Field Measurement of Vertical Strain in Asphalt Concrete

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Abstract— Recently developed Mechanistic-Empirical Pavement Design Guide (MEPDG) determines the probable total rutting by summing up the deformations of all layers of the trial pavement. If all distresses outcomes including rutting are within the specification the trial section is designed for construction. Therefore, vertical deformation (or strain) needs to be measured to validate the MEPDG for local conditions. However, no direct procedure for measuring the vertical strain in flexible pavement is available to this date. Traditionally, Earth Pressure Cell (EPC) is used to measure the vertical stresses at different layers of pavement. Then, vertical strain is calculated using the measured stress and the stiffness of the corresponding material. The present study describes a procedure to measure the vertical strain of asphalt concrete based on field instrumentation. The vertical strain is measured using the Vertical Asphalt Strain Gauge (VASG) in an instrumented pavement section on Interstate 40 (I-40) in the state of New Mexico, USA and compares the results with numerical model developed using ABAQUS. The numerical model is validated with stress responses measured with installed four EPCs. The stiffness input of the numerical model is obtained from Falling Weight Deflectometer (FWD) test. Promising agreement is observed between the strains measured in the field and determined from the numerical model. Therefore, the VASG can be considered an effective sensor to measure the vertical strain of asphalt concrete in flexible pavement.

Index Terms— Asphalt concrete, Vertical stain, Vertical stress, Vertical asphalt strain gauge, Earth pressure cell, Falling weight deflectometer test, Numerical analysis, Validation

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1   INTRODUCTION

Rutting is one of the major distress outcomes of Mechanistic-Empirical Pavement Design Guide (MEPDG). It is determined by summing up of permanent deformations of all layers along the wheel path [1]. Therefore, measuring vertical strain is so important for accurate rut prediction. Eq. 1 is used to calculate the permanent deformation in asphalt concrete:

$$\Delta_{p(HMA)} = \varepsilon_{p(HMA)} h_{HMA} = \beta_{1r} k_z \varepsilon_{r(HMA)} 10^{k_{1r}} n^{k_{2r}\beta_{2r}} T^{k_{3r}\beta_{3r}} \quad (1)$$

where $\Delta_{p(HMA)}$= Accumulated plastic vertical deformation in Hot Mix Asphalt (HMA) (in.),
$\varepsilon_{p(HMA)}$= Accumulated plastic vertical strain in HMA layer,
$\varepsilon_{r(HMA)}$= Elastic strain calculated by structural response model at mid-depth of each sub layer,
h_{HMA}= Thickness of HMA layer, (in.),
n= Number of axle-load repetitions,
T= Pavement temperature (^{0}F),
k_z= Depth confining factor, function of HMA total depth and the depth concerned,
$\beta_{1r,2r,3r}$= Local field calibration constants,
$k_{1r,2r,3r}$= Global field calibration constants,
Therefore, $\varepsilon_{r(HMA)}$ is the only parameter needed to be measured to determine the plastic deformation. Accurate measurement of vertical strain is necessary for probable rut estimation.

Measuring vertical deformation or strain of asphalt con-crete is much cumbrous. Several researchers measured the vertical deformation or vertical stress, not the vertical strain. Scullion et al. [2] used Multi Depth Deflectometer (MDD) to measure the vertical deflection under Falling Weight Deflectometer (FWD) and vehicle loads. A 38 mm diameter (1.5") and 2.1 m (7.0 ft.) deep borehole was prepared in the pavement to install the sensors. The researchers measured the relative and the total permanent deformation. However, determining actual deformation from this data is near impossible.

Schaevitz HCD-500 Linear Variable Displacement Transducer (LVDT) was used to measure the vertical deformations of the asphalt and concrete and subgrade base in Minnesota Road Research Project [3]. A PVC pipe of 2.4 m (8 ft.) long and 112 mm (4.5") diameter was inserted into the pavement in which a reference rod of 3.6 m (12 ft.) long and 25 mm (1.0 in.) diameter was inserted into the pipe. The pipe was mounted to 25 mm (1.0") below the pavement surfaces. The LVDT was placed at a certain depth on the reference cap. The process is really cumbersome and the inserted 112 mm pipe also deteriorates the quality of pavement and the hole may act as stress focal point. This installation procedure was not followed in any future studies.

National Center for Asphalt Technology (NCAT) performed several instrumentation projects in 2003 and 2006 and studied the vehicle-pavement interaction and effects on pavement deterioration [4], [5]. Vertical stress and horizontal strain of asphalt concrete were measured in these studies with Geokon 3500 Earth Pressure Cells (EPCs) and Construction Technology Laboratories Inc. (CTL) supplied Horizontal Asphalt Strain Gauges (HASGs). Twelve flexible pavements were instrumented in Virginia Smart Road project [6], [7]. The researchers installed Dynatest Strain Gauges to measure horizontal strain in asphalt concrete and Geokon 3900 EPC to measure vertical

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stress at the layer interfaces.

The deformation of the asphalt concrete can be calculated by using the vertical stress with the stiffness of the asphalt concrete. However, HMA stiffness is fully dependent on age of the pavement, temperature profile of the pavement and frequency of loading. These factors make the output quite challenging to be accurate.

A new procedure is described in the present study to measure the vertical strain in asphalt concrete. CTL has developed Vertical Asphalt Strain Gauges (VASGs) which are capable of measuring vertical strain in asphalt concrete [8]. Six sensors are installed and the responses are evaluated with the numerical analysis. A promising performance is observed between the measured vertical strain and the numerical model determined vertical strain. The details of this sensor, working principle, installation procedure and functionality are described in the following sections.

2 OBJECTIVES

The main objective of this study is to evaluate the performance of the VASG to measure the vertical strain of asphalt concrete. Numerical model is developed to determine the strain response at the VASG sensors' elevation. This model is validated with the stresses responses measured with the pressure cells installed at four other depths.

3 VERTICAL ASPHALT STRAIN GAUGE

3.1 General

The VASG measures the vertical strain in asphalt concrete for repeated traffic loading. It has a sharp leg to be inserted into the underlying base layer. The gauge area is secured by two stainless steel circular plates as shown in Fig. 1.
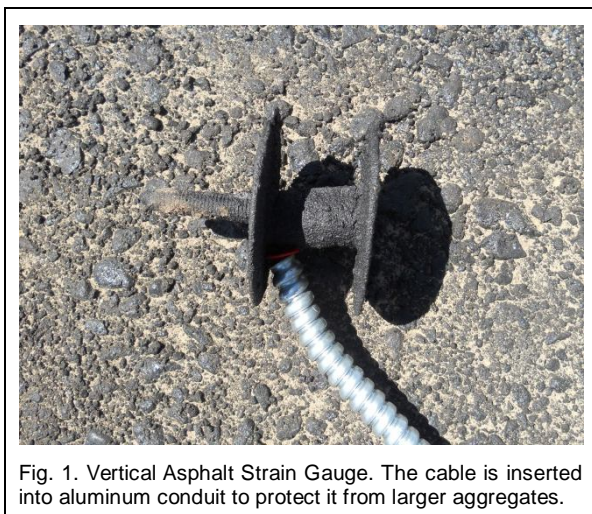

Fig. 1. Vertical Asphalt Strain Gauge. The cable is inserted into aluminum conduit to protect it from larger aggregates.

The bottom plate helps the sensor to remain in position without tilting. The top plate transfers the applied load uniformly on the sensors. HMA is inserted between these two

plates and hand compacted to acquire the required density. It has Teflon polymer coated braided lead wire to avoid electrical noise and withstands temperature up to 400 °F (205 °C). Fig. 1 also shows that the cable is inserted into aluminum conduit to protect it from larger aggregates.

3.2 Principle of Operation

The resistance to electrical current provided by a conductor of uniform cross-section is given by the well-known preliminary physics equation (Eq. 2) given below:

$$R = \rho \frac{L}{A} \qquad (2)$$

where R is the resistance of the conductor in ohms, ρ is the resistivity of the material, and L and A are the length and cross-sectional area of the conductor respectively. If the conductor is stretched the length increases and the cross-sectional area decreases. The relationship of the change in resistance with change in length and diameter is expressed as in Eq. 3:

$$\frac{\Delta R}{R_o} = F_G \frac{\Delta L}{L_o} \qquad (3)$$

The term F_G is commonly referred to as gauge factor, or strain sensitivity factor and is a function of the alloy characteristics, L_0 and R_0 are the initial length and resistance of the conductor respectively and ΔR is the change in resistance for change in length (ΔL). The change of resistance produces some voltage of a bridge circuitry (Fig. 2). An analog to digital converter changes the analog voltage to a digital signal that is interpreted by data acquisition system.
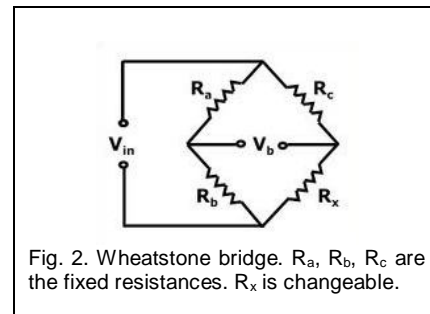

Fig. 2. Wheatstone bridge. R_a, R_b, R_c are the fixed resistances. R_x is changeable.

V_{in} is zero for balanced condition. It yields the following condition as in Eq. 4:

$$\frac{R_a}{R_b} = \frac{R_c}{R_x} \qquad (4)$$

where R_a, R_b, R_c and R_x are the four resistances of the bridge. The bridge becomes unbalanced if any resistance changes. One of the resistors, in this case R_x, is replaced by strain gauge to measure the strain. If the gauge experiences a change in resistance, the voltage across the meter is then related to the change in resistance. The strain in the gauge can be calculated from this voltage if gauge factor is known. The manufacture provides this factor and is to be verified in laboratory.

3.3 Installation Procedure

A small hole of around 0.375 mm diameter and 100 mm deep is drilled. Some sand binder mixtures are applied to fill the hole and cover the surroundings. The gauge is gently pressed down into the hole until the bottom plate comes into full contact with the surface. The top plate of the gauge is removed and HMA mixture is placed around each gauge immediately before paving. The mixture is then compacted with tamping rod without damaging the sensor. The top cap is then replaced and some mix is applied on top of it. Then, contractors can pave over it.

4 EARTH PRESSURE CELL

Earth pressure cell is used to measure the vertical stresses in base, subbase and subgrade. Two circular stainless steel plates are welded together along their boundaries as shown in Fig. 3. Fluid is used to fill the narrow gap between the plates. The fluid gets stressed when vertical load is applied on top of it. A pressure transducer is connected with stainless steel tube. The transducer transforms this fluid pressure into an electrical signal (usually voltage) which is noticed by the data acquisition system.
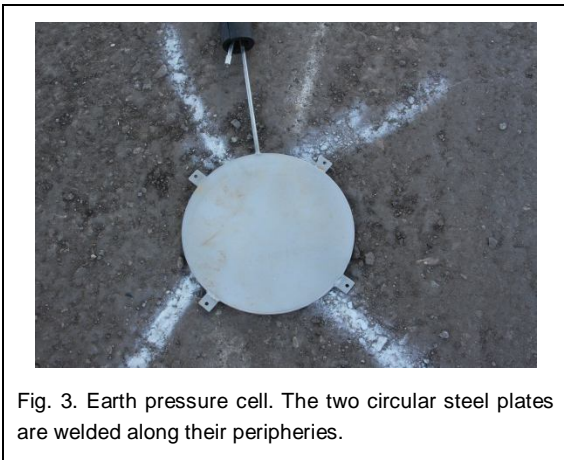

Fig. 3. Earth pressure cell. The two circular steel plates are welded along their peripheries.

5 FIELD INSTALLATIONS AND DATA COLLECTION

Pavement strain data was collected from an instrumented pavement section on Interstate 40 (I-40) east bound lane at mile post 141 near Albuquerque in the state of New Mexico, USA. The cross section of the instrumented section is shown in Fig. 4. The section has four layers with 300 mm (12") Surface, 144 mm (5.75") Base, 200 mm (8.0") Process Place and Compact (PPC) and Subgrade.

The asphalt concrete used in this pavement is a dense graded SuperPave (SP) mix, type SP-III, which is widely used in the New Mexico Department of Transportation (NMDOT). This mix contains plant screened Recycled Asphalt Pavement (RAP) materials around 35%. Performance Grade (PG) binder PG 70-22 is 4% (by weight of mixture). The maximum aggregate size is 25 mm (1 in.). About 5% of the materials passes through No. 200 sieve (0.075 mm).
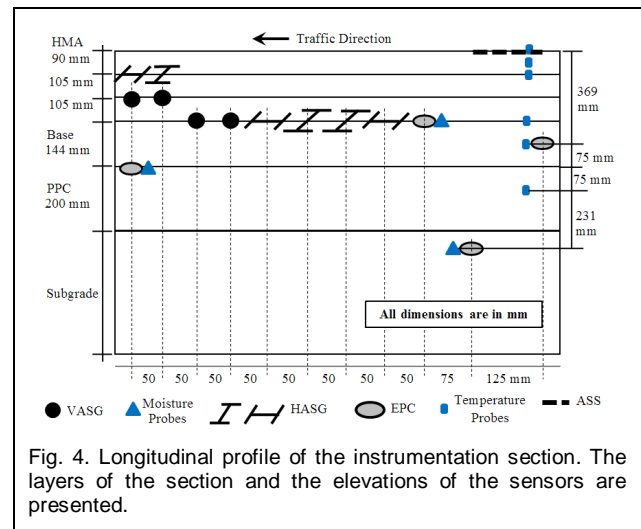

Fig. 4. Longitudinal profile of the instrumentation section. The layers of the section and the elevations of the sensors are presented.

A total of twenty two vertical and horizontal strain gauges, four pressure cells, three moisture probes, and six temperature probes were installed inside the pavement at different layers. Sensor data are gathered continuously by a high speed data acquisition system and recorded in a computer.

EPCs were installed at the layer interfaces and at the middle of the base. A 300 mm (12.0") square, was prepared to accommodate the 225 mm (9.0") diameter EPC as shown in Fig. 5. The depth of the hole was approximately 60 mm. A 75 mm (3.0") wide by 75 mm (3.0") deep trench was prepared with pick axes to accommodate the cable.
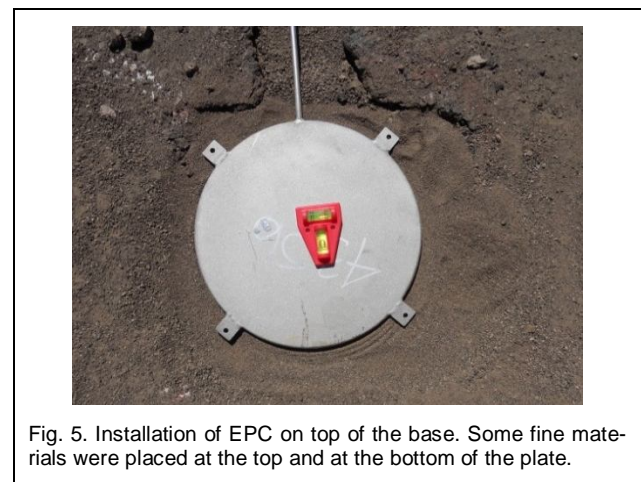

Fig. 5. Installation of EPC on top of the base. Some fine materials were placed at the top and at the bottom of the plate.

The bottom 25 mm (1.0") was filled with sieved PPC material passing #8 and compacted with Marshall Hammer to make a smooth and level bed. Then, the sieved PPC material passing #16 was placed approximately 18.75 mm (0.75") thick. The EPC was then placed such that it attained the exact eleva-

tion in the section. The EPC was also leveled as best as possible as shown in Fig. 5. All positions and elevations of the sensors were surveyed and recorded for analysis. Six vertical strain gauges were installed at the bottom of the asphalt layer. The holes for the gauges were made by drilling machine. Some sand-binder mix was placed into the hole and then the gauges were inserted into it.

Fig. 6. Installation of VASG. The top steel plate is removed for applying some sieved mixtures over it.

Prior to paving over the gauges, the top plate was taken off as shown in Fig. 6 and some -#4 HMA mixtures were applied and compacted with tamping rod. The top plate was then returned and covered with more sieved mixtures. Then, the truck dumped the mixture over the sensors and compacted with no vibration. The density of the compacted mix was checked through field coring and measuring with nuclear density measuring device.

6 FALLING WEIGHT DEFLECTOMETER TEST (FWD)

FWD tests were conducted on the final lift of the pavement in late May, 2012 in early morning as shown in Fig. 7.
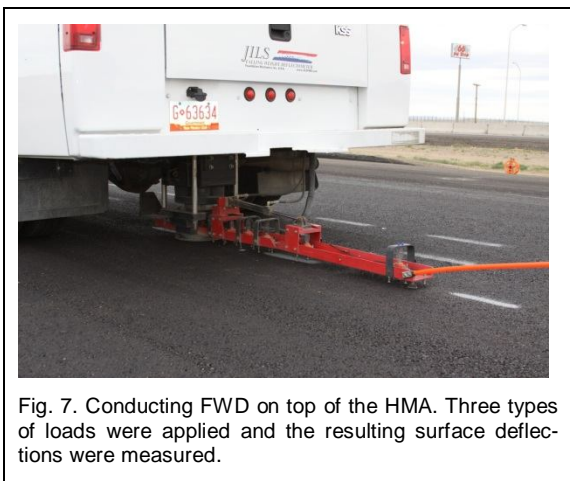

Fig. 7. Conducting FWD on top of the HMA. Three types of loads were applied and the resulting surface deflections were measured.

Two types of loads were used, 9 and 12 kips with two drops

of each at 0.6 m (2 ft.) interval for a length of 18 m. The resulting surface deflections at different radial distances were measured with the sensors. The tests data were analyzed by backcalculated software ELMOD. The stiffnesses were calculated using the linear elastic theory and the method of equivalent thickness. The average stiffness of both these methods was used numerical analysis. The pavement temperature during the FWD was not measured. However, both the FWD testing and sensors' data recording were conducted at the same time to avoid the temperature incongruity. The average stiffnesses are measured to be 2410 MPa (350 ksi), 185 MPa (27 ksi), 158 MPa (23 ksi) and 103 MPa (15 ksi) for HMA, base, PPC, and Subgrade respectively.

7 FINITE ELEMENT MODEL (FEM)

An axis-symmetric model is developed in ABAQUS to determine the vertical strain at the installed VASGs' elevation. The modeled section has four layers with 300 mm Surface, 144 mm Base, 200 mm Process Place and Compact (PPC) and Subgrade as shown in Fig. 8. The radius of the section and the tire pressure are used as 2.5 m (100") and 150 mm (6.0") respectively. The moduli of the material are taken from the Falling Weight Deflectmeter (FWD) test. These values are 2410 MPa, 185 MPa, 158 MPa and 103 MPa for HMA, base, PPC and subgrade respectively. Poisson's ratios are used as 0.35, 0.4, 0.45 and 0.45 for HMA, base, PPC and subgrade respectively [9].
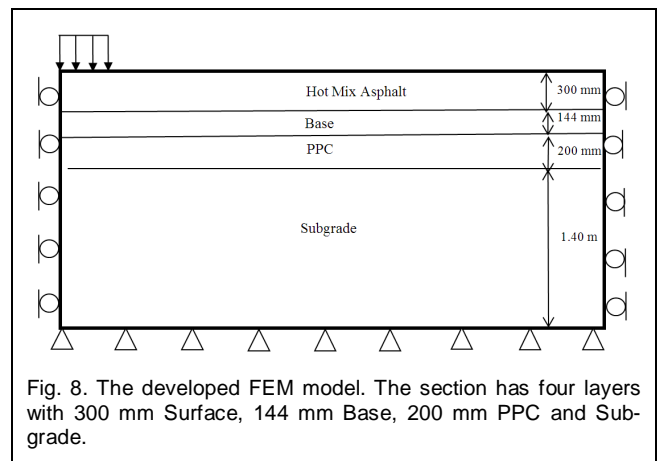

Fig. 8. The developed FEM model. The section has four layers with 300 mm Surface, 144 mm Base, 200 mm PPC and Subgrade.

A linear elastic analysis is performed with axisymmetric, second order, and quadrilateral element, CAX8. No lateral displacement at the edges of the pavement, no vertical displacement at the foundation and no slip between layers are assigned as boundary conditions. The tire inflation pressure of eighteen-wheel vehicle 0.83 MPa (120 psi) is assigned in static manner. The vertical stress and the vertical strain contour plots are presented in Fig. 9 and in Fig. 10 respectively. The vertical stress decreases with the depth. However, the vertical strain pattern depends on the stiffness of the material and

sharply changes with change in material. The detailed results are discussed in following section.
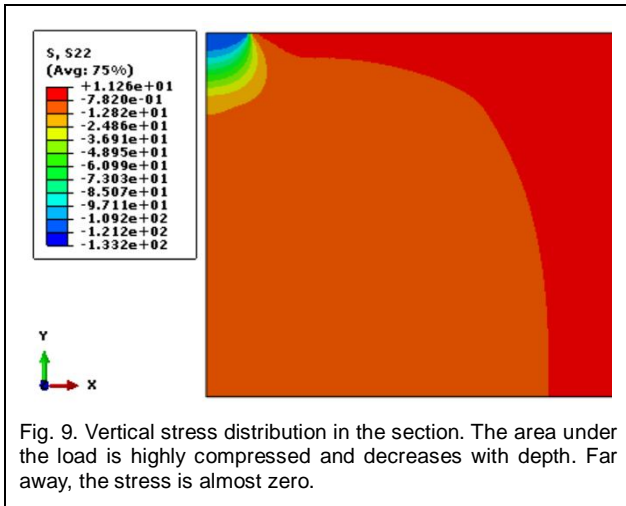

Fig. 9. Vertical stress distribution in the section. The area under the load is highly compressed and decreases with depth. Far away, the stress is almost zero.
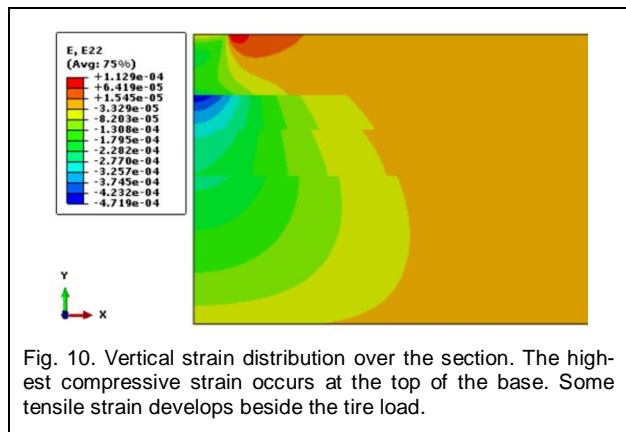

Fig. 10. Vertical strain distribution over the section. The highest compressive strain occurs at the top of the base. Some tensile strain develops beside the tire load.

8 RESULTS AND DISCUSSION

The VASG measures the vertical strain at 268 mm (10.7") depth. The EPC measures the stress response at 300 mm (12"), 369 mm (14.75"), 444 mm (17.75") and 750 mm (30") depths. Same depth response is needed to evaluate the results. FEM is developed to determine the vertical strain at 268 mm depth. The model is validated with the measured stresses at different depths. The stresses are measured with the installed EPCs. Therefore, the FEM response at 268 mm is representative of the EPC response. The stress responses at different locations of the pavement are compared with numerical analysis. The results are shown in Table 1. The vertical stress on the top of base is 0.0957 MPa which is very close to the measured value (0.0961 MPa). This value decreases to 0.0337 MPa on the top of subgrade and the measured value is 0.0333 MPa. The percentage error between stresses (FEM and measured) varies -0.43 to 1.04%, which is negligible. Thus, the EPCs responses validate the numerical model. Now, FEM determined strain is suitable for comparison with field measured strain.

Typical vertical stress response and vertical strain strain response are presented in Fig. 11 and Fig. 12 respectively. These are the screen shots of the outputs. These show that the responses of all the wheels are not same. In this study, the reading of the third axle wheel is considered. The calibration factors are provided by the manufacturers and verified in the laboratory.

TABLE 1
VERTICAL STRESS COMPARISON TO VALIDATE FEM

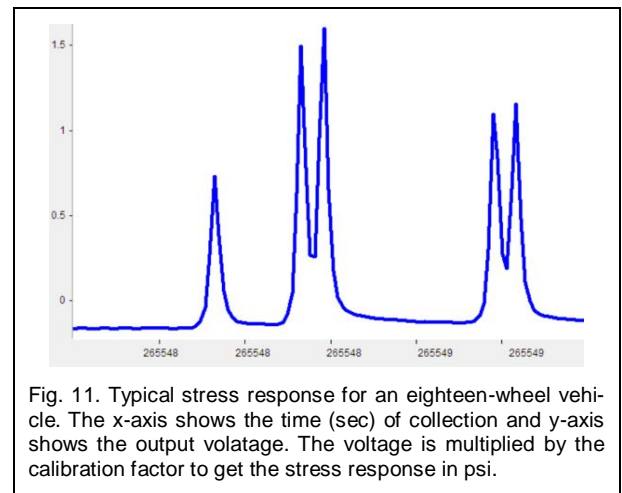| Depth	Vertical Stress (MPa)	
	Measured	FEM
Top of Base	0.0961	0.0957
At Mid-Base	0.0663	0.0670
Top of PPC	0.0575	0.0579
Top of Subgrade	0.0335	0.0337

Fig. 11. Typical stress response for an eighteen-wheel vehicle. The x-axis shows the time (sec) of collection and y-axis shows the output volatage. The voltage is multiplied by the calibration factor to get the stress response in psi.
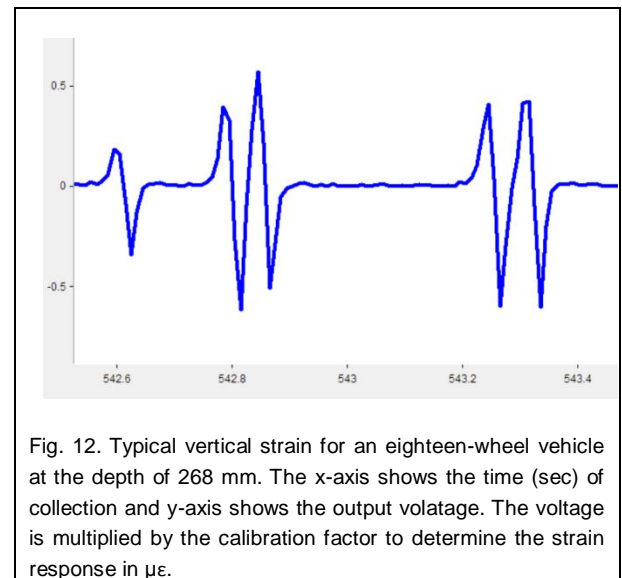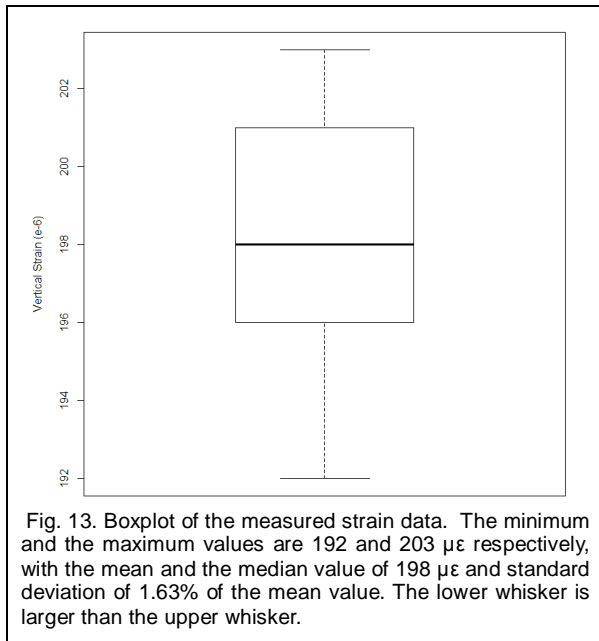

Fig. 12. Typical vertical strain for an eighteen-wheel vehicle at the depth of 268 mm. The x-axis shows the time (sec) of collection and y-axis shows the output volatage. The voltage is multiplied by the calibration factor to determine the strain response in με.

The strain value at the VASG location is determined by the numerical analysis. The FEM output is 196 με. The responses for VASGs are taken for 21 passes of the vehicle. The data

ranges 192-203 µε with the mean (same with median) value of 198 µε and standard deviation of 1.63% of the mean. The distribution of the data is plotted in Fig. 13. It shows that the mean and the mdian value are almost same. The maximum and the minimum value are 203 and 192 µε respectively. This mean value of the measured strain is 1.02% higher than the FEM (or EPC) response. This difference is very negligible. Therefore, it can be concluded that VASG correctly measurs the vertical strain in asphalt concrete.

Fig. 13. Boxplot of the measured strain data. The minimum and the maximum values are 192 and 203 µε respectively, with the mean and the median value of 198 µε and standard deviation of 1.63% of the mean value. The lower whisker is larger than the upper whisker.

9 CONCLUSIONS

The measured stress responses with the EPC at different locations of the pavement are correlated with numerical study. This correlation validates the developed numerical model. The numerical response (vertical strain at 268 mm depth) of this model is then compared with the VASG response. Results show an outstanding match between the FEM and the VASG readings. Therefore, the VASG can be considered an effective sensor to measure the vertical strain of asphalt concrete.

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