1-37A Copy No. ____________

Guide for Mechanistic-Empirical Design

OF NEW AND REHABILITATED PAVEMENT STRUCTURES

FINAL REPORT

PART 4. LOW VOLUME ROADS

NCHRP

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

Submitted by
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DISCLAIMER

This is the final draft as submitted by the research agency. The opinions and conclusions expressed or implied in the report are those of the research agency. They are not necessarily those of the Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or the individual states participating in the National Cooperative Highway Research Program.

Research Team Perspective, Future Research and Development Needs, and Acknowledgements

Perspective

The need for and benefits of a mechanistically based pavement design procedure were clearly recognized at the time when the 1986 AASHTO *Guide for Design of Pavement Structures* was adopted. The benefits are described in Part IV of that edition of the Guide. From the early 1960's through to the 1986 Guide, all versions of the Guide were based on limited empirical performance equations developed at the AASHO Road Test conducted near Ottawa, Illinois, in the late 1950's. Since the time of the AASHO Road Test, there have been many significant changes in trucks and truck volumes, materials, construction, rehabilitation, and design needs.

By 1986 it had become apparent that there was a great need for a design procedure that could account for changes in loadings, materials, and design features as well as direct consideration of climatic effects on performance. The AASHTO Joint Task Force on Pavements, in cooperation with the NCHRP and FHWA, sponsored the "Workshop on Pavement Design" in March 1996 at Irvine, California. The workshop participants include many of the top pavement engineers in the United States. They were charged with identifying the means for developing an AASHTO mechanistic-empirical pavement design procedure by the year 2002. Based on the conclusions developed at the March 1996 meeting, NCHRP Project 1-37A, Development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures: Phase II, was awarded to the ERES Consultants Division of Applied Research Associates, Inc. in February 1998. The project called for the development of a guide that utilized existing mechanistic-based models and databases reflecting current state-of-the-art pavement design procedures. The guide was to address all new and rehabilitation design issues and provide an equitable design basis for all pavement types.

Design Challenges

NCHRP Project 1-37A called for the development of a design procedure based primarily on existing technology. The many requirements and expectations of the procedure made this requirement very challenging. This was the first pavement design procedure that incorporated both the impact of climate and aging on materials properties in an iterative (biweekly, monthly) and comprehensive manner throughout the entire design life. Most of the existing models had only limited usage with equivalent or worst-case materials properties being used as inputs. When varying materials properties and climatic conditions were applied using an incremental damage approach over the design period, some of the models gave erroneous results. As a result, significant resources were required to modify and adapt these models to work within the incremental damage approach. In addition, the hourly, monthly, and annual variations in traffic loadings were superimposed on changes to materials and climate to more realistically reflect the way in which pavements exist in-service.

Perhaps the greatest challenge was to calibrate the mechanistic-based conceptual models with nationally observed field performance data. This also had never been successfully accomplished before nationally. After the theoretical distress models (e.g., fatigue cracking, rutting, thermal cracking, joint faulting, slab cracking, punchouts) were formulated they were compared and calibrated against observed data. The results were then evaluated which lead to improvements to the model, which in turn required another time-consuming calibration. This process was repeated many times to achieve each of the final acceptable mechanistic-based distress prediction models. In the end, this laborious approach proved to be extremely valuable in producing models that could reasonably predict observed pavement performance. After model calibration was completed, design reliability was incorporated into the design procedure by considering the residual between observed and predicted distress. This approach was necessitated because computer run times for the simulation approach were not practical at this time but will be in the future.

The final challenge was to incorporate the complex models and design concepts into a stable and user-friendly software package. The NCHRP 1-37A team realized that no matter how technically correct the design method is, adoption of the software will be hindered if the software is not accessible and easy to use. Therefore, extensive effort was expended in making the software user-friendly and minimizes potential input errors. This was accomplished as follows:

- Inputs: Assurance that proper inputs are utilized through use of carefully selected default values, recommended and absolute ranges for each input.
- Help: Context-sensitive and on-line help.
- Outputs: Tabular and graphical Excel/HTML based outputs to help the designer visualize the performance of their trial design.
- Climatic database: Hourly climatic data from over 800 locations in North America are included, which allows the user to easily select a given station or to generate virtual weather stations.

Another very important aspect of the design procedure and software is that improvements can be made over time in a piecewise manner to any of the component models (distresses, IRI, climatic, traffic, materials, and structural responses) and incorporated into the procedure for re-calibration. The framework has been laid for future updates. Ranges and default values of design inputs can be set by local agencies. The key limitation is the longer run time for flexible pavement design and rehabilitation. This can be improved through software optimization.

Future Needs for Continued Improvement of the Design Guide

Perhaps the most important characteristic of the Design Guide is its technological and modular framework for pavement design and its calibration-validation process. The bi-monthly/monthly incremental damage approach makes it possible to improve virtually any model and algorithmic subsystem over time. Any model or algorithm, from the various structural responses models to modulus prediction models to fatigue damage models, can be replaced with improved versions as they become available with further research. However, changes to models or algorithms that affect distress and smoothness predictions may require re-calibration with field data. The Design Guide provides the needed "focal" point for development and improvement of pavement design over time.

The NCHRP 1-37A project was required to use proven state-of-the-art technology. While this gave the research team a lot of possibilities, it restricted the team and prevented the use of some technology that might, after additional development, have resulted in better prediction models. However, it soon became apparent that even supposedly proven technology had major problems and required significant improvements and modifications before it would work within the mechanistic design framework. Many needed improvements were accomplished, but within the complex engineering system developed there exists several areas that need further development. The research team and the many individuals who assisted in reviewing the design procedure over the past several years identified a number of aspects that could be improved. This section provides a brief summary of those improvements.

Climatic Modeling

One of the major advances of the Design Guide was to integrate the weather station driven EICM model (Enhanced Integrated Climatic Model) directly with procedures to predict pavement and subgrade layer material modulus changes and gradients due to changes in temperature and moisture content within the pavement structure. The layer moduli values and temperature and moisture gradients and their integration within a comprehensive structural analysis methodology were implemented into the Design Guide to provide capabilities never before available. However, there are still several issues that need to be addressed in order to improve the accuracy of the overall climatic-materials interactive subsystem. Major changes in the subsurface moisture distribution had to be made in the EICM version to improve the predictions of the subsurface moisture content. These changes, predominantly in the SWCC relationships used to define the state of soil suction, were implemented and are now a part of the latest EICM version used in the Design Guide.

NCHRP 9-23 is nearing completion to enhance the subsurface moisture prediction methodology in the EICM and it is recommended that the NCHRP 9-23 results, conclusions, and suggested modifications to the EICM moisture model be directly incorporated into the Design Guide. There are several other minor areas that need further improvement in the EICM model. Problems still exist with the prediction of moisture in quality granular bases. The problem that occurs is that, due to the soil suction properties of these materials, little, if any, moisture can be drawn into the layer due to suction. For flexible pavement, no surface infiltration was allowed. As a consequence, moisture contents become exceedingly low, and base moduli are predicted to be abnormally high. A better infiltration model for both rigid and flexible pavements that predicts infiltration over time is needed. Finally, the current version of the EICM model in the Design Guide still uses an “empirical” recovery period, based upon soil type, to define the moisture – time changes after thaw weakening has occurred. It is recommended that a more mechanistic solution for this recovery process be developed.

Another aspect which will require continual, periodic updates to the Design Guide software involves updating the weather station databases with the latest information from the NCDC. The design guide at the present time contains historical hourly weather information for approximately 800 weather stations in North America. At the time the performance models were calibrated, for most of these stations, the historical records contain information that spans over a five-year period. However, it is recognized that an enhanced database will perhaps lead to a better calibrated models and will also help establish the key climatic variable more accurately.

Design Reliability

The procedure for design reliability included in the Design Guide while considered adequate for initial implementation should be considered as a place holder for a more comprehensive procedure. The identification of an improved methodology for design reliability is considered a top priority by the research team. The current method for incorporating reliability into the Design Guide is based upon the assessment of the overall standard error of the predicted distress as compared to observed distress. An improved procedure should make it possible to consider all of the key components of variability and uncertainty involved in pavement design. This would make it possible for the designer to input the mean, variance, and distribution of many key inputs and also incorporate the errors associated with the prediction models providing for a much more accurate design reliability. The designer would then be able to determine the sensitivity of the outputs (cracking, rutting, faulting, IRI, etc.) to variations in the inputs providing designers with improved knowledge of the most critical inputs that should be estimated with greater accuracy.

It is highly recommended that a continuing effort be made to incorporate such a design reliability approach in a reasonable and practical manner. It is cautioned, however, that a critical factor in this solution will be related to the computational time required for such an analysis which makes a Monte Carlo simulation approach somewhat impractical. There exist a number of modern approaches to reliability that can be explored that should provide a reasonable solution that makes it possible to have the above desired characteristics.

However, with such a more comprehensive reliability approach, the estimation of all associated variances and uncertainties will be required. This will require a large major research effort. This would include estimation of variations and uncertainties associated with traffic loadings, climate, material properties, layer thickness, and many other design inputs. It would also include errors associated with all models included in the design guide. An improved reliability procedure should not be attempted if a large allocation of resources is not available to estimate all of the applicable variations and uncertainties associated with all inputs and models. Such a procedure without good estimates of variances of all key inputs and prediction models would be completely misleading and erroneous.

Calibration-Validation of Prediction Models for Level 1, 2, and 3 Inputs

The major premise, upon which the hierarchical input system was devised, is that the standard error associated with the prediction of a given distress mode decreases as the level of engineering effort, intensity and testing is increased. This can be stated in an alternate manner by understanding that the reliability of the design prediction should logically increase when the level of the engineering effort used to obtain inputs is increased. This would logically lead to a reduction in life cycle costs of pavements.

In the Design Guide, it was only possible to demonstrate that this concept was applicable and valid for the thermal fracture module. It is recommended that this hypothesis be confirmed, to the practicing profession, for at least one major mode of load-associated distress. This is necessary because it is very important to illustrate to the engineering community that additional time, effort and design funding will actually result in a lower cost and longer performing product. If this is not demonstrated quickly, it is possible that engineers may simple be lulled into using a Level 3 (empirical correlations and default values) as the primary (and perhaps only) procedure to obtain inputs.

Conduct Additional Sensitivity Studies

A significant effort was expended in this study to complete a series of comprehensive sensitivity studies on a very wide range of design variables for several models. These included alligator (bottom up) and longitudinal (surface down) fatigue cracking and permanent deformation in flexible pavements. Bottom up and top down fatigue cracking for JPCP, joint faulting for JPCP and punchouts for CRCP were also included. While this was a monumental effort; there are still several major additional sensitivity studies that need to be completed for various other models related particularly to rehabilitation.

A major effort needs to be made to assess the sensitivity of reliability for the complex issue of rehabilitated flexible pavement and rigid pavement systems. Limited sensitivity runs were evaluated in the initial development of the Design Guide. However, a more extensive study needs to be completed for all major asphalt rehabilitation categories developed: HMA overlays of existing HMA pavements; HMA overlays of fractured PCC slabs and HMA overlays of sound (intact) PCC systems. For PCC rehabilitation categories it includes restoration, unbonded PCC overlays, bonded PCC overlays, and PCC overlays of flexible pavements.

Improve Accuracy of LTPP Database for Calibration-Validation of Distress/Smoothness Models

The LTPP database was a major asset for the calibration and validation studies performed in the development of the Design Guide. It also became apparent that there were many limitations associated with the LTPP database relative to its usefulness as a major tool in the performance calibration of the Design Guide. A large amount of project resources were expended to improve on the LTPP database for use in calibration. For instance, many time-series distress data varied considerably over time, requiring the research team to examine every field data sheet to clear up as many as possible. It is recommended that action be taken to improve the accuracy of entries in the LTPP database. As such improvements are made, the LTPP sections within each state could become more useful to local implementation and calibration efforts. LTPP should revaluate the importance of the national database as an essential tool that should feed directly into national and regional calibration studies of the Design Guide.

Two very important elements of the database that are missing are as follows. It is critically important that trench studies be completed on certain LTPP flexible test sections that would be designated as pavements to be used in any subsequent layer rutting calibration-validation project. Without trenching data; it is physically impossible to accurately calibrate any type of rutting model for flexible pavement systems. The second factor noted already relates to the field verification of the surface down (longitudinal) fatigue cracking mechanism for both flexible pavements and JPCP. It is very apparent that the existence of top down cracking can only be completely ascertained by conducting a field core-crack depth assessment study on selected LTPP sections.

Another important issue related to the LTPP distress identification procedure used is to modify the existing procedure to better identify longitudinal cracking. It is necessary to identify types of longitudinal (and even alligator cracking) that occur within the wheel paths. At present, there is no known way for researchers, using the database, to distinguish cracking that is solely related to load cracking (it would be assumed that all cracking in any wheel path is load associated) and cracking that is non load related, such as longitudinal cracking reflected from existing construction joints or lane widening. The manner in which distresses are recorded should be reexamined, with the intention that the ultimate goal of the distress database is to use the distress measurements in some form of structural (or even non-structural) models for calibration-validation purposes.

It is recommended that the seasonal levels of Ground Water Table (GWT) be measured. The same level of importance can also be stated for the depth to bedrock. The sensitivity runs of these two variables have pointed out that they may be significant variables influencing pavement distress and performance. Best estimates and county soil maps were used to estimate these parameters for the calibration.

<u>National Center for the Coordination of State Calibration Efforts for Flexible and Rigid Pavement Systems</u>

It is recommended that a concerted national effort be made to establish a center that would serve to develop and house a complete materials database on a variety of tests that are required (or will be required) for implementing the Design Guide. It is hoped that as State DOT / Universities conduct material evaluations for their own DOT; their results can be placed in the National Center database to add to those material responses that were originally used in the development of the Design Guide models. The center could also house traffic databases developed by various States that would help to fulfill or help validate the needs of each agency for traffic inputs. Information and contents of the database would be freely accessible to all agencies supporting the Center. There may be other dta that could also be houses by such a center such as climatic data.

<u>Improve Accuracy of Smoothness (IRI) Models</u>

The Guide includes several models for IRI prediction for various types of flexible pavements, rigid pavements, and various overlays. These empirical based models were developed based on a limited number of LTPP sections. These models have serious deficiencies that will become evident as they are used in pavement design and are in great need of improvement. These models should be considered placeholders for new and improved models that could be implemented in the future. There exists today substantially more data from which improved models could be developed. However, since smoothness is such a critically important user consideration, and is also the only performance indicator that is common between flexible and rigid pavements, it is recommended that a major effort be initiated to predict smoothness in a more mechanistic based manner. The smoothness models would input the M-E based distress prediction, the initial as-built smoothness, and other parameters (e.g., foundation movement) needed for the prediction over the design life. This would undoubtedly improve the accuracy and capability of smoothness in the Design Guide.

<u>HMA Pavements and Overlays</u>

An enhanced calibration-validation effort is greatly needed. Although the research team spent a lot of resources trying to obtain valid LTPP data, there was much missing data and only a small fraction could be used in calibration for new and overlaid pavements. The results of the effort shown in flexible pavement calibration-validation appendices for data (Appendix EE), fatigue cracking (II), permanent deformation (GG), and thermal cracking (HH) reflect a major effort of calibration and validation of the initial distress models for new asphalt pavement systems. However, it is quite obvious that some significant limitations were associated with the available performance data used from the LTPP sections that are in need of a considerable effort to improve their accuracy. A major recommended future need is to greatly increase the number of design sections used in the calibration of the fatigue and permanent deformation modes of distress.

A very important element of these additional test sections is that they should conform to two critical recommendations that were suggested by Witczak et al and the Superpave Support and Performance Models Management Team (FHWA Contract DTFH61-95-C-00100) in the 30 September 1996 "Models Evaluation Report". In this report to the FHWA, it was urged (and repeated in several other ensuing report documents) that "In addition to measurement and classification of surface distress, all pavement sections included in the experimental designs for load related distress, particularly permanent deformation, will require trench studies to apportion distress (rutting) distributions between the bound and unbound layers. These studies will be conducted in conjunction with material sampling required for the unbound materials test plan described in Section 6.2". None of the LTPP test sections used in this study effort for the main calibration effort had trench data. Only surface (total) rutting was available. As such, it is the belief of the research team that a very large portion of the "predictive rut depth error" is directly due to the fact that actual deformations within material layer types were not available for the initial calibration study.

Longitudinal surface (top-down) cracking prediction model was based on the assumption that all longitudinal cracking in the LTPP database (in the wheel paths) were load associated and propagates from the surface down. As pointed out by Witczak et al and the Superpave Support and Performance Models Management Team (FHWA Contract DTFH61-95-C-00100) in the 30 September 1996 "Models Evaluation Report"; it was noted that "Substantial field data from the United States, the Middle East, and Southeast Asia suggests that significant fatigue cracking can initiate and propagate from the surface of asphalt concrete pavement layers. This is in contrast to the traditional model, which considers the bottom of these layers as the only locus of fatigue cracking. The performance model for fatigue cracking must account for this failure mechanism if it is confirmed through careful field studies. Thus, the materials data collection plan requires the sampling of pavement cores directly through fatigue cracks in order to evaluate the location of crack initiation and the direction of its propagation in the asphalt layers." It will not be possible to pursue further calibration-validation studies for either permanent deformation (bound and unbound layers) or top down longitudinal surface cracking until LTPP sections can be trenched and a field core-crack study completed. Once this is completed, the additional sections would be quite helpful to verify (modify) several critical assumptions made in the initial effort as well as being combined with the original sections used to develop the initial national calibration factors developed in this study. It is noted that a study (NCHRP 1-42) is already underway on this topic.

In addition to more LTTP sections for enhancing the calibration of fatigue and rutting in new sections; it is recommended that additional efforts be made to expand the calibration-validation of the rehabilitated sections as well. Here, the selection of additional sections having HMA overlays over existing HMA pavements, PCC fractured slabs (crack-seat; break-seat and rubblized PCC); JPCP, and CRCP pavements as well as pavements having chemically stabilized layers needs to be analyzed with a much more comprehensive calibration effort that was possible within the time and funding restraints of the initial study.

Enhance/improve existing models to increase accuracy. It should be recognized that several key model selections and approaches were decided several years ago in the early stages of the project. Since this time, the "state of the art" has continuously advanced as well as other technologies that were available but required additional development may have produced more accurate distress models. While the current methodology is felt to provide a strong foundation for the prediction of distress in a mechanistic-empirical framework, there are several model advances that should be undertaken to assess if they can significantly increase the accuracy of the predicted distress.

The reflective crack model for HMA overlays is an empirical place holder for the future development and implementation of a M-E based reflective crack model. This is one of the most critical research needs for flexible pavements. The enhancement of the top-down surface fatigue model with a more fundamental approach is also considered as a top research need.

One of the major goals of the NCHRP 1-37A project was to integrate the major HMA mixture response results from the NCHRP 9-19 (Superpave study) which is nearing completion. In essence, the ultimate goal is to integrate HMA mixture design within a structural design framework. It is recommended that the enhancement of this process should be to integrate the NCHRP 9-19 work with Flow Time (Ft) and Flow Number (Fn) into the permanent deformation models for asphalt mixtures used in the current Design Guide. Both the Ft and Fn values are Tertiary flow mix parameters of an asphalt mixture. In the current Design Guide, only the secondary rutting phase is modeled by the $\varepsilon p/\varepsilon r$ power model used. Thus the inclusion of a methodology to also consider tertiary (plastic shear failure) in a structural model would be a very significant enhancement to the Design Guide.

The current Design Guide rut model for HMA rutting was found to need an empirical relationship to adjust the rutting as a function of the depth within the asphalt thickness. This equation turned out to be a 5^{th} order polynomial that accurately predicted the in-situ rutting-depth profile for several MnRoad sections. While this modification was statistically developed; it has the general appearance of the typical relationship of shear stress with depth within a Boussinesq solid. It would be quite important to assess if this depth relationship would actually conform to a more rational distribution associated with the maximum shear stress-depth relationship found from mechanics, rather than from pure empiricism.

Reduce the computational time for flexible pavement design. The flexible pavement team devoted a continuous effort in trying to reduce the computational time for the flexible pavements analyzed in the Design Guide. A very significant decrease in runtime has simply been a result of the generation of the microprocessor used in the analysis. In the early stages of the software development; average runtime on what was then conceived to be a "fast" microprocessor (500 MHz system) was about 5.1 minutes per analysis year. With present day 2.8 GHz units, the time has been reduced to under 1.4 minutes per analysis year. Without any major changes in software code, it is estimated that for future 4.0+ GHz units; the average runtime may actually approach about 1 minute per analysis year. When one considers the complexity of the asphalt portion of the Design Guide, along with the hundreds of thousands of incremental damage computations conducted within an analysis run; the time is not excessive. Nonetheless, it is apparent that significant trade-off in time reduction could be made if certain assumptions were "relaxed" more than they currently are. It is recommended that continuous efforts be undertaken to reduce the computational time for the program.

Enhancements to the Witczak et al E* predictive model are needed. The dynamic modulus predictive equation for asphalt mixtures, developed by Witczak and a vast array of colleagues, is an important component of the hierarchical structure of the Design Guide. While this equation is considered quite accurate and has been developed from the E* lab test results of nearly 150 HMA mixtures and 1500 data points; there is an opportunity to nearly double the number of mix types and increase the total number of data points to approximately 6000 by adding a significant number of E* results that have been collected at ASU from several new major studies that have been completed (NCHRP 9-19; ADOT 2002 DG Implementation; ADOT AR Projects). The objective of this study would be to combine all available E* results and perform a new round of statistical studies to develop a new, more accurate predictive model. The intention of this effort would be focused upon keeping the same "sigmoidal" functional form as the current model; but trying to develop a more accurate assessment of the volumetric components of the mix (air voids, asphalt volume etc.). This minor change would definitely lead to more rational distress predictions in the Design Guide, particularly for HMA rutting and fatigue fracture. A final effort should also be focused upon assessing whether or not the current "Ai-VTSi" viscosity characterization could be completely replaced by the new Performance Grade (PG) binder properties such as G* (Dynamic Shear Modulus). If the use of the G* (binder) is found to be feasible, the use of this binder property, rather than the use viscosity, would bring the entire HMA material characterization process into a much more current methodology.

Conduct initial calibration trials of FEM technology for asphalt pavement systems. All of the load associated calibration efforts used in the Design Guide has been based upon the linear elastic layered pavement response model (JULEA). However, a finite element pavement response model is also included for the case when a Level 1 input is desired for the use with non-linear resilient modulus (Mr) of any unbound base, subbase and/or subgrade layer. The limitation of this approach, however, is that it has not been calibrated. It is therefore recommended that an initial effort be undertaken to start a calibration with LTPP sections that have been used in the initial NCHRP 1-37A study. Because the complexities and problems that may surface with the FEM calibration process are unknown at this time; it is recommended that only a handful (6-8) LTPP sections be initially selected, Level 1 Mr testing be completed on all unbound layers, and a pilot calibration study completed. After this pilot study is completed, plans and scheduling of a major FEM calibration can be developed, using insights obtained from the pilot effort.

<u>Concrete Pavements & Overlays</u>

The current Design Guide can only handle PCC overlay thickness of 6 in and greater. A major effort is needed to develop procedures for thinner PCC overlays including the ultra thin overlays that are bonded to the asphalt surfacing. More adequate characterization of the existing HMA pavement will also be required. This may require a more comprehensive structural modeling as well as improved knowledge on the bonding of PCC to HMA. This is considered a priority for improvement of the PCC rehabilitation design procedure.

Shrinkage of the top portion of the PCC slab is directly considered in design in two modes: permanent and transitory (varying with monthly relative humidity). The methodology, however, is not nearly as comprehensive or reliable as is needed to match the level of accuracy that exists for temperature gradients through PCC slabs. The method of incorporating permanent shrinkage into the permanent curl/warp needs to be improved. The existing Design Guide shows a continuing increase in shrinkage over many years resulting in the opening of cracks and joints over a long time period. While this does occur, the magnitude needs better estimation procedures.

Zero-stress temperature is the temperature at which after placement the PCC becomes solid enough to go into tension. This temperature is used as the basis to compute the openings of cracks and joints which affect the transfer of shear and load and crack load transfer over time. Improved procedures are needed to estimate this important parameter in design of JPCP and CRCP.

Permanent curl/warp effective temperature difference is a critical input that needs further calibration and amplification. This input is used to predict top down and bottom up slab cracking and also joint faulting. This value was obtained nationally through optimization of cracking of JPCP for many LTPP and other sections across the U.S. There area no procedures to adjust this input to consider other construction situations (e.g., night time construction, wet curing, hot desert paving, and so on). Obtaining better estimates of this input for varying construction conditions would greatly improve the ability to take construction and materials into consideration in the design phase.

The coefficient of thermal expansion/contraction (CTE) is a new and most significant input to the new rigid design procedure. Since this input has not before been measured and used in design much more information is needed to help the designer estimate this input adequately. The extensive LTPP data could be analyzed to further develop improved recommendations for CTE as well as extensive additional lab studies carried out for a variety of aggregates and other components of today's PCC mixtures.

The CRCP procedure includes methodology to predict both crack spacing and crack width. While these models are very comprehensive and mechanistic based, additional validation is greatly needed since they play a very critical role in the performance of CRCP. The crack deterioration model which controls punchout development depends greatly on crack width and thus development of punchouts is critical. Very little validation of the crack deterioration model was possible and more is needed. One variable that is missing is top aggregate size which has a major effect on crack load transfer efficiency.

An enhanced calibration-validation effort is greatly needed for rigid pavements. Although the research team spent a lot of resources trying to obtain valid LTPP data, there was much missing data and only a small fraction could be used in calibration for new and overlaid pavements. The results shown in various calibration-validation appendices include data (Appendix FF), CRCP punchouts (Appendix LL), joint faulting (Appendix JJ), transverse fatigue cracking (appendix KK), and rehabilitation (Appendix NN) reflect a major effort of calibration and validation of the load associated distress models for new and rehabilitated concrete pavements. However, it is quite obvious that some significant limitations were associated with the available performance data used from the LTPP sections that are in need of a considerable effort to improve their accuracy.

There is a great need for additional PCC rehabilitated sections including concrete pavement restoration, unbonded PCC overlays, bonded PCC overlays, and PCC overlays of flexible pavements. Particularly needed are JPCP and CRCP overlay sections which are being used routinely by several states. With these data, a much more comprehensive calibration-validation effort could be conducted with the result of improved distress prediction models for all these PCC rehabilitations. There is also a great need for low volume road sections for use in better calibration of these types of pavements.

Enhance/improve existing models to increase accuracy in prediction. It should be recognized that several key model selections and approaches were decided several years ago in the early stages of the project. Since this time, the "state of the art" has continuously advanced. In addition, there were other technologies that with further development could likely have produced improved distress prediction models. While the current methodology is felt to provide a strong foundation for the prediction of distress in a mechanistic-empirical framework, there are several model advances that should be undertaken in the future to assess if they can significantly increase the accuracy of the predicted distress.

One of the major goals was to integrate some PCC mixture and construction factors into the structural design process. It has been long recognized that PCC mixture design and construction aspects strongly relate to ultimate long term performance of all types of rigid pavements and thus this capability would provide a major enhancement to the structural design of a PCC pavement. A major initial effort was made to incorporate several key mixture and construction factors, however, addition development and improvement is greatly needed. PCC mixture parameters incorporated include the various measures of strength (and its gain over time), the elastic modulus (and its gain over time), the w/c ratio, cement content and type, thermal coefficient of expansion, and relative drying shrinkage through the slab over time. Construction factors include the zero-stress temperature of the slab after placement and the permanent curl/warp equivalent temperature difference. While these important factors are included in the design process, methods to estimate them for design are limited and several are considered only rudimentary. Thus, great improvement is possible and needed.

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Project Management
Mr. John P. Hallin of ERES Consultants Division of Applied Research Associates, Inc. (ERES) served as the Principal Investigator, and Mr. Ken McGhee with Fugro-BRE, Inc. served as the Co-Principal Investigator.

Flexible Pavement Team
Dr. Matthew W. Witczak of Arizona State University headed the flexible pavement team. Members of the flexible pavement team were:

- Arizona State University: Mohamed El-Basyouny, Waseem Mirza, Claudia Zapata, Dragos Andrei, and Manuel Ayres.
- Fugro-BRE, Inc.: Harold Von Quintus (also served on the ERES team).
- University of Maryland: Charles Schwartz.
- Advanced Asphalt Technologies, LLC: Ray Bonaquist.
- University of Illinois, Urbana-Champaign: William Buttlar.
- Consultant: Jacob Uzan.

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- Amy Simpson, Ahmed Eltahan, Weng-on Tam, Amber Yau, (Fugro-BRE, Inc.).
- Yongyi Feng and Yiquan Hu (University of Maryland).

Rigid Pavement Team
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- Manuel Ayres and Waseem Mirza, (Arizona State University).

Consultants

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