Proposed National Pooled Fund Project

MONITORING AND MODELING OF PAVEMENT RESPONSE AND PERFORMANCE

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Table of Contents

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1. General

Transportation agencies are continuously striving to provide highway pavements which carry increased traffic loading for longer periods of time, and at minimal cost and inconvenience to motorists. In the near future, these agencies will be asked to implement guidelines currently being developed under NCHRP Project 1-37A for designing, evaluating and managing these pavements. The NCHRP Project 1-37A guidelines use mechanistic-empirical (ME) procedures to predict pavement response and performance from design parameters of the pavement, physical properties of materials used in the pavement, estimated traffic loading, and climatic conditions typical of the pavement site. Unfortunately, response and performance data are not sufficiently available to properly calibrate the 1-37A guidelines in most states. Since data obtained in this study will be used for validating and calibrating the 1-37A guidelines in Ohio and New York State, these data can also be used directly or modified slightly by states with similar conditions. Calibration procedures used in this study can be replicated in other states with different conditions.

The Ohio Department of Transportation (ODOT) is currently constructing a perpetual asphalt concrete (AC) pavement and a long life Portland cement concrete (PCC) pavement on a new section of US 30 bypassing the city of Wooster. These pavements are being promoted by industry as providing 50 years of service without requiring major rehabilitation. A contract has been awarded to the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University (OU) to install sensors in both pavements during construction to monitor temperature and moisture conditions and to measure dynamic strain, deflection and pressure responses in the completed pavement structures using Falling Weight Deflectometer (FWD) and controlled vehicle testing. A second contract was awarded to ORITE to determine the physical properties of materials incorporated into both pavements.

The New York State Department of Transportation (NYSDOT) is employing a number of techniques to rehabilitate a section of PCC pavements on NYS 17 which, after construction, will be identified as I 86. These rehabilitated sections also will be instrumented by ORITE to monitor environmental conditions and to measure dynamic strain, deflection, and pressure during Non-Destructive Testing (NDT) and controlled vehicle testing. Another section of new PCC pavement on I 490 was instrumented earlier by ORITE. Dynamic response and performance observed on the new extended life AC and PCC pavements in Ohio, on the pavements in New York State, and on other instrumented pavements in Ohio, including the Ohio SHRP Test Road, will provide a basis for validation and calibration of the NCHRP 1-37A guidelines in these areas. Other states can adopt the same calibrations, adjust the calibrations for similar conditions in their area, or use the same procedures to develop their own calibrations.

Experience gained during construction of the extended life pavements in Ohio and on the pavements in New York State will be invaluable to other states considering similar ventures. By having access to all design, material and construction records, and to personnel involved in these projects, states participating in this study can avoid problems encountered during these initial trials.

2. RESEARCH NEEDS STATEMENT

Mechanistic-empirical (ME) based pavement design procedures are being used by some DOTs to determine the adequacy of layer thicknesses in new and existing AC and PCC pavements and to verify pavement designs with expected material properties, traffic loading, and climatic conditions. Similarly, the influences of weather related factors and construction practices on pavement response and performance have not been sufficiently examined. Harsh weather conditions and/or improper construction techniques may lead to the development of premature functional and structural types of distress that may ultimately affect pavement serviceability. Thus, the need exists to review and verify ME design methods, along with accompanying climatic models, and to document construction processes for perpetual AC pavements, long-lasting PCC pavements, as well as for several types of reconstruction applied to existing rigid pavement. This includes an investigation of the influence of the mechanical properties of individual material layers on pavement response and performance.

Guidelines have been developed under NCHRP Project 1-37A for designing and analyzing AC and PCC pavement structures. All states will be urged to implement these guidelines which rely largely upon ME techniques for calculating response and performance using projected load, material, and environmental conditions. As with most analytical procedures, actual measured results will likely disagree to some extent with theoretical predictions because of inherent localized variations in material properties, construction techniques, climatic conditions, traffic loading, etc. Consequently, state DOTs need to validate the 1-37A guidelines for their areas and make necessary adjustments to the guidelines for accurate predictions of response and performance. States containing diverse materials, different levels of construction expertise or more than one climatic zone may need to perform multiple calibrations. These calibrations entail the comparison of measured and calculated strains, deflections, and pressures for response, and the comparison of measured and calculated distress. Once these data become available, appropriate adjustments can be made to the 1-37A guidelines.

The Ohio Department of Transportation (ODOT) is currently constructing perpetual AC and long life PCC pavements on a new section of US 30 ("WAY 30") bypassing the city of Wooster. Both pavements will contain extensive instrumentation to continuously monitor pavement temperature and subsurface moisture, and to measure strain, deflection and pressure response during controlled vehicle and FWD testing. A weigh-in-motion (WIM) system to monitor traffic loading and a weather station to monitor climatic conditions will also be installed at the site. These data will permit the comparison of measured and predicted responses, the reconstruction of the strain history of the test sections, and the calculation of the amount of fatigue or rutting distress that would be expected to have accumulated at any given time. A comprehensive parallel plan has been established to determine the mechanical properties of materials and other input parameters applicable to both pavements for the eventual application and verification of ME pavement design procedures. ODOT has awarded research contracts to ORITE to instrument both pavements and to determine the physical properties of materials used to construct the pavements, but no contracts are currently in place to monitor these pavements after construction.

Within the past few years, several configurations of perpetual pavements have been introduced and built not only in the U.S. but other countries in Europe and also in the country of South Africa. However, because of the very recent introduction of perpetual pavements no specific performance data is available that would indicate the most advantageous configuration under a given set of climatic and traffic conditions. A comparative study of several perpetual pavement configurations under controlled conditions would help to select and recommend the best performing alternative. Such a comparative study could be conducted in an indoor testing facility where the variables affecting the performance of the pavements can be controlled.

The New York State Department of Transportation (NYSDOT) is planning to reconstruct an existing section of PCC pavements on NYS 17 (to become I 86) with the following techniques: AC over rubblized PCC, PCC over cracked and seated PCC, and conventional unbonded PCC over PCC. The NYSDOT awarded a research contract to ORITE to instrument the reconstructed PCC sections similar to the WAY 30 pavements, with variations being tailored to the specific types of pavements. A comprehensive laboratory testing program will also be necessary to determine the mechanical properties of materials included in the New York State test sections, and monitoring will be required after construction. Two additional test sections will be instrumented at the NYSDOT test site as part of this project.

NYSDOT, in cooperation with ORITE, also instrumented two adjacent PCC slabs along the westbound driving lane of I 490, 10 miles southeast of Rochester. These slabs were instrumented with linear variable differential transformers (LVDTs), vibrating wire strain gages and thermocouples to monitor deflection, strain, and temperature during curing and at subsequent times thereafter. A wealth of information regarding load response and the effect of environmental factors on the performance of PCC pavements will be obtained if these slabs continue to be monitored in the future.

Laboratory and field data collected in these and other projects will be organized into user-friendly databases, so that basic data and findings can be easily applied to other projects. Access to these databases will be provided to participating agencies for validation and calibration of ME procedures in their areas.

In addition to the project described above on US 30, ODOT has funded the instrumentation of several test pavements located throughout the state of Ohio for over ten years. These experimental test sections were designed to provide information on how specific parameters affect the response and performance of several types of pavement in Ohio. In a few instances, control sections were constructed to determine the influence of environmental factors on pavement performance alone. These test pavements have been monitored for some time to: verify design procedures, verify climatic models, select suitable paving materials, determine the effects of drainage and base type on pavement performance, determine the performance of high performance concrete containing ground granulated blast furnace slag, and assess the influence of construction practices on the development of pavement distress, etc. Some findings, such as the use of stiff bases under AC pavement and the use of less stiff bases under PCC pavements have already been implemented in Ohio. The locations of these instrumented pavements include: the Ohio SHRP Test Road on US 23 in Delaware County, US 50 in Athens County, US 33 in Meigs County, US 33 in Logan County, US 33 in Nelsonville, and I-77 in Stark County.

To consider the effects of climate on the design of new pavements, reconstructed pavements and overlays, the Enhanced Integrated Climatic Model (EICM) will be included as a part of the AASHTO Pavement Design Guide being introduced under project NCHRP 1-37A. The EICM is capable of predicting temperature gradients in the pavement and moisture distributions within the subgrade utilizing locally available climatic information. Climatic and environmental data have been collected continuously at the US 23 site since 1996, and more recently on US 50 in Athens County and US 33 in Meigs County. These data will be used to validate and calibrate the EICM model for these sites.

Periodic distress as specified in Section 8 (Data Collection Detail Table) surveys and NDT testing can be used to monitor the performance of all experimental pavement sections over time. These data are essential for the calibration of ME pavement design procedures. When test pavement sections have reached the end of their serviceability, forensic investigations will disclose the primary cause(s) of failure and suggest proper remedial measures that can be adopted on future projects to extend pavement life. While some of this instrumentation has exceeded its normal longevity and ceased to function, the majority of sensors are still generating high quality data that can continue to be added to existing databases. Non-performing sensors could either be discontinued or replaced, depending upon the importance of the measurement.

Thus, the need exists on these previously instrumented pavements discussed above to:

- Continue monitoring seasonal and climatic parameters. The reliability of any environmental (seasonal) predictions obtained with theoretical models will be improved as data becomes available for longer periods of time.
- Conduct periodic distress and Non-Destructive Testing (NDT) surveys to document test section performance over time.
- Conduct forensic investigations in test pavement sections that have reached an unacceptable level of serviceability to document the causes of distress and to identify deficiencies which led to premature failure.

The Ohio and New York State DOTs plan to combine their resources to fund the activities discussed in this proposal. It was decided, however, to propose this study as a national pooled fund project in order to afford other DOTs the opportunity to participate by contributing some nominal amount of funding. This arrangement will be beneficial to the advancement of the project, and furthermore with their technical contributions the results will be more applicable to the entire pavement community. Participating states in the Midwest will benefit by, perhaps, being able to adapt findings for calibrating the NCHRP 1-37A guidelines directly to their area or adapting the findings with some minor modifications. States outside the Midwest will benefit by being involved in the process and using similar procedures to develop their own calibrations.

3. STUDY OBJECTIVES

The concepts of perpetual AC and long-lasting PCC pavements are relatively new to the pavement community. These newer pavements require the use of innovative ME design procedures, advanced climatic models, updated specifications, test methods providing detailed material properties, and construction techniques that have not been entirely incorporated into standard practice. Standard practice for rehabilitating distressed highway pavements generally involves the application of AC overlays. When AC overlays are placed on distressed PCC pavements, slab movements cause stress concentrations to develop at joints and cracks, which often results in premature cracks reflecting through to the surface at these locations. By breaking the PCC slabs into smaller pieces prior to overlay, stresses are distributed over a wider area. Instrumentation installed in these pavement sections will provide data regarding measured response under known environmental and loading conditions.

Thus, the four primary objectives of the proposed research are to: (1) monitor the new perpetual AC and long-lasting PCC pavements being constructed in Ohio, the rehabilitated PCC pavements in New York State, and other existing instrumented pavements in both states, (2) verify ME design procedures for all pavements in the study by comparing theoretical calculations with measured response and performance, (3) calibrate ME procedures presented in the NCHRP 1-37A AASHTO Pavement Guide for Ohio and New York State using data collected in this and other previous studies, and (4) document all research findings in a final report. Within each of these primary objectives are other secondary objectives which must be completed to achieve the primary goal. Accordingly, the following objectives are set forth for this project:

(1) Monitor the new perpetual AC and long-lasting PCC pavements in Ohio, the rehabilitated PCC pavements in New York State, and other existing instrumented pavements in both states. Within this objective are the following secondary objectives:

A. Monitor construction of the US 30 and I 86 pavements to observe construction practices and environmental conditions which may affect pavement response and performance. Identify specific deficiencies which should be corrected on future projects.

B. Determine the physical properties of materials incorporated into the rehabilitated PCC pavements on I 86 in New York State. Organize these data and material data from the US 30 project into a Microsoft Access database for validation and calibration of NCHRP 1-37A guidelines.

C. Periodically collect response and performance data on the study pavements in Ohio and New York State for the duration of this project, as the availability of functional sensors permits. In addition to US 30 in Ohio and I 86 in New York State, locations will include: I 490 in New York State; the Ohio US 23 SHRP Test Road in Delaware County, Ohio; US 50 in Athens County, Ohio; US 33 in Meigs County, Ohio; US 33 in Logan County, Ohio; US 33 in the city of Nelsonville, Ohio; and I 77 in Stark County, Ohio. Specific data collected will include:

   i. Climatic data obtained at on-site weather stations located on the US 30, US 50, I 86 test sections, and at the Ohio SHRP Test Road (US 23).
   ii. Temperature and moisture conditions monitored in all pavement structures with sensors similar to those installed on Long Term Pavement Performance (LTPP) projects.
   iii. Traffic loading obtained with weigh-in-motion scales mounted in the US 30, I 86 and US 23 SHRP pavements.
   iv. Condition surveys collected at all sites according to LTPP protocol and profile measurements to determine rutting on AC pavements and curling/warping on PCC pavements. The profiles will be performed with a dipstick and/or a rolling wheel profilometer developed and constructed at ORITE. These data will be

analyzed to note trends with environmental factors, and to determine possible links to the development of pavement distress.

v. Pavement stiffness measured with the Falling Weight Deflectometer (FWD) and skid resistance measured with available test equipment. These tests will be performed on all projects by state DOTs responsible for the individual projects. The FWD data will be used to identify weakened zones in the pavement structures, to document the potential areas of distress, and to backcalculate stiffness properties of the pavement layers.

vi. Strain, deflection and pressure responses measured on the US 30 and I 86 projects using the FWD and a matrix of truck loads, truck speeds, pavement temperatures, and subgrade moisture.

D. Conduct a maximum of three forensic investigations on pavement sections exhibiting severe distress to determine the specific causes of the distress. Each investigation will include in-situ tests and laboratory testing of cores and samples collected at the site. These investigations will follow procedures established by LTPP with additional guidelines developed by ORITE during previous forensic investigations in Ohio. State DOTs will furnish all equipment and personnel required to perform NDT and to dig trenches and repair them after the forensic investigations are complete. ORITE will conduct all field measurements and perform all laboratory tests necessary to identify the cause(s) of distress.

E. Enter all data collected by ORITE and by the Ohio and New York State DOTs into a Microsoft Access database. Develop a web page with supporting files to allow the display and downloading of climatic and environmental data to be posted on a web site residing or linked to one of ODOT's computer servers. Provide assistance to parties interested in accessing and using the environmental and structural databases created by ORITE.

(2) Verify ME design procedures for all pavements in the study by comparing theoretical calculations with measured response and performance.

A. Review and determine the accuracy of available pavement analysis and design procedures, including the new mechanistic-empirical procedures introduced in the 2002 Guide through project NCHRP 1-37A and peripheral models, such as VESYS, using response and performance data collected during this project and during earlier monitoring efforts in Ohio.

B. Determine how environmental factors such as temperature and moisture affect PCC slab curling and warping, AC layer stiffness, subgrade stiffness, and overall pavement response and performance.

C. Determine the accuracy of existing models, including the LTPP Model, for estimating temperature in asphalt concrete pavements. These models will be calibrated if no suitable agreement is found.

D. Obtain input parameters and determine the accuracy of the Enhanced Integrated Climatic Model (EICM) to be released with the 2002 Guide for predicting temperature and moisture profiles in rigid and flexible pavements. Evaluate specific inputs to the EICM, develop a user friendly manual, and compare calculated temperature and moisture profiles with actual measurements obtained at test sites in Ohio and New York State.

(3) Calibrate ME procedures presented in the NCHRP 1-37A AASHTO Pavement Guide for Ohio and New York State using data collected during this study and previously in Ohio. Develop factors which can be used to adjust output from the NCHRP 1-37A Guide so calculated response and performance on projects in this study agree more closely with actual measured response and performance.

A. Review Level 1, 2, and 3 hierarchies in the 2002 Guide and perform a sensitivity analysis of input parameters to determine the relative effect of each parameter in each hierarchy. A decisive effort will be made to use the results of sensitivity analyses being conducted on other projects, i.e. the Kansas pooled fund study TPF-5(079), FHWA, and AASHTO.

B. By comparing calculated and measured response and performance on the study pavements, recommend modifications to procedures in the 2002 Guide that would improve the accuracy of designs in Ohio and New York State. Pavement analysis codes for both flexible and rigid pavements adopted by the 2002 Guide will be used in this part of the study

C. Determine information required to perform Level 1, 2, and 3 analyses and develop guidelines for selecting input values. Recommend appropriate values based on the results of Part B.

D. Considering the estimated accuracy of Level 1, 2, and 3 designs, and the effort required to obtain input data for each design, evaluate the relative effectiveness of each design level and recommend levels appropriate for different functional classes of pavement.

(4) Controlled Testing of Perpetual Pavement Systems to Determine their Relative Performance and to Recommend the Most Promising Layer Configurations (Materials and Thicknesses).

A. Select no less than three perpetual pavement configurations to be tested under carefully controlled conditions. These will include an asphalt concrete surface layer over a very stiff base, a buildup based on the South African method of perpetual pavement design, and a pavement consisting of a thick asphalt concrete layer on a thick granular base.

B. Build the proposed test sections at the Accelerated Pavement Load Facility at the Ohio University Campus in Lancaster, Ohio. Each section will be instrumented with strain gages, pressure cells, LVDTs, and accelerometers to monitor pavement response to applied loads. Prior to construction of pavement layers, the subgrade will be tested to primarily determine its stiffness and other properties needed for the complete characterization of materials. As new layers are added characterization tests will be conducted in the finished surface of each layer. Tests will be of both destructive and non-destructive nature

C. Collect pavement response data from embedded gages to obtain their response time series and conduct other primarily non-destructive tests to monitor material property changes after scheduled number of load repetitions have been applied to the pavement sections

D. Analyze pavement performance data and validate available pavement analysis methods. Once testing is completed, a comparative study will help determine what pavement configuration is more advantageous under the tested conditions, from which future design recommendations can be developed. Similarly, pavement response and material characterization data obtained during the controlled indoor testing will be used in the additional verification of pavement analysis models. If suitable analysis methods are found, they can be used in the development of mechanistic-based design charts, which may be used by practitioners in future designs.

(5) Document all findings of the research.

A. Prepare annual interim reports documenting the construction of test sections and reviewing trends in environmental data, sensor status, and performance of the test sections.

B. Prepare technical notes (one per year) on topics related to data collected and analyzed on this project.

C. Prepare a final report documenting all work performed on this study and all important findings.

D. Any major findings with immediate application will be reported in an appropriate format as the project progresses.

The availability of instrumented pavement sections to be constructed on WAY 30 in Ohio and on NYS 17 (I-86) in New York State, along with existing test sections at the Ohio SHRP Test Road, US 50 in Athens County, US 33 in Meigs County, US 33 in Logan County, US 33 in the city of Nelsonville, and I 77 in Stark County in Ohio, and I 490 in New York State offer a unique opportunity to meet the objectives of this proposed national pooled fund research project. While these projects were constructed to obtain specific data for ODOT and NYSDOT, they can continue to be monitored, and the data adapted to the broader goal of calibrating the NCHRP 1-37A 2002 Guide.

4. BACKGROUND AND REVIEW

The WAY 30 and I 86 Projects

As part of the construction of the Wooster by-pass on WAY 30 (US 30) in northeast Ohio, and the reconstruction of NY 17 (to become I 86) in western New York State, the Ohio and New York State Departments of Transportation, in cooperation with the asphalt and Portland cement concrete pavement industries, are proposing to construct innovative pavement sections designed for extended serviceability. These sections include perpetual asphalt concrete and long-lasting economical concrete pavements in Ohio, and AC and PCC overlays of an existing PCC pavement in New York State. Construction of the Ohio and New York State pavements will start in 2004 and 2005, respectively. The installation of a weather station and suitable pavement instrumentation to gather both climatic and load response data at the WAY 30 site has already been funded by ODOT through the project “Instrumentation of the WAY 30 Test Pavements” previously awarded to Ohio University. In a second project entitled ”Determination of Mechanical Properties of Materials Used in the WAY 30 Test Pavements,” Ohio University will determine stiffness and other properties of materials used in the WAY 30 test pavement for subsequent studies and validations.

The WAY 30 project will contain extensive instrumentation to continuously monitor climatic conditions with an on-site weather station, pavement temperature with a thermistor array and subsurface moisture with Time Domain Reflectometery (TDR) probes, and to measure pavement response during FWD and controlled vehicle testing. Traffic will be continuously monitored with weigh-in-motion (WIM) systems installed in the AC and PCC pavements. These data will permit the reconstruction of the strain history of the test sections and the calculation of the amount of fatigue or rutting damage that would be expected to have accumulated at any given time. A parallel and comprehensive plan has been established to determine the mechanical properties of materials and other input applicable parameters for the eventual verification and calibration of ME pavement design procedures.

The WAY 30 and I 86 projects will include novel pavement designs not previously constructed in the states of Ohio and New York State. These designs are receiving increased interest and acceptance by other highway departments. Thus, it is logical to examine their viability and performance in the rather harsh climatic conditions prevalent in northeastern Ohio and western New York State.

Existing Test Pavements

A detailed review of previously instrumented test pavements to be monitored during this research for database enhancement and design validations and calibrations is included in the Appendix. These are: the Ohio SHRP Test Road (US 23) in Delaware County, US 50 in Athens County, US 33 in Meigs County, US 33 in Logan County, US 33 in the city of Nelsonville, and I 77 in Stark County.

These projects were intended to identify more durable pavement sections, to examine construction methods and specifications, to clearly identify the influence of weather related factors on pavements and, ultimately, to validate or modify existing pavement design procedures. The highlight of this effort was the construction and monitoring of the Ohio SHRP Test Road on US 23 north of Delaware. This project is providing extremely useful information on pavement performance by identifying:

- Effects of various design parameters on pavement performance,
- Effects of drainage and moisture propagation beneath the pavement surface,
- Variations in the mechanical properties of pavement materials under changing environmental factors, and

- Effects of traffic loading on the response and performance of various pavement sections.

Carefully controlled load tests using non-destructive testing techniques and moving trucks on the Ohio SHRP Test Road also generated valuable data for researchers and designers alike, thus facilitating the validation of analysis codes that could be used as the basis of mechanistic-empirical pavement design procedures. Additional pavement sections have been monitored throughout the state with the primary aim of elucidating the influences of environment and load on pavement performance.

Validation Example

Finite element and elastic layer theory computer codes model pavement response as a "statically" applied load. These codes have been used as the basis of back calculation procedures to infer pavement layer moduli from FWD measurements. While peak FWD deflections have traditionally been used for back calculation, recent improvements in the FWD now permit recording of the load pulse and time histories of the geophones. A more realistic and rigorous analysis of pavement structures could be achieved by considering the time-varying nature of FWD loading, since it more closely resembles loads applied by moving vehicles.

Over the past two years, dynamic finite element analyses of some asphalt concrete pavement sections constructed on the Ohio SHRP Test Road have been conducted using material properties determined in the laboratory, and response deflections, strains and pressures measured with sensors embedded in the pavement. Analyses were conducted using the finite element computer code PLAXIS, which includes a dynamics module specifically developed to analyze problems in soil and rock as well as in pavement materials. Time integration in PLAXIS is achieved through an implicit Newmark Scheme. The analysis of a pavement section during FWD measurements can be appropriately conducted using an axisymmetric finite element grid with the axis of symmetry coinciding with the center of the FWD loading plate, fixed nodes at the base, and nodes capable of displacing vertically on both sides of the grid.

Instrumentation installed at the Ohio SHRP Test Road includes structural response sensors, such as LVDTs, strain gages, and pressure cells arranged similar to those planned for the WAY 30 and NY 17 test sections. Strain responses were calculated at key locations to evaluate PLAXIS as a pavement analysis tool. Selected plots of stress-strain time history response in LTPP Section 390104 are shown in Figures 1 and 2. The vertical stress time histories shown in Figure 1 were generated at one position corresponding to the top of the subgrade soil, just below the base layer and directly under the center of loading. Strain time history responses were recorded at nine positions along the axis of symmetry and along the bottom of the asphalt layer. Each curve in the strain time history plot along the axis of symmetry corresponds to a depth below the AC surface, as shown in Figure 2, where positive strain indicates tension and negative strain indicates compression.

These examples show some of the methodology available for validating analysis procedures from field sensors or for inferring input material properties for calculating pavement response. Pavement responses measured with LVDTs, pressure cells and strain gages, and recorded in real time with a MEGADAC data acquisition system can be compared to responses calculated with codes like PLAXIS.

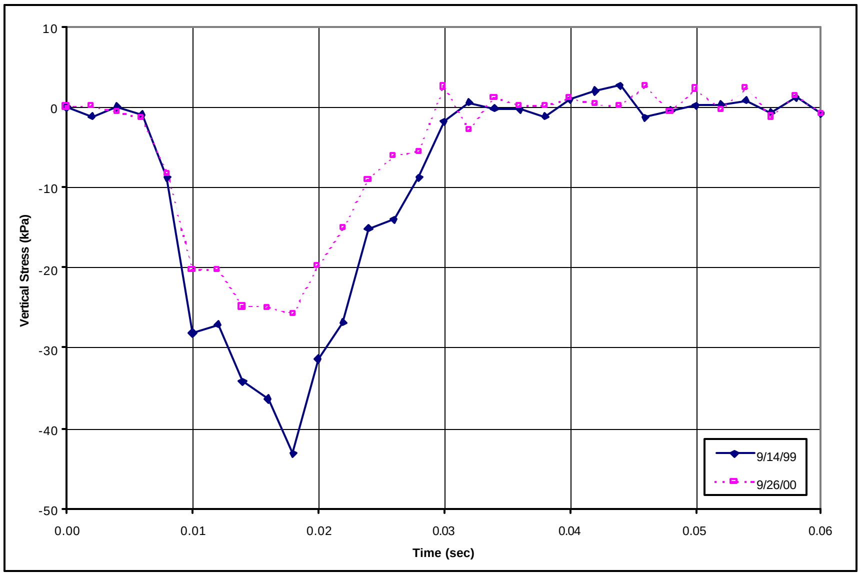


FIGURE 1 Vertical subgrade stress time history under center of loading Section 390104 (FWD tests: 9/14/99 and 9/26/00)

Once suitable analysis procedures are verified, they can be combined with transfer functions, traffic requirements, material properties and seasonal effects to set up a mechanistic-based pavement design procedure.

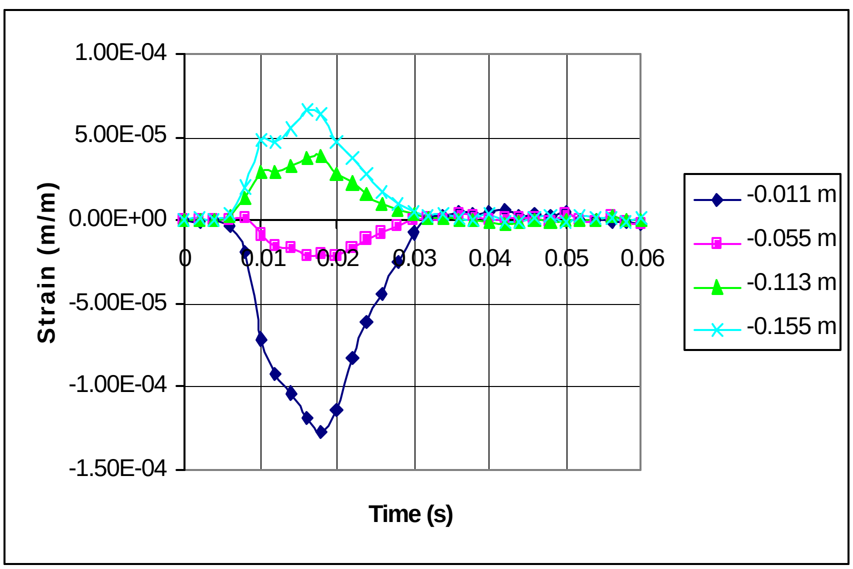


FIGURE 2 AC radial strain time history along axis of symmetry Section 390104. (FWD test: 9/14/99)

Construction Practices Affecting Pavement Performance

Pavement performance can certainly be affected by climatic conditions and construction techniques. While pavements cannot be placed under certain harsh conditions known to adversely affect performance, other conditions or combinations of conditions, not thought to have a severe impact on performance, may be permitted in situations where the contractor is under pressure to complete a project. A few of these marginal situations include:

- Placing PCC pavements during the warmest times of the day, and on hot and dry summer days. The inherent shrinkage of PCC under these conditions can initiate micro cracks that continue to grow during service. Excessive warping and curling also may result under unfavorable curing conditions, resulting in reduced slab support.
- Cold "jointing" in AC pavements. When a new AC layer is placed adjacent to an existing cold lift, the new AC may not properly bond to the cold asphaltic material, thereby creating a "longitudinal" joint between the sections. These joints may "ravel" as moisture infiltrates the joint and temperature changes cause the joints to widen.
- Treatment of existing PCC sections scheduled for rehabilitation. This process has a major impact on performance, whether it be rubblizing, cracking and seating with stress relief courses being placed between the existing PCC and the overlay, or leaving the slabs intact and overlaying with AC.

Effects of Weather-Related Factors on Pavement Performance

The effects of temperature on the rheological properties of AC have been well documented for several decades. It has also been recognized that asphaltic mixes should have a narrow temperature-stiffness range to prevent low temperature cracking and high temperature deformation or rutting. At times, asphaltic mixtures may need to be modified for conditions prevalent at a specific site.

A recent study of precipitation and moisture measurements conducted by Case Western Reserve University at the Ohio SHRP Test Road, (Figueroa, 2004) indicated that a lag existed between increased precipitation in the spring months and an increased degree of saturation in the subgrade. Subgrade moisture is consistently higher during mid-summer than at any other time of the year. This weakening of the subgrade, coupled with a lower AC stiffness prevalent in the summer months, results in a pavement structure with diminished load-carrying capacity. Thus, environmental factors play a fundamental role in designing pavements for an expected service life.

Studies have also documented measurable losses of PCC slab support caused by moisture and temperature differentials between the top and the bottom of the slab during curing and during daily curling and warping of the slabs. This condition can lead to higher slab stresses than those generated by traffic loads alone. Slabs continuously experience the compound effects of temperature, moisture and traffic loading. Under certain combinations of circumstances, slabs may experience significant tensile stresses at the top leading to the propagation of cracks from the top down, contrary to the traditional belief that PCC slabs crack at the bottom and propagate upward.

No less important in rigid pavement design is the selection of base type. Unfortunately, what is thought to be an advantageous choice to diminish the effects of loads by providing a very stiff base translates into accentuated temperature and moisture effects on PCC slabs. When PCC slabs are placed on a very stiff base, warping and curling results in a "cantilever or simply supported beam" effect with reduced slab support.

Thus, it is of extreme importance to properly document how weather related parameters affect PCC slab curling and warping, AC pavement stiffness, and subgrade stiffness and how these factors affect pavement response and performance at particular locations.

AC Temperature Prediction Models

A number of models have been developed to predict AC pavement temperature from measured climatic conditions. Examples of these are the LTPP model and equations recently developed by Figueroa (2001) relating average asphalt concrete pavement temperature to air temperature from data obtained at eight monitoring stations located throughout Ohio. These station sites were selected to show how latitude affects asphalt concrete temperature for a given air temperature, even within a single state.

Figure 3 shows average AC temperature as a function of air temperature for one of the monitored stations. Statistical regression analyses were conducted on the combined daytime and nighttime values to develop equations relating average AC temperature and air temperature. Such equations are useful for inferring average AC modulus from air temperature readings. A polynomial relationship yielded a best fit for the field data.

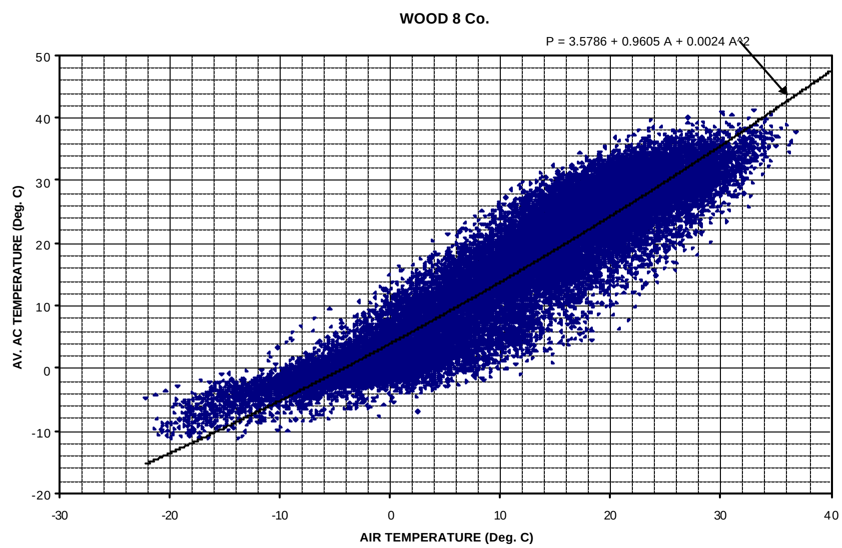


Figure 3 Air Temperature vs. Average AC Temperature (Wood 8 Co Station)

$$P = C1 + C2(A) + C3(A^2) \quad (1)$$

Where

C1, C2, and C3 = Regression constants.
P = Average AC temperature (°C).
A = Air temperature (°C).

An examination of the regression equation coefficients obtained from data at individual stations indicated that the state of Ohio can be subdivided into three general temperature zones: North, (from the northern state line to Mansfield – Mount Vernon) Central (from Mansfield – Mount Vernon to Lancaster) and South (from Lancaster to the southern state line). This division is useful in assessing average AC modulus on a seasonal or monthly basis for any future implementation of mechanistic pavement design procedures. Individual regression coefficients for each climatic zone and average coefficients for all of Ohio are included in Table 1. It is worth noting that average coefficients are similar to those determined for the central zone of the state and that coefficients of determination, R^2, were greater than 0.84 in all cases, indicating highly significant relationships between air temperature and average pavement temperature.

Table 1 Average AC Temperature vs. Air Temperature Coefficients

Site	No. of Points	C1	C2	C3	R^2
NORTH	75414	4.1409	0.9423	0.0027	0.8640
CENTRAL	118290	4.8118	0.8860	0.0052	0.8418
SOUTH	61152	5.2834	0.9113	0.0055	0.8431
ALL SITES	254856	4.7055	0.9107	0.0045	0.8475

Lukanen et al. (2000) modified the BELLS model, which was patterned after the original Southgate's work, using extensive LTPP data to estimate AC temperatures below the pavement surface. These modified BELLS2 (LTPP Testing Protocol) and BELLS3 (Routine Testing Methods for shade adjusted temperatures) models also maintained the basic parameters of the Southgate method. Equations 2 and 3 are models recommended for predicting temperature at specific depths within asphaltic pavements.

BELLS2 (LTPP testing Protocol)

$$T_d = 2.78 + 0.912 * IR + \{\log(d) - 1.25\}\{-0.428 * IR + 0.553 * (1\text{-day}) + 2.63 * \sin(hr_{18} - 15.5)\} + 0.027 * IR * \sin(hr_{18} - 13.5) \quad (2)$$

Adjusted $R^2 = 0.977$

where:

T_d = Pavement temperature at depth d in °C

IR = Infrared surface temperature measured at the time of FWD testing in °C

Log = Base 10 logarithm

d = Depth at which mat temperature is to be predicted, mm

1-day = Average air temperature the day before testing

sin = Sine function on an 18-hr clock system, with 2 radians equal to one 18-hr cycle

hr_{18} = Time of day, in 24-hr clock system, but calculated using an 18-hr asphalt concrete (AC) temperature rise and fall time cycle

BELLS3 (Routine Testing Methods)

$$T_d = 0.95 + 0.892 * IR + \{\log(d) - 1.25\}\{-0.448 * IR + 0.621 * (1\text{-day}) + 1.83 * \sin(hr_{18} - 15.5)\} + 0.042 * IR * \sin(hr_{18} - 13.5) \quad (3)$$

Adjusted $R^2 = 0.975$

These models use the previous day average air temperature as opposed to the 5-day average air temperature that is more difficult to obtain.

Superpave algorithms to calculate AC temperature are specified by two regression equations for maximum and minimum AC temperature, as follows:

For maximum pavement temperature:

$$T_{20mm} = (T_{Air} - 0.00618Lat^2 + 0.2289Lat + 42.2)(0.9545) - 17.78 \quad (4)$$

where:

T_{20mm} = AC temperature at 20mm. below the surface where the high pavement temperature is define by Superpave

Lat = latitude of the location,

T_{Air} = seven-day average high air temperature in °C.

For minimum pavement temperature (Mohseni, 1998):

$$T_{Surface} = -1.56 + 0.72T_{Air} - 0.004Lat^2 + 6.26\log_{10}(H + 25) - z(4.4 + 0.52\sigma^2)^{1/2} \quad (5)$$

where:

$T_{Surface}$= Low pavement temperature below the surface (from –33.01 to 13.67°C)

Lat = Latitude of the section (from 26.983 to 51.908 degrees),

T_{Air} = Low air temperature (from –41.53 to 4.61°C),

H = Depth to surface in mm (from 25.4 to 274.32mm),

z = 2.055 for 98% reliability,

σ = Standard deviation of the mean low air temperature.

Statistics: R^2 = 96%, N = 411, SEE = 2.1

These correlations are based on a pavement solar absorption of 0.9, radiation transmission through air of 0.81, an atmospheric radiation of 0.7, and an average wind speed of 4.5 m/s (15 ft/s).

These and other models can be validated by analyzing data obtained at the Ohio and New York State test sites.

Monthly and Seasonal Asphalt Concrete Resilient Modulus Variation

Research conducted by Figueroa (2001) indicated that, as a result of daily and seasonal temperature differences, the resilient modulus of asphalt concrete varies significantly during the year. To examine this temperature susceptibility, a typical mid-season 3-day sequence was selected to illustrate daily variations of air temperature during the four seasons. Using the regressions between air and AC temperature given in Table 1 and Figure 3, and well-know relationships between AC modulus and temperature, typical three-day resilient moduli may be determined for spring, summer, fall and winter. The times of the day of equal stiffness may also be inferred from these sequences, along with average resilient moduli for a typical mid-season day. For all of Ohio, the AC modulus may be selected as:

3791.7 MPa (550 ksi) in the spring (+/- 1034.1 MPa or +/- 150 ksi)
1723.5 MPa (250 ksi) in the summer (+/- 1034.1 MPa or +/- 150 ksi)
8272.8 MPa (1200 ksi) in the fall (+/- 1378.8 MPa or +/- 200 ksi)
15511.5 MPa (2250 ksi) in the winter (+/- 1551.1 MPa or +/- 225 ksi)

Perpetual pavements normally consist of three layers including:

- A high quality hot mix asphalt (HMA) layer located at the surface, considered to be the zone of high compression
- An intermediate layer of high modulus, rut resistant asphaltic material
- An HMA base consisting of flexible fatigue resistant material capable of resisting high tensile strains.
- A pavement foundation, normally consisting of the prepared natural soil

Stiffness of the asphaltic layers will be affected by temperature changes within the layers as heat is transferred with changes in air temperature and solar radiation. It may be desirable to specify a minimum thickness for one or more asphaltic layers to reduce variations in the stiffness of asphaltic materials lower in the pavement structure to reduce pavement distress.

Laboratory and Field Databases

Existing databases such as DATAPAVE provide the knowledge-based documentation necessary to select successful alternatives for pavement design and construction. With the advent of the Mechanistic-Empirical design procedures developed under NCHRP 1-37A, these databases become an even more significant source of information for implementing the new AASHTO Guide. Comparable data from the new pavements to be constructed in Ohio and New York State will provide additional information for pavement engineers to use in the future.

The 2002 Design Guide Review

Traditional and empirical pavement design procedures based on the results of the AASHO Road Test have served the pavement community reasonably well for over 40 years. However, increasing demands of traffic in number, magnitude, and axle configurations along with better awareness of the effects of weather related factors on materials included in pavement construction dictates the need for more rigorous design procedures. The following limitations in the AASHTO *Guide for Design of Pavement Structures* support the need for improved design methods:

- Lack of consideration of rehabilitation techniques including overlays during the AASHTO Road Test.
- Difficulty in extrapolating results of tests to other climatic conditions existing throughout the country.
- Only one type of subgrade supported all test sections.
- A dense graded granular base was the primary type used in the pavement profiles; although a very limited number of treated bases were included in the flexible pavement sections.
- No lateral drainage was included in any of the sections.

Pavement engineers are limited to the use of traditional materials such as Portland cement concrete, asphalt concrete, stabilized materials and natural aggregates because of the large quantities required for roadway projects. They are also challenged by the ever-present effects of climatic factors on material properties and the inherent aging that naturally occurs with exposure to the elements. No less important is the influence of dynamic loads applied by traffic on materials that do not respond linearly, as described by elastic theory.

Engineers and researchers have for a number of decades recognized the need to incorporate principles of engineering mechanics to improve the reliability of pavement designs. These principles however, must be coupled with empirical performance observations to properly adapt the designs for local conditions. With the improvement in computer hardware and software, it is now expedient to use computationally intensive techniques incorporating elastic layer theory for linear materials and finite element techniques for non-linear materials. A mechanistic-empirical design method thus incorporates rational mechanical modeling, coupled with adjustments derived from observations on in-service pavements.

The advantages of M-E pavement designs, such as those specified in the 2002 Guide include:

- Create more efficient and cost-effective designs
- Improve design reliability
- Reduce life cycle costs
- Increase support for cost allocation
- Predict specific distress modes, so they may be addressed prior to failure
- Extrapolate from limited field and laboratory data
- Better evaluate the impact of changed traffic loading and new types of vehicles
- Make better use of available materials
- Better characterize climatic and drainage effects
- Improve rehabilitation design
- Incorporate daily, seasonal, and yearly changes in materials, climate, and traffic into the design process

The following section summarizes the main characteristics of the 2002 Guide including the fundamentals followed in its development, input data, and results

<u>The 2002 Design Guide</u>

The 2002 Design Guide includes methods for analyzing and designing most types of new and rehabilitated flexible, rigid, and composite pavements, without favoring any specific material type. It is based upon the use of existing models and databases and upon the sound principles of engineering mechanics. The guide specifically emphasizes rehabilitation design in view of the fact that a high percentage of pavement expenditures in the US involve the rehabilitating of existing pavements. Specifically, the Guide includes:

- Methods for evaluating existing pavements
- Recommendations on rehabilitation options, drainage, and subgrade improvement
- Methods for life cycle cost, reliability, and traffic analyses
- Methods for calibration to local conditions
- Guidelines to establish procedures tailored to a given DOT
- An easy to follow step by step approach offering a number of design options suited to the type of road under consideration

The design approach selected for the 2002 Design is divided into three major parts:

1. Development of input values
2. Structural/Performance analysis

3. Evaluation of feasible alternatives

Part 1 of the design process starts with the selection of a trial pavement profile along with required inputs such as material strength and stiffness, volume change potential, freeze and thaw damage, as well as subgrade improvements by stabilization and drainage in new pavements.

Rehabilitation options for existing pavements are focused on investigating the cause(s) of occurring distress and in assessing the strength and stiffness of layers primarily by surface deflection measurements and backcalculation methods. Provisions are also offered for in-situ sampling through coring, undisturbed sample extraction, and penetrometer testing for better assessment of in-situ material properties.

The types of pavement materials considered by the guide include:

- Dense-graded hot mix asphalt
- Open-graded asphalt treated materials
- Cold mix asphalt
- Portland cement concrete
- Cementitious stabilized materials
- Non-stabilized granular base/subbase
- Subgrade soils
- Bedrock

These materials are characterized in terms of elastic properties, such as modulus and Poisson's ratio. For bound materials such as PCC, AC and other stabilized materials, the modulus of elasticity or the dynamic modulus suffices since these materials exhibit a nearly elastic behavior and the modulus is independent of stress. Unbound materials such as subgrade soils, granular bases and granular subbases exhibit a stress-dependent behavior such that the resilient modulus increases on granular material and decreases with increased stress on fine-grained material according to well-established models. Material response to load is essentially insensitive to Poisson's ratio, thus assumed values of this parameter are usually sufficient. However, the guide recommends testing procedures and typical values that can be assumed for this parameter.

In selecting appropriate moduli values for design, three levels of reliability from high to low are offered by the guide with:

- Level 1 including measured dynamic, elastic, or resilient modulus
- Level 2 including estimated dynamic, elastic, or resilient modulus
- Level 3 including default dynamic, elastic, or resilient modulus

Besides typical material property inputs relating pavement response to loading, the guide requires the use of less common material parameters associated with strength and pavement distress, such as shear strength, compressive strength, modulus of rupture, repeated load permanent deformation characteristics, and fatigue. Still other material properties involve the calculation of critical stresses and the coefficients of thermal expansion for AC and PCC. In addition to these material properties, Step 1 requires the input of traffic and climatic data.

The 2002 Guide considers traffic in terms of the full axle load spectra for single, tandem, tridem, and quad axles. Traffic loading may also be converted to ESALs in order to facilitate the use of earlier mathematical models developed for this type of traffic input.

Traffic data collected in the LTPP-SPS program may easily be adapted to the requirements of the guide.

The guide adopts a novel approach in considering site-specific environmental effects (primarily by temperature and moisture) on pavement performance. Given the seasonal and daily variations in moisture and temperature that affect stiffness and strength, as well as the dimensional stability of pavement materials, the FHWA Enhanced Integrated Climate Model (EICM) offers the most promising approach to integrate site specific environmental effects into the design process. This model includes the following four sub-models: 1) Precipitation, 2) Infiltration and Drainage, 3) Climate-Materials-Structure, and 4) Frost Heave and Thaw Settlement.

The last segment of Step 1 includes the input of variability or uncertainty expected within each of the previous inputs. These are required along with the probability distribution of each input to conduct the Monte Carlo Simulation (MCS) in the reliability analysis.

Part 2 of the 2002 Guide consists of an iterative approach for the structural/ performance analysis of a selected trial design. Each trial section is analyzed using the structural response and performance models to determine cumulative damage with time. Details such as layer thickness, required repairs to the existing pavement, if appropriate, and material properties are provided. The MCS yields the distribution of each important distress while the risk of exceeding its critical level is determined. With the expected amount of damage over time calculated, the distress over time and traffic is estimated through calibrated distress models. The trial section may be modified and the iteration continues until a satisfactory level of reliability is reached.

Since pavement rehabilitation was one of the main reasons why the guide was developed and is a fundamental portion of it, a sufficient number of flexible and rigid pavement rehabilitation methods are included as options.

Part 3 includes the evaluation of technically viable alternatives through an engineering and life cycle cost analysis of alternatives meeting the reliability requirements in Part 2

<u>2002 Design Guide Software</u>

The 2002 Guide is accompanied by a user-friendly software package to expedite the determination of suitable alternatives prescribed by the guide. This package is written in C++ language for a WIN32 platform and it is based on existing mechanistic-empirical models. An effort was made to keep a consistency between the rigid and flexible pavement modules to allow for the same inputs and interfaces, whenever possible, giving the user the ability to examine alternatives with either type of pavement. The software is easily interfaced with any database having the open database connectivity (ODBC) interface and makes it possible for its use with more advanced database management systems, if required.

Example input and output screens obtained from the 2002 Design Guide for a problem consisting of an AC overlay over Fractured PCC (Level 3 –Default Properties) are included in the Appendix. Input data may be provided through individual sub screens or by pointing the program towards the files containing the pertinent values of the parameter. Results as well as input data summaries are displayed in EXCEL-based worksheets or plots, as shown in the Appendix. Only the rutting vs. time plot has been included in the results section of the Appendix, however the number of input and output worksheets and plots add to a total of 16 for this particular problem, which took approximately 1 hour and 20 minutes to solve when processed with a Pentium processor with a clock speed of 1.4 GHz.

2002 Guide Training and Implementation

The 2002 Guide represents the first time mechanistic-empirical pavement design procedures are being introduced at a national level. Since many of the concepts and fundamentals will be new to the highway community, training and implementation materials are imperative to aid in its recognition and acceptance amongst potential users. These will be provided in an effort to facilitate the full and broad implementation of the guide, emphasizing the benefits to be gained by the acceptance of the procedure, compared to traditional pavement design methods.

Pavement Material Properties Required by the M-E Procedures

The following is a summary of the rationale used in the new 2002 Guide for designing pavements, testing materials and applying relationships to describe fatigue characteristics and material stiffnesses required in the design procedures.

Rigid Pavements (See Table 2)

- Slab thickness design is based on fatigue.
- Important factors in the design procedure include: slab thickness, concrete properties, shoulder support, subbase material properties, bonding and thickness of subbase, subgrade support, load transfer across joints, joint spacing, subsurface drainage, and climate conditions.
- The total design process includes a slab thickness design procedure, a joint design procedure, and a subbase design procedure.
- Only comprehensive finite element models can provide all necessary tools to fully analyze slabs of any size, multiple loading conditions, load transfer across cracks and joints, and subbase effects. However, finite element models are too time-consuming for routine use.
- An elastic plate theory (Westergaard) model was adapted for the slab thickness procedure, with the results of the model being modified using results from finite element models to make necessary adjustments for joint spacing, load transfer, load location, load configuration, curling, etc.
- Slabs on the dense liquid (Winkler) foundation are used for design analysis.
- Corner load deflections are based on results from the ILLI-SLAB finite element model.
- Subbase material must be strong with sufficient durability to support load applied by construction equipment, to resist erosion due to water ejection from under the pavement, and to withstand the effects of repeated freezing and thawing. Appropriate materials include cement stabilized aggregates, asphalt stabilized aggregates, and open graded crushed stones (with low fines content).
- Several equations are available to estimate the fatigue life of concrete, including:

$$\text{Log}(N) = 17.61\,(1 - R) \qquad (6)$$

$$\text{Log}(N) = -1.7136\,R + 4.284 \qquad \text{for } R > 1.25 \qquad (7)$$

$$\text{Log}(N) = 2.8127\,R^{-1.2214} \qquad \text{for } R < 1.25 \qquad (8)$$

where N = mean number of load repetitions to failure and R = ratio of flexural stress (due to load and climate) to the mean modulus of rupture.

Table 2: M-E Design Inputs for Rigid Pavements

No.	Material	Properties Required	Methods
1	Concrete	Elastic Modulus E_c	Level 1: Determine by ASTM C469. Level 2: Estimate from 28-day compression strength. Level 3: Use a typical value of 4 million psi.
		Poisson's Ratio μ	Level 1: Determine by ASTM C469. Levels 2 & 3: Or, assume a typical value of 0.15.
		Modulus of Rupture S_c or Flexural Strength at 28 days	Level 1: Determine by ASTM C78 or AASHTO T96 (3rd Point Load). Level 2: Estimate from 28-day compression strength or from measured elastic modulus. Level 3: Use a default value.
		Thermal Coefficient of Expansion β	Level 1: Determine by the FHWA method (?). Level 2: Select a typical value based on the aggregate type. Level 3: Use a typical value of 9×10^{-6} /°C.
		Coefficient of Drying Shrinkage α	Level 1: Determine by ASTM C490. Level 2: Estimate from strength data. Level 3: Use a typical value of 1×10^{-4}.
2.	Base/Subbase (Untreated & Treated)	Thickness	Level 1: Input actual thickness. Levels 2 & 3: Input design thickness.
		Composite Modulus of Subgrade Reaction *k*	See the notes below.
3	Subgrade	Composite Modulus of Subgrade Reaction *k*	Level 1: Determine by AASHTO T222. Level 2: Estimate from CBR, FWD, or other available test data. Level 3: Select a default value.

[Notes]

- Static modulus of elasticity of concrete (E_c) may be estimated from the 28-day compressive strength (f_c') and/or unit weight (w_c) using the formula:

$$E_c = 57{,}000\,(f_c')^{1/2} \quad \text{or} \quad E_c = 33(w_c)^{3/2}\,(f_c')^{1/2} \qquad \text{ACI 318-89} \qquad (9)$$

- Flexural strength of concrete is usually about 15% of the compressive strength. The relationship between them is given by:

$$S_c = K\,(f_c')^{1/2} \quad \text{where K = 0.7 for } S_c \text{ (MPa) and = 8.4 for } S_c \text{ (psi).} \qquad (10)$$

- PCC coefficient of thermal expansion (β) depends on the coarse aggregate type, as:

$\beta = 6.6 \times 10^{-6}$/°F for quartz
$\beta = 6.5 \times 10^{-6}$/°F for sandstone

$\beta = 6.0 \times 10^{-6}/°F$ for gravel
$\beta = 5.3 \times 10^{-6}/°F$ for granite
$\beta = 3.8 \times 10^{-6}/°F$ for limestone

- PCC coefficient of drying shrinkage (α) is typically equal to:
  α = 0.00080 in./in. for PCC with split-tensile strength less than 300 psi
  α = 0.00045 in./in. for PCC with split-tensile strength of 500 psi
  α = 0.00020 in./in. for PCC with split-tensile strength greater than 700 psi
- Elastic modulus of cement-treated base may be assumed to be about 2×10^6 psi.
- Poisson's ratio of the cement-treated base may be assumed to be equal to 0.15.
- Composite modulus of subgrade reaction (k) for base/subbase and subgrade combined can be estimated if the subgrade resilient modulus, base/subbase thickness, and base/subbase elastic modulus are known.
- The elastic modulus and Poisson's ratio of cement stabilized aggregates can be estimated by the formula recommended in the Illinois DOT Procedure (Leahy, 1989):
  E (ksi) = 500 + Compressive Strength (psi) (11)
- Flexural strength of cement stabilized aggregates can be estimated as 20% of the compressive strength.
- Recommended Poisson's ratio for stabilized materials are:
  Cement stabilized Aggregates ------------------- Poisson's Ratio = 0.20
  Asphalt stabilized Aggregates ------------------- Poisson's Ratio = 0.35
- Measured deflections of slabs with and without 4 to 8 in. thickness unstabilized subbase layers is essentially the same as for slabs on a natural subgrade. Therefore, a composite modulus of subgrade reaction (*k*) is the only property needed in the design procedure. And, often the *k* value of the natural subgrade soil can represent the composite *k* value.
- Use the modulus of subgrade reaction (*k*) of the subgrade soil, if the pavement is placed directly on top of the roadbed (i.e., no base/subbase). This property can be measured by ASTM D1195/1196 (Level 1), estimated from the resilient modulus (Level 2), or assumed to be equal to a typical value listed in the M-E procedure literature (Level 3).
- The modulus of subgrade reaction (*k*) can be estimated from correlations with soil type and soil strength measures such as the California bearing ratio (CBR). Part II of the 1986 AASHTO Guide contains a series of figures that can be used to estimate the effective modulus of subgrade reaction based on subgrade resilient modulus, subbase thickness, subbase elastic modulus, subgrade thickness, slab thickness (relative damage), and effect of subbase erosion (loss of support).
- According to Yoder and Witczak (1975), typical k values are:

Soil Type	Range of k value (pci)
Plastic clays	50 to 100
Silts and silty clays	100 to 200
Sands and clayey gravels	200 to 300
Gravels	300+
CTB and ATB	400+

In some cases, the effective static *k* value of the subgrade is assumed to be equal to one half of the Falling Weight Deflectometer (FWD) dynamic value.

Flexible Pavements (See Table 3)

- Design procedures can be based on an elastic layer program (ex. DAMA, SPDM-PC) or stress dependent finite element models (ex. ILLI-PAVE, MICH-PAVE, FLEX-PASS).
- Elastic layer programs and ILLI-PAVE structural models are adequate to support the M-E thickness design procedures for flexible pavements.
- Resilient modulus and strength are significant material properties for structural analysis and thickness design.
- Temperature and moisture are two important environmental factors. Asphalt concrete (AC) modulus is influenced by temperature. Resilient modulus of cohesive subgrade soils is sensitive to moisture content (i.e., degree of saturation) and freeze-thaw action.
- There is not a unique relationship between the resilient modulus (E_{AC}) and the indirect tensile strength (ITS) for all asphalt concrete specimens. Test temperature, compaction procedure, and mix composition all influence the relationship. However, for a given AC mixture under similar compaction procedure and temperature, it is possible to establish a reliable regression equation for predicting the E_{AC} from ITS.
- Flexible pavement structural responses are significantly influenced by the subgrade.
- For general flexible pavement design, the "average" subgrade modulus should be inputted. If subgrade rutting is the controlling criterion, the "critical" subgrade modulus should be considered. The critical value is the one during the spring thaw period.
- FWD test data are useful in back-calculating moduli of subgrade soils. It is possible to estimate the resilient modulus of fine-grained subgrade soils from commonly determined index properties (ex. clay content, PI). See the notes below.
- Resilient modulus of granular materials is often described by the "theta model":

$$M_R = k\,\theta^n \qquad (12)$$

where θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$. AASHTO Design Guide (1986)

- One freeze-thaw cycle is sufficient to drastically lower the resilient modulus of fine-grained soils.
- It is generally known that the subgrade resilient modulus goes through seasonal fluctuations in each year. The resilient modulus tends to be very high during the winter (due to frost penetration), lowest during the spring (thawing), and stays at intermediate levels during the summer and fall.

- The AASHTO 1993 Guide contained a simple method for determining seasonal values of the subgrade resilient modulus:

$$(M_R)_{eff} = (3{,}005) * (u_f)^{-0.431} \tag{13}$$

where u_f = average relative seasonal damage.

= 0.01 in January
= 0.01 in the first half of February
= 0.31 in the second half of February
= 1.01 in the first half of March
= 0.52 in the second half of March
= 0.52 in April
= 0.20 in the first half of May
= 0.14 in the second half of May
= 0.14 in the first half of June
= 0.10 in the second half of June
= 0.08 in the first half of July
= 0.06 in the second half of July
= 0.05 in August
= 0.04 in September
= 0.06 in the first half of October
= 0.08 in the second half of Oct.
= 0.14 in the first half of November
= 0.20 in the second half of Nov.
= 0.01 in December

Table 3: M-E Design Inputs for Flexible Pavements

No.	Material	Properties Required	Methods
1	Asphalt Concrete (AC)	Dynamic Modulus |E*|	Level 1: Determine by ASTM D3496. Level 2: Estimate from creep compliance test data. Can use Witczak Equations Level 3: Use a default value available.
		Resilient Modulus M_R	Level 1: Determine by AASHTO T46. Level 2: Estimate from ITS. Level 3: Use a default value available.
		Poisson's Ratio μ	Level 1: Determine by ASTM D3496 or AASHTO T46. Levels 2 & 3: Assume a typical value of 0.1, 0.35, or 0.5 at temperatures of 5, 25, or 40°C.
2.a	Base/Subbase (Untreated)	Resilient Modulus M_R	Level 1: Determine by AASHTO T46. Level 2: Estimate from CBR or R value. Back-calculate from FWD data. Level 3: Use a default value available.
		Poisson's Ratio μ	Assume a typical value of 0.40.
2.b	Base/Subbase (Treated)	Resilient Modulus M_R	Level 1: Determine by AASHTO T46 (ATB) or by ASTM D3496 (CTB, LCB). Level 2: Estimate from CBR or R value. Level 3: Use a default value available.
		Poisson's Ratio μ	ATB: Determine by ASTM D3496 or AASHTO T46. Or, assume typical values of 0.1, 0.35, and 0.5 at temperatures of 5, 25, and 40^{o}C respectively.
			CTB/LCB: Use a typical value of 0.15.
3	Subgrade	Resilient Modulus M_R	Level 1: Determine by AASHTO T46. Level 2: Estimate from CBR or R value. Level 3: Use a default value available.
		Poisson's Ratio μ	Assume a typical value of 0.45.

[Notes]

- The Witczak equation for |E*| requires the following basic properties of the AC mixture:
  - bitumen viscosity (dynamic shear rheometer)
  - effective bitumen content
  - air voids
  - loading frequency
  - aggregate gradation data (% passing values for 19-mm, 9.5-mm, 4.76-mm, and 0.075-mm sieves)

Witczak Equation for |E*|

$$|E^*| = 100{,}000 \times 10^{b1} \qquad (14)$$

where:

$$b1 = b3 + 0.000005\, b2 - 0.00189\, b2\, (f)^{-1.1}$$

$$b2 = (b4)^{0.5} \times (T)^{b5}$$

$$b3 = 0.553833 + 0.028829\, (F_{200})\, (f)^{-0.1703} - 0.03476\, (V_a) + 0.070377\, (\lambda) + 0.931757\, (f)^{-0.02774}$$

$$b4 = 0.483\, (V_b)$$

$$b5 = 1.3 + 0.49825\, \text{Log}\, (f)$$

where b1 through b5 = temporary constants, f = loading frequency (Hz), T = temperature (^oF), F_{200} = % passing No. 200 sieve, V_a = volume of air void (%), λ = asphalt viscosity at 70 ^oF (10^6 poise), and V_b = volume of bitumen (%). If no data is available to specify λ, the following equation may be used to estimate it:

$$\lambda = 29{,}508\, (P_{77°F})^{-2.1939} \qquad (15)$$

where $P_{77°F}$ = penetration at 77 °F (25^{o}C).

Table 4. Typical Values of Asphalt |E*|

Temperature (°F)	Loading Frequency					
	1 Hz		4 Hz		16 Hz	
	Range	Mean	Range	Mean	Range	Mean
40	6.0-18.0	12.0	9.0-27.0	16.0	10.0-30.0	18.0
70	2.0-6.0	3.0	4.0-9.0	5.0	5.0-11.0	7.0
100	0.5-1.5	0.7	0.7-2.2	1.0	1.0-3.2	1.6

[Note] All the |E*| values are in terms of x 10^5 psi.

- An AC modulus - temperature relationship was developed by the Asphalt Institute for an AC-20 asphalt cement (viscosity @ 70°F = 2 x 10^6 poises; 4.5% asphalt, 4% air voids, 5% passing #200 sieve; loading frequency 10Hz):

$$\text{Log}\,(E_{AC} \text{ in ksi}) = 4.038 - 0.017\, T\, (F) \qquad (16)$$

- The Illinois DOT (1989) established a chart correlating temperature to the design EAC in their mechanistic-empirical design procedure for full-depth AC pavements.

- The University of Illinois developed the following relationships between the resilient modulus (E_{AC}) and the indirect tensile strength (ITS) of the AC mixtures at 77 °F:

AC-10: E_{AC} (ksi) = - 183 + 5.87 * ITS (psi) (17)

AC-20: E_{AC} (ksi) = - 173 + 6.03 * ITS (psi) (18)

All: E_{AC} (ksi) = - 176 + 6.06 * ITS (psi) (19)

- Baladi (1988) proposed the following equation for estimating AC resilient modulus (M_R):

$$\ln (M_R) = 16.092 - 0.03658 (T) - 0.1401 (AV) - 0.0003409 (P) + 0.04353 (ANG) + 0.0008793 (KV) \quad (20)$$

  where T = test temperature (°F), AV =air voids (%), P = magnitude of applied cyclic loading, ANG = aggregate angularity (1 to 4), and KV = kinematic viscosity at 275 °F (135 °C).
- The elastic modulus of cement-treated base may be assumed to be about 0.75 million psi. Poisson's ratio of the cement-treated base may be assumed to be equal to 0.15.
- The resilient modulus of the asphalt-treated base material may be determined by ASTM D3496 or AASHTO T46.
- The elastic modulus of asphalt-treated base may be assumed to be about 0.25 million psi at moderate temperature (25 °C). Poisson's ratio of the asphalt-treated base may be assumed to be equal to 0.35.
- The resilient modulus of subgrade soils can be estimated from basic index properties through:

$$M_R (OPT) = 4.46 + 0.098 (C) + 0.119 (PI) \quad (21)$$

  Thompson and LaGrow (1988)

  where M_R (OPT) = resilient modulus at optimum moisture content, C = clay content (%), and PI = plasticity index (%).

  Thompson and LaGrow also proposed the following moisture adjustment factors to adjust the M_R (OPT) values for moisture contents in excess of optimum:

USDA Class	Moisture Sensitivity (ksi)
Clay, silty clay, silty clay loam	0.7
Silt loam	1.5

  where moisture sensitivity represents a M_R decrease for each 1% moisture increase.
- Carmichael and Stuart (1985) developed the following formulas for predicting the resilient modulus of both cohesive and granular soils:

  Cohesive Soils

$$M_R (ksi) = 37.431 - 0.4566 (PI) - 0.6179 (\%W) - 0.1424 (S200) + 0.1791 (\sigma_3) - 0.3248 (\sigma_d) + 36.422 (CH) + 17.097 (MH) \quad (22)$$

  where %W = water content (%), S200 = % passing sieve #200, CH = 1 for CH soil and = 0 for other soils, and MH = 1 for MH soil and = 0 for other soils.

  Granular Soils

$$\text{Log } M_R (ksi) = 0.523 - 0.0225 (\%W) + 0.544 (\log \theta) + 0.173 (SM) + 0.197 (GR) \quad (23)$$

where θ = first stress invariant, SM = 1 for SM soil and = 0 for other soils, and GR = 1 for gravelly (GM, GW, GC, GP) soils and = 0 for other soils.

- According to the University of Illinois data (1979), the resilient modulus of subgrade soils can be estimated from unconfined compression strength as well:

  $M_R = 0.86 + 0.307\ (q_u)$ (24)

- The most widely used correlation between the resilient modulus and CBR is the one by Shell (1962):

  M_R (psi) = 1,500 (CBR) (25)

- Other correlation equations are:

  M_R (psi) = 2,554 $(CBR)^{0.64}$ for $2 \le CBR \le 12$ (26)
  by TRRL (1984)

  M_R (psi) = 1,500 (CBR) (27)
  by AASHTO 1993 Guide

  M_R (MPa) = 10.3 (CBR) (28)
  by Asphalt Institute

  The validity of these M_R - CBR correlations has been questioned. The resilient modulus of fine-grained soil is a function of the deviatoric stress level as well, and there cannot be a unique M_R - CBR correlation.

- According to Allen and Thompson (1974), the typical resilient modulus of granular soils can be summarized by:

  M_R (psi) = $k\ \theta^{n}$ (29)

  With k and n as specified in the following table:

Type	No. of Data Points	Mean k Value	Mean n Value
Silty Sands	8	1,620	0.62
Sand-Gravel	37	4,480	0.53
Sand-Aggregate Mix	78	4,350	0.59
Crushed Stone	115	7,210	0.45

The South African Mechanistic-Empirical Design Method (SAMDM)

An M-E pavement design method for perpetual pavements has been developed in South Africa by the Council for Scientific and Industrial Research (CSIR) (Theyse, 2004). This classical M-E design method is based on a single point estimate of structural capacity with the aim at preventing fatigue failure, rutting as well as shear failure of pavement materials. Any existing weak subgrade materials are isolated from the high shear stress region generated by traffic loads, by providing enough thickness in the overlying structural layers.

Pavement materials are designated and classified following the “G” system as follows:

LAYER	MATERIAL	RELATIVE COMPACTION
Base	G! G2 G3 and G4	 100-102% mod AASHTO 98% mod AASHTO
Subbase	G3 to G6	95% mod AASHTO
Selected Subgrade	G7 to G9	93% mod AASHTO
In Situ Subgrade	G10	90% mod AASHTO

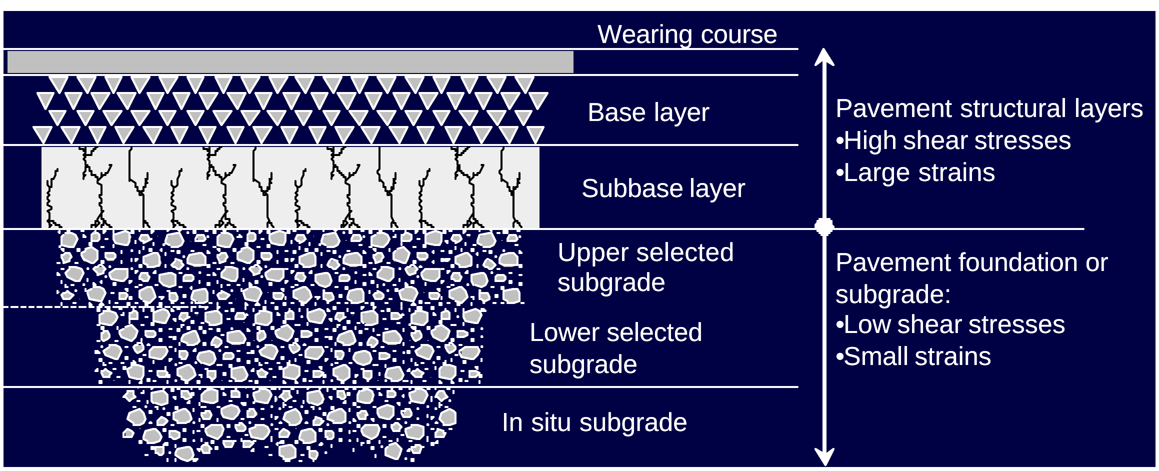
In which:

- G1
  - Crushed, unweathered rock
  - Grading adjusted by adding fines from the crushing of the parent rock only
- G2/G3
  - Crushed boulders or course gravel
  - 50% of +4,75 mm material one fractured face
  - Classification based on CBR, PI
- G4 to G6
  - Natural gravel or crushed boulders
  - Classification based on CBR, PI

- Material | CBR | Relative Compaction

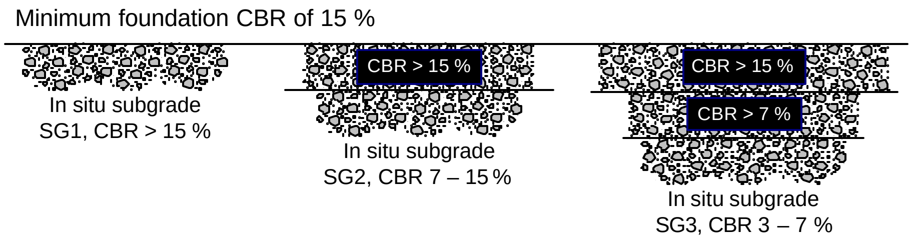
Material	CBR	Relative Compaction
G7	15%	93% mod AASHTO
G8	10%	in situ density
G9	7%	in situ density
G10	3%	in situ density

The typical layer arrangement is presented below (Theyse, 2004):



Following are the minimum subgrade strength requirements, prescribing a minimum CBR of 15% on the improved subgrade, before any subbase layer is placed over it. If necessary the subgrade may be improved in stages, as shown in the figure presented below, when the existing subgrade originally has a very low CBR value. If necessary, stabilization with lime may be necessary to adequate the upper portion of the subgrade.

- Minimum foundation strength
  - In situ subgrade classified (SG1 – SG4)
  - If in situ subgrade not SG1, import material to provide minimum CBR of 15 %
  - If in situ subgrade SG4, special treatment



5. ANTICIPATED BENEFITS

This proposed national pooled-fund project will permit the extended monitoring of environmental and response instrumentation installed on the extended life AC and PCC pavements currently being constructed on US 30 in Ohio, on the existing PCC pavements to be rehabilitated on NYS 17 (I 86) next year in New York State, and on other previously instrumented pavements in both states. By carefully monitoring these environmental and mechanical parameters, early assessments can be made regarding the response and performance of these pavements, and the data will be preserved for other study analyses and for future reference. Design and construction deficiencies observed on these projects will be identified for correction on subsequent projects. Since non-traditional design and construction methods, specifications and testing procedures are required for these pavements, there must be careful validations to ensure that all aspects of the design/construction process are well documented so necessary adjustments can be made to avoid problems and provide predictable performance in the future. The end result will be more economical and more durable pavements designed using mechanistic/empirical procedures. All participating transportation agencies can benefit from this project because of the general types of pavements and materials being used in the test pavements.

This proposed project will also extend the monitoring of environmental and climatic instrumentation installed in the past at six sites throughout Ohio, including the Ohio SHRP Test Road. The continued monitoring of this instrumentation will provide more extensive data as input for implementation of the 2002 pavement design procedures, which place increased emphasis on climatic factors and traffic loading. By providing additional environmental, seasonal and climatic data to existing databases, the reliability of the databases will be improved, along with the accuracy of designs based upon these data. A web page with supporting files will be developed to allow easy access and downloading of data from the existing Ohio SHRP Test Road climatic and seasonal databases.

Specifically, states will receive both short term and long term benefits by participating in this proposed research. Short term gains will include:

- Knowledge of the relationships between response and environmental factors on test pavements studied in this project will provide a basis for understanding, validating, and calibrating ME pavement design procedures at other locations.
- The development of material databases that can be accessed for various ME design procedures, including the 2002 Guide developed under NCHRP 1-37A, will serve as a valuable reference tool. Several material properties not normally required for current procedures will be included in databases developed on this project.
- Various analytical pavement models including most commonly known finite element and elastic layer based models as well as those recommended by the participant project panel will be verified and calibrated through the comparison of measured and calculated response and performance parameters. Participating states can determine which procedures are most applicable for their conditions.
- Improved design, specification and construction guidelines will be provided for extended life AC and PCC pavements, and rehabilitated PCC pavements. States constructing these types of pavements will find these guidelines to be a valuable resource.
- Detailed analysis and performance observations related to perpetual AC pavements tested at the Accelerated Indoor Pavement Test Facility will be obtained, and design recommendations concerning these types of pavements will be developed.
- The Enhanced Integrated Climatic Model (EICM) to be included in the 2002 Design Guide makes use of climatic data to predict temperature profiles in the pavement and moisture profiles in the subgrade. Data collected on this project will be used to validate and calibrate temperature and moisture prediction models included in the EICM. Easy to follow guidelines for use of the EICM will be developed to facilitate its application by pavement engineers in all states.
- Up to three forensic investigations will be conducted in the proposed project as pavements fail or develop significant levels of distress. These will contribute to the identification of causes leading to the observed deficiencies. Remedial measures can be incorporated into future projects to avoid similar occurrences.

Long-term benefits will include the calibration of ME pavement design procedures by comparing calculated and observed response and performance on a range of pavement designs in this study. In addition, a permanent database containing measured parameters and material properties collected at the test sections will be available for future reference, validation, and calibration.

ME design procedures proposed by the 2002 Design Guide will allow the incorporation of material and construction variations in the actual design to better account for the effects of climate, aging, new materials, and non-traditional vehicle loadings. This flexibility will improve performance prediction and reduce the incidence of premature failures. Unlike empirical methods, ME design procedures can readily accommodate future procedural enhancements and changes in construction materials, traffic loading, and vehicle types. ME design procedures can also be used to provide input to pavement management systems, such that the type and timing of rehabilitation alternatives can be planned well in advance, resulting in a more efficient allocation of resources.

By observing construction and collecting environmental, climatic, and response data on a number of new, existing, and rehabilitated pavements in Ohio and New York State, researchers will be able to develop an extensive permanent database that can be used for validation and calibration of the NCHRP 1-37A Guide and other pavement design procedures well into the future. The Ohio and New York State DOTs are providing all funds required to construct and instrument the pavements included in this project. This proposal was originally prepared by ORITE to monitor the pavements, to archive the data in a database, and to use the data to validate and calibrate the NCHRP 1-37A Guide for these two agencies. It was decided, however, to offer this study as a national pooled fund project to afford other DOTs the opportunity to participate by contributing some nominal amount of funding. This arrangement would be beneficial to everyone. By having the input of several states, the results will be more applicable to the entire pavement community. Participating states in the Midwest will benefit by being able either by adopting results of the NCHRP 1-37A Guide directly for their area or by adopting the results with some minor modifications. States outside the Midwest will benefit by observing the activities and using similar procedures to develop their own calibrations.

6. ANTICIPATED RESULTS AND DELIVERABLES

The primary results of this project will revolve around the collection of measured environmental and response data required with ME design procedures and the use of these data to verify and calibrate various pavement analysis and ME design procedures, including those incorporated into the 2002 Guide, for perpetual asphalt concrete pavement, long-lasting economical concrete pavement, other types of AC and PCC pavements, and reconstructed existing rigid pavements. Upon completion of the project, the following items will be provided to all participating agencies:

- Comprehensive Microsoft Access databases containing all historical response, environmental, and climatic information, and all data obtained during this and previous contracts on the extended life pavements constructed in Ohio, the rehabilitated PCC pavements in New York State, and the previously instrumented pavements in both states, including the Ohio SHRP Test Road. They will be made available on compact disk or other secure medium, with some data also being made available in HTML format for distribution at web sites, if the participating agencies desire to have this option.
- Complete summaries of seasonal parameters recorded throughout the monitoring period and a detailed examination of relationships developed between these parameters and certain types of distress.
- Clear identification of input parameters and a concise user's manual for the Enhanced Integrated Climatic Model (EICM) and a calibration of the recommended parameters for Levels 1, 2, and 3 designs with actual on-site measurements.
- Results of forensic investigations to be performed on monitored sections that fail during this project. Interim reports discussing the probable causes of failure and possible corrective measures will be published for distribution. This information will be helpful in properly evaluating the performance of pavements in this study.
- Succinct design recommendations for perpetual AC pavements.

- A listing of the input variables, with recommended values, for the 2002 Design Guide. The listing will include a discussion of the sensitivity of the analysis to the input variable and the source of the recommended input value. If a recommended value cannot be determined from the data collected on this project or from the literature, guidelines will be provided on how to determine the needed value.
- Project documentation will include: annual interim reports on seasonal parameter trends, annual technical notes on topics related to the effects of seasonal factors on pavement performance, and a final report to be published at the conclusion of the project. Additional reports, including one containing the verification and validation of ME design procedures will be submitted as results become available and as the importance of the findings dictates dissemination.

It is expected that the results of this research will complement and enhance the 2002 Design Guide with broad applications throughout the country.

Results and recommendations from this proposed project will be consigned to a final report, initially submitted as a draft in 5 copies 120 days prior to the scheduled completion date. A revised final report will be published once comments are received from the participating agencies and reviewed by the researchers. In addition to the submission of 60 printed copies of the final report and 120 copies of the executive summary, the investigators will include 2 CDs containing electronic versions of the report in Adobe (.pdf), MS Word (.doc) or WordPerfect (.wpd) formats.

7. RECOMMENDED IMPLEMENTATION PLAN

This research is part of a series of projects conducted by ODOT and NYSDOT, including the pooled fund study SPR 2(203), aimed at the verification of ME design and analysis procedures, including those prescribed in the soon to be released 2002 Design Guide. It also aims at verifying pavement rehabilitation and ME overlay design procedures on PCC pavements, on PCC pavements being rehabilitated on NY 17 (I 86) and on other previously constructed and carefully monitored pavement sections. The project objectives will be achieved through the comparison of predicted and actual field responses to validate ME design procedures.

As previously indicated, this project will make extensive use of the mechanical properties of materials determined in the laboratory at the time of construction of the WAY 30 and NY 17 (I 86) pavements, seasonal data, and pavement response data collected on the test sections during carefully controlled load tests, as well as existing databases related to other test sections. If the verification is successful, and if the pavement configurations are deemed suitable for further use, recommendations will be made for design and construction of similar sections elsewhere. The scope of the project is sufficiently general that the findings can be applied to other states interested in constructing similar types of pavement.

It is also foreseen that the results of analyses of the expanded long term monitoring of existing instrumented pavements with respect to the climatic and environmental factors effects on pavement performance may lead to revision of the ODOT's Pavement Design and Rehabilitation Manual (Section 200) to include the long-term and seasonal variation of the subgrade modulus. Data collection and monitoring of PCC test sections may also lead to changes to Item 452 in the CMS Manual and to

Sections 300 and 400 of the Pavement Design and Rehabilitation Manual. Similar manuals from NYSDOT and other participating DOTs may also be modified.

Once findings of this research have been reviewed by ODOT and NYSDOT, seminars will be conducted in the two states to review the project, explain technical aspects of the new 2002 Guide, and present proposed modifications to existing design procedures, construction techniques, specifications, and testing methods to maintain compliance with the Guide, while adjusting Guide parameters for local conditions.

8. WORK PLAN

The required effort to complete objectives of this project includes the following tasks:

Group A Tasks

Funding for Group A Tasks will be provided by the Ohio Department of Transportation and will include the subtasks indicated below.

Task A1. Data Collection, Field Sampling and Pavement Surveys

This task which extends for the complete duration of the project includes extending the overall monitoring period at the WAY 30 project to 6 years beyond the initial one year proposed by the project "Instrumentation of the WAY-30 Test Pavements." All data will be collected using SHRP protocols.

Periodic coring and sampling, and in-situ testing with the FWD (by ODOT), and DCP (penetrometer by Ohio University-ORITE) measurements will be necessary, in conjunction with the controlled vehicle testing in Task A3.

All laboratory test results and collected field data will be organized in a user-friendly database.

In addition, this task will continue the data collection efforts on projects and sections with existing environmental instrumentation in Ohio. Besides gathering environmental data consisting of weather, pavement profile temperature, base and subgrade moisture, and resistivity (where applicable), periodic condition surveys will be conducted to document pavement performance and to note the progression of distress. These observations will be accompanied by measurements of rutting in AC and curling in PCC with a dipstick profiler. ODOT will also conduct FWD and water table depth measurements at selected sections and ORITE will analyze the resulting data. As in previous projects, ORITE will also coordinate the collection of environmental data on 5 sections at the Ohio SHRP Test Road being conducted by The Ohio State University. This work will also include keeping the sensors and data acquisition equipment operational and entering all environmental data into existing databases. A complete data collection detail is given in the tables shown below and titled: DATA COLLECTION DETAIL (Part A and B). Damaged sensors may be replaced if they measure a key parameter within the pavement profile.

All data collection procedures will follow SHRP protocols. Surface condition surveys will follow the guidelines prescribed by the "Distress Identification Manual for the Long-Term Pavement Performance Program." (Publication No. FHWA-RD-03-031, June 2003). SHRP Test Road environmental data will be submitted to the LTPP project.

DATA COLLECTION DETAIL (Part A)

PROJECT	TEST/SURVEY	No. of Sections	ACTIVITY	FREQUENCY
US 23 Delaware Co.	Weather Station	1	Data Collection/Analysis	Downloaded Twice a year
	TDR Moisture	9 *	Data Collection/Analysis	12 times a year
	Temperature/ Resistivity	9 *	Data Collection/Analysis	12 times a year
	Water Table Level by ODOT	9	Data Analysis	12 times a year
	FWD by ODOT	All core sections	Data Analysis	Once a year
	Surface Visual Survey	All +	Data Collection/Analysis	12 times a year
	Distress Survey and Dipstick/Profiler	All	Data Collection/Analysis	Once a year
	Forensic	As required	Field & Lab Testing / Analysis	As required
US 50 Athens Co.	Weather Station	1	Data Collection/Analysis	Downloaded Twice a year
	TDR Moisture	5	Data Collection/Analysis	12 times a year
	FWD by ODOT	5	Data Analysis	Once a year
	Surface Visual Survey	All +	Data Collection/Analysis	12 times a year
	Distress Survey and Dipstick/Profiler	All	Data Collection/Analysis	Once a year
	Forensic	As required	Field & Lab Testing / Analysis	As required
US 33 (SR 124) Meigs Co.	TDR Moisture	24	Data Collection/Analysis	12 times a year
	FWD by ODOT	8	Data Analysis	Once a year
	Surface Visual Survey	All +	Data Collection/Analysis	12 times a year
	Distress Survey and Dipstick/Profiler	All	Data Collection/Analysis	Once a year
	Forensic	As required	Field & Lab Testing / Analysis	As required
US 33 Logan Co.	FWD by ODOT	6	Data Analysis	Once a year
	Surface Visual Survey	All +	Data Collection/Analysis	Once a year
	Distress Survey and Dipstick/Profiler	All	Data Collection/Analysis	Once a year
	Forensic	As required	Field & Lab Testing / Analysis	As required
US 33 Athens Co. Nelsonville	FWD by ODOT	2	Data Analysis	Twice a year
	Surface Visual Survey	All +	Data Collection/Analysis	Twice a year
	Distress Survey and Dipstick/Profiler	All	Data Collection/Analysis	Twice a year
	Forensic	As required	Field & Lab Testing / Analysis	As required

DATA COLLECTION DETAIL (Part B)

PROJECT	TEST/SURVEY	No. of Sections	ACTIVITY	FREQUENCY
I-77 Stark Co	Surface Visual Survey	All +	Data Collection/Analysis	Once a year
	Forensic	As required	Field & Lab Testing / Analysis	As required
US 30 Wayne Co.	Weather Station	1	Data Collection/Analysis	Downloaded Twice a year
	TDR Moisture	2	Data Collection/Analysis	12 times a year
	Temperature	2	Data Collection/Analysis	12 times a year
	Water Table Level by ODOT	4	Data Analysis	12 times a year
	FWD by ODOT	All	Data Analysis	Twice a year
	Surface Visual Survey	All +	Data Collection/Analysis	12 times a year
	Distress Survey and Dipstick/Profiler	All	Data Collection/Analysis	Twice a year
	Truck Load Tests	All [x]	Data Collection/Analysis	Once a year
	Forensic	As required	Field & Lab Testing / Analysis	As required

NOTES:

- * 3 Sections from OU and remaining active 6 Sections previously assigned to Case Western Reserve University and University of Toledo
- + Surface Visual Surveys are intended to check not only for the development of distress but to inspect for any possible hazardous conditions that may develop from the dislodging of installed instrumentation over time.
- [x] Truck Load Tests will be conducted according to SHRP Protocol to obtain the pavement's load response.
- All data collected according to the details presented above and previous existing data such as that collected at the ERI/LOR 2 project in Ohio will be used in all analyses and validations

Task A2 Reconstruction of Strain Histories

Controlled vehicle tests and NDT testing with the FWD conducted in the previous task at the WAY 30 test sections are fundamental requirements to validate ME design procedures. They provide mechanistic response parameters in the form of deflections, strains and stresses that researchers need for the validation of any pavement analysis and design procedure. Dynamic response data needs to be measured at critical locations within the pavement structure and compared with the same parameters calculated theoretically using material properties obtained from material samples. Controlled vehicle tests also expedite the reconstruction of the strain history of a pavement using traffic data collected with a weigh-in-motion (WIM) system. FWD data will be provided by ODOT to ORITE researchers for analysis.

Task A3. Forensic Investigations

As test sections fail, it is vital that forensic investigations be performed to determine which components of the pavement structure failed and why they failed. Prior to doing a forensic investigation on Sections 390101 and 390110 at the Ohio SHRP test Road, ODOT conducted a detailed series of FWD tests in the right wheel path to determine the stiffness profile along a 500-foot length. OU then performed several Dynamic Cone Penetrometer tests along the same path to investigate whether particularly weak layers were present in the subgrade. Based upon these results, three areas of low, medium and high stiffness were identified, and transverse trenches were dug across the wheel path at these locations. To the casual observer, the severely distressed pavement surface would suggest rutting in the asphalt concrete. Transverse profiles of the subgrade and base surfaces and thickness measurements of the layers clearly indicated, however, that rutting had occurred in the base and subgrade, and the asphalt concrete pavement layer was merely conforming to the top of the base. This type of information is important in identifying specific causes of pavement failure and being able to correct them in future installations. A detailed procedure for conducting forensic investigations is contained in the report "Final Report on Forensic Study for Section 390101 of Ohio SHRP U.S. 23 Test Pavement" submitted to ODOT by ORITE. These procedures will be followed, along with well-established LTPP Guidelines, on any future investigations in this project. A total of three forensic investigations are anticipated during the initial three-year contract. Each forensic investigation will be documented with the publication of an interim report.

FWD tests will be scheduled through ODOT prior to coring and trenching to conduct the forensic investigation. NDT results will be analyzed and compared with previous records taken at the same location, if they exist. Dynamic Cone Penetrometer tests will be conducted through the core holes to obtain stiffness and strength profiles that may be used in future analyses. Base and subgrade samples will be collected at various depths for further testing and documentation of moisture variation with depth and for correlation and comparison with the cone penetrometer results.

Task A4. Laboratory Testing

In addition, laboratory testing of soils and pavement materials obtained during the forensic investigations will be conducted during this task to complement the results of field observations and testing and to help elucidate the cause of failure or development of excessive distress. Laboratory testing will also be helpful in documenting the aging of pavement materials by comparison of parameters previously obtained within the same project. Among others, the following tests will be conducted on materials and soils obtained at the forensic investigation sites:

- Dynamic modulus and indirect tensile strength of asphaltic material. These will be conducted at no less than 3 temperatures if sufficient cores are available.
- Elastic modulus and compressive strength of Portland cement concrete
- Petrographic analysis of Portland cement concrete samples, volumetrics and Superpave binder tests of asphalt concrete samples
- Moisture content, index properties, and resilient modulus of base materials
- Moisture content, index properties, and resilient modulus of subgrade materials
- Other additional tests as specified in the report: "Final Report on Forensic Study for Section 390101 of Ohio SHRP U.S. 23 Test Pavement."

Results of these tests will be analyzed jointly with the field exploration and testing to pinpoint the cause of failure. These results will also be compared with test records at the time of construction and thereafter to document the aging of these materials or changes throughout the life of the project.

All tests will be conducted following procedures and using equipment specified by the SHRP protocol.

Task A5. Data Summary and Environmental Data Analysis Annual Reports

On a yearly basis, interim reports will be prepared documenting the variation of temperature and moisture at each of the seasonal sections available within the projects under study. An inventory of active and faulty sensors will also be included in the interim report.

Task A6. Data Summary and Environmental Data Analysis Relating to Distress

Environmental data will be analyzed jointly with the results of condition surveys to document the progressive development of pavement distress. If appropriate, regression analyses will be conducted to develop relationships describing the trend of volumetric moisture content and average pavement temperature with respect to day of the year in the Julian calendar. With the release of the new AASHTO Design Guide through project NCHRP 1-37A prior to the start of this research project, a selected number of sections will be analyzed using the accompanying software. Since this software is capable of predicting the performance of pavements in terms of developed distress, actual material, climatic, and traffic data can be used to model the development of stress, which can be compared with actual observations obtained through visual surveys. Since some load response characteristics have been obtained in the past for some of the monitored sections, these data may be used to examine the performance of pavement sections with the consideration of load and climatic factors jointly.

Task A7. Climatic Modeling

Determine the input parameters for the Integrated Climatic Model used in the software developed for NCHRP 1-37A. Compare results from the model with actual field data.

Group B Tasks

Funding for Group B Tasks will be provided by the New York State Department of Transportation (NYSDOT) and will include the subtasks indicated below.

Task B1. Monitoring of NY 17 (I 86) Test Pavements

ORITE has installed instrumentation in the reconstructed NY 17 (I 86) pavements and will continue to monitor both environmental and response parameters. Instrumentation will be installed in new test sections as requested by NYSDOT and monitored for the duration of the study.

Weather parameters being monitored include: air temperature, rainfall, relative humidity, solar radiation, wind speed, and wind direction at an on-site weather station. Pavement and soil temperature, base and subgrade volumetric moisture content, depth of frost penetration, and water table depth will be monitored by thermistors and/or thermocouples (temperature), Time Domain Reflectometry (TDR) probes (moisture), resistivity probes (depth of frost penetration), and wells (water table depth). Slab curling will also be measured using a dipstick and either a traveling laser or traveling wheel beam.

Load response parameters to be measured include surface and intermediate layer deflection, horizontal pavement strain, and subgrade pressure; these measurements will be made by means of LVDTs, strain gages, and pressure cells. Data acquisition systems capable of collecting real time dynamic data will gather inputs from these sensors. WIM traffic monitoring stations are providing information on traffic volume and loads required for the analyses and verifications.

Task B2. Construction Practices Review

The performance of Portland cement concrete (PCC) pavement can be affected dramatically by environmental conditions during the placement and initial set of the mix, and by the timing of the sawing of contraction joints to control shrinkage cracking. Due to the enormous investment contractors have in PCC paving equipment and the fact that much of their profit on a rigid pavement project is tied to placement of the concrete, little else other than the anticipation of rain or extremely cold temperatures affects the scheduling of concrete placement. These monetary considerations make it impractical for owner agencies to impose strict controls on placement during construction or to control placement for research purposes. There are instances, however, where evidence points to environmental conditions or improper sawing as the causes of early distresses such as cracking.

In this project, the contractor will schedule and place concrete as desired. The researchers in close coordination with project engineers will monitor the time and location of placement, and the timing of the joint sawing. Air temperature, relative humidity, and wind speed will be monitored at the on-site weather station. Thermocouples will be installed at a few locations to monitor temperature of the concrete as it cures. These data will be used to investigate any early distresses noted in the concrete and any differences in joint response measured with the FWD that might be explained by differences in slab support resulting from climatic conditions at the time of initial set.

Other construction activities including form and placement of asphalt concrete, sequences, and times of the day and year will be carefully documented to note any possible effects on the development of distress. Construction monitoring will also include close observation of test section construction to identify and document any deviations from the prescribed specifications and to determine the effects of any specification enhancements necessary to construct these non-traditional pavements. Specific attention will focus in measuring geometric parameters, placement conditions, compaction control, material uniformity, and quality control in general.

Task B3. Data Collection, Field Sampling and Pavement Surveys

This task consists of the monitoring of the NY 17 (I 86) and other new sections for 6 years and of the NY I490 test section for an additional period of 6 years. All data will be collected using SHRP protocols.

Periodic coring and sampling, and in-situ testing with the FWD (by NYSDOT), and DCP (by ORITE) measurements will be necessary, in conjunction with the controlled vehicle testing in Task B5.

All laboratory test results and collected field data will be organized in a user-friendly database.

Besides gathering environmental data consisting of weather, pavement profile temperature, base and subgrade moisture, and resistivity (where applicable), periodic condition surveys will be conducted to document pavement performance and to note the progression of distress. These observations will be accompanied by rutting in AC and curling in PCC measurements with the dipstick profiler. This work will also include keeping the sensors and data acquisition equipment operational and entering all environmental data into existing databases. A complete data collection detail is given in the tables shown below and titled: DATA COLLECTION DETAIL (Part C). Damaged sensors may be replaced if they measure a key parameter within the pavement profile.

All data collection procedures will follow SHRP protocols. Surface condition surveys will follow the guidelines prescribed by the "Distress Identification Manual for the Long-Term Pavement Performance Program." (Publication No. FHWA-RD-03-031, June 2003).

DATA COLLECTION DETAIL (Part C)

PROJECT	TEST/SURVEY	No. of Sections	ACTIVITY	FREQUENCY
I-86 (NYS 17)	Weather Station	1	Data Collection/Analysis	Downloaded Twice a year
	TDR Moisture	2	Data Collection/Analysis	12 times a year
	Temperature	2	Data Collection/Analysis	12 times a year
	Water Table Level by NYSDOT	4	Data Analysis	12 times a year
	FWD by NYSDOT	All	Data Analysis	Twice a year
	Surface Visual Survey	All +	Data Collection/Analysis	12 times a year
	Distress Survey and Dipstick/Profiler measurement	All	Data Collection/Analysis	Twice a year
	Truck Load Tests	All [x]	Data Collection/Analysis	Once a year
	Forensic	As required	Field & Lab Testing / Analysis	As required
I 490 NYSDOT	FWD by NYSDOT	All	Data Analysis	Twice a year
	Surface Visual Survey	All +	Data Collection/Analysis	12 times a year
	Distress Survey and Dipstick/Profiler measurement	All	Data Collection/Analysis	Twice a year
	Forensic	As required	Field & Lab Testing / Analysis	As required

NOTES:

- + Surface Visual Surveys are intended to check not only for the development of distress but to inspect for any possible hazardous conditions that may develop from the dislodging of installed instrumentation over time.
- [x] Truck Load Tests will be conducted according to SHRP Protocol to obtain the pavement's load response.
- All data collected according to the Details A, B, and C presented above and previous existing data such as that collected at the ERI/LOR 2 project in Ohio will be used in all analyses and validations

Task B4. <u>Reconstruction of Strain Histories</u>

Controlled vehicle tests and NDT testing with the FWD conducted in the previous task at the I 86 test sections are fundamental requirements to validate ME design procedures.

They provide mechanistic response parameters in the form of deflections, strains, and stresses that researchers need for the validation of any pavement analysis and design procedure. Dynamic response data needs to be measured at critical locations within the pavement structure and compared with the same parameters calculated theoretically using material properties obtained from material samples. Controlled vehicle tests also expedite the reconstruction of the strain history of a pavement using traffic data collected with a weigh-in-motion (WIM) system. FWD data will be provided by NYSDOT to ORITE researchers for analysis.

Task B5. Forensic Investigations

As test sections fail, it is vital that forensic investigations be performed to determine which components of the pavement structure failed and why they failed. Procedures developed during ORITE's experience with the SHRP test road on US23 in Ohio will be followed, along with well-established LTPP Guidelines, on any future investigations in this project. A total of three forensic investigations are anticipated during this three-year contract. Each forensic investigation will be documented with the publication of an interim report.

FWD tests will be scheduled through NYSDOT prior to coring and trenching to conduct the forensic investigation. NDT results will be analyzed and compared with previous records taken at the same location, if they exist. Dynamic Cone Penetrometer tests will be conducted through the core holes to obtain stiffness and strength profiles that may be used in future analyses. Base and subgrade samples will be collected at various depths for further testing and documentation of moisture variation with depth and for correlation and comparison with the cone penetrometer results.

Task B6. Laboratory Testing

Initially, the characterization of all materials used in the reconstruction of the NY 17 pavements will be conducted in this task. Testing will include the determination of the dynamic modulus of asphaltic materials and the resilient modulus of subgrade soils, and the modulus of elasticity for PCC. Cores obtained during each field sampling program in Task B3 will also be tested to determine variations in material stiffness with time and after the pavements have been subjected to traffic loading. Material testing and characterization will follow the guidelines presented in Tables 2 and 3, depending upon the hierarchical Level, as specified in the 2002 Guide. In all cases, Level 1 testing will be the preferred option for material property input in any subsequent analyses and validations. Materials used in construction of the NY 17 (I 86) experimental sections will be tested following the specific details shown in Tables 2 and 3 for rigid and flexible pavements. Alternatively, existing and sufficiently proven relationships will be proposed to determine input material properties when direct testing is not available.

In addition, laboratory testing of soils and pavement materials obtained during the forensic investigations will be conducted during this task to complement the results of field observations and testing and to help elucidate the cause of failure or development of excessive distress. Laboratory testing will also be helpful in documenting the aging of pavement materials by comparison of parameters previously obtained within the same project. Among others, the following tests will be conducted on materials and soils obtained at the forensic investigation sites:

- Dynamic modulus and indirect tensile strength of asphaltic material. These will be conducted at no less than 3 temperatures if sufficient cores are available.
- Elastic modulus and compressive strength of Portland cement concrete
- Petrographic analysis of Portland cement concrete samples, volumetrics and Superpave binder tests of asphalt concrete samples
- Moisture content, index properties, and resilient modulus of base materials
- Moisture content, index properties, and resilient modulus of subgrade materials
- Other additional tests as specified in the report: "Final Report on Forensic Study for Section 390101 of Ohio SHRP U.S. 23 Test Pavement."

Results of these tests will be analyzed jointly with the field exploration and testing to pinpoint the cause of failure. These results will also be compared with test records at the time of construction and thereafter to document the aging of these materials or changes throughout the life of the project.

All tests will be conducted following procedures and using equipment specified by the SHRP protocol. Results of the laboratory analysis and backcalculation will be used to determine materials properties required for Level 1, 2, and 3 design guidelines. Variations in stiffness with time and after traffic loading will be determined.

Task B7. Data Summary and Environmental Data Analysis Annual Reports

On a yearly basis, interim reports will be prepared documenting the variation of temperature and moisture at each of the seasonal sections available within the projects listed in Task B3. An inventory of active and faulty sensors will also be included in the interim report.

Task B8. Data Summary and Environmental Data Analysis Relating to Distress

Environmental data will be analyzed jointly with the results of condition surveys to document the progressive development of pavement distress. If appropriate, regression analyses will be conducted to developed relationships describing the trend of volumetric moisture content and average pavement temperature with respect to day of the year in the Julian calendar. With the release of the new AASHTO Design Guide through project NCHRP 1-37A prior to the start of the research project, a selected number of sections will be analyzed using the accompanying software. Since this software is capable of predicting the performance of pavements in terms of developed distress, actual material, climatic and traffic data can be used to model the development of stress, which can be compared with actual observations obtained through visual surveys. Since some load response characteristics have been obtained in the past for some of the monitored sections, these data may be used to examine the performance of pavement sections with the consideration of load and climatic factors jointly.

Group C Tasks (both locations)

The tasks in this group are independent in the sense that if any of these tasks is omitted, the others may still be conducted. However, the subtasks under task C4 are linked – either all of them must be done or none of them.

Tasks in Group C are linked to the monitoring and analysis of data obtained in Task A and B. Results of field section performance will be presented at the National Conference with all supporting documentation. As previously indicated, the testing of one of the field sections at the Accelerated Pavement Testing Load Facility will allow the comparison of performance between the two sections for further extrapolation of results in a controlled testing environment to actual field applications. Data collected in the first two tasks will also augment the wealth of data in available databases for the benefit of practitioners and researchers. Similarly, these data will contribute to the verification effort of M/E Design procedures and existing models to predict AC Temperature and Expected Stiffness, as well as the Enhanced Integrated Climatic Model (EICM).

Task C1 National Conference on Perpetual Pavement

Several states are currently planning to instrument and monitor pavement which is designed based on the concept of "perpetual pavement". The Ohio Department of Transportation has one of the most extensive instrumentation and monitoring programs for these types of long-life pavements in the nation.

Some departments of transportation have approached ORITE to request that ORITE organize a national conference to address such topics as instrumentation, monitoring, verification, and calibration of the design concept of perpetual pavement.

It is envisioned that the conference will have a duration of three days and will follow a format similar to that of the International Conference on Highway Pavement Data, Analysis and Mechanistic Design Applications, organized by ORITE in 2003. The conference will be a joint effort between ORITE, the Departments of Transportation involved and industry, from which a conference panel will be assembled. Prominent Keynote Speakers will be invited and a call for papers will be issued to assure the participation of researchers and practitioners with recognized experience in perpetual pavements. Abstracts initially submitted will be reviewed by the conference panel considering quality and pertinence of topic. Authors will be then invited to submit complete papers which will be peer-reviewed to decide on their acceptance for presentation and publication in the conference proceedings. Proceedings will be published in electronic form using pdf format and will be complemented with a printed set of abstracts. Proceedings will also be posted in a website to facilitate their dissemination.

In addition to the scheduled presentations, the conference will include pertinent workshops to facilitate the instruction of practicing engineers on topics related to perpetual pavements. An effort will be made to award CEUs to workshop participants if sanctioned by national organizations such as ASCE.

Task C2. Construction, Testing, and Monitoring of Perpetual Pavement Sections at the Accelerated Pavement Testing Load Facility

This task includes the construction of at least three perpetual pavement sections at the Accelerated Pavement Testing Load Facility (APTLF) along with the installation of necessary instrumentation to monitor stresses, strains, deflections, and accelerations under moving tire loads. Periodic pavement evaluation, response monitoring, and non-destructive and destructive testing (if necessary) will be conducted to document pavement response and behavior at a preset number of load applications. Test sections will include at least the mix design commonly utilized in the states of Ohio and New York.

Sections to be tested at the APTLF will be selected jointly by pavement engineers of the participant DOTs and researchers from ORITE, including sections aimed at reducing the possibility of fatigue failure. This can be achieved with the use of rich-asphalt AC mixtures, the use of very thick AC layers as well as of very stiff bases to reduce the tensile strain at the bottom of the AC layer. Even though the proposed sections may not fail during their controlled testing, their relative performance can be inferred by the comparison of the response parameters measured by the installed instrumentation. One of the selected sections to be tested at the APTLF will include one of the as-built sections at the Test Roads. This will allow the comparison of the relative performance of the same section in the two settings.

This testing will be of fundamental interest in developing design recommendations for these specific types of pavements, validating analysis procedures, and developing design charts or nomographs of practical application by transportation agencies involved in the proposed research.

Task C3. Database Update, Data Summary, and Environmental Data Analysis

Material, Structural, Climatic, and Seasonal data collected, according to the details presented in tasks A1 and B3, will be subjected to QA/QC controls to eliminate entries from faulty sensors. Climatic and Seasonal data files will be processed with the AWSCHECK and SMPCHECK programs, respectively, developed by SHRP. These two programs are capable of identifying numerical figures that fall outside the specified range and of prompting the user to delete the particular set of data not meeting the QA/QC checks. Once new data files meet QC Level C guidelines they can be uploaded to the database after the generation of a single ASCII file containing all data files within the selected analysis period. All climatic and seasonal data collected during the proposed research will be added to the existing databases including the Ohio SHRP Test Road Database

At the discretion of ODOT, NYSDOT and other interested agencies' engineers, these databases can be accessed and downloaded by users through a web site. Current efforts are directed at expanding the scope of the weather station and seasonal databases, offering a version in HTML for easy posting in the WWW. The following link shows an example of one year's worth of temperature data for Section H (390203) for 1998.

http://oak.cats.ohiou.edu/~figueroj/DEL23_Index.htm

It is envisioned that similar files can be created for the remaining sections and periods. The web pages presented below show an example of a trial web site that has been set up by ORITE at Ohio University to allow viewing of sample graphs or downloading of seasonal data in formatted EXCEL files previously subjected to QA/QC through SMPCHECK and AWSCHECK.

On a yearly basis interim reports will be prepared documenting the variation of temperature and moisture at each of the seasonal sections available within the projects listed in Tasks A1 and B3. An inventory of active and faulty sensors will also be included in the interim report.

Other data types such as FWD test results, Water Table depth, visual condition, and distress and dipstick surveys will be added to appropriate databases.

Environmental data will be analyzed jointly with the results of condition surveys to document the progressive development of pavement distress. If appropriate, regression analyses will be conducted to develop relationships describing the trend of volumetric moisture content and average pavement temperature with respect to day of the year in the Julian calendar. With the release of the new AASHTO Design Guide through project NCHRP 1-37A prior to the start of the research project, a selected number of sections will be analyzed using the accompanying software. Since this software is capable of predicting the performance of pavements in terms of developed distress, actual material, climatic, and traffic data can be used to model the development of stress, which can be compared with actual observations obtained through visual surveys. Since some load response characteristics have been obtained in the past for some of the monitored sections, these data may be used to examine the performance of pavement sections with the consideration of load and climatic factors jointly.

Collected data can also be used to verify the BELLS model for AC pavement temperature prediction with depth given the latitude and air temperature. Selected AC sections in different geographic locations will be included in the verification.


DEL23_Database - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Forward Stop Refresh Home Search Favorites Media History Mail Print Edit Discuss
Address http://oak.cats.ohiou.edu/~figueroj/DEL23_Index.htm
Go Links
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465 blocked
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OHIO UNIVERSITY
Ohio SHRP Test Road Environmental Data (Section 390203 - 1998)
Click this link to download the Excel File.
Click this link to see the Excel charts.
Contact Information | Civil Engineering Front Door | Russ College of Engineering and Technology | Ohio University Front Door
OHIO UNIVERSITY
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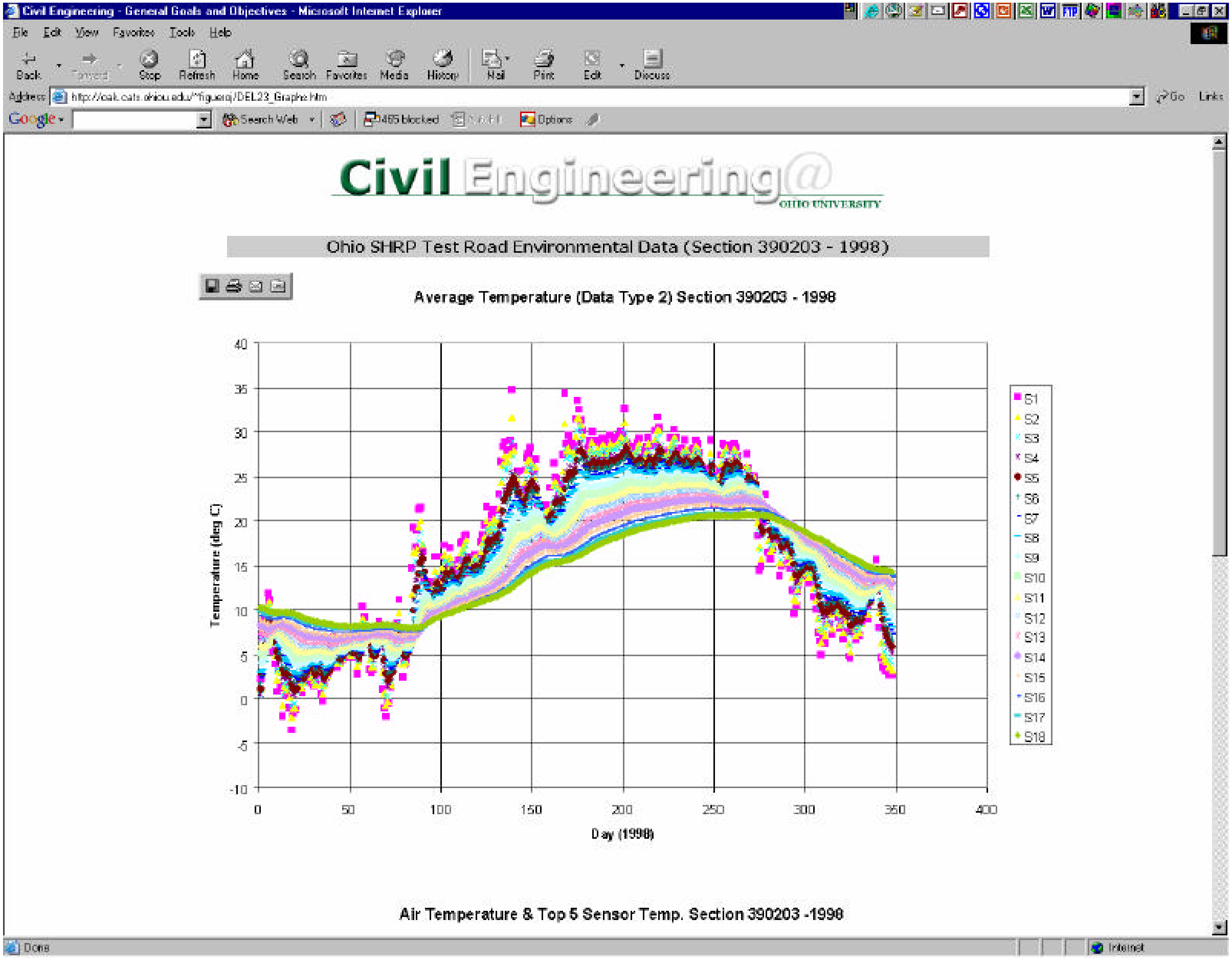
Internet


Civil Engineering - General Goals and Objectives - Microsoft Internet Explorer
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OHIO UNIVERSITY
Ohio SHRP Test Road Environmental Data (Section 390203 - 1998)
Average Temperature (Data Type 2) Section 390203 - 1998
Temperature (deg C)
Day (1998)
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
S16
S17
S18
Air Temperature & Top 5 Sensor Temp. Section 390203 -1998

Task C4. Verification and Calibration of Mechanistic/Empirical Design Procedures

The primary objective of this task is to validate and calibrate Mechanistic/Empirical pavement design procedures, with particular emphasis on those introduced by the 2002 Pavement Design Guide through project NCHRP 1-37A. This work will be coordinated with the activities of NCHRP project 1-40 and TPF-5(079). Since this constitutes one of the major thrusts in the proposed research project, it is appropriate to divide this task into 7 subtasks as follows:

Subtask C4a Literature Review

This subtask will be started with a literature review to document any efforts by other departments of transportation to implement ME procedures in their approach to pavement design. Reported relationships for material property determination and transfer functions will be noted for possible adaptation and calibration to Ohio conditions. Results of sensitivity analyses conducted by the same organizations will be considered in selecting material properties and parameters with the most and the least influence in the final satisfactory designs.

Subtask C4b Review of NCHRP 1-37A Report and Identification of Data Needed for M/E Design Procedures

This subtask will initially encompass a detailed review of the NCHRP 1-37A report and software to clearly identify required input data, for each of the three hierarchical design levels. Data requirements will be compared with the guidelines developed by ORITE through the ODOT-funded project “Material Properties for Implementation of Mechanistic-Empirical Pavement Design Procedures”, other pertinent reports, as well as the LTPP database to identify sources of and any deficiencies in available data with application to conditions prevalent in the state of Ohio. Current ODOT material testing procedures will also be reviewed to ascertain whether or not they meet 2002 Guide requirements.

A sensitivity analysis of input parameters will also be conducted during this task to determine the relative effect of each parameter in each hierarchy and to rank them in terms of importance.

Available traffic, weather, and other environmental data required by the Guide will also be reviewed. Deficiencies in all data categories will be noted and methods to bridge the gaps will be suggested. Modifications to current testing and data collection procedures will also be developed such that they meet Guide requirements. This task will be concluded with the preparation and submission of an interim report detailing the work performed during subtasks C4a and C4b.

Subtask C4c Develop Implementation Plan

A plan for implementing ME pavement design procedures developed under NCHRP 1-37A will be outlined and expanded during this subtask. Since the Guide proposes designing pavements by one of three hierarchical levels, a plan will be developed to facilitate the selection of the appropriate level according to the available data for the specific location of a project. It is envisioned that a flow chart will be prepared to query and guide the engineer to the suitable design level starting with the more stringent and preferred Level 1. Information regarding the test procedures, equipment, unit cost of equipment, and estimates of manpower requirements in terms of hours to conduct each test will be listed for each of the three design level approaches. Manpower requirements will be based on ODOT's current pavement construction program.

In order to facilitate the implementation of the ME design procedures on a statewide scale, summary presentation materials (PowerPoint and a concise manual) will be prepared based on supporting documentation provided by the AASHTO Guide. One-day instructional seminars conducted by the Principal Investigators will be scheduled to facilitate the training of ODOT's pavement engineers. Similarly the NCHRP Implementation Plan will be executed for the state of New York.

Subtask C4d Develop Input Data Guidelines

This subtask is initially aimed at consolidating the databases identified in subtask C4b for easy access to designers. Depending on their extent and availability in electronic form, CDs will be prepared or links and step-by-step procedures will be supplied to facilitate prompt data retrieval. A complete list of guidelines will be developed for the selection of input parameters that may include conducting tests, using existing databases or relationships to design pavements according to each of the three hierarchical levels specified by the Guide. Key input screens, links and references to databases will be saved in an easy-to-follow user's manual to be included in the final report. Finally, guidelines will also include copies of any testing protocols.

Subtask C4e Validation of Design Procedure

To validate the design procedure, a minimum of fifteen design examples will be developed including 5 types of pavements: new rigid, new flexible, and reconstructed (AC over AC, AC over PCC, and PCC over processed PCC) and the 3 hierarchical levels specified in the procedure. Design projects will be selected in cooperation with ODOT and NYSDOT pavement engineers and they could very well be actual projects scheduled for construction or reconstruction within the normal budget cycle. Alternatively, already built pavement sections could be used as design examples, especially if their material properties, climatic conditions, and performance are known to eventually aid in the calibration of the ME design procedures. These design examples will also be useful in noting any necessary modifications to the input data requirements. Of particular interest will be the validation of the design procedure for perpetual asphalt concrete, long-lasting economical concrete pavements, and overlays placed on rigid pavements to be constructed at the WAY30 and NY I86 test sections.

Prior to proceeding with the validation of the ME design procedure proposed by the 2002 Pavement Design Guide, the researchers will conduct a thorough review of design assumptions and specification enhancements used to construct these pavement sections. Researchers will review design, bidding, and construction documents to note particular assumptions and specifications tailored to the WAY 30 and I 86 test sections. Other documentation and procedures will be gathered and summarized after interviewing ODOT and NYSDOT pavement engineers directly involved in these design projects. It is expected that an internal summary report and tabulations, when appropriate, will be generated to expedite work during subsequent tasks.

In order to validate the ME design procedure, researchers propose to compare measured and calculated responses using mechanical properties of materials determined on the project entitled "Determination of Mechanical Properties of Materials Used in the WAY-30 Test Pavements," load response data collected from instrumented test sections on project, "Instrumentation of the WAY-30 Test Pavements," and data collected in Tasks A1 and B3 of this project. Additional required data will be procured from cores collected and supplied by ODOT and NYSDOT, and from the observation of specification enhancements identified and documented during Tasks B2. Appropriate material properties will need to be procured or selected for prevalent seasonal conditions existing at the time of FWD and controlled vehicle tests proposed as part of any necessary forensic studies.

To complete the validation of the design procedure, checked design configurations will be compared among their corresponding pavement types and with designs conducted using ODOT's traditional pavement design procedures to note any significant differences in layer thicknesses and expected pavement performance.

Similarly, a generalized example of a comparison between calculated and measured pavement response by PLAXIS was presented in Section 3 of this proposal. Other analysis codes, such as OUPAVE, ILLIPAVE, JSLAB, ILLISLAB, and various 3-D finite element procedures may be used to examine the sensitivity of pavement analysis and design procedures to a range of input parameters. If any of these codes or procedures is found to accurately model pavement response to loading, it may be used to generate nomographs to back calculate subgrade stiffness properties from FWD deflection measurements.

Traditional pavement design procedures such as those by AASHTO, PCA, The Asphalt Institute, etc, will also be used to predict pavement life in terms of ESALs. Test section design will also be checked with the new Mechanistic/Empirical design procedures developed through project NCHRP 1-37A. The Enhanced Integrated Climatic Model (EICM), to be provided as part of the new 2002 Guide, will also be calibrated with moisture and temperature measurements obtained from instrumentation installed in the test sections.

In addition, the HIPERPAV (HIgh PERformance PAVing) software package developed by the Transtec Group, Inc. and the FHWA will be evaluated and verified during this subtask. HIPERPAV is capable of modeling the early-age development of concrete strength and stresses resulting from moisture and temperature changes within the pavement. It assesses the influence of PCC pavement design, concrete mix design, construction methods and environmental conditions on the early-age behavior of Portland cement concrete pavements. (http://www.hiperpav.com/)

Subtask C4f Proposed calibration procedure

To calibrate the ME design procedures introduced by the 2002 Guide a series of in-service pavements with known performance will be selected in cooperation with ODOT pavement engineers. Of particular interest is the selection of pavement sections located at carefully controlled and instrumented projects such as the Ohio SHRP Test Road among others. An effort will be made to select new and reconstructed pavements comprising the most common types of pavement configurations used throughout the state.

In the specific case of the Ohio SHRP Test Road, a number of sections have already failed and accurate, geometric, material property, traffic, environmental conditions, NDT, and controlled-load vehicle testing as well as performance records are available to researchers. Pavement sections in other instrumented and carefully monitored sections on US 50 and US 33, among others, may also be selected during the calibration procedure, especially if their periodic distress development and performance are known through data previously collected by ORITE. These sections offer the unique opportunity for ME design procedure calibration using the three hierarchical levels offered by the Guide. The expected performance determined by the 2002 Guide will be compared with the measured performance. If discrepancies are noted, an effort will be made to modify the transfer function(s) constants in order to achieve a close match between the measured and calculated performance. Sensitivity to these variables will be noted and guidelines to best select them in future designs will be developed. If significant differences are noted in the calculated response and performance, as compared to actual measured values, modifications to the procedure will be recommended to improve the accuracy of designs in the states of Ohio and New York.

Considering the estimated accuracy of Level 1, 2, and 3 designs and the effort required to obtain input data for each design, the relative effectiveness of each design level will be evaluated and the appropriate level(s) for different functional classes of pavement will be recommended.

Of special interest in the calibration procedure is the review of transfer functions used by the Guide to determine whether or not they are suitable for application to conditions found in Ohio. Transfer functions relate a mechanical response parameter such as strain or stress to the number of loads applied. When the performance of a pavement section is known, such as in the case of failed sections at the Ohio SHRP Test Road, where traffic counts in terms of number and magnitude are continuously obtained by a WIM station, it is expedient to use this data in combination with reconstructed strain or strain time-histories for transfer function calibration. Strain or stress time histories can be reconstructed from the results of Controlled Load Vehicle (CLV) tests that have been conducted at the DEL23 project in combination with a validated pavement analysis program and data from the WIM station. This approach will be followed in the transfer function review and possible modification to be performed during this task. Additional LTPP data for sections where complete performance and documentation data are not available in Ohio may be used in the calibration of transfer functions. If modifications to the transfer functions are needed they will provided in the form of an algorithm that can be implemented in the 2002 Guide software.

Subtask C4g Partial Final Report on M/E procedures Verification and Validation

The final subtask includes the preparation of a partial report containing not only a concise version of the interim report submitted after Subtask C4b, but a complete detail of findings and guidelines developed during Task C4.

Specifically, this partial final report will include a detailed description of input parameters and data collection and testing procedures and/or specific databases needed in each of the three levels offered by the guide. Guidelines will also be offered as to how to select the appropriate Level of design, according to available data at the specific location. If any input data deficiencies are found they will be reported along with recommendations on how to bridge these gaps in shortest amount of time. Results of calibration using typical sections representative of Ohio conditions will also be documented, along with recommendations to best tailor input data to achieve a pavement design offering the highest reliability. A concise user's manual for NCHRP 1-37A software usage and all training materials adapted or developed to aid in the implementation of the Guide will also be included in electronic and/or written for as appropriate. This partial final report will be submitted in both electronic and written form (60 copies) to facilitate its posting in websites and dissemination.

Task C5 Verification of Models to Predict AC Temperature and Expected Stiffness and Review of the Enhanced Integrated Climatic Model (EICM)

It is well known that temperature largely determines the stiffness of asphaltic materials. Temperature assessment is important in the design of pavements and overlays containing asphaltic mixtures and in the stiffness evaluation of asphalt concrete by Non-Destructive Testing (NDT). Several AC temperature prediction models were reviewed in Section 4 of this proposal. They were formulated on easy to obtain parameters, such as air temperature and site latitude, or from infrared surface temperature measurements during FWD testing, thus facilitating the assessment of AC stiffness if the air temperature regime is known.

Test sections to be constructed on the WAY 30 and NY 17 (I 86) projects will be instrumented with thermistors and thermocouples to monitor pavement temperature and an on-site weather station will monitor air temperature. Data collected with these sensors will be used to verify Superpave and LTPP AC temperature prediction models. Pertinent data collected in previous projects funded by ODOT (Figueroa, 2001) and possibly by NYSDOT will be used for additional verification to include sections of the state at other latitudes. If needed, regressions will be conducted to determine corrected coefficients for equations included in section 4 of this proposal.

Once the AC temperature prediction models are verified or modified, and knowing the air temperature regime through the year at different geographic locations, expected variations in AC stiffness will be determined during typical mid-season days as well as on a monthly and seasonal basis.

As previously indicated, the Enhanced Integrated Climatic Model (EICM) is to be included in the analysis and design software to be distributed with the new AASHTO Pavement Design Guide. This task also includes the review of input data, the development of a easy-to-follow user's manual, the examination of existing climatic databases applicable to Ohio to make sure the EICM can be easily applied within the state, and the verification of outputs of this model versus actual data collected along the test sections.

The EICM is capable of predicting both the temperature gradients within the upper pavement layers and moisture distribution within the base and subgrade, if suitable long-term climatic data is available. The EICM latest version 3.01 includes 4 modules:

- The Climatic/Material/Structures (CMS) module uses weather station data (sunshine percentage, wind speed, temperature, and solar radiation) to calculate the heat propagation through the pavement surface for the eventual calculation of the temperature profile within the pavement. All input parameters are measured by a typical SHRP weather station installation. Outputs from the CMS module will be compared with actual data collected at the instrumented sites.
- The Precipitation (PRECIP) module uses average climatic data along with verified mathematical relationships to simulate precipitation at a project location. This module contains 30 years of precipitation data gathered by the National Oceanic and Atmospheric Administration (NOAA) for 9 nine climatic zones in the US. Outputs from this module will be compared with data collected at the projects containing a weather

station where the amount of precipitation is collected on an hourly basis when it occurs.

- The Infiltration and Drainage (ID) module conducts a drainage analysis of granular bases for the purpose of evaluating the suitability of their design. This module may use input precipitation data provided by the analyst or generated by the PRECIP module. The module effectively computes, through an empirical procedure, the time necessary to attain a critical degree of saturation in the pavement evaluation segment. The infiltration segment of this module analyzes the degree of precipitation to compute the probability of reaching a wet or dry pavement profile as a result of infiltration of water through cracks. Volumetric moisture contents obtained at the instrumented station locations will permit discerning the capabilities of this module.
- The CRREL Frost Heave and Thaw (FT) Settlement module is the latest added to the EICM to predict frost heave and thaw deformations. Input of thermal and hydraulic properties of pavement layers are required to model these deformations by this one-dimensional method of heat and moisture transport in soils. It computes moisture phase changes to predict FT deformations while using results from previous modules to set up the initial temperature and moisture profiles as well as boundary conditions to start execution. Depth of frost penetration calculated by this module will be compared with values measured either by thermistors or resistivity probes installed at some of the monitored stations.

Task C6 Final Report Preparation

A final report containing significant results and recommendations of the proposed research project will be prepared and submitted to agencies participating in this study. Special consideration will be given to results of the ME design procedures verification process. The report will also include specific recommendations on any necessary modifications that may be needed in material testing, construction, and design procedures concerning perpetual asphalt concrete, long life economical concrete pavements, and overlays built on existing rigid pavements as well as reconstructed sections from existing rigid pavements.

Special consideration will be given to note seasonal parameters data trends during the monitoring period and to summarize the required input data and the results of verification of the Enhanced Integrated Climatic Model (EICM) to be included in the new AASHTO Design Guide.

No less important is the reporting of forensic investigation findings focused on the determination of causes and factors contributing to the rapid development of distress. In addition, if the analysis of data leads to any major findings with immediate application as the project progresses separate interim reports will be prepared and submitted to the agencies involved in this research.

The final report will be revised based on comments received from funding agencies' reviewers on the 5 copies of the draft report submitted 120 days in advance of the end of the project. The report will be submitted in both electronic and written form (60 copies) to facilitate its posting in websites and dissemination. In addition, 120 copies of the executive summary will be made. The investigators will include 2 CDs containing electronic versions of the report in Adobe (.pdf), MS Word (.doc) or WordPerfect (.wpd) formats.

9. ITEMIZED BUDGET

Following is a task by task itemized budget, specifying the funding agency's responsibility:

Tasks A1-A7	$396,000	ODOT's responsibility
Tasks B1-B8	$600,000	New York pays
Task C1	$250,000	Pooled funds
Task C2	$60,000	Pooled funds
Task C3	$170,000	Pooled funds
Task C4*	$120,000	Pooled funds
Task C5	$80,000	Pooled funds
Task C6	$2,000	Pooled funds
Total:	$1,678,000	Pooled funds total $682,000

*The seven subtasks included in Task C4 are interdependent and all of these subtasks will need to be performed jointly, thus no individual cost detail for them is provided

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11. APPENDIX

Review of Existing Test Pavements

The existing test pavements mentioned above comprise a group of pioneering efforts initiated at the Ohio Department of Transportation to monitor the performance of pavement sections in the three climatic zones identified within the state of Ohio. These projects were intended to identify more durable pavement sections, examine construction methods and specifications, clearly identify the influence of seasonal weather-related factors on pavements, and ultimately to validate or modify existing pavement design procedures and temperature and moisture prediction models. Other benefits of test section monitoring and construction include the expansion of databases with application in future designs and the identification of construction practices leading to reduced early PCC pavement cracking and extended pavement serviceability.

The following section summarizes the characteristics of each of the test pavements built in Ohio that will be monitored throughout the current project.

The Ohio SHRP Test Road

The highlight of test pavement construction and monitoring in Ohio is the Ohio SHRP Test Road on US 23 in Delaware County. This project, started in 1994, is generating extremely useful pavement performance information, by identifying:

- Performance information for various pavement designs,
- Information on drainage and moisture propagation beneath the pavement surface,
- Variation in the mechanical properties of pavement materials under changing environmental factors, and
- The effect of traffic loads on pavement response and performance.

Carefully controlled load tests using non-destructive testing techniques and moving trucks on the Ohio SHRP Test Road are also generating invaluable data for researchers and designers alike, thus facilitating the validation of analysis codes that could be used as the basis of mechanistic-empirical pavement design procedures. Additional test sections have been monitored throughout the state with the primary aim of elucidating the influence of environment and load on pavement performance.

The project consists of a total of 4 general types of pavements designated according to the Specific Pavement Studies (SPS) guidelines set forth by the Strategic Highway Research Program (SHRP). The SPS-8 (Environmental effects in the absence of heavy traffic – Asphalt and concrete) sections on the ramp coming south from the village of Norton were completed late that season and opened to traffic on November 18, 1994. The new mainline lanes comprising the SPS-1 (Asphalt Concrete - AC), SPS-2 (Portland Cement Concrete – PCC) and SPS-9 (Asphalt Program Field Verification)) experiments were completed in the summer of 1996 and opened to traffic on August 14 and 15 of that year. The SPS-1 experiment included 14 test sections, the SPS-2 experiment included 19 sections, the SPS-8 experiment included 4 test sections and the SPS-9 experiment included 3 sections, making a total of 40 test sections on the project.

Ohio University has been involved in four distinct phases of this project. The objective of the first contract, "Development of an Instrumentation Plan for the Ohio SPS Test Pavement," was to devise a plan for the instrumentation of several test sections to monitor environmental factors in the pavement structure and to measure dynamic response from moving trucks. This plan was intended to provide minimal dynamic instrumentation as established by SHRP for four core sections in each of the SPS-1 and SPS-2 experiments, with the addition of supplementary sensors to enhance the value of these data. The full complement of strain gauges, linear variable differential transformers (LVDTs), and pressure cells planned for these eight sections was expanded to 25 additional SPS-1, SPS-2, SPS-8 and SPS-9 sections for a total of 33 sections being instrumented for dynamic response. Eighteen sections were instrumented to monitor environmental factors in the pavement structure, including moisture, temperature, and frost depth.

The second contract was awarded to coordinate the installation of these sensors with five other universities in the state of Ohio, including the University of Akron, Case Western Reserve University, the University of Cincinnati, Ohio State University, and the University of Toledo. After the sensor installation was completed, one set of special controlled vehicle tests was performed for FHWA on the two instrumented SPS-8 sections and one set of standard SHRP controlled vehicle tests was run on six SPS-1 sections and five SPS-2 sections. This project was entitled “Coordination of Load Response Instrumentation of SHRP Pavements – Ohio University”

A third contract was funded to continue monitoring the project after it was constructed and to conduct additional controlled vehicle tests. Ohio University supervised a total of seven series of controlled vehicle tests, oversaw the collection of environmental data by three other universities, and performed a forensic investigation on Section 390101 to determine the cause of its failure in 1999. This five-year contract, entitled “Continued Monitoring of Instrumented Pavement in Ohio,” ended in 2001.

The fourth contract “Evaluation of Pavement Performance on DEL23” awarded to Ohio University is in progress and it is scheduled to be completed in 2005. The main objectives of this study are:

1. Develop an Ohio SHRP Test Road Database. The database consists of several modules including, but not necessarily limited to, the following:
    a. Description of the SPS-1, 2, 8, and 9 Experiments
    b. Project Layout and Structural Design of Test Sections
    c. Construction Details – Costs, construction diary, general observations, nuclear-density tests, as-built data, cores, etc.
    d. Material Properties – In-situ testing, lab tests at OU and LTPP (if available), depth to bedrock, dynamic cone penetrometer, etc.
    e. Instrumentation – Sensor coordinates, sensor descriptions, data acquisition
        Climatic – Weather station sensors, data acquisition and processing
        Seasonal – Temperature, moisture and freeze/thaw sensors at 18 sites, water table, data acquisition and processing
        Dynamic – Strain, deflection and pressure sensors at 17 PCC and 16 AC sections, data acquisition and processing
        Traffic – Mettler-Toledo and IRD weigh-in-motion systems
    f. Chronology of Events – Significant dates of interest
    g. Climatological Data Obtained from the Weather Station
    h. Environmental Data Obtained from the Seasonal Sensors
    i. Controlled Vehicle Testing Data – Test matrices, actual test parameters, lateral offsets, environmental summary during tests, tables of peak values
    j. Traffic Data Obtained from the WIM Systems

k. Condition Surveys – PCR, crack surveys, rut depths, skid, roughness, and longitudinal and lateral profiles
l. Nondestructive Testing – FWD and Dynaflect, environmental summary
m. Forensic Investigations

2. Collection of Data on Structural Performance – a) ODOT is conducting annual roughness measurements with a profilometer and annual nondestructive tests with the Dynaflect and Falling Weight Deflectometer on all test sections. Ohio University is reviewing these data, summarizing the NDT results in tabular form and presenting a written assessment of them for ODOT. b) OU and ODOT are performing distress surveys of each section according to SHRP and ODOT protocol, respectively, and OU is measuring rut depths annually with a dipstick. c) OU and ODOT have performed one set of controlled vehicle tests on the core SHRP sections once a year for the duration of the project. Because most of the strain gauges originally mounted in the pavement are no longer operational, new strain gauges were mounted on the pavement surface just prior to testing as deemed appropriate. All historical data and new data obtained in these tasks is being processed and entered into the Ohio Test Road database.
3. Incorporation of ODOT Survey Data into the Database – ODOT has monitored the test pavements with a non-contact profilometer, a skid trailer, and periodic evaluations of the physical condition of the individual test sections. Average skid resistance has been obtained for the SPS-1 (original and replacement sections), SPS-2, SPS-8 (AC and PCC), and SPS-9 experiments. These data are being summarized and entered into the Ohio Test Road database. Weigh-in-motion traffic data are also being added to the database.
4. Coordination of the Collection of Environmental Data – Ohio University, Case Western Reserve University (project ended in May, 2004), Ohio State University, and the University of Toledo (project ended in September, 2004) have cooperated over the years in the collection of data from the 18 environmental installations at the site. OU has coordinated this effort. This work has continued in the same manner up to the end of the individual contracts for each university. OU has assumed responsibility for the data collection at selected sections previously monitored by the universities no longer involved. OU's responsibility has also included keeping the sensors and data acquisition equipment operational and entering all environmental data into the database.
5. Prediction of Performance – Using the results of condition surveys, laboratory tests performed at OU and weigh-in-motion data obtained by ODOT, OU has predicted the expected performance of all sections constructed on the Ohio SHRP Test Road. Procedures used in these calculations included: NCHRP 1-26 for asphalt and concrete, ODOT/AASHTO for asphalt and concrete, PCA for concrete, and Asphalt Institute for asphalt concrete.
6. Forensic Investigations – As section 390110 failed and was later replaced by section 390165, OU conducted a forensic investigation to determine which components of the pavement structure failed and why they failed. Prior to doing a forensic analysis of Section 390110, ODOT conducted a detailed series of FWD tests in the right wheel path to determine the stiffness profile along its 500-foot length. OU then performed several Dynamic Cone Penetrometer tests along the same path to investigate whether particularly weak layers were

present in the subgrade. Based upon these results, areas of low, medium, and high stiffness were identified, and transverse trenches were dug across the wheel path at these locations. To the casual observer, the severely distressed pavement surface would suggest rutting in the asphalt concrete. Transverse profiles of the subgrade and base surfaces and thickness measurements of the layers clearly indicated, however, that rutting had occurred in the base and subgrade, and the asphalt concrete pavement layer was merely conforming to the top of the base. This type of information is important in identifying specific causes of pavement failure and being able to correct them in future installations.

7. Monitoring Other Experimental Pavement Installations - Three other active experimental installations were constructed in Ohio to evaluate specific design aspects of rigid and flexible pavement. These include: three types of dowel bars on ATH 50, a total of five joint spacings and six types of base under a rigid pavement on LOR 2, and five types of base under a flexible pavement on LOG 33. OU is providing this service at no additional expense to the project. This monitoring includes the review and summary of Dynaflect and FWD data obtained annually at the sites by ODOT and annual distress surveys by ODOT and OU.
8. Collection of all data obtained on ATH 50, LOG 33 and LOR 2 and entering it into a database developed by OU personnel. This database is structured after the US 23 database and contains the same types of data, but on a smaller scale than that for US 23. Because of the uniformity of the pavement materials at these other sites, one average skid number in the vicinity of the test sections each year is sufficient.
9. Documentation – Five technical notes, two interim reports, and two forensic reports have been prepared. In addition, one final report will be published to document the tasks performed under this contract.

US 50 in Athens County,

Reconstruction of a 10.5 km (6.5 miles) long section of US 50 between the cities of Athens and Guysville in southeastern Ohio was started in March 1996. The reconstruction consisted of the replacement of the deteriorated two-lane roadway with a divided four-lane rigid pavement highway. ORITE along with ODOT and the FHWA, made arrangements to have four sections of the new pavement instrumented and monitored in an effort to obtain field performance data for High Performance (HP) Concrete that incorporated Ground Granulated Blast Furnace Slag (GGBFS), as a partial replacement of Portland cement in three sections of the new pavement. For comparison, one section was constructed of PCC without GGBFS, and is referred to as “standard concrete pavement” (SP).

The three HP and the single SP test sections were instrumented with three types of gages: strain gages in each section to monitor strain within the 25.4cm (10 in) slab, thermocouples to monitor temperature within the slab, and TDR probes to monitor subsurface moisture. A weather station with identical specifications to the Ohio SHRP Test Road weather station was also installed in this project. The concrete slab was placed on top of 10.1cm (4 in) of non-stabilized New Jersey (NJ) Base, followed by 15.2 cm (6 in) of Dense Graded Aggregate Base (DGAB) in the eastbound lanes. Two selected segments of the westbound passing and driving lanes included 4 inches of non-stabilized Iowa Base (IA) placed on top of 6 inches of DGAB supporting the slab. NJ base type was used in other locations in the westbound lanes.

The TDR probes were placed in five different locations beneath the DGAB in the subgrade layer. Each location contains 3 TDR sensors at depths of 15.2, 30.5, and 61 cm (6, 12, and 24 in), for a total of 15 probes.

Data collected for a maturity of concrete study indicated that temperature gradients generated between the surface and the bottom of concrete slabs had a significant impact on the formation of early cracks. Large values of strain recorded in the field during the curing period indicated that the two sections of HP pavement constructed in October 1997 would likely experience early cracking, as was observed.

NDT with the FWD conducted by ODOT and condition surveys conducted by ORITE on an annual basis have been intended to compare the performance of individual sections, In addition, dipstick profile measurements have yielded data to monitor slab warping. FWD data indicated that the uncracked high performance section experienced slightly less deflection at the joints than did the section containing standard concrete, suggesting less curvature and less loss of support under these slabs than under slabs constructed with standard concrete. FWD joint deflections were higher in the cracked high performance sections after one year of service than before the sections were opened to traffic, probably due to the presence of cracks.

TDR data suggested that moisture in the subgrade at sealed and unsealed joints was similar and, in some cases, more under the sealed joints than under the unsealed joints. FWD deflections at sealed joints were generally higher than at the unsealed joints

US 33 (former SR 124) in Meigs County,

The Ohio Department of Transportation in conjunction with its District 10 planned the construction of this test section in Meigs County consisting of a concrete pavement supported by 10" of dense graded base without a free drain base. This project gave ODOT the opportunity to obtain information concerning the moisture in the subgrade and the pressure at the interface between the base and the subgrade. Data being obtained on this project is intended to complement the excellent information already obtained along the US 23 test road in Delaware, Ohio. It is also providing quality data to help ODOT pavement engineers in their base selection type decision making.

The location of the project is such that it displays two types of subgrades: coarse-grained and fine-grained. To investigate the influence of joint sealing on the moisture content beneath the slabs, some of the joints were sealed while some others were unsealed. The instrumentation installed at the site in May of 2002, consisted of a total of 120 TDR probes to measure the volumetric moisture content and 4 pressure cells to measure the pressure reaching the subgrade. The TDR probes were installed beneath 8 slabs, at three locations within each slab consisting of an array of 5 probes per location at depths of half the thickness of the base, and at 2, 12, 24, and 42 inches below the base-subgrade interface. One of the arrays is located beneath the geometric center of the slab, while the remaining two are located beneath the transverse joint (one at the center and the other at the outer corner of the slab).

Pressure cells were located at the subgrade-base interface. Two of the cells were installed beneath one of the slabs supported by coarse-grained soils, while the remaining two lay beneath one of the slabs supported by fine-grained soils. The geometric location was selected to approximately coincide with the typical wheel path at 30 inches from the outer edge and at 5 and 10 feet respectively from the transverse joint on the 15-foot long slab. Pressure cell readings are collected once a year during FWD testing conducted by ODOT.

In addition to the installation of the TDR probes and the pressure cells, a series of laboratory tests were conducted on soil samples collected at the site for classification and index property determination. TDR probes are being monitored once a month for a period of time to end in 2005. Annual distress surveys are conducted to monitor the development of distress. All instrumentation installation and data collection procedures followed well-known SHRP protocols.

US 33 in Logan County,

Instrumentation of this project located on US 33, east of the city of Bellefontaine in Logan County, was completed in November of 1993. The road was expanded from two to four lanes and six sections of a four-mile stretch were instrumented. The following table shows the test section geometric and layer characteristics:

Section	AC thickness (in)	Base thickness (in)	Base Type
1	11	4 4	Asphalt Treated 304 Aggregate
2	11	4 4	Cement Treated 304 Aggregate
3	11	4 4	Non-stabilized Drainage, NJ type 304 Aggregate
4	11	4 4	Non-stabilized Drainage, IA type 304 Aggregate
5	11	8	304 Aggregate
6	13	6	304 Aggregate

The instrumentation installed along the test sections was intended to monitor: 1) pressure between the base and the subgrade, 2) pressure between the pavement and the base, 3) pavement deflection in the wheel path, 4) volumetric moisture content of the base and subgrade, 5) temperature profile of the pavement, and 6) strain measurement from FWD loads.

Volumetric moisture content was monitored with two TDR probes at each of the 6 test sections. The individual probes were located at 6 inches from the top of the subgrade and at 4 inches below the top of the base since most bases had a total thickness of 8 inches. Soil moisture probes were located along the wheel path and they were aligned horizontally. For sections 1 and 2, moisture probes were installed in the 304 material immediately below the treated bases.

FWD testing and surface condition surveys have been conducted periodically. Important findings from the previous monitoring of this project include the fact that deflection of AC pavements with asphalt treated bases varies significantly with temperature changes, while the deflection of the pavement over cement-treated base was the lowest. It is worth noting that in pavements containing non-treated bases, those with larger aggregate bases experienced less deflection. The finite element modeling of

FWD deflections by OU-PAVE indicated that this program was capable of calculating the maximum deflection and the deflection profile with reasonable accuracy.

The moisture content of the subgrade stayed fairly constant in the base and subgrade in Sections 1 and 2, during the initial observation period. However the moisture content in the remaining sections varied with the seasons. Unfortunately as of the time of writing of this proposal, all moisture probes have stopped working.

US 33 in Athens County (Nelsonville)

Until early 2003, US 33, the main throughway in Nelsonville, a small town with a population of about 4560, located in Athens County, was a dilapidated two-lane road named Canal Street. This road essentially follows a backfilled section of the Old Ohio-Erie Canal. With increasing demands of traffic in both load and magnitude the road deteriorated rapidly after any previous rehabilitation efforts. The Ohio Department of Transportation thus scheduled the complete reconstruction of 3.61 miles of US 33 in and around the city of Nelsonville.

The rigid pavement was divided into three sections differing in the type of concrete mixes, according to the following detail:

MIX	A	B	C
Aggregate	No. 57	No. 357	ODOT
Slag	30%	30%	Normal

A plan was developed in conjunction with ORITE at Ohio University to study the maturity and the amount of warping and curling for each of the three sections. Each test section was approximately 1000 feet long. The first 500 feet of each test section were cured with a spray-on membrane, while the remaining 500 feet were cured with wet burlap. Two slabs at each test section were instrumented with a total of 4 thermocouple sticks: 2 at the center of each slab and 2 at the outside corners. Each thermocouple stick consisted of 4 T Type thermocouples spaced evenly from top to bottom.

The following parameters were monitored:

1. Temperature profile during curing with thermocouples,
2. Temperature as a function of time for the maturity test,
3. Shape of the slab with a Dipstick and the stationary ORITE profilometer,
4. Shape of the slab using ODOT profilers,
5. Joint Movement of the slabs, and
6. Deflection during non-destructive testing.

In addition, a total of 290 cylinders and beams were prepared, cured and tested under controlled conditions in the laboratory to obtain their compressive strength and modulus of rupture, respectively, and to establish the maturity functions for the three different mixes used on US 33.

I-77 in Stark County

The use of long-life (perpetual AC) pavements has been proposed in Europe, and the idea is rapidly gaining ground in the United States. While the ability currently exists to produce perpetual pavements, the engineering community is working to establish guidelines and procedures for building these structures. Studies are also being conducted in an effort to validate the promising expectations of this pavement technique before it is implemented on a broad scale. As part of this verification effort by ODOT in conjunction with ORITE, Interstate 77 in North Canton, Ohio, has been instrumented with a number strain gauges and pressure cells, and a controlled truck test has been conducted there. The test pavement consists of six inches of Dense Graded Aggregate Base (DGAB, ODOT 304) followed by 13 inches of Bituminous Aggregate Base (ATB, ODOT 302), placed in three lifts. A 1.75-inch intermediate layer was also placed beneath the upper 1.5-inch surface layer.

A 20-foot section in the driving lane of north bound I-77 between 38th Street and Everhard Road was instrumented with Geokon strain gauge pressure cells, Dynatest quarter bridge AC embedment gauges, and thermocouples on August 23, 2003.

On December 15, 2003, data were collected from these sensors in response to a load applied using an ODOT single axle truck. The axle weight of the truck was approximately 26,000 lb. Truck speeds varied between 5 mph and 50 mph. During the tests, which were conducted at night due to traffic restrictions, the average surface temperature of the asphalt was approximately 31ºF, while the average pavement temperature as measured by the thermocouples was 36 ºF. As expected, the maximum strain for a speed of 5 mph is greater than the strain for 40 mph due to the viscoelastic properties of asphalt concrete. At higher temperatures, the asphalt stiffness will decrease and the strain will increase. However, due to the thickness of the asphalt, the temperature at the bottom of the asphalt pavement will not fluctuate significantly. Therefore, the strain will still potentially be less than the maximum design strain.

Input and Output Data Summaries. 2002 Guide Software

Figure A1. Example Input Summary Screen for 2002 Design Guide for AC overlay over Fractured PCC (Level 3 –Default Properties)

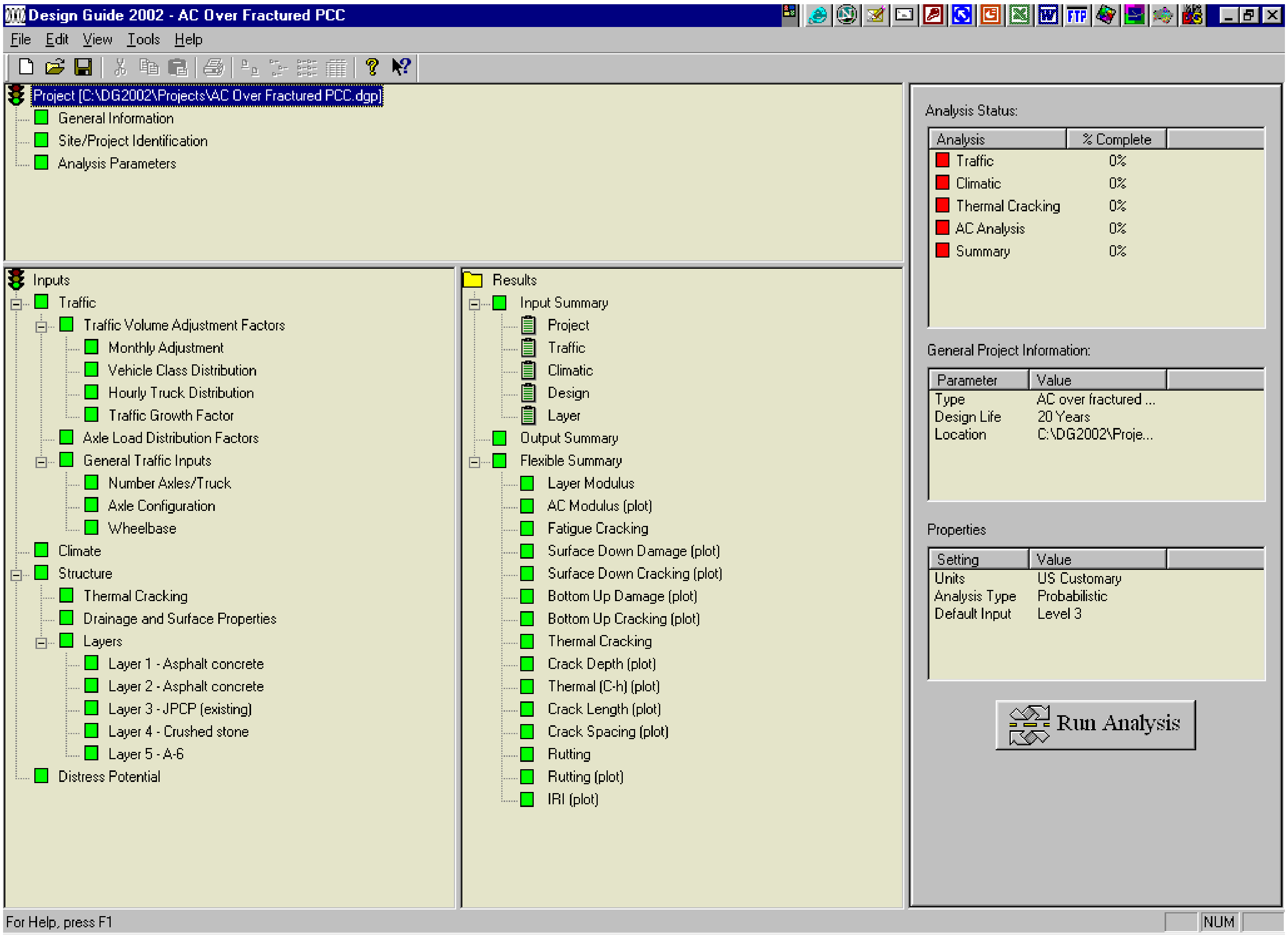

Figure A2. Example Output Summary Screen for 2002 Design Guide for AC overlay over Fractured PCC (Level 3 –Default Properties)

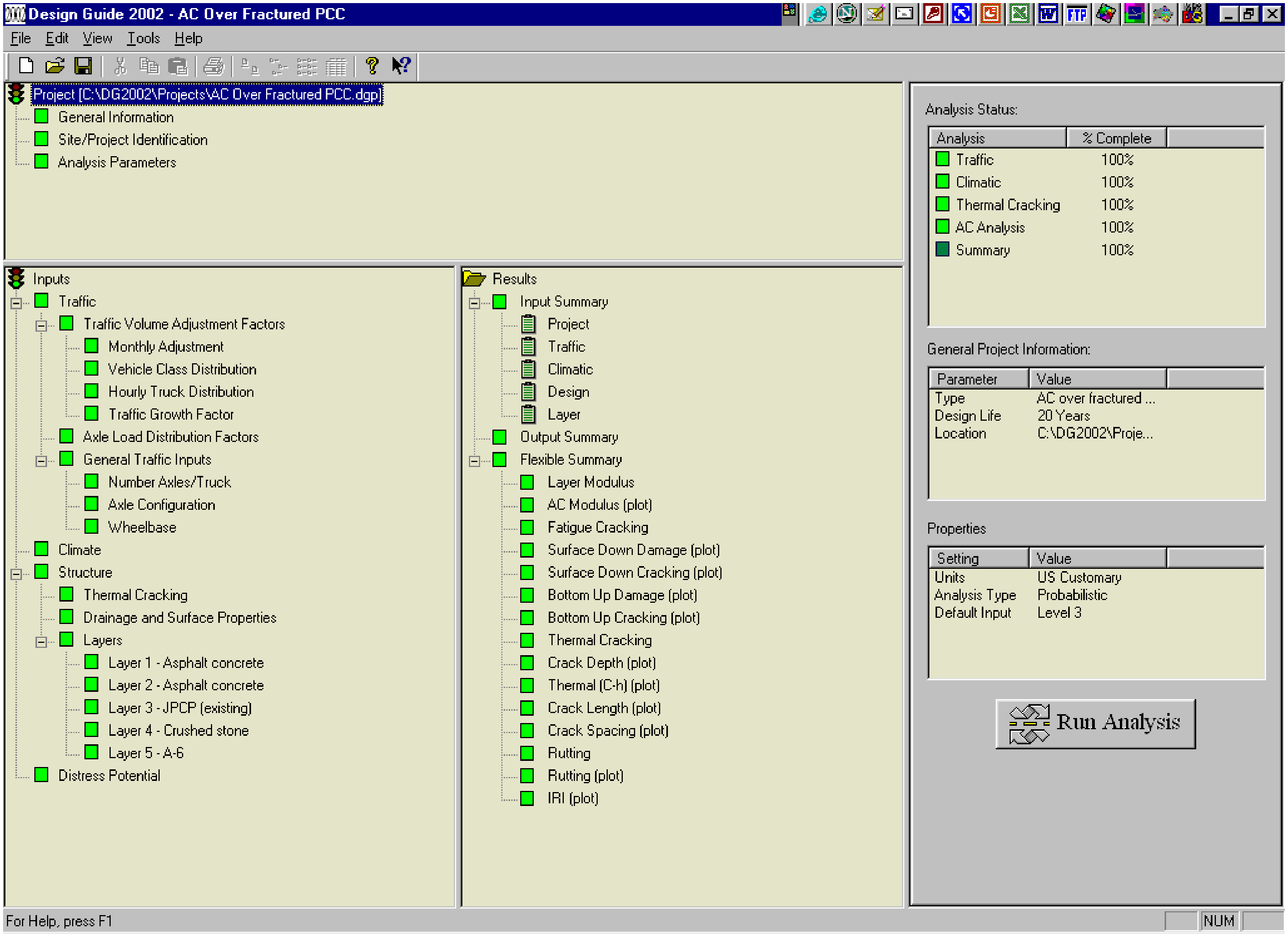

Figure A3. Example Output Permanent Deformation for 2002 Design Guide for AC overlay over Fractured PCC (Level 3 –Default Properties)

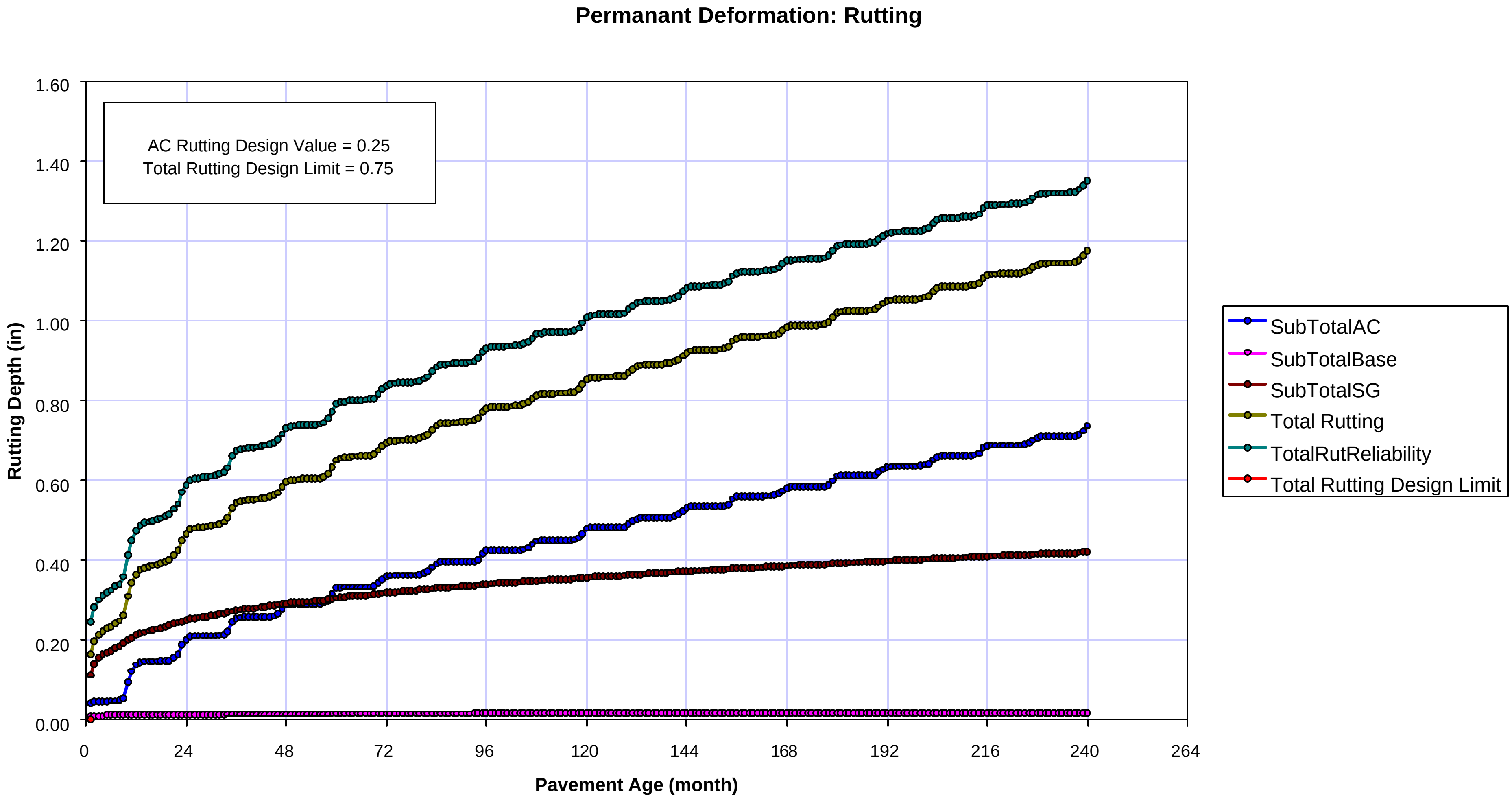

Figure A4. Example Input Table for 2002 Design Guide for AC overlay over Fractured PCC (Level 3 –Default Properties)

Project: AC Over Fractured PCC

General Information

Design Life	20 years
Existing pavement construction:	September, 1971
Pavement overlay construction:	September, 1991
Traffic open:	October, 1991
Type of design	JPCP Restoration

Description:

Analysis Parameters

Analysis type	Probabilistic

Performance Criteria

	Limit	Reliability
Initial IRI (in/mi)	63	
Terminal IRI (in/mi)	172	90
AC Surface Down Cracking (Long. Cracking) (ft/500):	1000	90
AC Bottom Up Cracking (Alligator Cracking) (%):	25	90
AC Thermal Fracture (Transverse Cracking) (ft/mi):	1000	90
Chemically Stabilized Layer (Fatigue Fracture)	25	90
Permanent Deformation (AC Only) (in):	0.25	90
Permanent Deformation (Total Pavement) (in):	0.75	90

Location:	
Project ID:	
Section ID:	
Functional class:	
Date:	8/12/03
Station/milepost format:	
Station/milepost begin:	
Station/milepost end:	
Traffic direction:	East bound

Default Input Level

Default input level	Level 3, Default and historical agency values.

Traffic

Initial two-way aadtt:	14000
Number of lanes in design direction:	2
Percent of trucks in design direction (%):	50
Percent of trucks in design lane (%):	95
Operational speed (mph):	60

Traffic -- Volume Adjustment Factors

Monthly Adjustment Factors (Level 3, Default MAF)

Month	Vehicle Class									
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
January	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
February	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
March	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
April	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
May	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
June	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
July	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
August	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
September	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
October	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
November	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
December	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Vehicle Class Distribution
(Level 3, Default Distribution)

AADTT distribution by vehicle class

Class 4	1.3%
Class 5	8.5%
Class 6	2.8%
Class 7	0.3%
Class 8	7.6%
Class 9	74.0%
Class 10	1.2%
Class 11	3.4%
Class 12	0.6%
Class 13	0.3%

Hourly truck traffic distribution
by period beginning:

Midnight	2.3%	Noon	5.9%
1:00 am	2.3%	1:00 pm	5.9%
2:00 am	2.3%	2:00 pm	5.9%
3:00 am	2.3%	3:00 pm	5.9%
4:00 am	2.3%	4:00 pm	4.6%
5:00 am	2.3%	5:00 pm	4.6%
6:00 am	5.0%	6:00 pm	4.6%
7:00 am	5.0%	7:00 pm	4.6%
8:00 am	5.0%	8:00 pm	3.1%
9:00 am	5.0%	9:00 pm	3.1%
10:00 am	5.9%	10:00 pm	3.1%
11:00 am	5.9%	11:00 pm	3.1%

Traffic Growth Factor

Vehicle Class	Growth Rate	Growth Function
Class 4	4.0%	Compound
Class 5	4.0%	Compound
Class 6	4.0%	Compound
Class 7	4.0%	Compound
Class 8	4.0%	Compound
Class 9	4.0%	Compound
Class 10	4.0%	Compound
Class 11	4.0%	Compound
Class 12	4.0%	Compound
Class 13	4.0%	Compound

Traffic -- Axle Load Distribution Factors

Level 3: Default

Traffic -- General Traffic Inputs

Mean wheel location (inches from the lane marking):	18
Traffic wander standard deviation (in):	10
Design lane width (ft):	12

Number of Axles per Truck

Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0.00	0.00
Class 5	2.00	0.00	0.00	0.00
Class 6	1.02	0.99	0.00	0.00
Class 7	1.00	0.26	0.83	0.00
Class 8	2.38	0.67	0.00	0.00
Class 9	1.13	1.93	0.00	0.00
Class 10	1.19	1.09	0.89	0.00
Class 11	4.29	0.26	0.06	0.00
Class 12	3.52	1.14	0.06	0.00
Class 13	2.15	2.13	0.35	0.00

Axle Configuration

Average axle width (edge-to-edge) outside dimensions,ft):	8.5
Dual tire spacing (in):	12

Axle Configuration

Single Tire (psi):	120
Dual Tire (psi):	120

Average Axle Spacing

Tandem axle(psi):	51.6
Tridem axle(psi):	49.2
Quad axle(psi):	49.2

Climate

icm file:
C:\DG2002\Projects\Minn60years.icm

Latitude (degrees.minutes) 45.04
Longitude (degrees.minutes) -93.21
Elevation (ft) 869
Depth of water table (ft) 20

Structure--Design Features

Structure--Layers

Layer 1 -- Asphalt concrete

Material type: Asphalt concrete
Layer thickness (in): 1.5

General Properties

~~General~~
Reference temperature (F°): 70

~~Volumetric Properties at construction~~
Effective binder content (%): 11.5
Air voids (%): 6
Total unit weight (pcf): 150

~~Poisson's ratio:~~ 0.35 (user entered)

~~Thermal Properties~~
Thermal conductivity asphalt (BTU/hr-ft-F°): 0.67
Heat capacity asphalt (BTU/lb-F°): 0.23

Asphalt Mix

Cumulative % Retained 3/4 inch sieve: 0
Cumulative % Retained 3/8 inch sieve: 15
Cumulative % Retained #4 sieve: 57
% Passing #200 sieve: 6

Asphalt Binder

Option: Superpave binder grading
A 10.2990 (correlated)
VTS: -3.4260 (correlated)

High temp. °C	Low temperature, °C						
	14	3.2	-7.6	-18.4	-29.2	-40	-50.8
114.8							
125.6							
136.4							
147.2							
158							
168.8							
179.6							

Layer 2 -- Asphalt concrete

Material type: Asphalt concrete
Layer thickness (in): 2.5

General Properties

~~General~~
Reference temperature (F°): 70

~~Volumetric Properties at construction~~
Effective binder content (%): 11
Air voids (%): 6.5
Total unit weight (pcf): 150

Poisson's ratio: 0.35 (user entered)

~~Thermal Properties~~
Thermal conductivity asphalt (BTU/hr-ft-F°): 0.67
Heat capacity asphalt (BTU/lb-F°): 0.23

Asphalt Mix
Cumulative % Retained 3/4 inch sieve: 5
Cumulative % Retained 3/8 inch sieve: 20
Cumulative % Retained #4 sieve: 64
% Passing #200 sieve: 5

Asphalt Binder
Option: Superpave binder grading
A 10.9800 (correlated)
VTS: -3.6800 (correlated)

High temp. °C	Low temperature, °C						
	14	3.2	-7.6	-18.4	-29.2	-40	-50.8
114.8							
125.6							
136.4							
147.2							
158							
168.8							
179.6							

Layer 3 -- JPCP (existing)
General Properties
Material type: JPCP (existing)
Layer thickness (in): 10
Unit weight (pcf): 150
Poisson's ratio: 0.2

Strength Properties
Elastic modulus (psi): 150000

Thermal Properties
Thermal conductivity (BTU/hr-ft-F°) : 1.25
Heat capacity (BTU/lb-F°): 0.28

Layer 4 -- Crushed stone
Unbound Material: Crushed stone
Thickness(in): 6

Strength Properties
Input Level Level 2
Analysis Type: ICM inputs (ICM Calculated Modulus)
Poisson's ratio: 0.35
Coefficient of lateral pressure,Ko: 0.9
Based upon PI and Gradation: -9999
Modulus (calculated) (psi): 39169

ICM Inputs
~~Gradation and Plasticity Index~~
Plasticity Index, PI: 1
Passing #200 sieve (%): 7.35
Passing #4 sieve (%): 53.5
D60 (mm): 5.88

~~Calculated/Derived Parameters~~
Maximum dry unit weight (pcf): 122.3 (derived)
Specific gravity of solids, Gs: 2.67 (derived)
Saturated hydraulic conductivity (ft/hr): 200 (derived)
Optimum gravimetric water content (%): 11.2 (derived)
Calculated degree of saturation (%): 82.6 (calculated)

Soil water characteristic curve parameters: Default values

Parameters	Value
a	11.3
b	1.75
c	0.515
Hr.	367

Layer 5 -- A-6

Unbound Material: A-6
Thickness(in): Semi-infinite

Strength Properties

Input Level: Level 2
Analysis Type: ICM inputs (ICM Calculated Modulus)
Poisson's ratio: 0.45
Coefficient of lateral pressure,Ko: 0.5
Based upon PI and Gradation: -9999
Modulus (calculated) (psi): 11609

ICM Inputs

~~Gradation and Plasticity Index~~
Plasticity Index, PI: 19
Passing #200 sieve (%): 43.7
Passing #4 sieve (%): 96.5
D60 (mm): 0.216

~~Calculated/Derived Parameters~~
Maximum dry unit weight (pcf): 110.9 (derived)
Specific gravity of solids, Gs: 2.73 (derived)
Saturated hydraulic conductivity (ft/hr): 5.87e-006 (derived)
Optimum gravimetric water content (%): 17.1 (derived)
Calculated degree of saturation (%): 87.2 (calculated)

Soil water characteristic curve parameters: Default values

Parameters	Value
a	48.6
b	1.2
c	0.638
Hr.	1840

Distress Model Calibration Settings - Flexible

AC Fatigue Level 3 (Nationally calibrated values)
k1 0.00432
k2 3.9492
k3 1.281

AC Rutting Level 3 (Nationally calibrated values)
k1 -3.51108
k2 1.5606
k3 0.4791

Standard Deviation Total Rutting (RUT): 0.1282*POWER(RUT,0.406)+0.001

Thermal Fracture Level 3 (Nationally calibrated values)
k1 5

Std. Dev. (THERMAL): 19+(24/(1+EXP(3-0.0025*THERMAL)))

CSM Fatigue Level 3 (Nationally calibrated values)
k1 1
k2 1

Subgrade Rutting	Level 3 (Nationally calibrated values)
Granular:	
k1	2.2
Fine-grain:	
k1	8

AC Cracking

AC Top Down Cracking	
C1 (top)	2.8
C2 (top)	1.4
C3 (top)	0
C4 (top)	1000
Standard Deviation (TOP)	77 + 114.8/(1+exp(0.772-2.8527*log(TOP+0.0001)))

AC Bottom Up Cracking	
C1 (bottom)	1
C2 (bottom)	1
C3 (bottom)	0
C4 (bottom)	6000
Standard Deviation (TOP)	32.7 + 995.1 /(1+exp(2-2*log(BOTTOM+0.001)))

CSM Cracking

C1 (CSM)	1
C2 (CSM)	1
C3 (CSM)	0
C4 (CSM)	1000
Standard Deviation (CSM)	CTB*11

IRI

IRI Rehabilitation over Flexible	
C1 (Flexible)	0.011505
C2 (Flexible)	0.003599
C3 (Flexible)	3.430057
C4 (Flexible)	0.000723
C5 (Flexible)	0.011241
C6 (Flexible)	9.04244
Std. Dev (Flexible)	0.179

IRI Rehabilitation over Rigid	
C1 (Rigid)	0.008263
C2 (Rigid)	0.022183
C3 (Rigid)	1.33041
Std. Dev (Rigid)	0.197

RESUMES