Field Performance Monitoring and Modeling of Instrumented Pavement on I-35 in McClain County

ANNUAL REPORT FOR FY 2010

ODOT SPR ITEM NUMBER 2200

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					***Approximate Conversions from SI Units***				
Symbol	***When you know***	***Multiply by***	***To Find***	***Symbol***	***Symbol***	***When you know***	***Multiply by***	***To Find***	***Symbol***
		LENGTH					***LENGTH***		
in	*inches*	*25.40*	*millimeters*	*mm*	*mm*	*millimeters*	*0.0394*	*inches*	*in*
ft	*feet*	*0.3048*	*meters*	*m*	*m*	*meters*	*3.281*	*feet*	*ft*
yd	*yards*	*0.9144*	*meters*	*m*	*m*	*meters*	*1.094*	*yards*	*yds*
mi	*miles*	*1.609*	*kilometers*	*km*	*km*	*kilometers*	*0.6214*	*miles*	*mi*
		AREA					***AREA***		
in^2	*square inches*	*645.2*	*square millimeters*	mm^2	mm^2	*square millimeters*	*0.00155*	*square inches*	in^2
ft^2	*square feet*	*0.0929*	*square meters*	m^2	m^2	*square meters*	*10.764*	*square feet*	ft^2
yd^2	*square yards*	*0.8361*	*square meters*	m^2	m^2	*square meters*	*1.196*	*square yards*	yd^2
ac	*acres*	*0.4047*	*hectacres*	*ha*	*ha*	*hectacres*	*2.471*	*acres*	*ac*
mi^2	*square miles*	*2.590*	*square kilometers*	km^2	km^2	*square kilometers*	*0.3861*	*square miles*	mi^2
		VOLUME					***VOLUME***		
fl oz	*fluid ounces*	*29.57*	*milliliters*	*mL*	*mL*	*milliliters*	*0.0338*	*fluid ounces*	*fl oz*
gal	*gallon*	*3.785*	*liters*	*L*	*L*	*liters*	*0.2642*	*gallon*	*gal*
ft^3	*cubic feet*	*0.0283*	*cubic meters*	m^3	m^3	*cubic meters*	*35.315*	*cubic feet*	ft^3
yd^3	*cubic yards*	*0.7645*	*cubic meters*	m^3	m^3	*cubic meters*	*1.308*	*cubic yards*	yd^3
		MASS					***MASS***		
oz	*ounces*	*28.35*	*grams*	*g*	*g*	*grams*	*0.0353*	*ounces*	*oz*
lb	*pounds*	*0.4536*	*kilograms*	*kg*	*kg*	*kilograms*	*2.205*	*pounds*	*lb*
T	*short tons (2000 lb)*	*0.907*	*megagrams*	*Mg*	*Mg*	*megagrams*	*1.1023*	*short tons (2000 lb)*	*T*
		TEMPERATURE (exact)					***TEMPERATURE (exact)***		
°F	*degrees Fahrenheit*	*(°F-32)/1.8*	*degrees Celsius*	*°C*	*°C*	*degrees Fahrenheit*	*9/5(°C)+32*	*degrees Celsius*	*°F*
		FORCE and PRESSURE or STRESS					***FORCE and PRESSURE or STRESS***		
lbf	*poundforce*	*4.448*	*Newtons*	*N*	*N*	*Newtons*	*0.2248*	*poundforce*	*lbf*
lbf/in^2	*poundforce per square inch*	*6.895*	*kilopascals*	*kPa*	*kPa*	*kilopascals*	*0.1450*	*poundforce per square inch*	lbf/in^2

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1. General

This combined laboratory and field study is conducted to better understand the mechanisms that cause pavement failure under actual traffic loading and environmental conditions. A 1,000-ft. long experimental pavement section was constructed on I-35 in McClain County and instrumented in collaboration with the National Center for Asphalt Technology (NCAT) and the Oklahoma Department of Transportation (ODOT) for field data collection. Figures 1 and 2 show sketches of pavement section and instrumentation plan, respectively. The field data collection is focused on pavement performance data (e.g., distribution of stresses within the pavement structure, longitudinal and transverse strains at the bottom of the asphalt layer, rutting, cracking), environmental data (e.g., air temperature, variation of temperature within the pavement structure), and traffic data (e.g., axle load, position, speed). From the field data, necessary correlations, namely rut transfer function and fatigue transfer function, will be developed. From the laboratory data, rutting and fatigue cracking susceptibility will be analyzed to address the behavior of asphalt concrete mixes used in the construction of the test section. From the data analyzed from both field and laboratory, a 'shift factor' will also be developed so that the rutting and fatigue behavior from laboratory data can be correlated with the field data. Activities performed in Fiscal Year 2010 included pavement performance data collection from the field**,** fatigue testing in laboratory, analysis of mechanical and environmental data, development of fatigue and transfer functions, analysis of the Falling Weight Deflectometer (FWD) data, and maintenance of the test section and instrumentation. An overview of these activities is given in the following.

2. Overview of Work Done

2.1 Field Rut Measurements

Five field trips and distress surveys were conducted during the reporting period (FY2010): October 28, 2009, February 16, 2010, March 10, 2010, May 18, 2010 and August 11, 2010 to address pavement distresses namely, rutting and fatigue cracking. During each survey, field testing was conducted at six stations, namely, Station No. 144, 235, 319, 540, 738 and 900, located at approximately 100-ft. intervals along the outer wheelpath. Rut data was collected across the wheel paths at each station using a Face Dipstick® using both a 12-in. and 6-in. moonfoot spacing. The rutting progressions in all the test sections are presented in Figure 3, where there are six rutting progression curves, each curve representing the rutting progression at a specific station. The first three points of each curve (pertaining to August 21, 2008, December 3, 2008 and January 8, 2009) present the highest rut depth of two wheelpaths, measured with the straight edge/rut gauge combination method. The last five points of each curve (from May 19, 2009 to May 18, 2010) present the highest rut values of the two wheelpaths measured with the Face Dipstick® using 6-in. moonfoot spacing. From Figure 3, it can be seen that the maximum rut depths from the data collected on May 19, 2009, October 28, 2009 and February 16, 2010 were 0.395-in., 0.483-in. and 0.476-in., respectively. These rut values were measured at Station 738. A close review of Figure 3 shows that rut depths increased at all the stations from May 19 to October 28 of 2009. But, if the rut depths are compared from October 28, 2009 to February 16, 2010, it can be observed that rut depths did not increase significantly at all stations. In some stations, the rut depths decreased by a small amount [from 0.001-in. to 0.019-in.], whereas in other stations the rut depths increased by a small amount [from 0.001-in. to 0.006-in.]. From these observations one could conclude that the rut depths did not change significantly between October 28, 2009 and February 16, 2010. Similar type of rut behavior was observed in the AASHO road test (Finn. et al., 1977) and NCAT test track (Selvaraj, 2007). In these field studies, it was observed that the rut depth exhibit a visible increase during summer and fall months, but not in winter months. Thus, the observations from the present study are in agreement with those from the AASHO road test and the NCAT studies. Further discussion of field rut test results is presented in Hossain (2010).

2.2 Field Crack Mapping

Crack mapping was also performed during the distress survey for the entire test section. For the Station No. 144, 319, 540, 738 and 900, crack mapping was performed at 50-ft. both way of each station. To eliminate overlapping of mapping area, crack mapping was performed at 41-ft. north and 34-ft. south of Station No. 235. No crack is observed, so far, at any station, except along the construction joint and localized pot holes near the LPS sensors.

2.3 Fatigue Test on Beam Specimens

A total of 25 beam specimens (15.0 in. x 2.5 in. x 2.0 in.) were compacted at OU and tested at NCAT in accordance with AASHTO T 321 test method. A summary of results are presented in Table 1 for 12 beams tested at a temperature of 20^{o}C under a loading strain level of 400 µstrain. Figure 4 shows the variation of initial stiffness (measured at 50th cycle) with air voids. It is evident that the initial stiffness decreases with increasing air void content, as expected. For example, an increase in air void from 2.18 to 9.41% decreased the initial stiffness by approximately 50% [from 1,438 ksi to 707 ksi].

2.4 Development of Rut Prediction Model

Currently, the project team is working on the development of rut prediction model (or rut transfer function). Two separate models are being developed. One based on the vertical strain on the top of the aggregate base layer and the other based on the shear strain in the asphalt concrete layer at vehicle tire edge. The basic form of the vertical strain-based rut prediction model is presented in Equation (1).

$$Rut_i = Rut_{i-1} + \lambda_1 (N_{si}^{\lambda_2 * \varepsilon_{si}} + N_{ti}^{\lambda_3 * \varepsilon_{ti}}) \tag{1}$$

where,

Rut_i = Rut at time “i” from field measurements,

Rut_{i-1} = Rut at time “i-1” from field measurements,

N_{si} = Total number of steering axle passes at time “i”,

N_{ti} = Total no. of tandem axle passes at time “i”,

λ_1 = Regression constant for traffic (both steering and tandem axles),

λ_2, λ_3 = Regression constants for vertical strain.

The basic form of the shear strain-based rut prediction model is presented in Equation (2).

$$Rut_i = Rut_{i-1} + \lambda_1' (N_{si}^{\lambda_2' * \gamma_{si}} + N_{ti}^{\lambda_3' * \gamma_{ti}}) \tag{2}$$

where,

Rut_i = Rut at time “i” from field measurements,

Rut_{i-1} = Rut at time “i-1” from field measurements,

N_{si} = Total number of steering axle passes at time “i”,

N_{ti} = Total no. of tandem axle passes at time “i”,

λ'_1 = Regression constant for traffic (both steering and tandem axles) ,

λ'_2 and λ'_3 = Regression constants for shear strain.

Further, a rut prediction model from laboratory APA rut tests was developed. The basic form of this laboratory rut prediction model is presented in Equation (3).

$$\frac{\mathrm{R}}{\mathrm{R}_0} = k_1 \left(\frac{N}{N_0}\right)^{k_2} e^{k_3\left(\frac{A}{A_0}\right)} e^{k_4\left(\frac{T}{T_0}\right)} \tag{3}$$

where,

R = Predicted rut depth,

A = Air voids of the specimen,

T = Temperature at which the rut depth is measured,

N = Number of loading cycles at which the rut depth is measured,

R_o = Reference rut depth (0.179-in.) obtained from the APA rut test at the reference temperature (T_0 = 64^oC), reference air void (A_0 = 7%) and reference number of cycles (N_0 = 8000 cycles),

k_1, k_2, k_3, k_4 = Model constants

A stepwise method of multiple linear regression (α = 0.05 option in SAS 9.1) was used for determining the model constants (k_1, k_2, k_3 and k_4). The F test for the multiple regressions was conducted using the same software to validate significance of the relationship between rut depth and independent variables included in the equations. The associated probability is designated as Pr > F or p-value. A small p-value implies that the model is significant in explaining the variation in the dependent variables. It was found that the rut depth values were significantly influenced by the air voids content, test temperature and number of loading cycles. The following laboratory rut prediction model was developed:

$$\frac{\mathrm{R}}{\mathrm{R}_0} = 0.0478\left(\frac{N}{N_0}\right)^{0.3795} e^{0.74303\left(\frac{A}{A_0}\right)} e^{2.27295\left(\frac{T}{T_0}\right)} \tag{4}$$

The Analysis of Variance (ANOVA) test on the developed model yield an F value of 1180 with a Pr of less than 0.0001 and an R^2 values of 0.91, which indicates that the model may be considered statistically significant in predicting the variation of rut depths with the selected parameters, namely air voids content, test temperature and number of loading cycles. A comparison between the predicted rut depths and actual rut depth is shown in Figure 5. From Figure 5, it is evident that the predicted rut values are closer to the equality line when the rut values are less than 0.10-in. (2.54-mm). This observation may be justified by the distribution of rut values in the dataset. Out of 750 rut values in the graph, 513 data points (about 68%) had rut values less than 0.10-in. (2.54-mm), whereas there are 237 (about 32%) data points having rut values less than 0.10-in. (2.54-mm).

2.5 Development of Fatigue Transfer Function

The pavement response is correlated to cycles to failure, N_{fi}, through empirically derived transfer functions. The expected traffic or number of load cycles to failure for the given design life, *n*, is then included to calculate a damage factor for that particular condition. The damage for each condition is typically added together using Miner's hypothesis (Miner, 1959), as shown in Equation (5):

$$D = \sum_{i=1} \frac{n_i}{N_{fi}} \tag{5}$$

where,

D = Incremental damage

n_i = Number of load applications at hour, *i*

N_{fi} = Number of load applications at failure for hour, *i*

To account for the asphalt concrete mixture modulus, varying temperature, and loading frequency, in the fatigue life, the following equation is used:

$$N_f = k_1 (\frac{1}{\varepsilon_t})^{k_2} (\frac{1}{E})^{k_3} \tag{6}$$

where,

N_f = Number of load cycles until fatigue failure

ε_t = Applied horizontal tensile strain

E = Asphalt concrete mixture modulus

k_1, k_2, k_3 = Regression constants

The strain magnitude, or the strain prediction model, is a function of the mid-depth temperature of asphalt concrete and is presented in the following equation:

$$\varepsilon_t = \beta_1 T^{\beta_2} \tag{7}$$

where,

ε_t = Horizontal tensile strain, micro strain

T = Mid-depth asphalt concrete temperature, °F

β_1, β_2 = Regression constants

The modulus–temperature relationship was developed by using the FWD deflection data collected over a wide range of temperatures. The basic form of this model is presented in Equation (8).

$$E = \alpha_1 e^{\alpha_2 * T} \tag{8}$$

Where,

E = asphalt concrete modulus, psi

T = Mid-depth asphalt concrete temperature, °F

α_1, α_2 = Regression constants

This approach is still under testing, and can only be finalized when the test section fails under fatigue cracking. However, the strain-temperature prediction model, which will be used in this approach, is completed by using field data collected from May, 2008 through May, 2010. The preliminary strain-prediction models for single and dual tires are presented in Figures 6 and 7, respectively. Figures 6 and 7 show variation of horizontal strain measurements generated due to vehicular loading with respect to mid-depth temperature of asphalt concrete. It is clear from Figures 6 and 7 that the magnitude of strain inceases with increase in temperature, as expected. The regression analysis on the data for single and dual tire yielded an exponential best-fit line of the form presented in Equation (7) with β_1 = regression constant (0.0668 for single tire and 0.0342 for dual tire), β_2 = regression constant (1.3212 for single tire and 1.3769 for dual tire), and T = mid-depth temperature of asphalt concrete from temperature sensors (Figures 6 and 7). It is interesting to note that the developed correlations are very similar to the equations reported by NCAT (Timm and Priest, 2006).

2.6 Analysis of FWD

A Dynatest model 8000 series (8002-057) type FWD was used in this study. The testing pattern was designed for a series of six stations located at approximately 100 ft. intervals along the outer wheel path. For conducting tests on the top of asphalt concrete layer, a plate of 11.8 in. diameter was used with seven deflection sensors spaced at 8, 12, 24, 36, 48, and 72-in. from the center, as recommended by the ASTM D 4694 test method. The loading pattern included three seating drops plus one load drop from different heights in progressive order. The FWD testing was conducted on the top of asphalt concrete layer by including four different loads (6, 9, 12 and 15 kips). The collected data was analyzed for layer modulus values using MODULUS 6.0 software. The asphalt concrete modulus-temperature correlation obtained by collecting data up to October 28, 2009 is presented in Figure 8. The regression analysis on back-calculated data from FWD yielded an exponential best-fit line of the form presented in Equation (8) with α_1 = regression constant (18,841 ksi), α_2 = regression constant (–0.045), and T = mid-depth temperature of asphalt concrete from temperature sensors. In general, Equation (8) is good predictor (R^2 = 0.863) of modulus value of asphalt concrete at different temperatures. At low temperature (50^{o}F) the average back-calculated modulus value is approximately 1792 ksi with a 40% coefficient of variation. On the other hand, at higher temperature of approximately 105^{o}F the average back-calculated modulus value and coefficient of variation is approximately 131 ksi and 4%, respectively.

2.7 Meeting with ODOT

On January 22, 2010 and May 19, 2010, meetings were held with ODOT personnel at the Planning and Research Conference Room, ODOT. In these meetings an update related to the progress of I-35 project was presented. Further details are presented in Appendix A and B.

2.8 Maintenance and Problems

- The lateral positioning sensors (LPS) were found defective on February 25, 2010. On March 10, 2010, these sensors were replaced successfully by IRD in the presence of ODOT and OU teams.

- The ADR 3000 unit from WIM Station 31 was removed for another project (Dr. Hazem Refai, PI) funded by ODOT on June 17, 2010. It was again successfully reinstalled on June 25, 2010 around 9.00 a.m. Some data loss occurred during this period.

- On September 2, 2010 the surface of the LPS was grouted again, using a more flexible material. The work was completed by IRD in the presence of ODOT and OU teams.

- Currently, two strain gauges (# 9 and # 11) are giving erroneous readings. This problem was first encountered on June 6, 2010.

3. Plan for Fiscal Year 2011

Overall, the project is on track. The FY 2011 activities will include the following:

a) Collection of traffic data, dynamic data, environmental data, and performance data, will continue.
b) Field testing and distress survey will be conducted periodically (at least quarterly).
c) Analysis of data for developing ‘Rut transfer function’ and ‘Fatigue transfer function’.
d) Processing of field data and establishing correlations among important parameters (e.g., ESAL vs. rut, ESAL vs. FWD modulus, temperature vs. strain, etc.) will be enhanced.
e) Bi-annual meeting with ODOT personnel to discuss the progress of the project.
f) Maintenance of the instrumentation such as temperature probes and axle sensors, as needed.

Selected References

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7. Miner, M.Milton A. (1959). "Estimation of Fatigue Life with Particular Emphasis on Cumulative Damage." *Metal Fatigue*, edited by Sines and Waisman, McGraw Hill, 1959, pp. 278-89.
8. Monthly reports of the project " Field Performance Monitoring and Modeling of Instrumented Pavement on I-35 in McClain County" submitted to ODOT by the University of Oklahoma team from October 2009 to September 2010.
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11. Solanki, P., Zaman, M. and Muraleetharan, K. K. (2008). "Field Performance Monitoring and Modeling of Instrumented Pavement on I-35 in McClain County," Construction and Instrumentation report, ODOT Item 2200, Oklahoma.

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Table 1: Variation of Fatigue Life and Flexural Stiffness of Laboratory Compacted Specimens with Air Voids (Temperature = 20^{o}C)

Temperature (^{o}C)	Specimen #	Strain Level (µs)	Air Voids (%)	Cycles to Failure (ASTM)	Cycles to Failure (AASHTO) 50%	Initial Beam Stiffness (ksi)	Termination Stiffness (ksi)
Laboratory Comapcted Specimens							
20	8-2	400	2.18	213,790	109,220	1,438	359
20	1-2	400	2.38	194,980	84,890	1,544	386
20	1-1	400	3.35	287,290	185,490	1,182	296
20	5-1	400	3.80	95,980	47,980	1,258	315
20	2-1	400	4.79	110,910	54,250	1,098	274
20	11-1	400	5.00	69,530	37,530	1,373	343
20	2-2	400	5.25	146,770	82,540	1,121	280
20	10-1	400	6.70	149,620	111,340	997	249
20	10-2	400	7.80	261,010	183,370	887	222
20	17-2	400	7.86	361,680	280,750	1,005	251
20	9-1	400	9.19	132,330	79,220	855	214
20	14-2	400	9.41	315,010	118,850	707	177

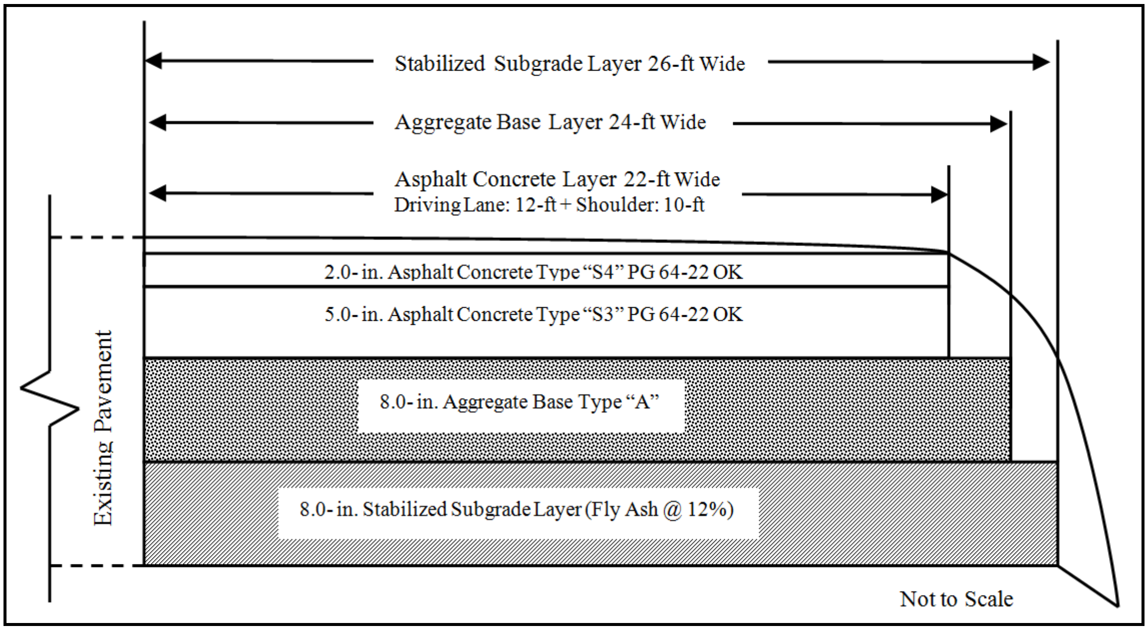

Figure 1: Sketch of Test Section (Looking South)

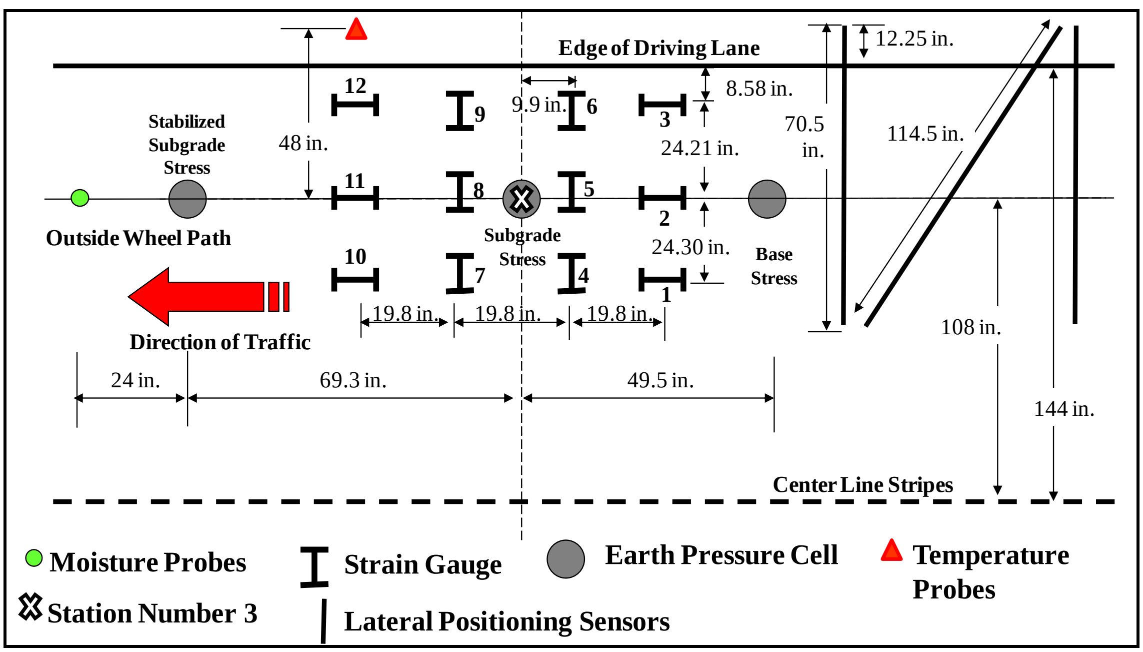

Figure 2: Sensors Layout

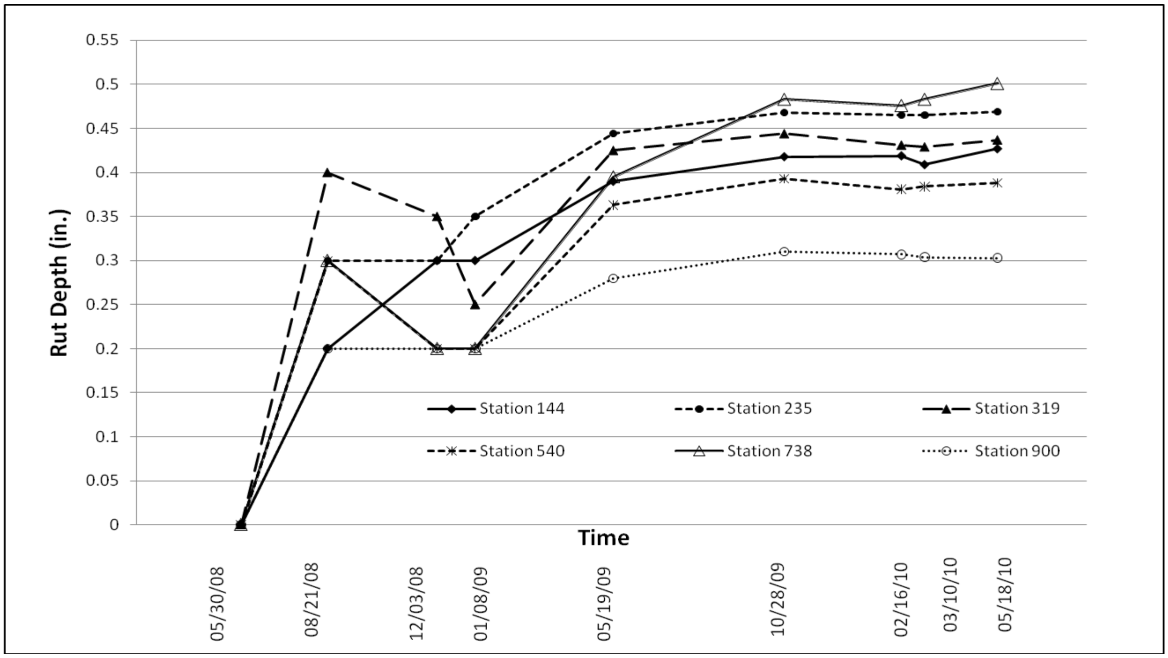

Figure 3: Rut Progression in the Test Section

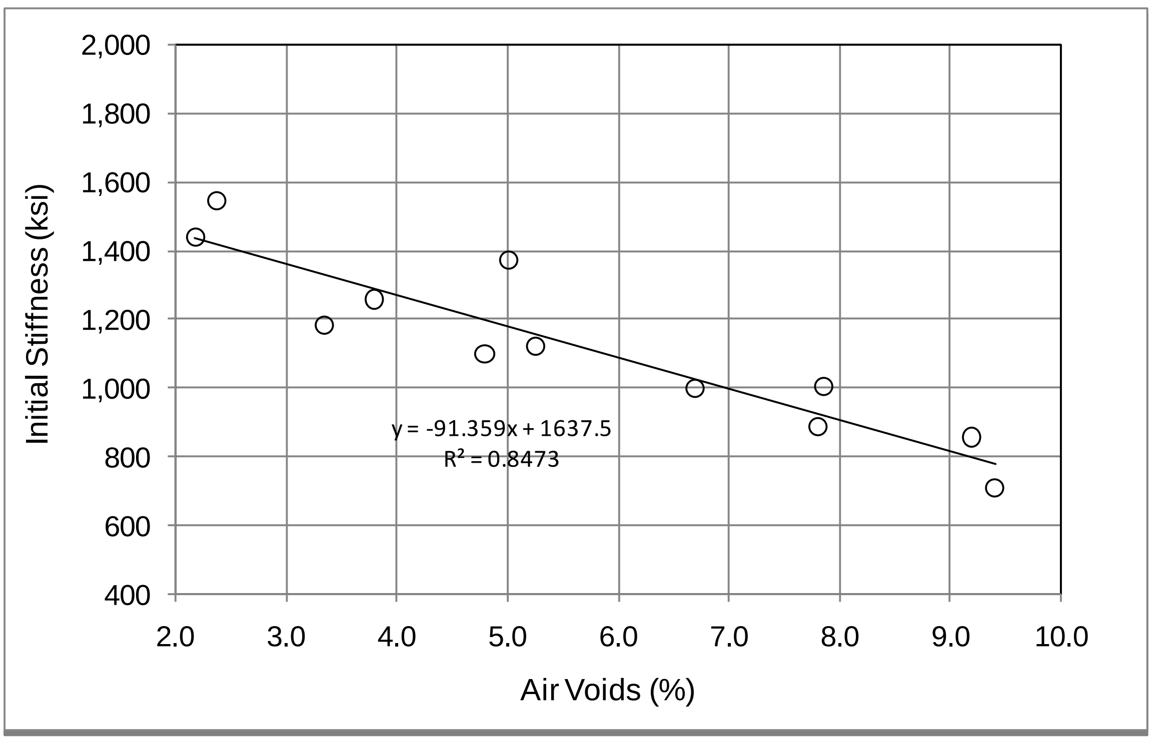

Figure 4: Variation of Initial Stiffness with Air Voids

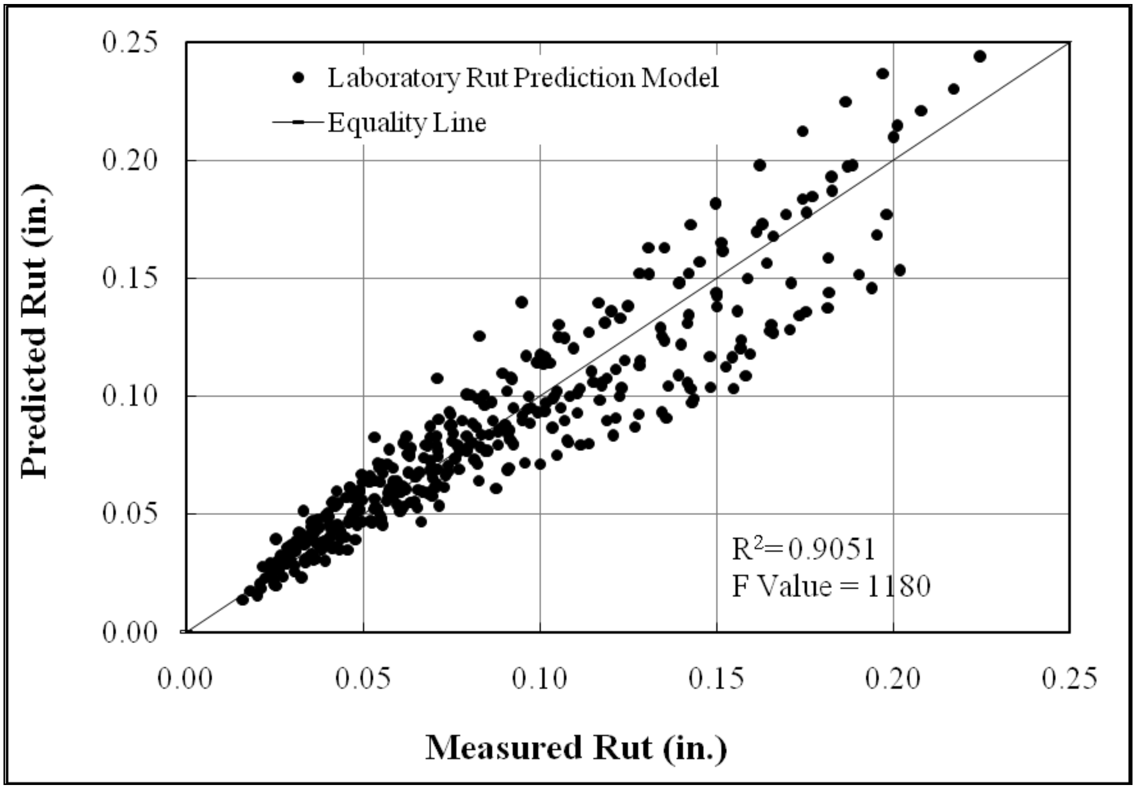

Figure 5: Rut Prediction from Developed Rut Prediction Model

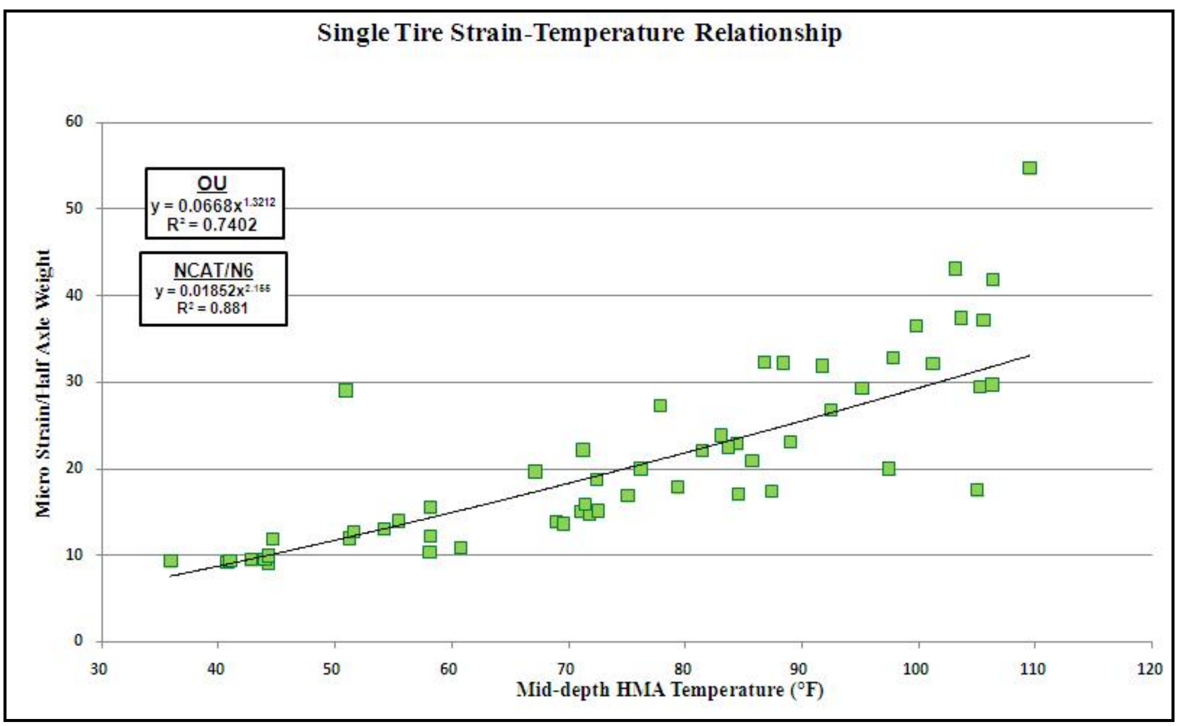

Figure 6: Strain-Temperature Prediction Model for Single Tire

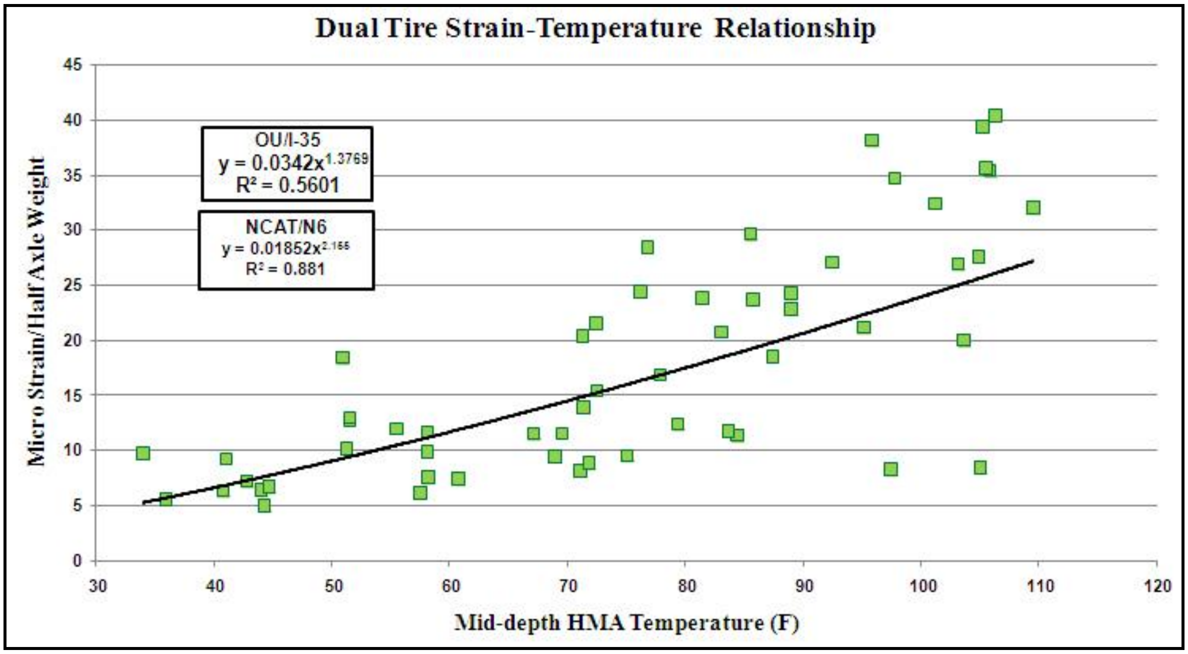

Figure 7: Strain-Temperature Prediction Model for Dual Tire

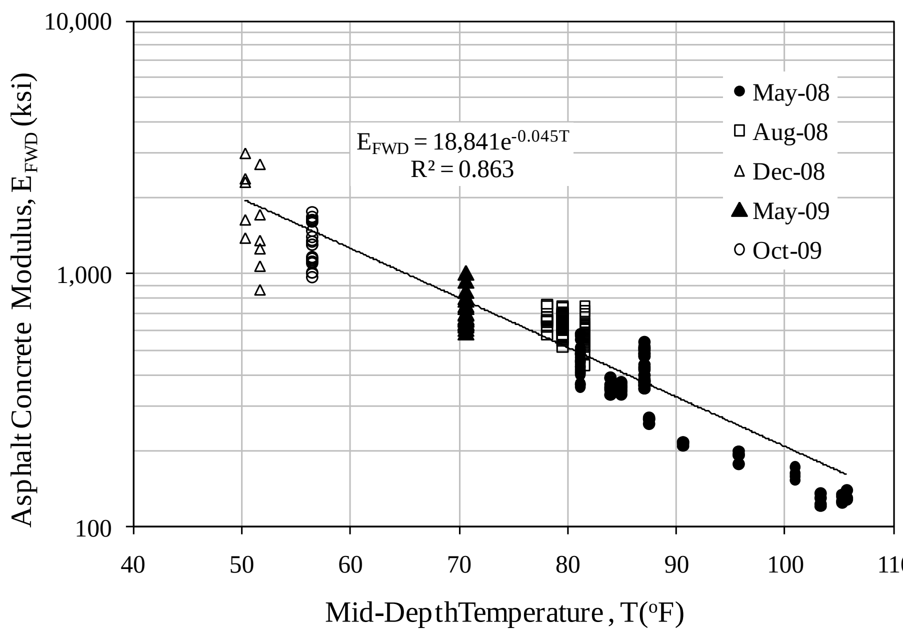

Figure 8: Back-calculated Modulus Values from FWD versus Mid-depth Temperature

Appendix A

I-35 Project Meeting

Time: 10:00 a.m. – 11:00 a.m., January 22, 2010

Location: Planning and Research Division Conference Room, Oklahoma Department of Transportation

Attendees: Ginger McGovern, Bryan Hurst, Jeff Dean, Chris Westlund (ODOT); Musharraf Zaman, K. K. Muraleetharan, Pranshoo Solanki, Nur Hossain, Marc Breidy (OU)

1. An update related to the progress of I-35 project was presented.
2. Rut data collection and analysis was an important issue of discussion. Ginger was concerned about effect of using different straight edge lengths for analyzing rut data. Bryan and Ginger noted possibility of using wire line method for field rut measurements. Jeff showed his concern about the contribution of different layers in rut measurements.
3. Jeff noted that back-predicting modulus value using the asphalt strain gage measurements will be an interesting study. Further, he noted that the FWD modulus can be compared with the modulus values back-predicted from strain gages.
4. All ODOT attendees showed interest in the percentage of overloaded trucks on I-35. Also, attendees noted comparison of I-35 overloaded truck data with traffic data from other states.
5. Jeff noted that the data collected from I-35 instrumentation and WIM site should be used for validation of MEPDG.
6. Ginger noted post-mortem of I-35 experimental section after failure for capturing actual rut profile.

   The suitable temperature and time frame for next lane closure was also discussed.

Appendix B

I-35 Project Meeting

Time: 10:00 a.m. – 11:00 a.m., May 19, 2010

Location: Planning and Research Division Conference Room, Oklahoma Department of Transportation

Attendees: Ginger McGovern, Bryan Hurst, Jeff Dean, Ron Curb, Chris Westlund (ODOT); Musharraf Zaman, K. K. Muraleetharan, Pranshoo Solanki, Nur Hossain, Marc Breidy (OU)

1. An update related to the progress of I-35 project was presented.
2. Rut data collection and analysis was an important issue of discussion of the previous meeting (held on January 22, 2010). Based on the suggestions of Ginger, different rut data collection methods were explored and compared with the rut data collection with Face Dipstick®. Information regarding the different rut data collection procedures was presented in the meeting of May 19, 2010.
3. Jeff noted that back-predicting modulus value using the asphalt strain gage measurements will be an interesting study. Further, Jeff noted that the FWD modulus can be compared with the modulus values back-predicted from strain gages.
4. Jeff showed interest about the date of next lane-closure, which will be sometime in mid August of 2010.
5. Jeff also showed interest about trenching the test section.
   The percentage air void of the asphalt layer was also discussed and Jeff suggested to check the percentage compaction measured using nuclear gage.