Executive Summary for the Field Verification of HIPERPAV

INTRODUCTION

Background

HIPERPAV is a computer program that predicts the time growth of portland cement concrete (PCC) strength and stresses in jointed concrete pavements (JCP) at early ages. After initial placement of the PCC (from 0 to 72 h), the concrete is weak in tension. However, it can be subjected to significant stresses as a result of temperature and moisture changes in the pavement. Knowledge of the stress magnitudes during this time period is extremely important because cracks formed at early age will significantly reduce pavement performance in the long term.

Aware that HIPERPAV can be used as a powerful predictive tool, the Federal Highway Administration (FHWA) provided funding for the experimental validation of this theoretical model. Experimental validation of the HIPERPAV software will give confidence that HIPERPAV is accurately predicting pavement performance at early ages. The HIPERPAV program can then be used at the State departments of transportation as an every day tool for the planning, design and construction of jointed concrete pavements (JCP).

To validate the HIPERPAV software, it is necessary that all of its models be calibrated and validated. In addition, HIPERPAV has to be applicable to all regions of the United States. Therefore, it was field tested in a wide range of environmental conditions, using a wide range of materials and construction practices commonly encountered in the United States.

Objective

The objective of this Executive Summary Tech Memo is to provide a summary of the experimental field instrumentation efforts undertaken to validate the theoretical models used in the HIPERPAV software. A description of the analyses performed and the results found are presented. The modifications made to the software as a result of the calibration are described and some recommendations for further improvements are made.

VERIFICATION PLAN

Field Test Sections

The specifics on slab instrumentation, data collection, and field verification plan are presented in a number of technical memorandums developed by the project team.[1-7] The variables monitored in the field which are used as HIPERPAV input include information on pavement design, concrete mix design, environmental factors, and construction procedures. Pavement Instrumentation

The slabs for each of the sites were instrumented with vibrating wire gages to measure concrete strains. Thermocouples were placed at 7 depths through the slab thickness to record pavement temperatures. LVDT's were installed at the pavement's edge to measure slab curling and warping displacements. Elastic modulus and slab set time of the concrete was estimated using pulse velocity equipment, a nondestructive testing (NDT) technique. Demec buttons were installed on 10 to 12 joints to measure axial slab movement after the joints were cut.

Data Acquisition Program

Data-loggers constantly recorded concrete strains, concrete temperature and vertical displacement. Weather conditions were also monitored during the 72-h period. At the estimated set time, pulse velocity readings were taken multiple times and then once a day thereafter. Condition surveys were performed on every section of instrumented slabs each day after construction and joint movements were measured using Demec calipers at least three times a day.

Laboratory Tests

Cement, admixture, additive and aggregate samples were collected at the construction site. These materials were then sent to the laboratory for testing and analysis. The following laboratory tests were performed: compressive strength, splitting tensile, creep, drying shrinkage, adiabatic heat of hydration tests, cement chemical analysis, modulus of elasticity, and concrete thermal coefficient of expansion.

CALIBRATION AND VALIDATION APPROACH

The individual models are calibrated using two instrumented slabs and validated using the remaining two slabs. The HIPERPAV calibration procedure consists of comparing measured field data to HIPERPAV predicted results. For example, the field concrete temperature measurements are compared to the predicted concrete temperatures obtained from the HIPERPAV temperature model. All the individual models were calibrated to ensure reasonable predictions are made. The coefficient of determination (R^2) is used to quantify the accuracy of the predictions. R^2 values close to 1 mean that predicted values fit the measured values well.

DESCRIPTION OF THE FIELD CALIBRATION/VALIDATION EFFORTS

The analysis performed for the field validation is briefly summarized below:

- The results from the adiabatic heat of hydration tests gave the total heat of hydration and yielded the hydration parameters used in the degree of hydration model (maturity).[8,9] The degree of hydration model is a fundamental part of HIPERPAV because it predicts PCC set time, concrete temperature, and PCC strength and stiffness.
- The temperature model was calibrated using the results from the adiabatic heat of hydration tests and the temperature readings collected in the field. As has been said, the degree of hydration influences the mechanical properties and the temperature development in the concrete, therefore, the calibration of each of these models was made in parallel with that of the temperature model to observe the influence of the degree of hydration.[10] In general, the calibration and validation results for the temperature model were

satisfactory.[11] To calibrate the temperature model and the concrete mechanical property models, it was found that a slight adjustment in the heat of hydration parameter "t_1" gave a better fit, other than what was measured experimentally. The absorptivity constant (β_s) was also modified slightly to account for the in-field curing of the concrete pavements. This modification improved the HIPERPAV temperature prediction at the top of the slab. Also, for some slabs, significant differences in predicted and measured convective heat transfer were found. They were attributed to tining of the PCC surface and wind obstructions.

- PCC set time has to be accurately determined because the majority of HIPERPAV models depend upon it. Set time was determined in the field using two procedures: the pulse velocity method and the split cylinder strain measurements.[12] These two set time measurements were compared to the set time predicted by the degree of hydration model. The results were satisfactory.[10,11]

- The HIPERPAV indirect tensile strength and modulus of elasticity models were validated using laboratory test results. The equivalent time concept had to be used to equate the age of the lab specimen to the age of the concrete in the field. [10,13] As a result of this analysis, it was found that using the 7-day value instead of the 28-day value as input to the HIPERPAV models provided a better prediction of the mechanical properties at early ages. This analysis suggests that it may be worthwhile exploring the use of 7-day values as inputs to these models. The influence of degree of hydration on the rate of increase to these mechanical properties was also assessed. According to previous research, the theoretical modulus of elasticity increases at a faster rate than does PCC tensile strength and this was confirmed in this analysis. However, significant deviations from this trend were observed in the States where fly ash class "C" was used (Nebraska and Minnesota).

- The drying shrinkage model was calibrated using laboratory drying shrinkage results from cylindrical specimens cured at 50-percent relative humidity.[14] The HIPERPAV drying shrinkage model satisfactorily predicted the experimental drying shrinkage strains at early ages.

- The coefficient of thermal expansion (CTE) for concrete was measured in the laboratory. However, calibrating the HIPERPAV model that predicts the dependence of CTE on temperature and moisture was beyond the scope of this work.

- Limited calibration was performed on the Creep/Relaxation model in HIPERPAV due to insufficient laboratory data. However, the creep model was modified to account for the effect of early age loads, which were not considered in the previous model. This modification increased the fit of the HIPERPAV model to experimental data.[15]

- The slab deflections measured in the field were compared to the deflections computed with the Westergaard/Bradbury model used in HIPERPAV.[13,16,17] In general, the model predicted the experimentally measured curling movements well. The accuracy of this model was improved when the time dependence of the Poisson ratio was incorporated. This relationship characterizes the behavior of early age concrete during its transition from a plastic to a solid state.

- The slab joint movement measured in the field with Demec equipment was modeled using the post-cracking slab restraint model in HIPERPAV.[18] The fit was good.
- The HIPERPAV slab restraint model was also used to predict the pavement cracking stresses. The model was deemed accurate because it was able to predict the transition in the pavement from a no crack state to a cracked state. A fracture mechanics approach was also presented for crack prediction in the pavement.
- The strains in the pavement prior to crack formation were modeled using the HIPERPAV slab restraint model. Measured strains were typically between $\pm 10\ \mu\varepsilon$ and the model correctly predicted this. The time of first crack formation in the field was also extracted from the time dependent strain gage data.[20]
- To determine the axial thermal stresses in the concrete at early ages, the effect of stress relaxation had to be accounted for. Relaxation of early-age concrete can create a zero-stress state near the maximum temperature. The maximum temperature has to occur within 36 h of set time. To incorporate the effect of stress relaxation into the HIPERPAV model, the time of zero stress corresponds to the time 90 percent of the maximum temperature is reached. This procedure used provided a good fit to all the instrumented pavements.[21]
- After all the individual theoretical HIPERPAV models were calibrated and validated, they were compiled in the HIPERPAV software. Then the HIPERPAV software was executed and the PCC strength and stresses were generated from 0 to 72 h. Using the experimental field data (environment, pavement design and construction procedures) as input, the HIPERPAV model had to accurately predict the correct time of failure crack formation. Because cracks were seen to form at the sawed joint and not in the middle of the slab experimentally, the HIPERPAV stresses were multiplied by stress magnification factors to account for cracking at the sawed joint using an infinite slab analysis. The comparison between experimental and theoretical crack prediction was satisfactory. At 50-percent reliability, the model predicted the time of crack formation within 5.4 h (on average). This difference could easily be accounted for by the variability in each of the factors affecting stresses and strength.

SUMMARY OF FINDINGS AND NEED FOR FUTURE RESEARCH

Creep / Relaxation

The effects of creep and relaxation at early ages in concrete are accounted for in HIPERPAV using a simple and reasonably accurate model. If an enhanced creep/relaxation model is to be incorporated later in HIPERPAV, it is recommended that the new model be based on visco-elastic theory and it should be capable of simulating the time dependence of creep/relaxation.

PCC Pavement Moisture

The current models in HIPERPAV that predict concrete mechanical properties depend primarily on the temperature model. A possible future enhancement would be to incorporate the effect of moisture on mechanical property prediction.

Characterization of Admixtures

HIPERPAV is capable of accounting for many additives in the concrete mix, such as fly ash, through modification of the heat of hydration parameters. Other admixtures, such as slag, silica fume and different chemical admixtures can be better accounted for in HIPERPAV once their hydration parameters have been validated. With additional data, HIPERPAV can be tailored to a specific mix design.

Fracture Mechanics

HIPERPAV predicts crack formation in the pavement using an elastic mechanics approach. As was concluded in the software validation, this analysis method is reasonably accurate. In future, the use of fracture mechanics to predict crack formation in the PCC pavements may be considered. It has been shown to be more accurate in the prediction of cracking in concrete structures, including pavements. Additionally, a fracture mechanics approach can allow for the modeling of micro-reinforcement, such as fibers.

HIPERPAV uses a one-dimensional linear frictional restraint model to account for friction between the pavement and the subbase. While this model is accurate, possible enhancements would be to extend this model to two dimensions so that the differential movement through the pavement thickness can be predicted.

Nonlinear Stress-Strain Relationship (Strain Based Failure Criteria)

HIPERPAV assumes that concrete has a linear stress-strain relationship when loaded. This relationship yields reasonable results when incorporated in the HIPERPAV models, however, it has been well documented that concrete deforms in a nonlinear manner at stress levels 50 to 70 percent of the failure load. In future, this “strain softening” behavior could be accounted for in the HIPERPAV models.

Heat Transfer

HIPERPAV is capable of accounting for the various methods of curing using the convective heat transfer function. If additional research is conducted, the application of this function can be expanded to other factors, such as PCC pavement texture.

Biaxial Effects on Axial Stresses

The current version of HIPERPAV calculates the axial stresses in the concrete. HIPERPAV can be expanded through use of Bradbury’s modified version of Westergaard’s classic curling model to account for secondary stresses in the transverse direction. The transverse stresses will be accounted for by Poisson’s effect.