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Evaluation of the FWD Moduli of a Flexible Pavement Using Finite Element Model

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***Abstract*—**This study evaluates the back calculation of stiffness of a pavement section on Interstate 40 (I-40)in New Mexico through numerical analysis. Falling Weight Deflectometer (FWD) test has been conducted on a section on I-40. Layer stiffness of the pavement has been backcalculated by a backcalculation software, ELMOD, using the FWD test data. Commercial finite element software, ABAQUS, has been used to develop the Finite Element Model (FEM) of this pavement section. Geometry and layer thickness are collected from field coring. Input parameters i.e. stiffnesses of different layers of the pavement are used as the backcalculated ones. Resulting surface deflections at different radial distances from the FEM analysis are compared with field FWD deflection values. It shows close agreement between the FEM and FWD outputs. Therefore, the FWD test method can be considered to be a reliable test procedure for evaluating the in situ stiffness of pavement material.

***Keywords*—**Falling weight deflectometer test, Finite element model, Flexible pavement, moduli, surface deflection.

I. Introduction

To evaluate the sustainability of a pavement structure, it is important to assess the present condition of the material. A pavement section on Interstate40 (I-40) has been assessed for its present quality and its degradation behavior. Falling Weight Deflectometer (FWD) test is a reliable method to achieve this goal. Backcalculated stiffness of pavement layer from FWD has a significant influence on the sustainability of pavement due its diversified applications. These applications include pavement structural condition evaluation, future pavement maintenance and rehabilitation, remaining life estimation etc. [1]. To ensure the quality of these applications, backcalculated stiffness has to be representative of the field condition. It may, otherwise, result unsafe pavement, excessive amount of budget allocation for rehabilitation and so on. Thus, it becomes an obstacle to maintain the sustainability of pavement. For this reason, backcalculated layer stiffness needs to be validated.

The present study validates backcalculated layer stiffness determined by FWD test through numerical analysis. FWD test has been conducted on a selected pavement section of I-40 east bound lane at mile post 141 near the city of Albuquerque. This pavement section has been selected to transform it to be an instrumented section. Layer thicknesses and material properties have been collected during the field coring. A Finite Element Model (FEM) has been developed using ABAQUS to validate this stiffness obtained from FWD test data.

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II. Objectives

The main objective of this study is to validate the backcalculated stiffness from FWD test through numerical analysis. Layer stiffness or moduli, i.e., E-value, have been backcalculated by ELMOD using the FWD test data. Specific objectives of this study are mentioned below:

- To develop a finite element model using the geometry of I-40 pavement section. Layer properties have been assigned obtained from backcalculated layer moduli and field core data.
- To compare the FEM resulting pavement surface deflections at the pre-defined location with FWD test data.

Fig. 1 Execution of FWD test

III. Falling Weight Deflectometer Test

An impulse load is applied on the surface by dropping a weight and transmitted to the pavement surface through a circular steel plate. The pavement surface deflects vertically forming a deflection basin. Surface deflections are measured through geophones locating at different distances from loading point. FWD tests were conducted on the pavement to measure the stiffness of Hot Mix Asphalt (HMA). Fig. 1 shows the execution of the test on top of the first lift of HMA. A impulse load equivalent to 550 kPa (79.6 psi) was applied to 150 mm (6 in) radius area at 600 mm (24 in) interval in a length of 18 m (60 ft). While backcalculating the stiffnesses, all the three methods available in ELMOD namely Linear Elastic Theory (LET), Method of Equivalent Thickness (MET) and Finite Element Method (FEM) were used. The results are plotted in

Fig. 2. The stiffness varies from 2025 to 3475 MPa for the HMA, 160-190 MPa for the base, and 103 to 123 MPa for the natural subgrade.The average stiffness were measured to be 2410 MPa (350 ksi), 187.5 MPa (27.2 ksi), and 103 MPa (15 ksi) for HMA, base, and subgrade respectively.

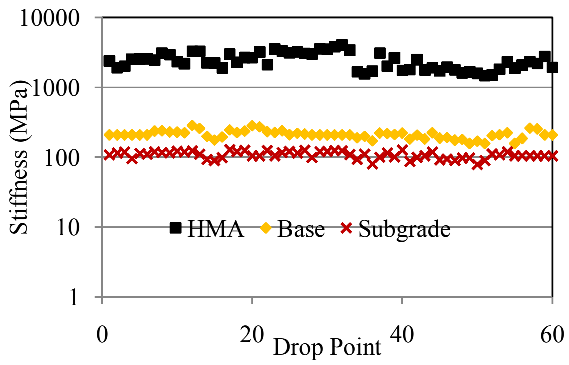

Fig. 2 Backcalculated stiffness

IV. Finite Element Model

The developed model using ABAQUS is an axis-symmetric two dimensional model as shown in Fig. 3. Thicknesses of these layers are 475mm (19in), 100mm (4in), and 4.43m (177in) respectively. Depth has been selected in such a manner that the depth to bottom boundary is greater than the depth to insignificant influence stress region. Effect of the bottom boundary, thus, has been remedied [2]. Materials of the layers of this model have been assumed linear elastic. Modulus of elasticity (E) of each material has been assigned according to the backcalculated layer moduli. Poisson's ratios (υ) are assumed 0.35, 0.4, and 0.45 for surface, base, and subgrade, respectively [3]

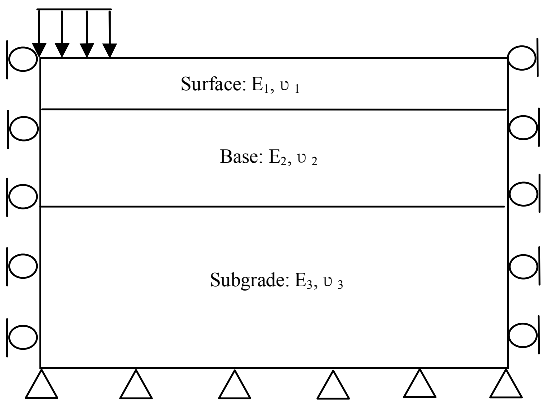

Fig. 3 Developed finite element model

An equivalent tire inflation uniform pressure of 550 kPa (79.6 psi) with an area of 150mm (6in) radius has been applied on the top of this model. This static pressure is vertical and compressive. During FWD test, pavement surface moves vertically downward. To maintain this fact in the model, two vertical edges are allowed to move only in vertical direction as mentioned in Fig. 2. 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 [2]. 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 [4].

V. Results and Discussion

Vertical stress distribution over the model is shown in Fig. 4. FWD test has been applied on 150mm (6in) radius of top left corner. This load has generated vertical compressive stress. In response to this compressive stress, the maximum compressive stress has been developed at the top left corner in surface layer. It gradually reduces along both vertical and horizontal directions. Thickness of surface layer has been recorded 475mm (19in) using the field core information, as mentioned in earlier section. Surface layer thickness of such a large magnitude has entrapped most of the stress variation. Stress varies from 550 kPa (79.6 psi) to around 69 kPa (10 psi) within surface layer. This phenomenon shows that FWD test load is mostly resisted by the surface layer. Compressive stress that has been developed in base and subgrade is relatively small.

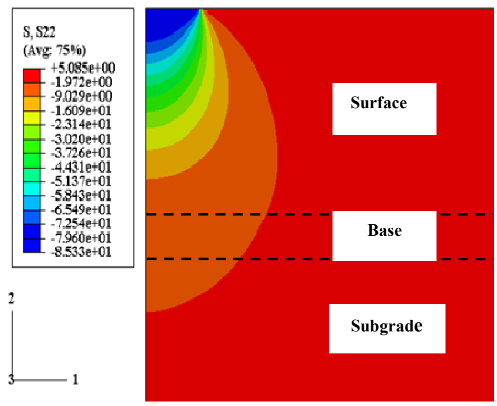

Fig. 4 Contour of vertical stress

The horizontal, i.e. radial, stress distribution over the model is shown in Fig. 5. At the top left corner of this model shows the compressive stress. This is due to the direct effect of boundary condition that restrains this model to move in horizontal direction. The most important observation is the greater tensile stress developed at surface-base interface. Tensile stress as large as 160 kPa (23.12 psi) has been developed just at the bottom of surface layer. Tensile stress has been dropped to smaller magnitude on top of the base layer at this interface.

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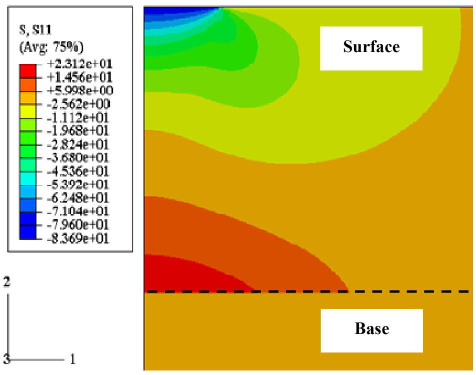

Fig. 5 Variations of horizontal stress with depth

Fig. 6 plots the variations of vertical stress distribution with depth. It has been evident that stress drops below 34.5 kPa (5 psi) within surface layer. Therefore, base and subgrade withstand very small amount of vertical compressive stress.

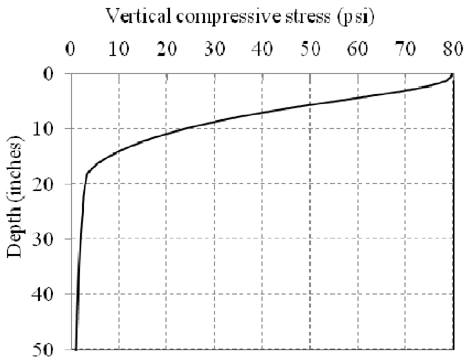

Fig. 6 Vertical stress distribution

Horizontal stress distribution with depth at the center of loading area is shown in Fig. 7. Compressive stress is observed within 225mm (9 in) from the surface. Below this depth, tensile stress has started to develop. It has attained its maximum value at the depth of 575mm (23 in), i.e. just at the bottom of the surface layer. There is a sudden fall in stress magnitude at the surface-base interface, i.e. top of the base layer. Horizontal or radial tensile stress is insignificant in base as well as in subgrade.

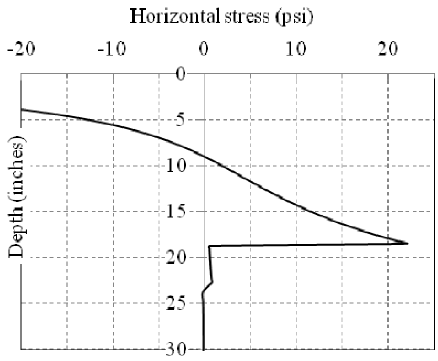

Fig. 7 Horizontal stress distribution

Fig. 8 shows the variations of vertical strain over the model. Compressive stress near to the loading is relatively large. It decreases gradually in both vertical and horizontal directions. Along the surface and adjacent small zone just after the loading area is subjected to vertical tensile strain. This is due to the punching effect of FWD test load. It has resulted downward movement of the model just underneath the loading plate relative to the adjacent area. For this reason, one region, i.e. area underneath FWD loading plate, is subjected to compressive strain whereas the other region under tensile strain.

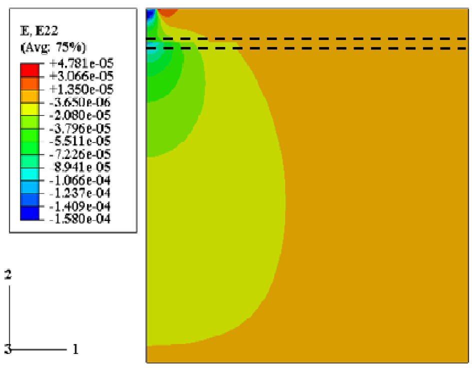

Fig. 8 Variations of vertical strain with depth

Maximum vertical strain is observed within surface layer as shown in Fig. 9. Strain has reduced with depth till the surface-base interface at the depth of 475mm (19 in). Strain shows a sudden jump to a greater magnitude. This is due to the smaller magnitude of base modulus, i.e. about 15 times smaller than surface modulus. Strain has started decreasing again in base layer. At the interface of base-subgrade, it is almost equal at the bottom of the base as well as the top of subgrade. This is due to that fact that base and subgrade modulus are very close in magnitude. In addition, vertical compressive stress variation is not significant near to the base-subgrade interface. In subgrade, strain decreases gradually with depth.

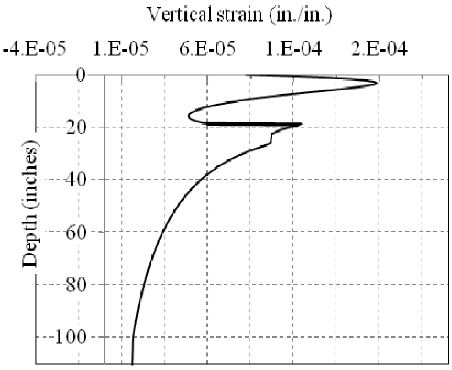

Fig. 9 Vertical strain distribution with depth

Horizontal strain is the maximum at surface-base interface as shown in Fig. 10. This tensile strain at the interface is observed within the loading radius. It decreases farther from this radius. Fig. 11 is plotted to observe the strain variation with at the center of loading area. At the top of the model, compressive strain is observed. This strain has decreased gradually with depth followed by a transformation to tensile strain. It is the maximum at the depth of 475mm (19 in) i.e. surface-base interface. In subgrade, it has been observed that strain decreases gradually with depth.

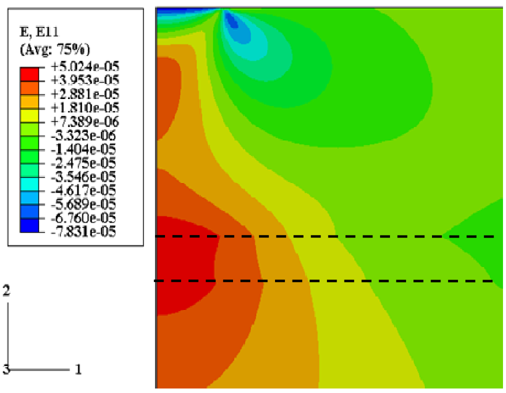

Fig. 10 Horizontal strain distribution

Variations of vertical deflection distributions over the model are plotted in Fig. 12 for both FWD and FEM analysis. Deflections are expressed in inches in this contour. Maximum deflection is observed near the loading area. It decreases gradually along both horizontal and vertical directions. For the comparison, surface deflections at different radial distances have been plotted in Fig. 12. Deflections are expressed in 'mil', i.e. thousand fraction of an inch. It is compared field FWD surface deflection basin. Maximum deflection at the center of loading area is equal to the field FWD maximum surface deflection. Distances far from the loading area differ from each other. Maximum difference is 0.03mm (1.25 mils). Field FWD deflections are greater than the FEM deflections.

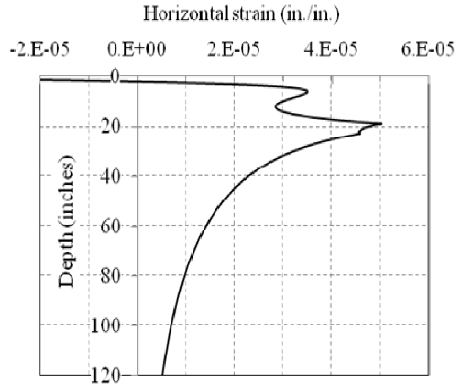

Fig. 11 Horizontal strain distribution

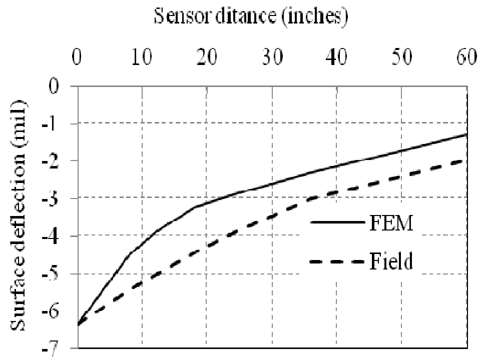

Fig. 12 Vertical deflection distribution

VI. Conclusions

In this study, FWD test was conducted to determine the stiffness of a pavement on I-40. The backcalculated stiffnesses obtained from this test were used in FEM development using ABAQUS. The output of FEM shows that vertical stress in pavement section is always compressive and decrease with depth. However, horizontal stress and strain is compressive at the surface and tensile at some depth. In addition, these responses are completely dependent on the stiffnesses of materials. Surface deflections from FEM and FWD have been compared. It is observed that surface deflections determined using backcalculated layer stiffness are close FWD surface deflections. Therefore, it can be concluded that FWD test can predict the results which are in good agreement with FEM.

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