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Executive Summary Report

Truck/Pavement/Economic Modeling and In-Situ Field Test Data Analysis Applications Volume 2: Verification and Validation of Finite Element Models for Rigid Pavement Using In Situ Data – Selection of Joint Spacing

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Problem

The performance of rigid pavements depends on the stresses and deflections imposed by repeated traffic and environmental loading. Thus, understanding the response of rigid pavement structures under dynamic loads and thermal gradients is important for the design of new pavements, as well as the rehabilitation of existing ones. Two- and three-dimensional finite element (2DFE and 3DFE) modeling are powerful tools that can be used to investigate the combined effect of moving axle loads, thermal gradient through the slab thickness, concrete slab geometry, dowel bars at joints, and stiffness of foundation layers on the stresses induced in rigid pavements.

Objectives

- Validation of four selected mathematical models for rigid pavement by direct comparison to experimental data collected from the Ohio SHRP Test Road (DEL23). The data include pavement strain, deflection, and vertical pressure. The models include two 3D-FE programs, EVERFE and OU3D, and two 2D-FE programs, ISLAB2000 and JSLAB.
- Verification and validation of ISLAB2000 rigid pavement response to curing, temperature cycling, and combined environmental and dynamic loading using the experimental data collected from the APLF. The 3D-FE program EVERFE is used to check the accuracy of the validation outcomes.
- Optimization of concrete slab joint spacing to reduce thermal and moving traffic induced stresses using the verified and validated ISLAB2000.

Description

Validation of FEM models with SHRP Test Road data

The outputs of four finite element programs, ISLAB2000, JSLAB, EVERFE, and OU3D, were compared to the experimental data obtained from four sections of the Ohio SHRP Test Road on US Route 23 in Delaware County (DEL23). JSLAB results were provided by a FHWA contractor, while the other three programs were run at Ohio University. The comparison focused on the trend rather than the absolute value of the computed pavement properties, which were dependent on input parameters. The different programs were also compared for usability in terms of modeling, input and output data, and speed.

Four core sections on DEL23 from the SPS-2 experiment were used in this study: 390201, 390205, 390208, and 390212. Material properties were looked up from the existing database of material properties for DEL23. Data from a dynamic loading test conducted July 30, 1997, were simulated with the FE programs. The load was applied using a tandem dump truck with axles at 15 ft (4.6 m) and 19.5 ft (5.9 m), traveling at a speed of 50 mph (80 km/h) with tire loads ranging from 8500 lb (37.8 kN) to 10,690 lb (47.6 kN).

The input data were similar for all four finite element programs. The input data were sufficient to model three continuous doweled slabs 15 feet (4.57 m) in length and 12 feet (3.66 m) in width. Strain, deflection, and vertical pressure were computed and compared to measured values from the original tests.

Generally, the FEM predictions follow the experimental trend of strains, deflections, and vertical pressure at the top of subgrade. However, it should be emphasized that loss of support caused by curling and warping was not accounted for in this study; the pavement was treated as a flat slab.

Validation of ISLAB2000 against APLF data

For complete verification and validation, ISLAB2000 strain and deflection predictions were compared with the experimental data collected for a previous study at the Accelerated Pavement Load Facility (APLF) where both dynamic and environmental loadings were considered. The slabs were 10 in (25 cm) thick Portland cement concrete on 6 in (15 cm) dense graded aggregate base, and their area was 12 ft (3.6 m) wide by 15 ft (4.6 m) long. Strain gauges and thermocouples were installed during concrete placement to measure strain and temperature in the concrete slab. LVDTs were installed along the pavement edges soon after placement to monitor vertical deflections. Slab profiles were monitored periodically using a Dipstick to determine the environmental response of the pavement during curing and temperature changes.

The environmental response testing included a curing period of five weeks under constant temperature followed by a period of controlled temperature changes for approximately three weeks. The testing schedule was as follows: air temperature was increased from 20°C (68°F) to approximately 35°C (97°F) for one week, decreased to 22°C (72°F) for three days, decreased further to 5°C (41°F) for three days, and finally returned to 21°C (70°F).

After the initial five-week curing period and temperature cycling, rolling single wheel loads of 9000 lb (40 kN), 12000 lb (53 kN), and 15000 lb (67 kN), traveling at 5 mph (8 km/h), were applied along five wheel paths: both edges, center, and standard wheel tracks 30 in (76 cm) from the edges.

The temperature gradient within the slab thickness was approximately zero after 5 days. The average corner upward warping due to the moisture gradient was observed to be 1.3117 mm (0.0516 inch) at the end of the fifth week. This amount of warping can be simulated as a built-in negative temperature gradient of -22F° (-12.2C°). The negative temperature gradient indicates the slab edge is lifting upward, causing a permanent loss of support to the pavement. Based on Dipstick measurements of warping, loss of support zones were estimated to include the outer 2.7 ft (0.83 m) of each slab, and rectangular areas with loss of support were integrated into modeling subsequent stages of the experiment in ISLAB2000. Measured and FEM predicted corner deflections during the temperature cycling period were then compared and found to be in reasonable agreement.

The software was then validated for different strain readings. The strain values show fairly good trend agreement. The divergence at some points can be explained by the approximate values used for material properties of base and subgrade, and the ongoing moisture loss, which was not accounted for in the analysis. On the other hand, the disagreement implies that the joint response to the temperature variations, a key issue in strain analysis, cannot be modeled correctly in ISLAB2000.

Deflections were then modeled for selected combinations of temperature gradients and loads. The experimental results show that the deflection of the corner and the edge increased due to the tire load with the decrease in temperature. The explanation of this is that when the temperature drops, the corner and edge curl up, thus creating a higher unsupported area that will deflect more upon the application of tire load. The predictions follow the general trend of deflections of both corner and edge points. The difference in the measured peak deflection between different LVDTs can be explained as due to the non-uniformity in the materials, construction, corner lift, etc. The FEM predictions of corner and edge deflections show good agreement with the measurement trend. The measured edge deflections were always higher than the predicted ones. This implies that a slightly modified loss of support needed to be considered in the model. The predicted peak strains in the longitudinal direction were always higher than the measured strain, due to the input material properties, and the joint modeling inaccuracy. Moreover, the rosette measured the experimental strain one inch (2.54 cm) below the top and one inch (2.54 cm) above the bottom of the slab, while the FE analysis produced the strain at the top and bottom of the slab. Nevertheless, the model with the loss of support described above showed an agreement with the general trend.

Optimization of joint spacing

The ODOT Weigh-in-Motion (WIM) database was utilized to obtain data regarding truck axle spacing, axle weight, and frequency from a period of four years on the Ohio SHRP Test Road. The FEM programs were used to obtain the slab stresses of Ohio SHRP Test Road sections. The most frequently observed axle spacings were in the 18-19 ft (5.5-5.8 m) range.

The main input in the fatigue model was the tensile stress at the top of the slab when the truck axles were placed at the two ends of the slab. This stress was roughly located at the center of the slab. Since the stress value depended on composition of the pavement section used, all of the four sections used for the validation were analyzed, using the same material parameters and dimensions except for the joint spacing, which was varied. ISLAB2000 was used to obtain the maximum tensile stresses, i.e., the longitudinal stresses at the top of the slab. These stresses were checked with EVERFE. The allowable number of repetitions for each slab length was calculated by the three models (PCA, Huang, and Domenichini) and compared to the actual number of truck repetitions from the WIM data. The ratio of the two numbers determined the time needed for the pavement to fail by fatigue.

It was experimentally shown that a positive temperature gradient (slab curl downwards) did not develop in the concrete slab during the usual variations in air temperature, due to the build up of a high negative temperature gradient during the slab curing. Another experimental fact is that the cracks in the concrete slab initiated at the top and developed downwards due to the same reason. Therefore, the critical tensile stresses are located on the top of the PCC slab. This happened when the two truck axle loads were positioned on the two ends of the slab, i.e. when the axle spacing was the same as the joint spacing.

The review of the three fatigue models (PCA, Huang, and Domenichini) showed that, under the given loading conditions, the tensile stress level overcame the frequency of load application. For example, the axle load repetition on the 15 feet (4.5 m) slabs was less than two thirds (0.62) of that on the 13 feet (4.0 m) slabs, however, the design life of 13 feet (4.0 m) slabs was higher. For each of the four pavement sections in the study, 13 feet (4.0 m) slabs showed the highest expected design life.

Conclusions

Verification of FEM Programs

- The computer simulations approximated the general experimental trend for strains measured under the right wheel path and at the pavement centerline, deflections, and vertical pressures at the top of subgrade.
- The pavement stress reversals between the first and second truck axles could be as high as the peak stresses under the truck axles. Maximum stress reversal occurred when the first two axles were positioned on the slab joints. Reversal stresses are critical in the pavement design, because they cause tension stress at the top of the slab.
- Slab rocking was noticed in the predictions of ISLAB2000 and JSLAB. The amount of slab rocking increases with higher modulus of subgrade reaction.
- Based on the experimental results, it was found that the increase in the PCC thickness reduces both peak stresses and deflections. Also the use of a thicker base slightly reduces peak stresses. The use of the stiffer LCB instead of DGAB reduces the reversal stresses.
- The different programs were also compared for usability in terms of modeling, input and output data, and speed. As regards to input parameters, ISLAB2000, JSLAB, and EVERFE require the value of subgrade modulus of reaction, k. The OU3D was designed to be fast and efficient, as it solves multiple load cases. For static load cases, ISLAB2000 is the most computationally efficient.
- Loss of support caused by curling and pumping was not accounted for in this study. The pavement was treated as a flat slab.

Validation of ISLAB 2000

- Moisture loss that occurred after five weeks of curing produced a residual negative temperature gradient of -22 F° (-12.2 C°). However, it was also found that the amount of curl continues to increase after the fifth week of curing. A curl of 1 mm (0.039 in) was measured between the fifth and eighth week even after a positive temperature gradient of 10 F° (5.5 C°) was applied. Thus, positive gradient based curling would only reduce the amount of loss of support (loss of support).
- With a good assumption of loss of support, ISLAB2000 proved to predict the trend of deflections and strains fairly well under the variation of temperature. However, strain

values need to be corrected to account for the joint opening.

- When the slab is curled due to environmental loads, the traffic induced deflections increase with a decrease in temperature. This is because reducing the temperature will produce a higher negative gradient, which in turn will produce a larger unsupported area. A similar conclusion was also reached concerning the strain reversals due to traffic load. These stresses increase with a decrease in temperature. On the other hand, if the slab is in full contact with the base, load induced strains will not change significantly with the temperature variations.
- ISLAB2000 predictions of combined load and temperature induced strains were higher than the actual measured strains. The divergence can be modified with a proper estimation of material properties and loss of support. On the other hand, ISLAB2000 showed some inaccuracy in modeling the joints under combined traffic and environmental loadings.
- EVERFE was unable to directly model the loss of support; instead an equivalent negative gradient was applied, after which the program showed good agreement with ISLAB2000 predictions.

Optimization of Joint Spacing

- With the presence of built-in negative temperature gradient due to the curing of concrete, the critical tensile stresses were located at the top of the slab and were maximized when the two truck axle loads were positioned on the two edges of the slab. This fact was confirmed experimentally; the slab cracks were observed to initiate at the top center of the slab and propagate towards the bottom of the pavement.
- The review of the three fatigue models (PCA, Huang, and Domenichini) showed that, under the given loading conditions, the tensile stress level overcame the frequency of load application. For example, the axle load repetition on the 15 ft (4.5 m) slabs was less than two thirds (0.62) that on the 13 ft (4.0 m) slabs, however, the design life of 13 ft (4.0 m) slabs was higher. This is due to the tensile stresses from the built-in negative temperature gradient. For the four pavement sections in the study, the shortest (13 ft (4.0 m)) slabs had the longest design life, or the best performance.

Recommendations

The idea that cracking initiates at the top of concrete slabs and spread towards the bottom, i.e., top-down cracking, contradicts the traditional rigid pavement design method, where critical tensile stresses were expected at the slab bottom. Based on the accomplishments made in the current study, the following plans are recommended by the author for future studies:

- A sensitivity study of the slab rocking and its effect on the rigid pavement design.
- The influence of early traffic on reducing the upward deflection due to warping effects.
- A detailed study of the change in loss of support under the slab due to variations in temperature, with and without traffic loading.
- The validation process needs to be carried out further to predict possible distresses in the pavement system and compare them to the actual distresses exhibited by the pavement system in the field.

Implementation Potential

The joint spacing results will be verified by constructing test sections on the SHRP test road on US 23 in Delaware County. Once the results are verified, ODOT construction specifications can be modified to incorporate the new information.

The load response analysis in this report can be used as input in implementing the mechanistic-empirical design process recommended in the guidelines developed under NCHRP Project 1-37A.

It is important to bear in mind that the long-term serviceability depends upon proper M-E design. For rigid pavements the critical design parameters are mainly slab deflection and tensile stresses. A key pillar of M-E Design is the software used to compute the load response. In this report, we have indicated how four different programs, EVERFE, ISLAB2000, JSLAB, and OU3D, predict load response. This report also discusses the limitations of these programs. For routine applications, ISLAB2000 is easy to use, practical, and fast. When more in-depth computation is needed then EVERFE may be used.