Available online at www.sciencedirect.com

ScienceDirect

Procedia - Social and Behavioral Sciences 104 (2013) 129 – 138

ELSEVIER

Procedia
Social and Behavioral Sciences

2nd Conference of Transportation Research Group of India (2nd CTRG)

Dynamic Modulus-based Field Rut Prediction Model from an Instrumented Pavement Section

Nur Hossain, E.I.[a], Dharamveer Singh, Ph. D.[b]*, Musharraf Zaman, Ph.D., P.E.[c]

[a]Project Manager, Professional Service Industries, Inc., 801 SE 59th St, Oklahoma City, OK 73129, USA
[b]Assistant Professor, Department of Civil Engineering, Indian Institute of Technology, Mumbai, 400076, India
[c]Associate Dean for Research and Graduate Education, College of Engineering, The University of Oklahoma, Norman, OK 73019, USA

Abstract

Flexible pavements comprise about 93 percent of paved roads in the United States. Although flexible pavements are widely used for reasons such as cost, constructability and consistent performance, they are often subject to severe rutting. To gain an insight of flexible pavement rutting under actual vehicular traffic and environmental conditions, a 305-meter long test section was constructed on I-35 (Southbound) in McClain County, Oklahoma, USA and instrumented for field data collection. Field rut measurements were conducted periodically to monitor performance of the test section using a straight edge/rut gauge combination and a Face Dipstick®. The loose mixes were collected from the field and dynamic modulus testing was conducted in the laboratory at different temperatures (i.e., 4, 21, 40, 55°C) and frequencies (i.e., 25, 10, 5, 1, 0.5, 0.1 Hz) in accordance with AASHTO TP62. The mechanistic-empirical pavement design guide (MEPDG) recommends dynamic modulus as a key input parameter to predict distresses (rutting and fatigue cracking) of a flexible pavement. Therefore, dynamic modulus based approach is used in the present paper to develop a rut prediction model. Dynamic modulus test data, along with the actual vehicular traffic and environmental data from the test section were used as inputs in multilayered linear elastic analysis software, WinJULEA, to model the test section and determine rutting. A total of approximately 18-million accumulated axles and four years of environmental data were used to develop the field rut prediction model. A vertical strain-based (VSB) rut prediction model was developed using the measured rut on test section and relating it to vertical strain on the top of the aggregate base layer due to passing of each vehicle. The correlation coefficient (R^2 value) for this model was around 0.78, based on the comparison of field measured and predicted ruts. The results from this study are expected to be useful in predicting rutting of state highway pavements under similar traffic and environmental conditions.

Keywords: Dynamic Modulus; HMA; Rut Prediction Model; Field Rut Measurement; Vertical Strain; Instrumented Pavement

---

[1] * Corresponding author. Tel.: +91-22-2576-7304; fax: +91-22-2576-7302.
E-mail address: dvsingh@civil.iitb.ac.in

doi:10.1016/j.sbspro.2013.11.105

1. Introduction

Flexible pavements comprise about 93 percent of paved roads in the United States. Although flexible pavements are widely used for reasons such as cost, constructability and consistent performance, they are often subject to severe rutting. Rutting is the accumulation of longitudinal depressions under the wheel paths caused by the repeated traffic loads. Rut is a major concern for the integrity of pavement structure and traffic safety. In past many laboratory based rut prediction models have been developed, however; a limited work is done to develop rut models based on field data, collected from an instrumented pavement. Accordingly, it is important to study progression of rut under actual vehicular loading and environmental conditions and to predict such rutting using field data.

Several researchers have developed rut prediction models from laboratory data (Allen and Dean, 1980, Leahy, 1989, Williams et al., 2005). But these models did not use dynamic modulus data of Hot Mix Asphalt (HMA) as a material input in their models. According to the MEPDG (AASTO, 2004), dynamic modulus data of HMA is a major material input parameter to predict performance (rutting, fatigue, and low temperature cracking) of a flexible pavement. Therefore, in this study dynamic modulus of HMA was used to develop the rut prediction model from actual vehicular traffic and environmental data.

Recently, numerous studies have been conducted to develop rut prediction models from the field data (Hand et al., 1999; Kim et al., 2000; Zhou et al., 2004; and Selvaraj, 2007). But these models used controlled traffic and condition to develop the rut models, rather than using actual interstate traffic and condition.

The present study was undertaken to develop a field rut prediction model from data collected along a 305-meter long instrumented test section in McClain County, Oklahoma. The pavement performance data, environmental data, and traffic data were collected at regular intervals. A series of Falling Weight Deflectometer (FWD) tests, dynamic modulus test and rut measurements were conducted to develop the rut prediction model. The mechanistic-empirical pavement design guide (MEPDG) recommends dynamic modulus as a key input parameter to predict distresses (rutting and fatigue cracking) of a flexible pavement. Therefore, dynamic modulus based approach is used in the present paper to develop a rut prediction model.

2. Objective

The objectives of this study are:

- To measure rut progression in the Test Section using two different methods: (i) straight edge-rut gauge combination and (ii) Face Dipstick®,
- To conduct dynamic modulus tests on the HMA mixes collected from the field and to develop master curves,
- To conduct FWD tests on the test section, and obtain back-calculated modulus for the pavement layers
- To develop vertical strain based rut prediction model using actual vehicular traffic loading and environmental conditions.

3. Construction and Instrumentation of the Test Section

3.1. Test Section

The instrumented Test Section used in this study is located in McClain County, Oklahoma, on the southbound (right) lane of Interstate-35. To record the traffic data a weigh-in-motion (WIM) station was installed approximately 1,200-meter south of the Test Section. The Test Section consists of five pavement layers. The top layer is 50-mm thick constructed with a S4 HMA mix having 12.5-mm Nominal Maximum Aggregate Size (NMAS). The mix is prepared with a Performance Grade (PG) 64-22 asphalt binder. The second layer is 125-mm thick and is constructed with a S3 HMA mix having a NMAS of 19-mm. This layer incorporates a recycled mix involving a PG 64-22 binder and 25% Reclaimed Asphalt Pavement (RAP). The third layer is a 200-mm thick aggregate base layer having Oklahoma Department of Transportation (ODOT) type “A” gradation. The fourth layer consists of a 200-mm thick subgrade layer stabilized with 12% Class C fly ash. The bottom layer is natural subgrade soil, consisting of lean clay with a liquid limit of 33 and a plasticity index of 15.

3.2. Instrumentation of the Test Section

Twelve asphalt strain gauges were installed to measure longitudinal and transverse strains at the bottom of the HMA layer. Also, one earth pressure cell was installed at the top of each pavement layer, namely, natural subgrade layer, stabilized subgrade layer and aggregate base layer to measure traffic-induced normal stresses. In addition, five temperature probes were installed to measure temperature variations in the HMA layer at selected depths (5-mm, 50-mm, 90-mm, 180-mm and 254-mm) from the pavement surface. Three lateral positioning sensors were also installed on the top of the HMA layer to determine vehicle wheel wander over the Test Section. From the instrumentation array, data from the temperature probes are being used for the model prediction in this study.

3.3. Traffic

After finishing the construction and instrumentation of the Test Section, it was opened to traffic on May 30, 2008. Traffic and environmental data are being collected since then. The WIM site was instrumented with inductive loops and piezoelectric sensors to capture axle configuration, weight, distance between axles and other pertinent data for each vehicle passing through the Test Section. These data, along with the field performance data were used in this study to develop rut models. Approximately four years of traffic data (i.e., from May 30, 2008 to May 2, 2012) were used to develop the rut prediction model in this study.

4. Field Test Facility and Data Collection

Field test facility and data collection activities included FWD tests, rut measurement through straight edge-rut gauge combination and Face Dipstick®, pavement temperature data, traffic data collection through the WIM station. Since the test section was located on I-35, which has extremely high and heavy traffic volume, it was not practical to close the lanes frequently to collect pavement performance data. Therefore, field performance tests were conducted once every three months.

4.1. FWD Tests

In this study, pavement layer (except HMA layer) moduli back-calculated from the FWD data was used to develop the models. A Dynatest model 8000 series (8002-057) type FWD, as recommended by the ASTM D 4694 test method, was used to conduct the tests. The FWD data was used to back-calculate the layer moduli, using MODULUS 6.0 software.

4.2. Rut Measurements

Rut measurements were conducted along the transverse direction of traffic flow at all six test stations (Stations 1 through 6). The rut measurements were taken along the road-straps laid on the test stations ensuring that the measurement locations did not change with time. Two significantly different methods: a straight edge-rut gauge combination and a Face Dipstick® were used to measure rut in the field. During the first three field tests (on August 21, 2008, December 3, 2008 and January 8, 2009), the straight edge-rut gauge combination method was used. The rut data obtained from the straight edge-rut gauge combination exhibited some inconsistencies. Consequently, a more sophisticated piece of equipment, the Face Dipstick®, capable of measuring rut with 0.0254-mm accuracy, was used for measuring ruts at the test section from May 19, 2009 onward.

5. Laboratory Test Facility and Data Collection

5.1. Collection of Asphalt Mixes

The pavement section was constructed with two HMA layers. The top (surface) layer was a mix with a nominal maximum aggregate size (NMAS) of 12.5 mm (S4) and the base layer was a mix with NMAS of 19 mm (S3). Both of these mixes were collected in loose condition and stored in Broce Laboratory at University of Oklahoma. Both the mixes were produced with a performance grade (PG) 64-22 asphalt binder collected from Valero at Ardmore. The gradation and other aggregates and binder properties of the mixes are given in Table 1.

5.2. Sample Preparation

To determine the target air voids for samples, the field core samples were cut from the pavement and their air voids were determined in the laboratory. Six cores were cut from each top and bottom layers of the pavement. The average air voids and standard deviation for the top layer (S4 mix) and the bottom layer were 9.1% and 0.63%; and 8% and 0.42%, respectively. Therefore the target air voids for laboratory samples was considered as 9±0.5% and 8±0.5% for the top and the bottom layers. To prepare cylindrical samples for laboratory testing, the loose mixes were directly preheated in an oven. The mixing and compaction temperatures for the mixes were obtained from the mix design sheet. Specimens were compacted using a Superpave Gyratory Compactor (SGC). The SGC machine was operated in height mode so as to stop automatically when the desired height is reached. For each mix, 3 replicates samples were compacted.

5.3. Dynamic Modulus Testing

Dynamic modulus values for both the mixes (S4 and S3) were conducted in the laboratory in accordance with AASHTO TP62 specifications (AASHTO, 2006). Tests were performed using a mechanical testing system (MTS) equipped with a servo-hydraulic testing system (MTS, 2011).

Table 1: Aggregate Gradations and Mix Properties

Aggregate Gradation			Mix Properties		
Sieve Size	Top Layer (S4)	Bottom Layer (S3)	Aggregate and Binder	Top Layer (S4)	Bottom Layer (S3)
(mm)	Passing (%)		Parameters	S4	S3
25.4	100	100	G_{se}	2.678	2.671
19	100	98	G_{sb}	2.658	2.645
12.5	98	87	G_{mm}	2.490	2.502
9.5	89	80	G_b	1.01	1.01
4.75	63	58	AC (%)	4.6	4.1
2.36	40	37	Binder Type	PG64-22	PG64-22
1.18	28	25	G_{se} = Effective specific gravity of aggregate		
0.600	22.00	19.00	G_{sb} = Bulk specific gravity of aggregate		
0.300	14.00	12.00	G_{mm} = Maximum theoretical specific gravity of mix		
0.150	6	4	G_b = Specific gravity of binder		
0.074	3.7	2.9	AC = Asphalt content (%)		

The test specimen was placed in an environmental chamber and allowed to reach equilibrium to the specified testing temperature ±0.5°C. The specimen temperature was monitored using a dummy specimen with a thermocouple mounted at the center. Two linear variable differential transducers (LVDTs) were mounted on the specimen at 100 mm gauge length. Two friction reducing end treatment or teflon papers were placed between the specimen and loading platens. A sinusoidal axial compressive load was applied to the specimen without impact in a cyclic manner. The test was conducted on each specimen at four different temperatures: 4, 21, 40, and 55°C, starting from the lowest temperature and going to the highest temperature. For each temperature level, the test was conducted at different loading frequencies from the highest to the lowest: 25, 10, 5, 1, 0.5, and 0.1 Hz. Prior to testing, the specimen was conditioned by applying 200 cycles of load at a frequency of 25 Hz. The load magnitude was adjusted based on the material stiffness, temperature, and frequency to keep the strain response within 50-150 micro-strains (Tran and Hall, 2006). The data was recorded for the last 5 cycles of each sequence. Dynamic modulus values were calculated for combinations of temperatures and frequencies. The coefficient of variation (COV) for the measured dynamic modulus values of the samples was found to be less than 15%, which satisfied the limits given in AASHTO TP62. The master curves were constructed using the principle of time-temperature superposition and approach developed by Bonaquist et al. (2005). The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. First, a standard reference temperature is selected (i.e., 21°C), and then data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. Figure 1 shows the master curves for both the mixes. It can be seen that the bottom mix (S3) has a higher dynamic modulus values compared to the top layer mix (S4) for different combinations of temperature and frequency. These master curves are required to estimate the dynamic modulus values for both the mixes at wide range of temperature encountered in the field.

5.4. Relationship between Temperature and Dynamic Modulus for Development of Rut Model

The temperature of the instrumented pavement was monitored through the temperature gauges installed in different layers of this pavement. It was observed that temperature ranges from -4°C to 60°C. The relationship between dynamic modulus and temperature was developed for both the mixes (S4 and S3). This relationship was developed at 5 Hz frequency. According to Loulizi et al. (2002), 5 Hz frequency simulates the loading duration of the FWD device which is currently used to measure modulus of different layers of a pavement. Equations (1) and (2) present the dynamic modulus-temperature relationships for S4 and S3 layers, respectively.

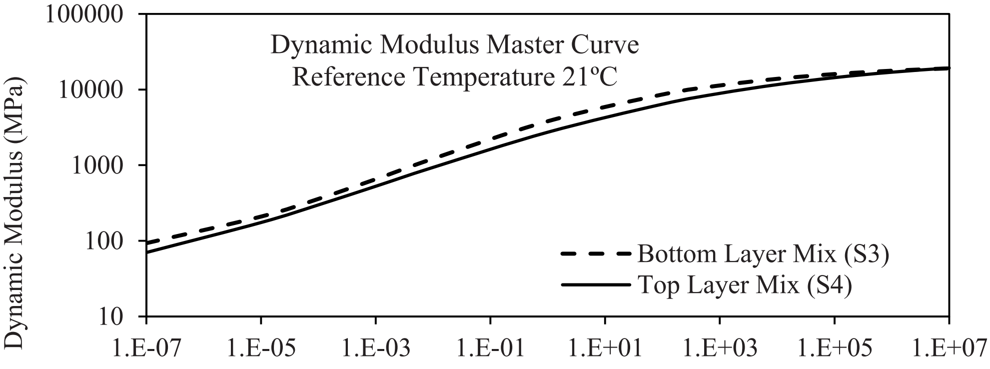

Fig. 1: Dynamic Modulus Master Curve for Top (Surface) S4 Mix and Bottom (Base) S3 Mix

$E^* = 4882.9\, e^{-0.032\,T}$ ($R^2 = 0.99$) for S4 layer (1)

$E^* = 6155.4\, e^{-0.032\,T}$ ($R^2 = 0.99$) for S3 layer (2) where,

E* = Dynamic modulus of HMA layers (ksi), and T = Mid-depth pavement temperature (°F).

6. Rut Progression in the Test Section

According to Zhou et al. (2004), flexible pavement rutting can be categorized into three distinct stages: primary, secondary and tertiary. The rutting progressions in all six test stations are presented in Figure 2, with each curve representing the rutting progression at a specific station. As of May 2012, approximately four years after the test section was opened to traffic, both the primary and secondary stages were observed in the test section. Tertiary stage has not been observed yet. During the primary stage (from May 30, 2008 through August 21, 2008), the rutting rate was relatively high. After the primary stage, the rutting progression rate decreased and reached a nearly constant value at the secondary stage (from around September 2008 to May 2, 2012). A similar rut progression trend was observed in the AASHO road test (HRB, 1962) and in the NCAT test tracks (Selvaraj, 2007), where the rutting rate decreased as the number of axles increased.

7. Development of Rut Prediction Model

7.1. Model Methodology

A methodology to develop the Vertical Strain-based (VSB) model is summarized in a flow chart in Figure 3. In the flow chart (Figure 3) the time stamp (i) is used to link variables, namely measured mid-depth pavement temperature (T_i) and traffic axle count (N_i) for a particular period. The calculated vertical strain on the top of the pavement layers at a particular time (ε_i) and number of axle passes at that time (N_i) were selected as the independent variables in the model. The total measured rut depth (Rut_i) at a particular time was calculated as a sum of the previous period's total rut (Rut_{i-1}) plus incremental rutting caused by additional traffic (N_i) at the calculated strain level (ε_i) for the current time increment.

The following data was used in developing the vertical strain-based rut model:

- Material properties data: Dynamic modulus data for the HMA layer was used in this study. Modulus of other pavement layers, namely, aggregate base layer, stabilized subgrade layer and natural subgrade layer, was back-calculated from FWD data. The average modulus of the aggregate base layer, stabilized subgrade layer and natural subgrade layer, obtained from the FWD test data, was 194.4-MPa, 480.6-MPa and 138.6-MPa, respectively.
- Environmental data: Mid-depth pavement temperature data measured from installed temperature sensors was used. Pavement temperature was measured every minute but only hourly averages were stored.
- Traffic data: Traffic configuration such as axle type and weight, irrespective of vehicle class, was recorded from the WIM station.
- Pavement performance data: Rut measurement data using straight edge-rut gauge combination and Face Dipstick® was used.
- Tire inflation pressure: A default hot tire inflation pressure of 827-kPa recommended in the MEPDG (AASHTO, 2004) was used in this study.

7.2. Vertical Strain Calculation on the Top of Aggregate Base

Measured vertical strain response on the top of pavement layers is an important element of the rut model. WinJULEA, a commonly used multi-layered linear elastic analysis software, was used to predict vertical strains on the top of the aggregate base and the natural subgrade layers due to vehicular traffic. WinJULEA analyses showed that, for a particular vehicular load, the maximum vertical strain is experienced on the top of the

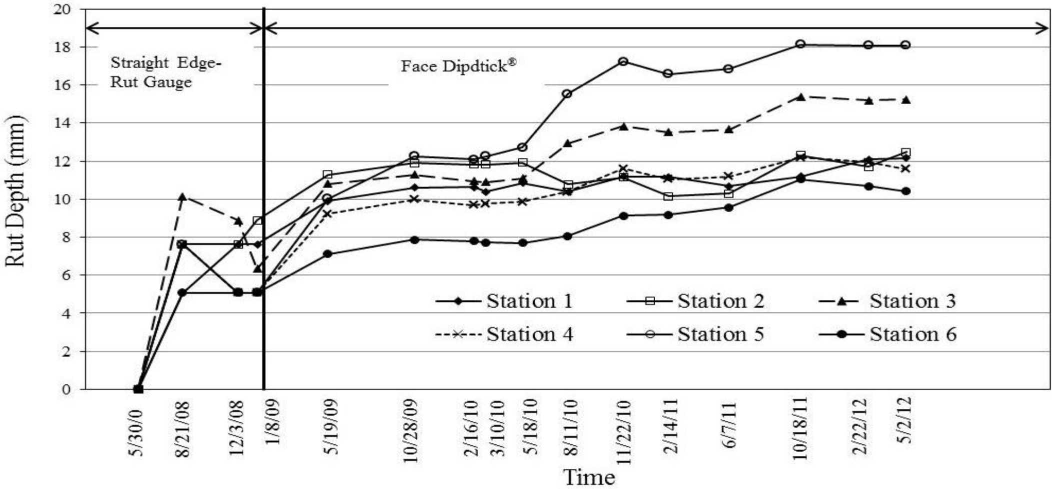

Fig. 2: Rut Progressions in the Test Section

aggregate base layer. Therefore, vertical strain on the top of the aggregate base layer was used to develop the VSB model.

7.3. Vertical Strain-Temperature Correlations

An important step in developing the VSB model was to develop correlations between vertical strain and mid-depth pavement temperature. The following steps were used to develop the vertical strain-temperature correlations:

Step-1: A mid-depth pavement temperature for a particular hour was selected. Then, the HMA dynamic modulus for that particular temperature was calculated using Equations (1) and (2) as described above.

Step-2: Then, for that particular hour, vehicular traffic data was obtained from the WIM station. In the WinJULEA calculations, steering axles and tandem axles were analyzed separately because of differences in vertical strain distribution. Several vehicles including the lowest and the highest steering axle weights were selected and half steering axle weights noted (irrespective of class).Vertical strains were calculated for each axle weight using WinJULEA and were used to obtain a correlation between vertical strain and half steering axle weights at that particular temperature. The general form of the correlation between vertical strain and half steering axle weights can be expressed by Equation (3).

$$\varepsilon_s = C_1(half\ steering\ axle\ weight) + C_2 \tag{3}$$

where,

ε_s = Vertical strain from steering axle, and C_1, C_2 = Variable Regression constants

Similarly, a linear correlation was developed for vertical strain and ¼th tandem axle weights for that particular temperature, as given by Equation (4):

$$\varepsilon_t = C_3(1/4\ th\ tandem\ axle\ weight) + C_4 \tag{4}$$

where,

ε_t = Vertical strain from tandem axle, and C_3, C_4 = Variable Regression constants

Step-3: In this step, vertical strains/kN for steering axles and tandem axles were calculated for that particular temperature. The vertical strain/kN from all the steering and tandem axles of different vehicles at that particular hour and temperature was calculated using Equations (5) and (6) as noted below:

$$\varepsilon_s = (\varepsilon_{s1} + \varepsilon_{s2} + \cdots + \varepsilon_{sn})/(W_{s1} + W_{s2} + \ldots + W_{sn}) \tag{5}$$

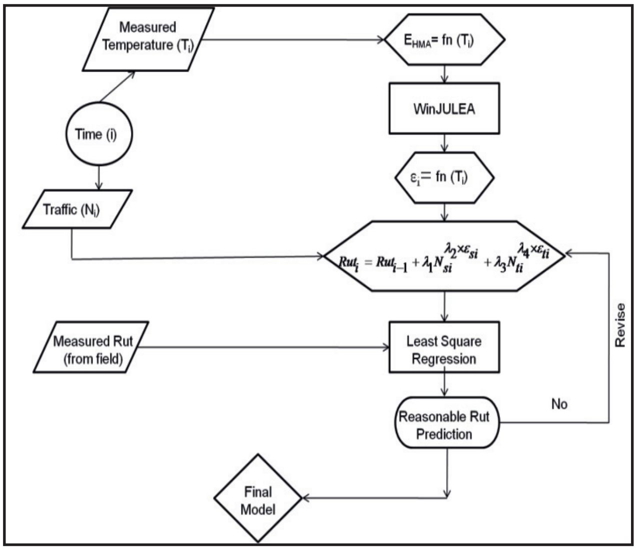

Fig. 3: Vertical Strain-based Rut Prediction Model Methodology Flow Chart

where,

ε_s = Vertical strain of steering axles/kN, ε_{s1}, ε_{s2}, ε_{sn} = Vertical strains due to half- steering axles of Vehicle 1, Vehicle 2, and Vehicle n, respectively, andW_{s1}, W_{s2}, W_{sn} = Half-weight (kN) of steering axles of Vehicle 1, Vehicle 3 and Vehicle n, respectively.

$$\varepsilon_t = (\varepsilon_{t11} + \varepsilon_{t12} + \ldots + \varepsilon_{tnn})/(W_{t11} + W_{t12} + \ldots + W_{tnn}) \tag{6}$$

where,

ε_t = Vertical strain of tandem axles /kN, ε_{t11}, ε_{t12} = Vertical strains due to ¼ tandem axles of Vehicle 1, εt_{nn} = Vertical strains due to ¼ tandem axle n of Vehicle n, W_{t11}, W_{t12} = ¼ Weight (kN) of tandem axles of Vehicle 1, and W_{tnn} = ¼ Weight (kN) of tandem axle n of Vehicle n.

Step-4: WinJULEA simulations were conducted (following Step - 1 through Step - 3 several times) for a wide range of temperatures (from 10°C to 43°C), which are representative of pavement temperatures in the test section, in order to obtain the vertical strain- temperature correlations. Two separate vertical strain-temperature correlations were obtained to predict vertical strain on the top of the aggregate base layer as a function of pavement temperature: one for steering axle and the other for tandem axle.

Following the steps described in Step-1 through Step-4, the final correlations between vertical strain on the top of the aggregate base layer and the mid-depth pavement temperature for single and tandem axles was established, as presented in Equations (7) and (8).

$$\varepsilon_s = 4 \times 10^{-06}\, T^{0.8432}\ (R^2 = 0.98) \tag{7}$$

$$\varepsilon_t = 8 \times 10^{-06}\, T^{0.7355}\ (R^2 = 0.98) \tag{8}$$

where,

ε_s = Vertical strain per kN per steering axle for a particular temperature, ε_t = Vertical strain per kN per tandem axle for a particular temperature, and T = Mid-depth pavement temperature (°C).

7.4. Traffic Data for Vertical Strain Calculation

As mentioned earlier, the vehicle category, axle weight and loading configuration of each vehicle travelled over the test section was recorded at the WIM station. From May 30, 2008 to May 2, 2012, approximately a total of 4.5 million single axles and 14.2 million tandem axles have passed over the test section, with a total of 32,600 hours of vehicle data was collected at the WIM station within that timeframe. Since temperature was recorded at every hour, vertical strains/kN from steering and tandem axles was calculated using Equations (7) and (8) for every hour. Then, average hourly vertical strains for both steering and tandem axles were calculated using Equations (9) and (10).

$$\varepsilon_{si} = \varepsilon_s(W_{s1} + W_{s2} + \ldots + W_{sn})/N_{si} \tag{9}$$

$$\varepsilon_{ti} = \varepsilon_t(W_{t11} + W_{t12} + \ldots + W_{nn})/N_{ti} \tag{10}$$

where,
ε_{si} = Average hourly vertical strain from steering axles, ε_{ti} = Average hourly vertical strain from tandem axles,
N_{si} = Total number of steering axle passes at that particular hour, and
N_{ti} = Total number of tandem axle passes at that particular hour.

The traffic data was linked with the environmental database (temperature) with the assistance of a time stamp (i) and thereby at any given time, the vertical strain produced by a certain number of axle passes was available.

7.5. The VSB Rut Prediction Model

Rut measurements, made at approximately every three months, were linearly interpolated to have a rut value for each hour of each day. Since rut was measured at six stations, each trip's rut values were averaged to obtain one rut value for that particular field trip. By relating the measured hourly rutting to the vertical strain on the top of the aggregate base layer and the total number of steering and tandem axle passes, the rut prediction model was developed by performing a non-linear regression analysis using the least–square technique in the Microsoft Excel spread sheet. The general form of the VSB rut prediction model is given in Equation (11). The formulation for Equation (11) was proposed by Selvaraj (2007) from National Center for Asphalt Technology, USA for developing a rut model from data collected from the field. Since the present paper focus on the development of rut model from the data collected from an instrumented pavement section, the proposed methodology in Selvaraj (2007) was used in the present paper, and subsequently Equation (12) is developed.

$$\mathrm{Rut}_i = \mathrm{Rut}_{i-1} + \lambda_1\left(N_{si}^{\lambda_2\varepsilon_{si}} + N_{ti}^{\lambda_3\varepsilon_{ti}}\right) \tag{11}$$

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 number of tandem axle passes at time 'i', λ_1 = Regression constant for traffic (both steering and tandem axles), and λ_2, λ_3 = Regression constants for vertical strain.

The final form of the VSB rut prediction model is given in Equation (12).

$$\mathrm{Rut}_i = \mathrm{Rut}_{i-1} + 2.49 \times 10^{-06}\left(N_{si}^{1.54\times10^2\varepsilon_{si}} + N_{ti}^{3.56\times10^2\varepsilon_{ti}}\right) \tag{12}$$

When rut was predicted using the developed VSB model (Equation (12)), the R^2 value, based on the predicted and the measured rut values, was found to be 0.78. Further, the positive coefficients for both traffic and vertical strains show that an increase in the number of axle passes and strain levels will increase the rutting, as expected. Figure 4 shows the predicted rutting from the VSB model and the measured average rutting of all stations, as a function of cumulative number of axles. The VSB model predicted rut and the field measured rut exhibit a similar trend as shown in Figure 4.

8. Conclusions

The following conclusions can be drawn based on the results presented in the preceding sections:

- The bottom mix (S3) was observed to have higher dynamic modulus values compared to the top layer mix (S4) for different combinations of temperature and frequency.
- Two significantly different methods, namely, straight edge-rut gauge combination and Face Dipstick® were

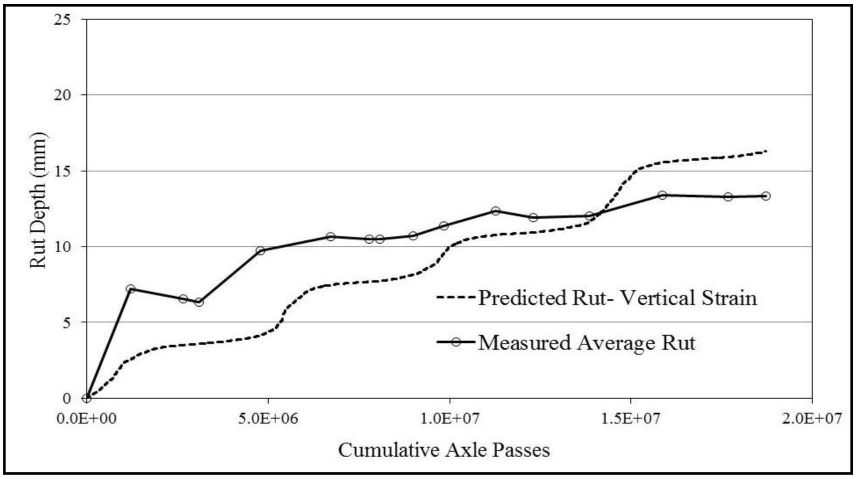

Fig. 4: Predicted and Measured Rut in the Test Section

used to measure rut in the test section. It was observed that Face Dipstick® provided more consistent and accurate rut measurements than straight edge-rut gauge combination.

- The VSB model predicted rut and the field measured rut exhibit a similar trend.
- Since the test section is on I-35, and has extremely high traffic volume, it was not practical to close the lanes frequently to collect rut data. The rut prediction model developed in this study could be improved by including additional field rut data.

References

AASHTO T166 (2006). Standard Method of Test for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimens. *American Association of State Highway and Transportation Officials*, Washington, D.C.

AASHTO TP62-03 (2006). Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures. *American Association of State Highway and Transportation Officials*, Provisional Standards.

AASHTO (2004). Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. *Final Report prepared for National Cooperative Highway Research Program (NCHRP), Transportation Research Board*, National Research Council, Washington, D.C.

Allen, D., and R.C. Deen, 1980. Rutting Models for Asphaltic Concrete and Dense Graded Aggregate from Repeated Load Tests. *Proceedings of the Association of Asphalt Paving Technologists*, Louisville, Kentucky, pp. 653-667.

Bonaquist, R., and Christensen, D.W. (2005). Practical Procedure for Developing Dynamic Modulus Master Curves for Pavement Structural Design. *Transportation Research Record, No. 1929, Journal of the Transportation Research Board*, Washington, D.C., pp. 208-217.

Hand, A. J., J. A. Epps, and P.E. Sebaaly, 1999. Development of APT Based Permanent Deformation Prediction Models Translatable to Other Environments. Accelerated Pavement Testing International Conference, Reno, Nevada.

Highway Research Board (HRB), 1962. The AASHO Road Test, Report 5 [online]. Available from: http://www.highways.gov.sk.ca/docs/reports_manuals/manuals/STP_DOC/stp240-20.pdf. Accessed August 11, 2010.

Kim, H.B., N. Buch, and D.Y. Park, 2000. Mechanistic-Empirical Rut Prediction Model for In-Service Pavements. Transportation Research Record: Journal of the Transportation Research Board, No. 1730, pp. 99-109.

Leahy, R. B., 1989. Permanent Deformation Characteristics of Asphalt Concrete. Ph.D. Dissertation. University of Maryland, College Park, Maryland.

Loulizi, A., Al-Qadi, I.L., Lahouar, S., and Freeman, T.E. (2002). Measurement of Vertical Compressive Stress Pulse in Flexible Pavements and Its Representation for Dynamic Loading Tests. *Transportation Research Record*, No. 1816, pp.125-136

MTS System Corporation (2011). URL: http://www.mts.com/ (Last accessed: May 31, 2013).

Selvaraj, S.I., 2007. Development of Flexible Pavement Rut Prediction Models from the NCAT Test Track Structural Study Sections Data. Ph.D. Dissertation, Auburn University, Auburn, Alabama.

Tran, N.H., and Hall, K.D. (2006). An Examination of strain levels used in the dynamic modulus testing. *Journal of Association of Asphalt Paving Technologist*, Vol. 75, pp. 321-343

Williams, R.C., D.W. Hill, and M.P. Rottermond, 2005. Utilization of an Asphalt Pavement Analyzer for Hot Mix Asphalt Laboratory Mix Design. Journal of ASTM International, 2 (4), pp. 16-40.