Backcalculation of HMA Stiffness Based On Finite Element Model

Md Rashadul Islam, Umme Amina Mannan, Rafiqul A. Tarefder

Abstract—Stiffness of Hot Mix Asphalt (HMA) in flexible pavement is largely dependent of temperature, mode of testing and age of pavement. Accurate measurement of HMA stiffness is thus quite challenging. This study determines HMA stiffness based on Finite Element Model (FEM) and validates the results using field data. As a first step, stiffnesses of different layers of a pavement section on Interstate 40 (I-40) in New Mexico were determined by Falling Weight Deflectometer (FWD) test. Pavement temperature was not measured at that time due to lack of temperature probe. Secondly, a FE model is developed in ABAQUS. Stiffness of the base, subbase and subgrade were taken from the FWD test output obtained from the first step. As HMA stiffness largely varies with temperature it was assigned trial and error approach. Thirdly, horizontal strain and vertical stress at the bottom of the HMA and temperature at different depths of the pavement were measured with installed sensors on the whole day on December 25th, 2012. Fourthly, outputs of FEM were correlated with measured stress-strain responses. After a number of trials a relationship was developed between the trial stiffness of HMA and measured mid-depth HMA temperature. At last, the obtained relationship between stiffness and temperature is verified by further FWD test when pavement temperature was recorded. A promising agreement between them is observed. Therefore, conclusion can be drawn that linear elastic FEM can accurately predict the stiffness and the structural response of flexible pavement.

Keywords—Asphalt pavement, falling weight deflectometer test, field instrumentation, finite element model, horizontal strain, temperature probes.

I. INTRODUCTION

MECHANISTIC Empirical Pavement Design Guide (MEPDG) was implemented in 2008 to eliminate the traditional empirical design procedure for designing the flexible pavement [1]. Mechanistic response is incorporated into this design guide. This method uses detailed information about traffic, climate conditions and material properties and responses. Based on the input parameters, the model predicts the possible distresses in its service life. Therefore, accurate measurement of input parameters is essential for safe and sustainable pavement which will eliminate the probable maintenance and rehabilitation cost. Falling Weight Deflectometer (FWD) test is usually conducted on pavement materials to determine the in situ stiffness of material. However, this test results should be validated for accurate

Md Rashadul Islam is with the Dept. of Civil Engineering, University of New Mexico, MSC01 1070, 1 University of New Mexico, Albuquerque, NM 87106, USA (PH (505) 363-6902; e-mail: mdislam@unm.edu).

Umme Amina Mannan and Rafiqul A. Tarefder are with the Dept. of Civil Engineering, University of New Mexico, MSC01 1070, 1 University of New Mexico, Albuquerque, NM 87106, USA.

stiffness measurement. Stiffnesses of base, subbase and subgrade are usually independent of temperature. However, stiffness of Hot Mix Asphalt (HMA) is largely depended on temperature. HMA stiffness must be correlated with temperature for better understanding of the value.

This study determines the stiffness of HMA using numerical analysis. The numerical model is validated with the field measured values. Linear elastic analysis is performed as this type of analysis is accurate enough for regular geometry [2], [3]. Another reason is that while measuring the field response it was observed that upon unloading the stress-strain return to origin at the same loading rate.

A total of 40 sensors were installed for this study including vertical and horizontal strain gauges, pressure cells, moisture probes, etc., with the help of New Mexico Department of Transportation (NMDOT) and National Center for Asphalt Technology (NCAT). In addition, temperature probes, Axle Sensing Strips (ASS), weather station etc. were installed inside the pavement at different layers. The instrumentation is implemented on Interstate 40 (I-40) east bound lane, at milepost 141 in the state of New Mexico, USA.

II. PAST STUDIES

Asphalt concrete is composed of crushed stones and asphalt binder. The crushed stone is not affected by small temperature variations. However, asphalt binder is largely dependent on temperature. The stiffness of HMA is thus dependent upon temperature. Therefore, HMA exhibits higher stiffness in lower temperatures and lower stiffness in higher temperatures. This is why, the stiffness of HMA is evaluated at different temperatures and the corresponding structural responses are predicted using numerical analysis or different design guides (i.e., AASHTO, MEPDG etc.) [4]-[6]. Thus, temperature is considered the leading factor for characterizing a particular asphalt concrete mixture. Schwartz and Carvalho [7] observed the seasonal variations of the stiffness of HMA using a parametric study in MEPDG and observed that the stiffness increased to more than 3.5 times for a 37.5 mm thick asphalt layer in the winter compared to the summer. Orr [5] performed FWD test to measure in situ stiffness of the pavement material at various temperatures. The researcher concluded that the stiffness of the HMA in the winter increased to more than 4 times than that in the summer. The above discussion concludes that monitoring the stiffness variations with temperature is very important and quite expensive. This study describes a procedure to determine or monitor the stiffness variations with temperature. This procedure can be followed if the stress-strain and temperatures of pavement materials are

known.

III. OBJECTIVES AND METHODOLOGY

This study determines the stiffness of HMA based on numerical analysis at different temperatures. The stiffnesses of pavement materials other than the HMA are determined using FWD test. The stiffness of the HMA is assigned as trial and error approach and the corresponding stress-strain are compared with the field measured value for a particular time of the day. If these values match, the trial stiffness is taken as the stiffness of HMA at that time. The average HMA temperature (mid-depth HMA temperature) is then measured for that time and the trial stiffness is reported the stiffness at this temperature. The schematic diagram of the methodology is presented in Fig. 1. In this chart, σ and ε denote vertical stress and horizontal strain at the bottom of HMA respectively. The symbol, EHMA represents the stiffness of HMA and the E symbolizes the stiffness in general.
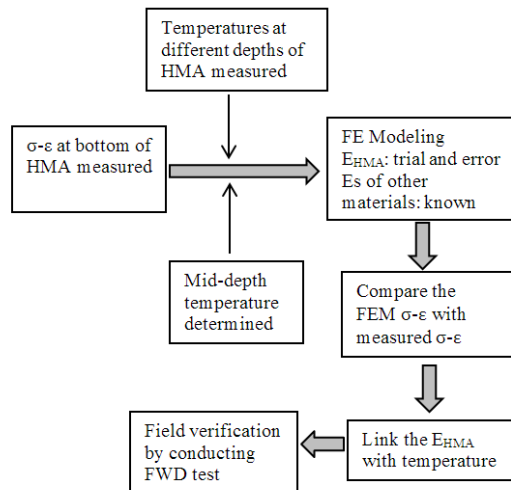

Fig. 1 Schematic of the work procedure

IV. FIELD INSTALLATION

A. Instrumentation Section

The instrumented section has four layers. The top 300mm (12 in) layer is Hot Mix Asphalt (HMA). Then, there is a 144 mm (5.75 in) crushed stone base course followed by a 200mm (8 in) Process Place and Compact (PPC) and finally, underlain by the natural soil. The instrumentation plan view is shown in Fig. 2. The layout of the sensors and the roadside construction plan are shown. The sensors are installed in the driving lanes only.
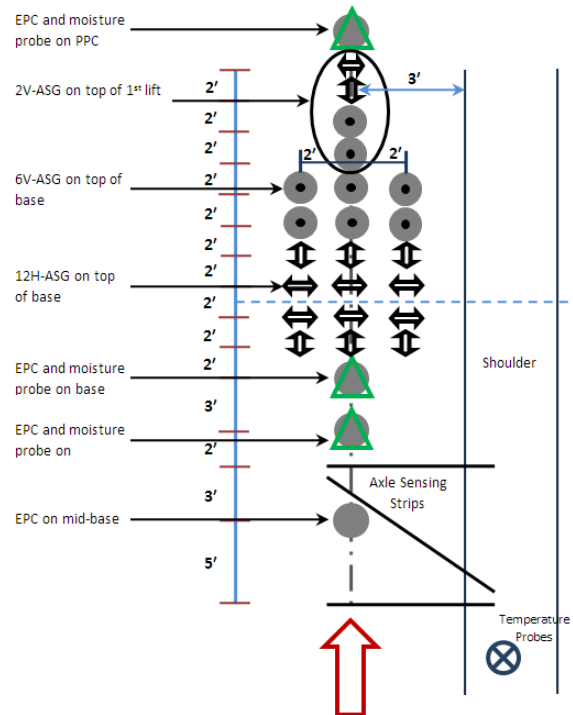

Fig. 2 Plan view of the instrumented section

B. Horizontal Asphalt Strain Gauges

A total of 12 Horizontal Asphalt Strain Gauges (HASGs) (six oriented in longitudinal direction and six oriented in transverse direction) were installed at the bottom of the asphalt layer to measure the tensile strains due to temperature and vehicle load. The array of gauges is centered in the outside wheel path with 600mm (2 ft) offset from center to capture the wheel wander of the traffic. The HASGs at the bottom of the HMA is shown in Fig. 3. HASGs have been held in position with some sand binder mixture. Prior to the paving, some sieved HMA mix was placed and compacted with a tamping rod. The data of these gauges are used in this study to validate the developed numerical model.

Fig. 3 Installation of horizontal strain gauges

C. Earth Pressure Cell

Earth Pressure Cell (EPC), a device to measure vertical

pressures, was installed at the top of the granular base layer, at the middle of base, on top of the PPC layer and on top of the subgrade respectively. Sieved materials were used at the top and bottom of the EPC to protect it from larger aggregates. Prior to covering, it was leveled impeccably for better response as shown in Fig. 4. The functionality of the sensors was checked throughout the construction and compaction process. The data of the sensor installed at the bottom of the HMA is used in this study to validate the numerical model.

Fig. 4 Installation of earth pressure cell

D. Axle Sensing Strips

Determination of wheel wander is critical during the assessment of the sensors response. The axle sensor arrangement, embedded at the surface of the pavement, allows for very accurate wheel placement measurements. These sensors are intended to use for classifying vehicles, axle spacing and determining vehicle speeds. Three axle sensing strips were installed just before the array of the sensors as shown in Fig. 5. The vehicles that pass through the centerline of the sensors are used in this study.

Fig. 5 Installation of axle sensing strips

E. Temperature Probes

Six temperature probes, model 108 by Campbell Scientific (www.campbellsci.com) were installed at different depths of the pavement. These probes were bundled together such that after installing they remained at the surface level and at 50, 100, 300, 375, 525mm depths of the pavement. Then, the asphalt cement was applied to the bundled probes as best as

possible. This cement has the same thermal properties of asphalt concrete.

Fig. 6 Installation of temperature probes

A 25mm diameter hole was drilled with electric drill machine. Then, the hole was cleaned with vacuum cleaner. Some asphalt cement was also inserted into the hole prior to inserting the probe in to it. The probes were then inserted into the hole as straight as possible keeping the top one at the same level to the surface as shown in Fig. 6. The temperature probes were installed around 300mm outside the shoulder and 1.2m before the first Axle Sensing Strips. The functionality of the installed temperature probes were checked by connecting the probe with the data acquisition system.

All the probes are working and the continuous data are being collected through the slow speed data acquisition system. These are recording the average, the maximum and the minimum temperature each half an hour at surface, at 50, 100, 300, 375 and 525mm depths of the pavement. The readings of the probes installed at surface and at 300mm depth (bottom of HMA) are used to calculate the average temperature of the HMA at any time of the day in this study.

F. Other Sensors

The section also has eight Vertical Asphalt Strain Gauges (VASGs) and three moisture probes at the layer interfaces. A roadside weather station was erected for the accurate measurement and modeling of the climate. A weigh-in-motion was installed to measure the weight of the vehicles and characterize the traffic.

G. Hot Mix Asphalt

The asphalt concrete used in the pavement is a dense graded SuperPave (SP) mix, type SP-III, which is widely used in New Mexico. This mix contains 35% recycled asphalt materials (RAP) materials. The RAP materials were collected from local street millings which were screened by the contractors prior to mixing with the aggregates. PerformanceGrade (PG) binder PG 70-22 is used 4% (by weight). The gradation of the SuperPave mix aggregate is shown in Table I. Maximum aggregate size was 25mm (1.0 in.). About 5% materials passed through no 200 sieve (0.075mm).

TABLE I
GRADATION OF AGGREGATES USED IN HMA

Sieve Size	% Passing
25 mm (1.0 in)	100
19.0 mm (0.75 in)	99
12.5 mm (0.5 in)	87
9.5 mm (0.375 in)	72
4.75 mm (No. 4)	42
2.375 mm (No. 8)	26
1.185 mm (No. 16)	20
0.67 mm (No. 30)	16
300 μm (No. 50)	11
150 μm (No. 100)	7.9
75 μm (No. 200)	5.0

V. FALLING WEIGHT DEFLECTOMETER TEST

Falling Weight Deflectometer (FWD) is a widely used nondestructive test to determine the stiffness of pavement materials. In this test, an impulse load is applied on surface by dropping a weight and transmitted to pavement through a circular steel plate. Pavement deflects vertically downward forming a deflection basin. Geophones measure these surface deflections at different distances from loading point. Backcalculated stiffness of underneath layers is determined by using the load and deflection data with a backcalculation software such as ELMOD, BAKFAA, Modulus etc.

Fig. 7 Conducting FWD test

FWD tests were conducted on each layer of construction i.e. on PPC, Base and HMA. The tests data were analyzed by ELMOD software. The date and the time of day of conducting the tests were cautiously recorded. Fig. 7 shows the execution of the test on top of the first lift of HMA. The average stiffness of Base Course, PPC and subgrade are 162.7 MPa (23.6 ksi), 187.5 MPa (27.2 ksi) and 122 MPa (18 ksi) respectively. The HMA stiffness changes with temperature and age of pavement. This is why, the HMA stiffness is not taken from this FWD test. However, further FWD test was conducted to verify the developed relationship.

VI. DATA COLLECTION

The vertical stress and the horizontal strain at the bottom of the asphalt concrete are measured with the installed EPC and HASGs. The data are gathered with slow speed data acquisition system and recorded in a computer. The stress and the strain value for an eighteen-wheel vehicle (120 psi tire pressure) on December 25th, 2012 are used in this study. These strain-strain values are used to validate the developed numerical model and backcalculate the HMA stiffness. The maximum, the minimum and the average temperature values of each half an hour were recorded at the surface and at the bottom of the asphalt concrete. The average of these two temperatures is taken as the average pavement temperature at any time of the day. The measured structural responses and the temperature variations are listed in Table II.

TABLE II
STRESS-STRAIN RESPONSES WITH TEMPERATURES ON DECEMBER 25TH, 2012

Time	Stress (psi)	Strain (μm/m)	Average Temperature (°C)
12:00 am	2.75	43.86	4.6
4:00 am	2.65	43.67	3.4
9:00 am	2.43	43.43	1.9
12:00 pm	2.74	44.65	5.8
4:00 pm	2.83	47.85	9.6
8:00 pm	2.74	44.65	5.8
12:00 am	2.67	43.81	3.8

VII. FINITE ELEMENT MODELING

An axis-symmetric model is developed in commercial finite element software, ABAQUS. Thicknesses of the surface, base, PPC and subgrade layers are 300mm (12 in), 144mm (5.75 in), 200mm (8 in) and 6.86m (274 in) respectively as shown in Fig. 8. The radius of the section is assigned 1m. These depths are chosen such that the depth to bottom boundary is greater than the depth to insignificant influence stress region to eliminate the effect of the bottom boundary [8]. The tire inflation pressure is assumed 830 kPa (120 psi) for an eighteen-wheel vehicle acting on a 150mm radius circular area [1]. The materials of the layers of this model are assumed linear elastic. The stiffness of the base, PPC and subgrade layers are taken from backcalculated layer moduli and the stiffness of the surface layer (HMA) are assigned as trial and error basis. The average stiffness of Base Course, PPC and subgrade are 162.7 MPa (23.6 ksi), 187.5 MPa (27.2 ksi) and 122 MPa (18 ksi) respectively. Poisson's ratios are assigned 0.35, 0.4, 0.4 and 0.45 for surface, base, PPC and subgrade respectively.
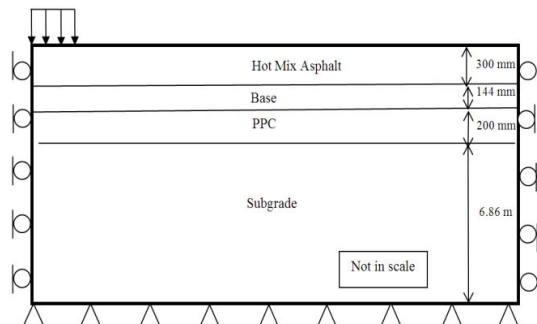

Fig. 8 Developed finite element model

Two vertical edges are allowed to move only in vertical directions. The bottom edge is assumed to have no displacement since it is deeper than the insignificant stress zone. This is restrained to move in either direction. Both vertical edges and bottom edge are restrained to move along transverse direction. This model is assigned with axis-symmetric, second order, and quadrilateral element, CAX8 for mesh. Region near to the loading area is finely meshed to obtain the gradual stress distribution [8]. Coarser mesh is assigned farther from the loading zone to reduce the required memory storage for this analysis. Aspect ratio of the mesh elements in this zone is 1 to ensure better analysis.

The vertical stress distribution over the depth is shown in Fig. 9. The stress is the minimum (highest in compressive) below the tire. The stress decreases with increase in depth. The measured vertical stress at the bottom of the asphalt concrete (300mm depth) ranges 16.75-19.53 kPa (2.43-2.83 psi) for the 830 kPa (120 psi) tire inflation pressure.
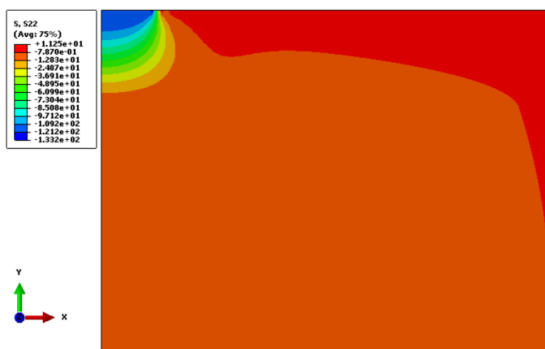

Fig. 9 Contour plot of vertical stresses

The horizontal strain variation over the depth is plotted in Fig. 10. The strain is the maximum (tensile) at the bottom of the asphalt concrete. There should be no strain in base and in subbase course, as the layers are assumed fully bonded the strain occurs in these layers. The measured strain at the bottom of HMA (300mm depth) ranges 43.43-47.85 microstrain (μm/m) for the day for an eighteen-wheel vehicle.
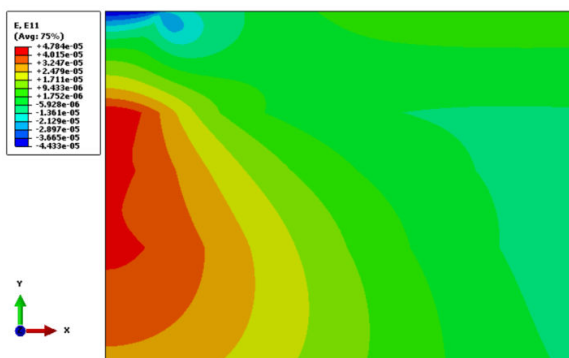

Fig. 10 Contour plot of horizontal strain

VIII. RESULTS AND DISCUSSION

The vertical stress and the horizontal strain at the bottom of the asphalt concrete (300mm depth) for an eighteen-wheel vehicle (120 psi tire pressure) on December 25th, 2012 are measured and used to validate the developed numerical model. The maximum, the minimum and the average temperature values of every half an hour were recorded at the surface and at the bottom of the asphalt concrete. The average of these two temperatures is taken as the average pavement temperature at any time of the day. The measured structural responses and the temperature variations are listed in Table II.

The pavement surface absorbs the heat from sunlight and transfers it to the underneath colder material. At night, the surface material draws up the heat from the underneath materials and transmits it to the air. Therefore, temperatures of the pavement materials vary all day long. The surface, the bottom and the mid-depth HMA temperatures are plotted in Fig. 11. The mid-depth temperatures are determined from the best fitted temperature distribution curve. It is observed that the surface temperature ranges -1.9 to 13.9^{0}C whereas the temperature at the bottom ranges 4.7 to 7.2^{0}C. The mid-depth temperature varies 1.6^{0}C to 9.6^{0}C with the average value of 5.6^{0}C.
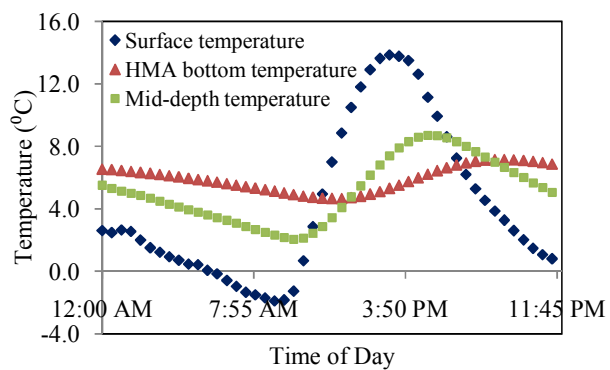

Fig. 11 Variations of temperature with time

The estimated HMA stiffness variations over the day and with temperatures are plotted in Figs. 12 and 13 respectively. The stiffness is the maximum (13.28 GPa) around 9:30 am and the minimum (11.59 GPa) around 4:00 pm. The temperature variations of the pavement also match with these stiffness variations. The stiffness is the maximum at the minimum temperature and vice versa.
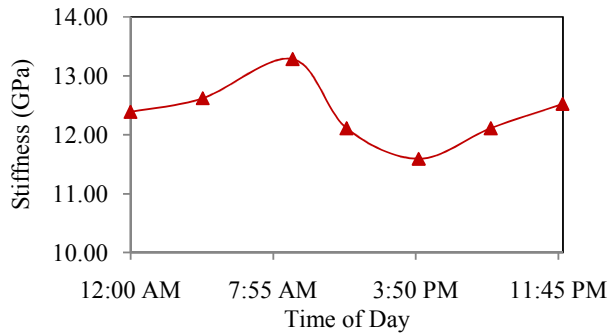
Fig. 12 Variations of HMA stiffness over the day

The peak to peak difference between the maximum and the minimum of the average temperature is 8.1⁰C and the peak to peak difference between the maximum and the minimum stiffness is 1.69 GPa. This yields that the stiffness of the asphalt concrete decreases by 0.21 GPa for unit increase in temperature in ⁰C.
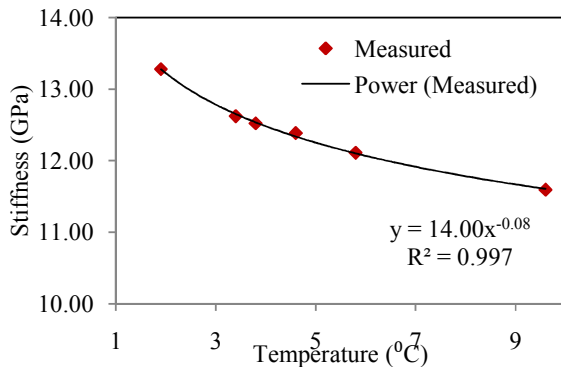

Fig. 13 Stiffness variations with mid-depth HMA temperatures

Based on Fig. 13, the variations of stiffness with temperature can be expressed as:

$$y = 14.007x^{-0.083} \qquad (1)$$

where x and y are the mid-depth HMA temperature (⁰C) and HMA stiffness (GPa) respectively. Note that this relationship is developed based on backcalculation procedure using FEM.

IX.   FIELD VALIDATION

To verify the above mentioned relationship between the stiffness of HMA and temperature, another FWD test was conducted on February 5th, 2013 at 1:15 pm. A total of thirty drops of loads were applied at three different loads (ten drops of each). Temperature data were also recorded. The mid-depth temperature was measured to be 49.47⁰F (9.67⁰C). The average backcalculated modulus of HMA was measured to 10.8 GPa with standard deviation of 1.2 GPa. The maximum and the minimum values are measured to be 13.9 and 9.1 GPa respectively. Using the best fitted power relationship (1), the stiffness of HMA at 49.47⁰F (9.67⁰C) are calculated to be

11.69 GPa which is 7.6% less than the average FWD stiffness. This difference can be neglected.

X. CONCLUSIONS

This study backcalculates the stiffness of the asphalt concrete based on numerical analysis. The linear elastic numerical model is observed to be capable enough to determine the properties of asphalt concrete correctly. This study also describes a procedure to determine the stiffness of pavement material if the stress-strain of pavement material is known. This procedure can be used to determine the diurnal and the seasonal variations of the HMA stiffness. Based on this study it is concluded that the stiffness of the asphalt concrete decreases by 0.21 GPa for unit increase in temperature in ⁰C if the relationship is considered linear. However, power function represents the result better.

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