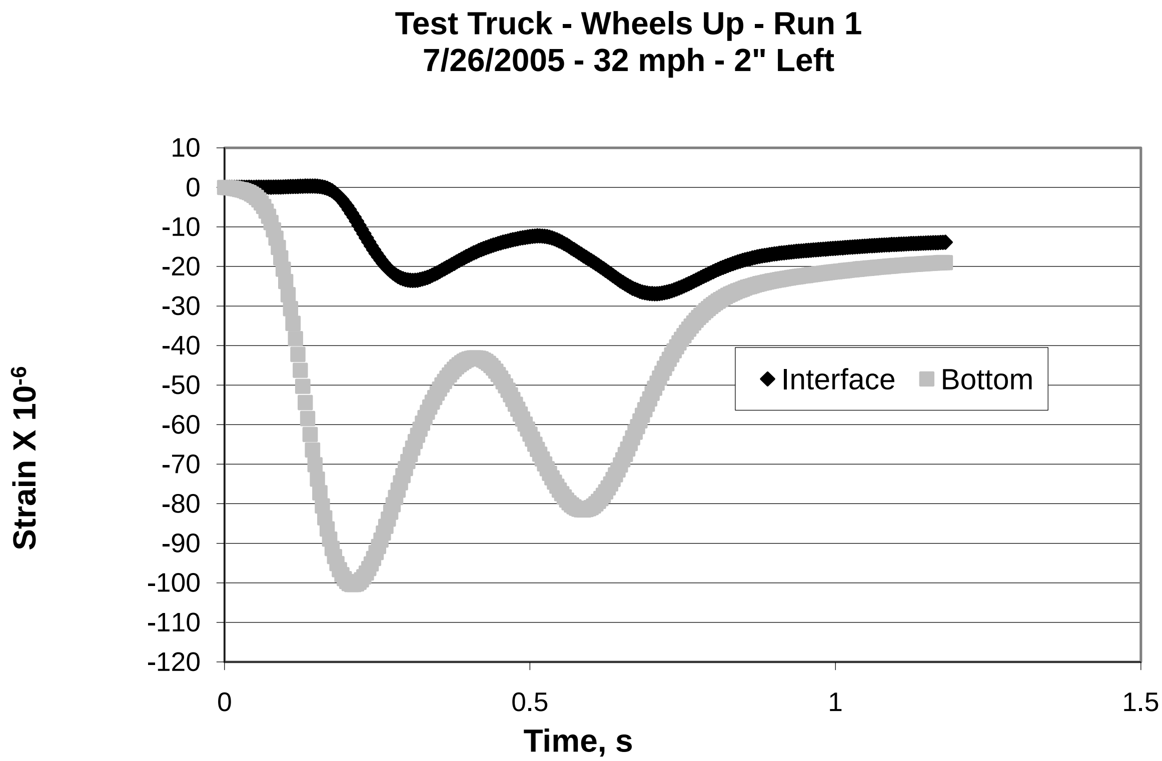

Figure 15: Strain Measurement from Truck Run 5 – July 2005

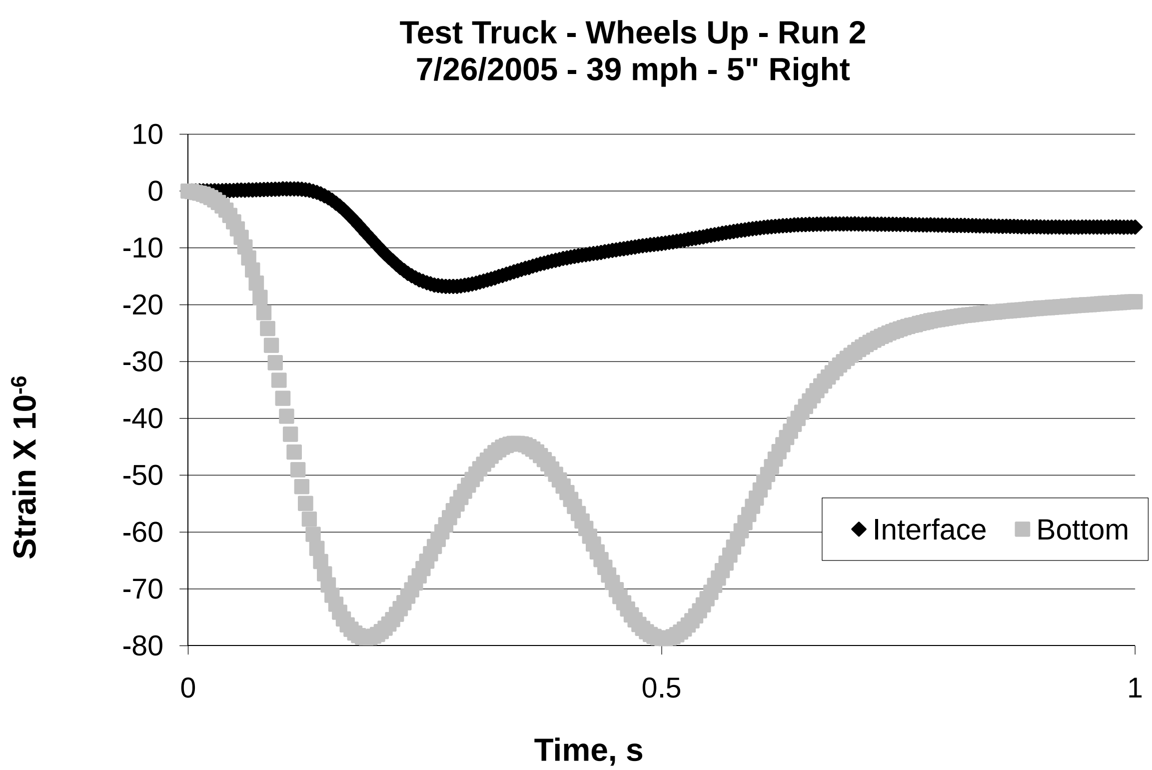

Figure 16: Strain Measurement from Truck Run 6 – July 2005

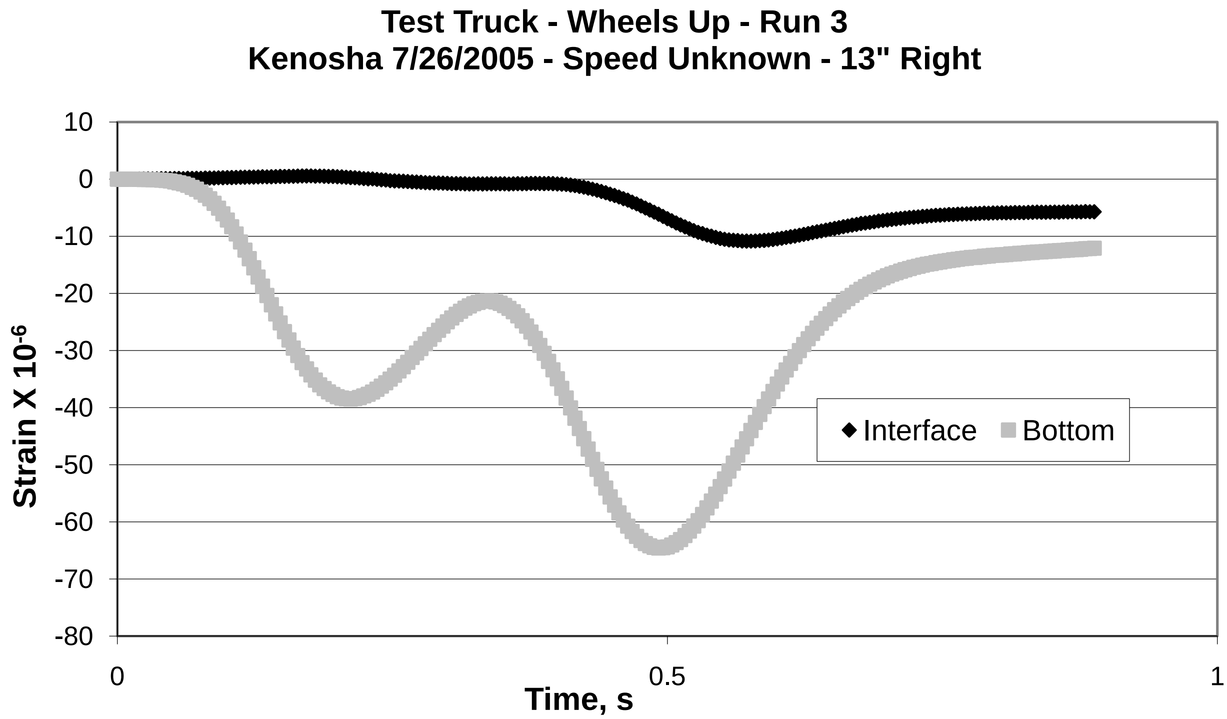

Figure 17: Strain Measurement from Truck Run 7 – July 2005

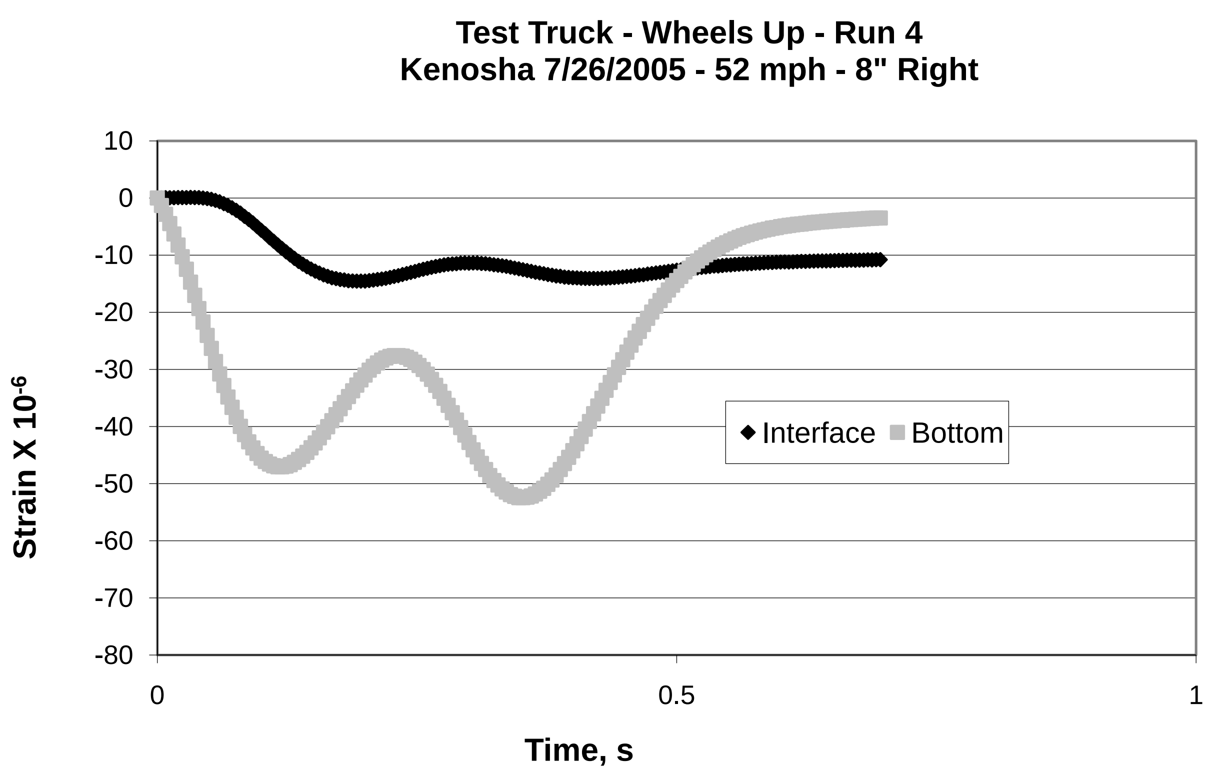

Figure 18: Strain Measurement from Truck Run 8 – July 2005

MECHANISTIC PAVEMENT APPRAISAL

The HMA perpetual pavement sections were analyzed for critical strains at the bottom of the HMA layer under the action of an 18,000 lb single axle loading using the EVERSTRESS pavement analysis program. These critical strains can be related to an allowable number of axle loadings using a fatigue transfer function. The actual applied loadings can then be used to compute the load-induced pavement damage. For typical applications a damage level of 100% indicates fatigue failure, which corresponds to a pavement with bottom-up fatigue cracking covering approximately 50% of the total lane area of the HMA pavement surface.

For this analysis, the 125 million ESALs were assumed to be applied equally throughout the calendar year, i.e., approximately 0.521 million ESALs per month for the 20 year design life. Each ESAL loading is modeled as a pair of dual tires, each carrying 4,500 lbs, with an inflation pressure of 90 psi and a dual tire spacing of 18 inches. Because of the large transverse distance between dual loadings, i.e., an axle length of 72 – 84 inches, the "other-end" dual tire load would not affect pavement responses at its corresponding pair. Therefore, only one set of dual loadings per axle need be analyzed.

The mechanical properties of each component pavement layer must be varied to account for seasonal variations in temperature and moisture. For the HMA layer, the mean monthly air temperatures were used to compute the mean monthly mid-depth pavement temperature using the equation:

$$MMPT = MMAT\,[1+(1/\{Z+4\})] - [34/(Z+4)] + 6 \qquad \text{Eq. 7}$$

Where: MMPT = mean monthly pavement temperature, F
MMAT = mean monthly air temperature, F
Z = depth below surface, inches
Z = 1 for 12.5mm surface layer and 8.75 for 25mm lower layer

Figure 19 illustrates the variations in MMAT and MMPT established for Kenosha, WI.

Relations between the resilient HMA modulus and pavement temperature were developed under WHRP Project 0092-03-14, Development of Modulus-to-Temperature Relations for HMA Mixtures in Wisconsin. During this study, cores were taken from the in-place shoulder at the Kenosha Safety and Weigh Station. These shoulders were constructed using the same surface and middle layer HMA mixtures used for the by-pass lane, but were compacted to air voids content different than specified for the by-pass lane. The shoulders were constructed with 175 mm (7 inches) HMA Type E-30X, and excluded the lower 114 mm (4.5 inch) HMA layer used for the by-pass lane. Table 5 provides comparative data for the shoulder and by-pass lane pavements.

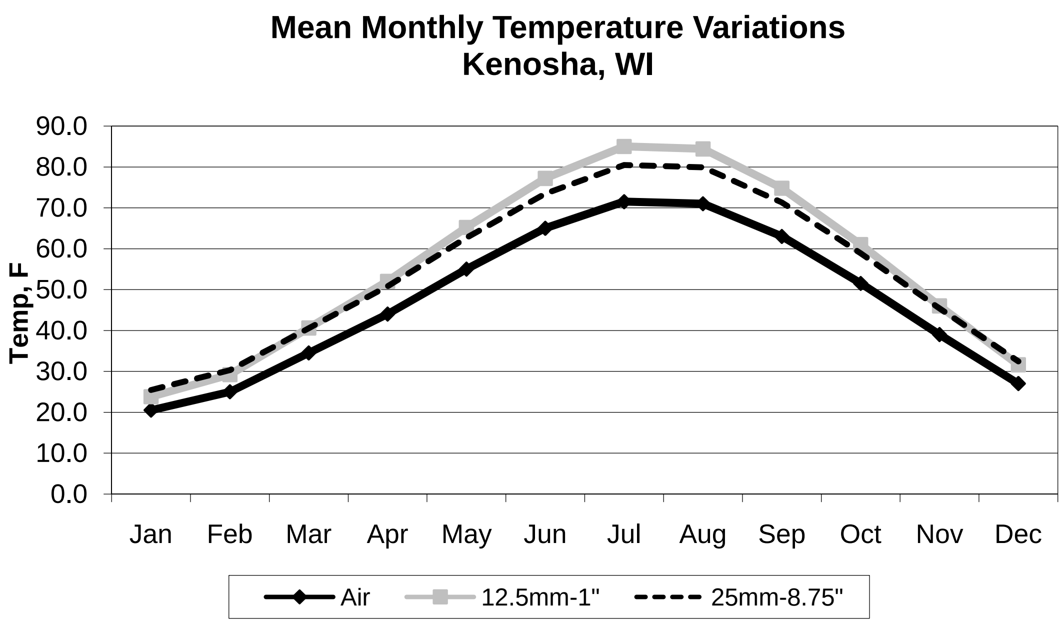

Figure 19: Mean Monthly Temperature Variations for Kenosha, WI

Table 5: Comparative Pavement Data

Test Section	Pavement Layer	By-Pass Lane Target %Voids	By-Pass Lane In-Place % Voids*	By-Pass Lane In-Place % Voids**	Shoulder In-Place %Voids
1	Upper	6	7.4	7.3	7.3
	Middle	6	5.0	7.2	5.0
	Bottom	4	6.3	4.1	n.a.
2	Upper	6	9.3	7.3	8.9
	Middle	6	7.6	5.1	5.7
	Bottom	6	7.1	2.6	n.a.

*Average values obtained from Contractor nuclear density test records
**Average values obtained from pavement cores extracted in April 2007

Equations for predicting the resilient HMA modulus versus NMAS, pavement temperature, % voids and % AC were developed during WHRP Project 0092-03-14 for the HMA shoulder layers used at the Kenosha facility. Figures 20 and 21 illustrate the trends in predicted HMA modulus versus pavement temperature based on the in-place % air voids and design % AC for the HMA shoulder in each test section. Also shown on Figure 20 are the FWD estimates of the by-pass lane combined E_{AC} layer values backcalculated from deflection data obtained during comparative strain measurements. As shown, the combined modulus estimated from the FWD data closely match the 25 mm NMAS E-30X predicted modulus for Test Section 1. The bias of the 25 mm NMAS layer modulus in the combined modulus is expected, as this NMAS mixture dominates the pavement structure (225 mm of the total 275 mm HMA thickness).

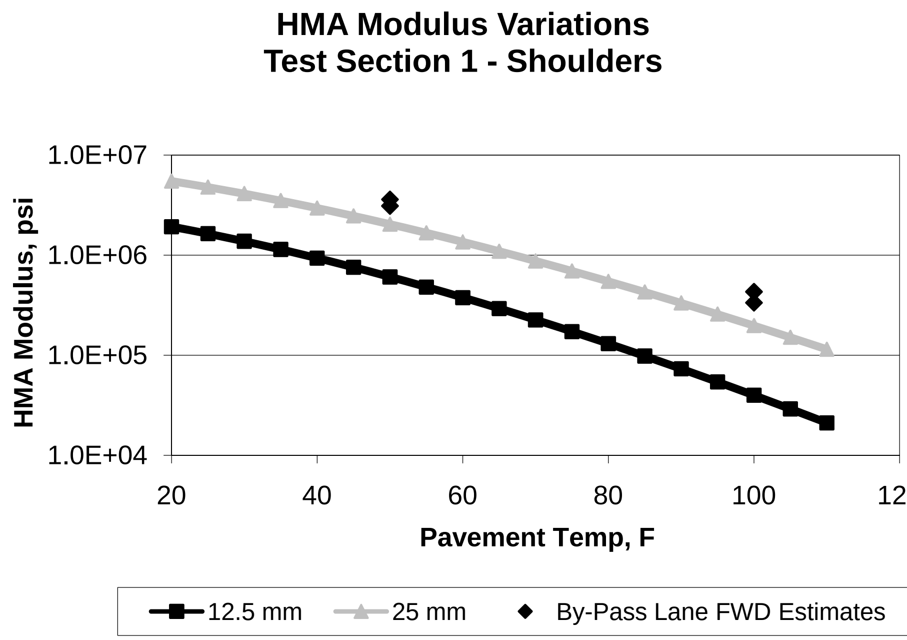

Figure 20: Predicted HMA Moduli Variations for Test Section 1 Shoulders

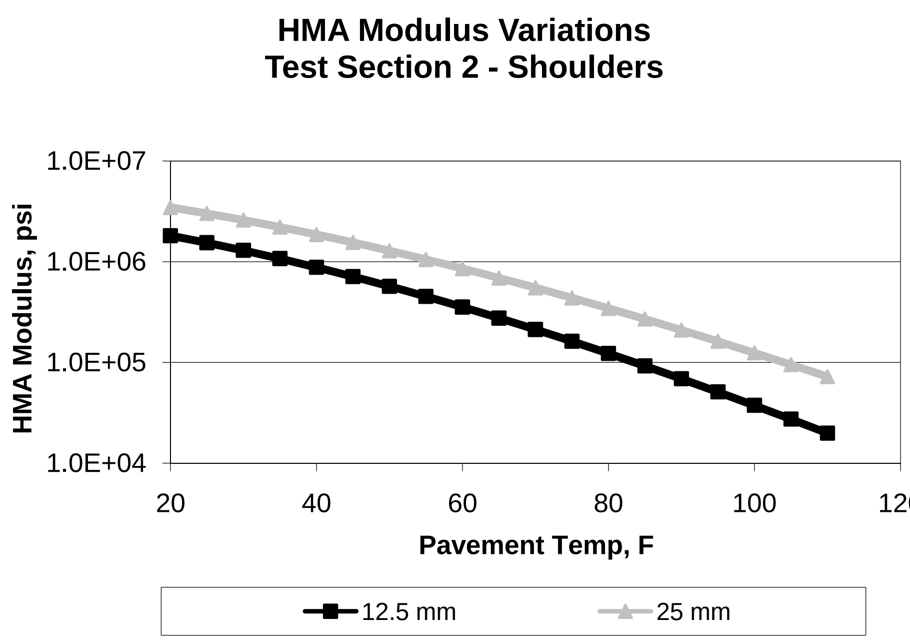

Figure 21: Predicted HMA Moduli Variations for Test Section 2 Shoulders

The general trends of HMA modulus versus temperature were combined with the monthly pavement temperature variations typical for Kenosha, WI to develop a trend of average monthly HMA moduli values for the 12.5 mm surface layer at the design values of 6% air voids and for the 25 mm lower layers at air void contents ranging from 4% to 6%, as shown in Figure 22 and Table 6. It should be noted that the average monthly moduli values shown for September are significantly higher than values backcalculated during September 2003 FWD testing (Tables 1–3). This is due to the significant differences in the MMPT = 70^{o}F and the FWD test temperature of 100^{o}F. Conversely, the average monthly moduli values shown for October are less than those backcalculated from FWD testing in October 2003 (Table 4). This is again due to the difference in temperatures (MMPT = 59^{o}F, FWD Test Temp = 50^{o}F).

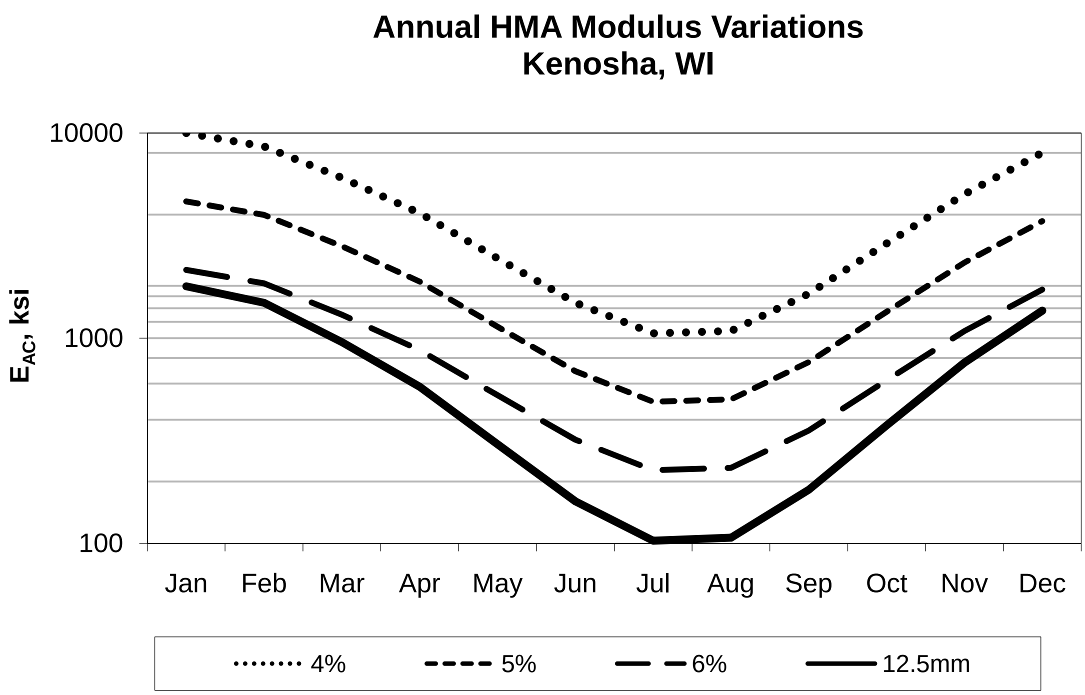

Figure 22: Monthly HMA Moduli Trends for Layer Type

Table 6: Monthly HMA Moduli Values for Each Test Section

Month	MMPT		Dynamic HMA Moduli, ksi			
	12.5mm 1”	25mm 8.75”	12.5mm 6% AV	25mm 4% AV	25mm 5% AV	25mm 6% AV
Jan	23.8	25.4	1,788	9,998	4,638	2,151
Feb	29.2	30.3	1,486	8,602	3,990	1,851
Mar	40.6	40.5	956	6,041	2,802	1,300
Apr	52.0	50.8	579	4,064	1,885	874
May	65.2	62.6	304	2,450	1,137	527
Jun	77.2	73.4	160	1,487	690	320
Jul	85.0	80.4	103	1,055	489	227
Aug	84.4	79.9	106	1,084	503	233
Sep	74.8	71.3	182	1,648	764	355
Oct	61.0	58.9	375	2,893	1,342	622
Nov	46.0	45.4	759	5,032	2,334	1,083
Dec	31.6	32.5	1,362	8,017	3,718	1,725

The remaining unbound aggregate and soil pavement layers were characterized as stress dependent materials following general trends for each material type, i.e., stress-stiffening for granular materials and stress-softening for cohesive materials. Within EVERSTRESS, the general equation for estimating the resilient modulus of granular materials is of the form:

$$M_R = A\,(\theta/Pa)^{B} \qquad \text{Eq. 8}$$

Where: M_R = resilient modulus, ksi
θ = bulk stress state, psi
Pa = atmospheric pressure, psi
A,B = regression constants

For fine-grained, cohesive materials, the general equation is of the form:

$$M_R = A\,(\sigma_D/Pa)^{B} \qquad \text{Eq. 9}$$

Where: M_R = resilient modulus, ksi
σ_D = deviator stress, psi
Pa = atmospheric pressure
A,B = regression constants

Table 7 provides the regression constants used to describe each aggregate and soil layer, which are typical values used for the layer material types used within the by-pass lane at the Kenosha Weigh Station.

Table 7: Regression Constants for Each Unbound Pavement Layer

Pavement Layer	A, ksi	B
Crushed Aggregate, Open Graded No. 2	19.2	0.50
Crushed Aggregate, Dense Graded	23.4	0.40
Clayey Soil	16.0	-0.28

The critical monthly HMA strains calculated by EVERSTRESS for the standard 18,000 lb single axle load are provided in Table 8. These strains were used to compute allowable load to failure based on the Asphalt Institute's fatigue equation:

$$N_f = 0.0796\,(\varepsilon_{ac})^{-3.291}\,|E_{AC}|^{-0.854}$$

Where: N_f = allowable loading to 50% fatigue cracking (% of total lane area)
ε_{ac} = critical HMA strain at the bottom of the HMA layer
E_{AC} = asphalt modulus, psi

The expected monthly fatigue damage is computed as:

$$\%D = 100\% \times Napp / N_f$$

Where: %D = monthy % damage
Napp = expected monthly loading applications (= 0.521 million)

The expected yearly damage is computed as the simple summation of the expected monthly damage values. An estimate of the pavement fatigue life can be computed as the inverse of the yearly damage (decimal value). Table 8 provides the outputs of the HMA fatigue cracking analysis conducted for the range of 4% - 6% air voids within the lower 25mm layers. As shown, the cumulative yearly damages estimated increase significantly as the void content increases. These damage values can be used to estimate the service lives to varying levels of bottom-up fatigue cracking, as shown in Table 9 and Figure 24. As indicated, the estimated fatigue life of the pavement sections is significantly reduced as air voids are increased.

Table 8: HMA Fatigue Cracking Analysis Outputs

25mm Lower Layer - 4% Voids

Month	12.5mm Surface 6% Voids E_{AC}	25mm Layers 4% Voids E_{AC}	Strain $x10^{-6}$	Na	Nf	%D
Jan	1,788	9,998	7.88	5.21E+05	1.23E+10	0.00%
Feb	1,486	8,602	8.94	5.21E+05	9.03E+09	0.01%
Mar	956	6,041	12.01	5.21E+05	4.43E+09	0.01%
Apr	579	4,064	16.64	5.21E+05	2.03E+09	0.03%
May	304	2,450	24.99	5.21E+05	7.79E+08	0.07%
Jun	160	1,487	36.88	5.21E+05	3.18E+08	0.16%
Jul	103	1,055	47.77	5.21E+05	1.77E+08	0.29%
Aug	106	1,084	46.81	5.21E+05	1.86E+08	0.28%
Sep	182	1,648	34.08	5.21E+05	3.80E+08	0.14%
Oct	375	2,893	21.9	5.21E+05	1.06E+09	0.05%
Nov	759	5,032	13.97	5.21E+05	3.08E+09	0.02%
Dec	1,362	8,017	9.48	5.21E+05	7.84E+09	0.01%
					Yearly Damage =	1.06%
					Expected Fatigue Life =	94.1

25mm Lower Layer - 5% Voids

Month	12.5mm Surface 6% Voids E_{AC}	25mm Layers 5% Voids E_{AC}	Strain $x10^{-6}$	Na	Nf	%D
Jan	1,788	4,638	14.00	5.21E+05	3.39E+09	0.02%
Feb	1,486	3,990	15.86	5.21E+05	2.51E+09	0.02%
Mar	956	2,802	21.20	5.21E+05	1.26E+09	0.04%
Apr	579	1,885	29.14	5.21E+05	5.94E+08	0.09%
May	304	1,137	43.17	5.21E+05	2.41E+08	0.22%
Jun	160	690	62.56	5.21E+05	1.05E+08	0.49%
Jul	103	489	79.76	5.21E+05	6.27E+07	0.83%
Aug	106	503	78.22	5.21E+05	6.54E+07	0.80%
Sep	182	764	58.09	5.21E+05	1.24E+08	0.42%
Oct	375	1,342	38.02	5.21E+05	3.21E+08	0.16%
Nov	759	2,334	24.57	5.21E+05	8.86E+08	0.06%
Dec	1,362	3,718	16.81	5.21E+05	2.19E+09	0.02%
					Yearly Damage =	3.17%
					Expected Fatigue Life =	31.5

Table 8: HMA Fatigue Cracking Analysis Outputs (Continued)

25mm Lower Layer - 6% Voids

Month	12.5mm Surface 6% Voids E_{AC}	25mm Layers 6% Voids E_{AC}	Strain $x10^{-6}$	Na	Nf	%D
Jan	1,788	2,151	24.02	5.21E+05	1.08E+09	0.05%
Feb	1,486	1,851	27.15	5.21E+05	8.04E+08	0.06%
Mar	956	1,300	36.01	5.21E+05	4.15E+08	0.13%
Apr	579	874	49.00	5.21E+05	2.04E+08	0.26%
May	304	527	71.26	5.21E+05	8.89E+07	0.59%
Jun	160	320	100.58	5.21E+05	4.32E+07	1.21%
Jul	103	227	125.22	5.21E+05	2.82E+07	1.84%
Aug	106	233	123.21	5.21E+05	2.91E+07	1.79%
Sep	182	355	93.84	5.21E+05	4.98E+07	1.05%
Oct	375	622	63.19	5.21E+05	1.16E+08	0.45%
Nov	759	1,083	41.55	5.21E+05	2.98E+08	0.17%
Dec	1,362	1,725	28.74	5.21E+05	7.03E+08	0.07%
					Yearly Damage =	7.67%
					Expected Fatigue Life =	13.0

Table 9: HMA Fatigue Life Estimates for Bottom-Up Cracking

Bottom-Up Cracking % of Total Area	Bottom-Up Fatigue Damage, %	Estimated Service Life, years		
		25mm 4% Voids	25mm 5% Voids	25mm 6% Voids
5	5	5	2	1
10	13	12	4	2
20	26	25	8	3
30	47	44	15	6
40	68	64	21	9
50	100	94	32	13

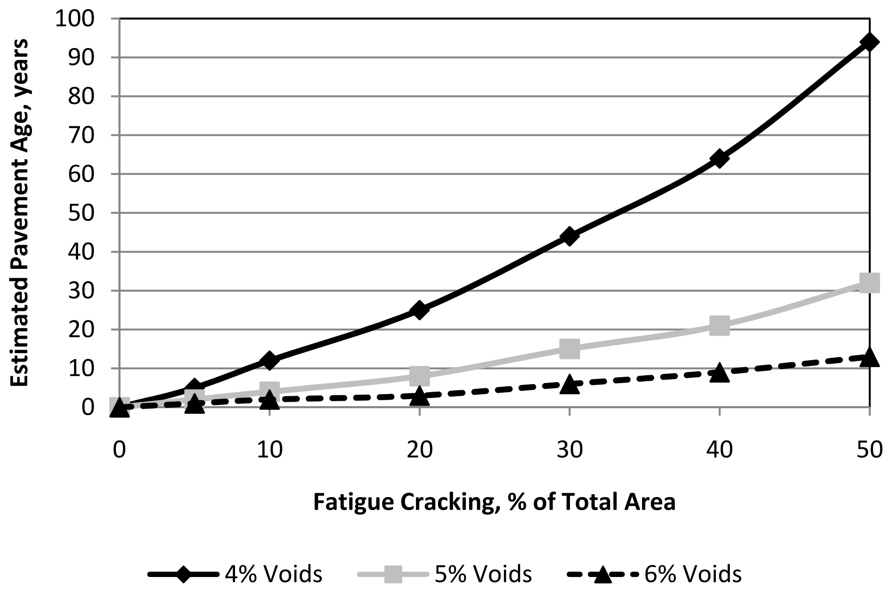

Figure 24: Fatigue Life Estimates Based on Lower Layer Air Void Content

SUMMARY AND CONCLUSIONS

This report presents the results of testing and analysis conducted for the HMA perpetual pavement sections constructed along the by-pass lane of the Kenosha Safety and Weight Station Facility. Analyzed field data includes FWD deflections measurements and companion load-induced strain data measured by sensors installed at the bottom of the HMA pavement and at the interface between HMA layers. A comparative analysis of measured strains to those predicted from FWD measurements provided generally good agreement.

The data from FWD testing was also used to estimate the combined dynamic HMA layer moduli at the time of testing and to develop monthly trends of dynamic HMA layer moduli as a function of the expected mean monthly pavement temperature at the mid-depth of the 12.5 mm surface layer and the 25 mm lower layer. A mechanistic appraisal of the constructed test sections was completed using the outputs of the EVERSTRESS pavement analysis program. This analysis computed the expected monthly damage induced by the application of 521,000 monthly ESAL loadings for a range of air voids within the 25 mm lower layers. The mechanistic appraisal indicates the expected fatigue life to bottom-up cracking failure (50% of the total pavement area) in excess of 90 years when the air void content is at 4% in the lower layers. However, this estimated fatigue life is significantly reduced for air void contents of 5% - 6%. This illustrates the critical importance of density in the lower, fatigue resistant layer of HMA perpetual pavements.