
Computer-Based Guidelines for Concrete Pavements, Volume I: Project Summary

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FOREWORD

This report documents the investigation, modeling and validation of the enhanced High Performance PAVing (HIPEPAV[®]) II, a comprehensive, yet user-friendly software package. HIPERPAV II primarily incorporates a set of guidelines for the proper selection of design and construction variables to minimize early-age damage to Jointed Plain Concrete Pavement (JPCP) and Continuously Reinforced Concrete Pavement (CRCP). In addition, the software determines the effect of early-age behavior factors on JPCP long-term performance. This report, Volume I of a three-volume set, is the Project Summary documenting the efforts undertaken for the development of the guidelines. Volume II is the Construction and Design Guidelines HIPERPAV II User's Manual, which provides general instruction on the use and application of the HIPERPAV II. Volume III is the Technical Appendixes, which documents the investigation, modeling and validation of the HIPEPAV II. HIPERPAV II software program will be available on a CD, or will be downloadable from FHWA Web site <http://www.tfhrc.gov/pavement/pccp/hipemain.htm>.

This report will be of interest to those involved in concrete pavement mix design, as well as the design and construction of concrete pavements. Sufficient copies of this report and CD software program are being distributed to provide two copies to each FHWA Resource Center, two copies to each FHWA Division Office, and a minimum of four copies to each State highway agency. Additional copies for the public are available from the National Technical Information Services (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

T. Paul Teng, P.E.
Director, Office of Infrastructure
Research and Development

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16. Abstract This report documents enhancements incorporated in the (High PERFORMANCE PAVing) HIPERPAV [®] II software. Enhancements made within this project include the addition of two major modules: a module to predict the performance of jointed plain concrete pavement (JPCP) as affected by early-age factors, and a module to predict the early-age behavior (first 72 hours) and early life (up to 1 year) of continuously reinforced concrete pavement (CRCP). Two additional Federal Highway Administration (FHWA) studies were also incorporated: one that predicts dowel bearing stresses as a function of environmental loading during the early age, and a module for optimization of concrete paving mixes as a function of 3-day strength, 28-day strength, and cost. Additional functionality to the software was also incorporated by reviewing and prioritizing the feedback provided by users of the first generation of the software, HIPERPAV I. To accomplish the above, an extensive literature search was conducted in search of mechanistic and mechanistic-empirical models that could be used for this purpose. A system approach was followed for incorporating additional developments in the software following the same methodology employed during the development of the original HIPERPAV I software. Evaluation of the enhancements was accomplished with the help of a Technical Expert Panel (TEP). Likewise, validation of the model predictions was accomplished by employing existing databases and investigation of pavements during construction and in service. This report summarizes the work conducted to enhance the HIPERPAV concrete pavement design guidelines. This is the first volume in a series of three volumes that document the different tasks carried out in accomplishing the objectives for this project. <table border="0" style="width: 100%;"> <thead> <tr> <th style="text-align: left;"><u>FHWA No.</u></th> <th style="text-align: left;"><u>Vol. No.</u></th> <th style="text-align: left;"><u>Short Title</u></th> </tr> </thead> <tbody> <tr> <td>FHWA-HRT-04-121</td> <td>Volume I</td> <td>Project Summary</td> </tr> <tr> <td>FHWA-HRT-04-122</td> <td>Volume II</td> <td>Design and Construction Written Guidelines and HIPERPAV II User's Manual</td> </tr> <tr> <td>FHWA-HRT-04-127</td> <td>Volume III</td> <td>Technical Appendixes</td> </tr> </tbody> </table>				<u>FHWA No.</u>	<u>Vol. No.</u>	<u>Short Title</u>	FHWA-HRT-04-121	Volume I	Project Summary	FHWA-HRT-04-122	Volume II	Design and Construction Written Guidelines and HIPERPAV II User's Manual	FHWA-HRT-04-127	Volume III	Technical Appendixes
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO: American Association of State Highway and Transportation Officials
ACI: American Concrete Institute
ASCE: American Society of Civil Engineers
ASTM: American Society for Testing and Materials
ADO: ActiveX[®] Data Objects
AQC: Acceptance Quality Characteristics
BCO: Bonded Concrete Overlays
BP: Bazant-Panula
CCRI: Swedish Cement and Concrete Research Institute
CEB-FIP: Euro-International Concrete Committee (Comité Euro-International du Béton)-International Concrete Federation (Fédération Internationale du Béton)
COM: Component Object Model
COMET: Concrete Optimization, Management, Engineering, and Testing
COPES: Concrete Pavement Evaluation System
COST: Concrete Optimization Software Tool
COTR: Contracting Officer's Technical Representative
CPTP: Concrete Pavement Technology Program
CRCP: Continuously Reinforced Concrete Pavement
CRSI: Concrete Reinforcing Steel Institute
CTB: Cement-Treated Base
CTE: Coefficient of Thermal Expansion
CTR: Center for Transportation Research
DOM: Document Object Model
DOT: Department of Transportation
ESAL: Equivalent Single Axle Loads
FEM: Finite-Element Method
FDM: Finite-Difference Method
FHWA: Federal Highway Administration
FWD: Falling Weight Deflectometer
GIS: Geographic Information System
GPS: General Pavement Studies
GUI: Graphical User Interface

HIPERPAV: High PERFORMANCE Concrete PAVing.
ICM: Integrated Climate Model
IRI: International Roughness Index
JCP: Jointed Concrete Pavement
JPCP: Jointed Plain Concrete Pavement
LCC: Life Cycle Costs
LCC_{DES}: “As-Designed” Life Cycle Costs
LCC_{CON}: “As-Constructed” Life Cycle Costs
LTE: Load Transfer Efficiency
LTPP: Long-Term Pavement Performance
M&R: Maintenance and Rehabilitation
MOR: Modulus of Rupture
MRU: Most Recently Used
NCHRP: National Cooperative Highway Research Program
NIST: National Institute of Standards and Technology
PCC: Portland Cement Concrete
PCCP: Portland Cement Concrete Pavements
PRS: Performance-Related Specifications
PSI: Present Serviceability Index
PSR: Present Serviceability Rating
QA: Quality Assurance
RIPPER: Performance/Rehabilitation of Rigid Pavements
SHA: State Highway Agency
SHRP: Strategic Highway Research Program
SDS: Software Design Specification
SMP: Seasonal Monitoring Program
SRS: Software Requirement Specification
TEMP: Total Environmental Management for Pavements
TEP: Technical Expert Panel
XML: Extensible Markup Language

CHAPTER 1. INTRODUCTION

This report describes the efforts undertaken to enhance the Federal Highway Administration (FHWA) High Performance Concrete Paving (HIPERPAV[®]) computerized design and construction guidelines by incorporating jointed concrete pavement (JCP) long-term performance prediction models, continuously reinforced concrete pavement (CRCP) early-age behavior models, and two additional modules with results from related FHWA studies.

1.1 BACKGROUND

When the first generation of the software, HIPERPAV I, was first developed in 1996, a new approach was born: a total systems approach to concrete paving. In this simple to use, yet technically complex piece of software, the power to simulate problems before they happen is now a reality. In the past few years, FHWA has sponsored the expansion of this concept into a usable and reliable tool. Contractors, suppliers, agencies, and academics all can utilize the power in this approach.

The total systems approach has now proven itself with the end-user. This project continued this development by incorporating additional modules in a new software generation, termed HIPERPAV II. For example, a CRCP module has been added. CRCP has been used by a number of States as a durable concrete paving alternative. Although more expensive initially, many CRCP sections have given excellent performance with little to no maintenance.

Long-term pavement performance (LTPP) is also now being considered in HIPERPAV II. As a result of the work done under the Strategic Highway Research Program (SHRP), an extensive database has been compiled that contains a wealth of valuable data related to design, construction, and performance of hundreds of pavements throughout North America currently available to the pavement community. A number of additional models have been developed since that time.

In 1996, as part of the LTPP program, a critical gap was identified to predict properly the performance of concrete pavements: the early-age conditions. “Early-age” in this case is the period of performance (typically 48–96 hours) that is critical in establishing the benchmark for future pavement performance. In this project, the early-age mechanisms that influence long-term performance have been investigated. Experienced practitioners have always recognized this cause and effect, and now the total systems approach to concrete paving is the vehicle to tie these mechanisms together.

In recent years, FHWA has sponsored a number of projects related to various aspects of concrete paving. The end results of these studies are valuable assets. These assets, however, must be shaped into a form that the end-user can readily accept. Findings from two of these FHWA studies were incorporated into the total systems approach vis-à-vis HIPERPAV II. As a result, two new modules were integrated; a dowel analysis module and a concrete mix optimization module.

1.2 PROJECT OBJECTIVES

There are three objectives for the work conducted in this project:

1. Develop a module capable of predicting the impact on long-term jointed plain concrete pavement (JPCP) performance as a function of early-age behavior.

2. Develop a module capable of predicting the early-age behavior of CRCP.
3. Develop additional modules that incorporate results from existing FHWA studies related to concrete paving.

Table 1 graphically depicts these additions to the HIPERPAV II software. HIPERPAV I is characterized by cell 1 in this table. Project objectives 1 and 2 have been accomplished by developing the modules shown in cells 2 and 3, respectively. An additional module that might be developed in the future would meet the attributes of cell 4. This additional module could characterize the long-term performance of CRCP as a function of early-age behavior.

Table 1. Proposed additions to the HIPERPAV II software.

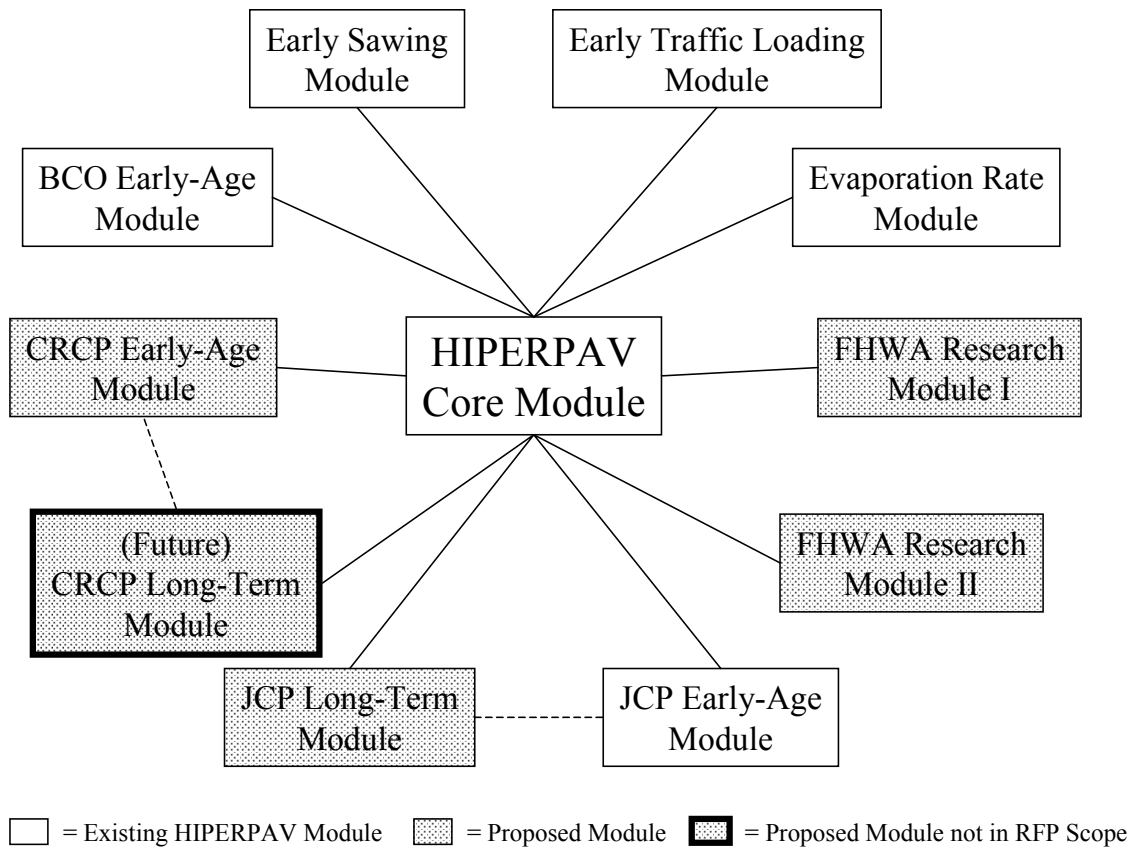
	JPCP	CRCP
Early-Age Behavior	1 HIPERPAV I	3 Proposed Module (Objective #2)
Long-Term Performance	2 Proposed Module (Objective #1)	4 Identified Module for Future

1.3 PROJECT SCOPE

The scope of this study is to assemble these key elements into a user-friendly, practical, and reliable end product using a total systems approach. In this document, this approach is described and its benefits are demonstrated. This unique approach allows the project objectives to be accomplished and helps ease the integration of new features in the future. The total systems approach allows the various components of the current HIPERPAV I to be integrated easily to work in conjunction with the proposed modules to be developed in HIPERPAV II. Figure 1 demonstrates the interaction of the various modules within the overall HIPERPAV II system. The baseline element of this approach is the core of the HIPERPAV system. The core predicts the temperature transport as well as key portland cement concrete (PCC) behavior such as curling, warping, and shrinkage. The various shaded modules orbiting about the core are modules that make up the HIPERPAV II system. In some cases, modules are interrelated. For example, the Early-Age JPCP module (from HIPERPAV I) drives the Long-Term Performance module for JPCP developed in this effort.

The user interface also has been modified to accommodate the additional modules and to add the flexibility for the addition of future modules.

The system is analogous to a puzzle; however, instead of beginning to assemble the pieces from the outside toward the center, the opposite is true here. Each piece is a module, and the final look of the puzzle will continue to change as the pieces continue to be added. Continuing this analogy, for the puzzle to be assembled, each of the pieces must be shaped correctly for an exact fit. This describes the work conducted for this project.



BCO = bonded concrete overlays

Figure 1. Schematic of total systems approach to the HIPERPAV II system.

1.4 REPORT STRUCTURE

This report describes the work conducted to enhance the HIPERPAV concrete pavement design and construction guidelines.¹ The remaining chapters of this report are organized as follows:

Chapter 2: Previous HIPERPAV Feedback and Provisions for Future Implementation

Chapter 2 presents a description of implementation efforts of the computer guidelines. Comments from current users of the guidelines and desired enhancements are listed and prioritized. This chapter also documents the creation of the technical expert panel (TEP) for HIPERPAV II. The guidance and direction received from the TEP members throughout the development of the enhanced guidelines is summarized.

¹ HIPERPAV alone with no preceding numeral refers to the overall concrete pavement design and construction guidelines, while HIPERPAV I and HIPERPAV II refer to the two different software generations.

Chapter 3: Information Search and Model Selection

This chapter documents the identification of the models that were incorporated in the guidelines. This includes the literature review conducted for identification and selection of updated theoretical models on JPCP early-age pavement behavior, JPCP long-term performance models, and CRCP early-age behavior models. In addition, this chapter describes the efforts to identify and incorporate two additional FHWA studies related to the design and construction guidelines. A detailed description of each individual model incorporated is reported in volume III of this report series. Also presented in that volume is a detailed annotated bibliography on the primary references reviewed during the information search performed in this study.

Chapter 4: Guidelines Enhancements and Evaluation

This chapter describes the approach taken for development of the final HIPERPAV II software product, including a description of the functionality of the JPCP long-term performance, CRCP early-age behavior, and additional FHWA modules. The design of the user interface, and development approach for incorporation of each of the individual modules into the total analysis tool, is also described.

In addition, this chapter briefly describes the approach for validation of the software guidelines. A detailed description of the validation efforts is reported in volume III of this report series.

Chapter 5: Summary, Conclusions, and Recommendations

A brief summary of the steps taken throughout the project for enhancing and evaluating the guidelines is presented in chapter 5. Major findings identified throughout development of the guidelines are summarized in this chapter. In addition, recommendations for future enhancement of the guidelines with additional modules and features, as well as incorporation of more sophisticated models, are outlined.

CHAPTER 2. PREVIOUS HIPERPAV FEEDBACK AND PROVISIONS FOR FUTURE IMPLEMENTATION

This chapter summarizes feedback collected during previous implementation efforts of HIPERPAV. In addition, provisions for a successful implementation of the final products from this study are discussed, along with the formation of a technical expert group and the recommendations they provided throughout the development of this project.

2.1 USER SURVEY

In the spring of 1996, the HIPERPAV System was first introduced to FHWA. Since that time, HIPERPAV has been presented at numerous meetings and workshops worldwide. During many of these presentations, a number of suggestions for additional features and advancements to the system were made.

2.1.1 Primary Identified Suggestions

A number of suggestions have been identified from a variety of sources and are compiled in this section. From these recommendations, three are the most predominant:

- Mix proportioning.
- Maturity.
- Bridge deck applications.

2.1.1.1 Mix Proportioning

A large percentage of current users believe that the mix design/proportioning element could give HIPERPAV a twofold purpose. The first is to calculate/predict the stresses in the pavement as a function of concrete mix designs. The second would be to design, proportion, and record mix design information in a complete database. The thought here was that if a mix tool is developed, HIPERPAV's utility might double. Eventually, the user would begin to interrelate mix properties with slab properties and stress development. Mix proportioning can also encompass concepts such as the use of fibers, materials compatibility issues, recycled materials, and durability.

2.1.1.2 Maturity

Many practitioners asked that HIPERPAV expand its capabilities to determine and manage strength gain in the slabs for two reasons: opening-to-traffic requirements and mix economics. Opening to traffic in a timely manner can mean a cost savings to the traveling public, and possibly be a financial incentive to the contractor. Maturity is a method that nondestructively predicts the strength gain in a concrete mix. The core of HIPERPAV is based on temperature and maturity prediction. The majority of the early-age properties that HIPERPAV predicts are a function of the maturity. A common suggestion is to improve the maturity prediction in HIPERPAV by giving the user more power to characterize mixes. This can be accomplished by inputs for adiabatic heat signatures as well as improved default properties for the use of mineral and chemical admixtures. In short, maturity is closely tied to traffic management, quality control, and ultimately, cost of the final product.

2.1.1.3 *Bridge Deck Application*

At nearly every HIPERPAV presentation, someone asks: “Can I use this software for my concrete bridge decks?” The answer at this time is: “Not without proper modification of the models for this application.” However, this is certainly an application that has a lot of demand. A bridge deck (or bridge deck overlay) application of HIPERPAV would allow a user to predict the potential for uncontrolled cracking just as it does currently for pavements. In truth, since the majority of the models inherent in the HIPERPAV system are based on structural engineering models for concrete, this application could be achieved with only minimal validation.

2.1.2 **Detailed List of Identified Suggestions**

A detailed list of the suggestions received from the users of HIPERPAV is given here. This list of suggestions and advancements has been grouped into four main categories:

1. Advancements included in HIPERPAV I.
2. Advancements incorporated during the HIPERPAV II effort.
3. Suggestions that relate to but are beyond the scope of the HIPERPAV II effort.
4. Suggestions requiring new major efforts.

The list is further subcategorized as:

- Pavement design inputs suggestions.
- Mix design inputs suggestions.
- Environmental inputs suggestions.
- Construction inputs suggestions.
- Output suggestions.
- Graphical user interface modification suggestions.
- Model improvement suggestions.
- Suggestions for additional modules.
- Other suggestions.

2.1.3 **Advancements Included in HIPERPAV I**

Features observed from previous comments were addressed in HIPERPAV I (software version 2.4.1). These additional features and advancements are listed below:

2.1.3.1 *Pavement Design Inputs Advancements*

- Additional subbase types were included.
- Laboratory 28-day PCC tensile strength was required as an input, rather than the flexural strength.

2.1.3.2 *Mix Design Inputs Advancements*

- The default values of the aggregate thermal coefficient of expansion are now displayed for the selected coarse aggregate type.
- Class “C” fly ash was incorporated into the mix design.

2.1.3.3 *Model Advancements*

- The effect of changes in the Poisson's ratio at early age was taken into account.
- The prediction of the creep relaxation model for early age was slightly improved.

2.1.3.4 *Additional Modules Incorporated*

- A joint sawing module was incorporated based on a FHWA study (but disabled until validated).
- An earliest traffic loading module was incorporated based on a FHWA study (but disabled until validated).

2.1.3.5 *Other Advancements*

- An autoscale feature of the output screen was included.
- Icons related to each one of the modules were included in the control panel.
- A warning note was added to explain the need for laboratory-measured values of strength and modulus of elasticity.
- A warning note was included in the maturity data box to explain the maturity method used in HIPERPAV.
- Online help for chemical and mineral admixtures, cement chemistry, and different curing methods was provided.

2.1.4 **Advancements Incorporated During the HIPERPAV II Effort**

Each recommendation is categorized with a high (H), moderate (M), or low (L) rank based on the level of user desirability.

2.1.4.1 *Pavement Design Inputs Advancements*

- Improve the stress prediction accuracy by adding paving width as an input, adjusting the models accordingly. (H)

2.1.4.2 *Mix Design and PCC Properties Inputs Advancements*

- Allow the user to enter the coefficient of thermal expansion (CTE) of the mix or the aggregate. (M)
- Add a conversion calculator to estimate splitting tensile strength from other strength types (i.e. compressive, flexural). (M)
- Add graphical representation of maturity input data. (H)
- Add an input option for Arrhenius maturity data in addition to Nurse-Saul. (H)
- Add an input for cement fineness and adjust the models accordingly. (H)
- Allow the user to enter drying shrinkage test results. (M)

2.1.4.3 *Environmental Inputs Advancements*

- Allow for solar radiation, windspeed, and humidity to be user-defined over the 72-hour period. (H)
- Add a grid control for the air temperature input data to allow the user to manually enter it in a gridline (as numbers) instead of only graphically (point dragging). (H)
- Use a simplified geographic information system (GIS) for climatic inputs. This data is stored on a CD-ROM along with the software. (H)

2.1.4.4 *Construction Inputs Advancements*

- Add a “no sawing” input option instead of setting saw time to 72. (H)
- Add a “green sawing” input option instead of setting saw time to 0. (H)
- Add a skip saw option. Add an input for the time of the intermediate cuts. (H)

2.1.4.5 *Output Advancements*

- Save output in Microsoft[®] Excel format. (H)
- Improve the print dialog; add zoom, printer configuration, and multiple pages. (M)
- Allow the user to change the scale of output plots (autoscale). (H)
- Show stress and strength when the mouse is hovered over them. (H)

2.1.4.6 *Graphical User Interface Modification Advancements*

- Add input bounds checks. (H)
- Add a multiple document interface (allowing multiple analysis files to be opened simultaneously.) (H)
- Change to a Microsoft Outlook[®]-style (document object model) graphical user interface. (H)
- Add better tool tips. (M)
- Add pulldown menu to change units but not value. (M)
- Add more units—e.g., millimeters (mm) for thickness. (M)
- Add a most recently used file list under the file menu option. (M)
- Add default option to reset the variables back to default values. (H)

2.1.4.7 *Model Advancements*

- Make efforts to improve and/or validate the creep relaxation model. (H)
- Improve materials characterization for mineral and chemical admixtures. (H)
- Add autogenous shrinkage model. (H)

2.1.4.8 *Additional Modules Incorporated*

- Add a JPCP long-term performance module. (H)
- Add a CRCP early-age behavior module. (H)

2.1.4.9 *Other Advancements*

- Add warning/guidance screens with the “do’s” and don’ts” on the use and interpretation of HIPERPAV. (H)
- Add online documentation by digitizing the final report and user’s manual. (H)
- Develop a technology transfer package for implementing HIPERPAV. (H)

2.1.5 **Suggestions Related to, but Beyond the Scope of the HIPERPAV II Effort**

2.1.5.1 *Pavement Design Inputs Suggestions*

- Add a database for the customization of subbase types. (L)
- Add more cementitious subbase types with better descriptions to account for large variance in different types. (L)

2.1.5.2 *Mix Design Inputs Suggestions*

- Add a mix-design and proportioning module. (H)
- Add an option for aggregate blending. (H)
- Add volumetric flags for unbalanced (incorrect) total volumes of PCC. (H)
- Add a mix proportions pie chart feature “by volume.” (M)
- Add import/export feature for maturity data. (H)
- Add a cements database that can be customized to a specific location. (H)
- Add mix design database that can be customized to a specific location. (H)
- Add type IV cement as a default cement type. (L)

2.1.5.3 *Environmental Inputs Suggestions*

- Add (as an advanced input) the latitude to estimate solar radiation. (M)
- Add a feature to save/load ambient air temperature distributions to disk, and provide default files for various climatological events. (M)
- Include the ability to account for the effects of rainfall on the early-age slab temperature. (M)
- For clarity, make the mouse cursor shape a function of the selected environment tool (e.g., cold front). (L)
- Add an air temperature “spline” tool to allow the user to define maxima and minima at any time. (L)

2.1.5.4 *Construction Inputs Suggestions*

- Add application rates for curing method, and perhaps brand names. (H)
- Add a mix temperature calculator that will calculate the estimated initial PCC temperature (a HIPERPAV input) as a function of the aggregate, cement, and water temperatures. (M)
- Add an option to automatically calculate the base temperature before placement, instead of making it a user input only. (M)

2.1.5.5 *Output Suggestions*

- Add a feature to show all of the stresses in the pavement (top, mid, bottom). (H)
- Make a three-dimensional plot of stress and strength for different placement times of day—color code surface for closeness to failure—green, yellow, and red. (M)
- Make analysis period variable (e.g., anywhere from 24 to 96 hours). (M)
- Add animations for stresses and displacements (in post-processor). (M)
- Separate the curling, shrinkage, and axial stresses on plot. (M)
- Show evaporation rate, air temperature, concrete temperature, relative humidity, and windspeed for points on the evaporation rate output curves as the mouse is hovered over them. (M)
- Add a feature for user-defined plot color schemes. (M)
- Add a toggle to show the compressive stresses in the pavement (instead of just zero stress). (L)
- Add a button to switch between absolute (megapascals (MPa)) and relative (percent) stress vs. strength. (M)
- Add tool tip showing absolute (MPa) and relative (percent) stress vs. strength. (M)

2.1.5.6 *Graphical User Interface Modification Suggestions*

- Color code the inputs for specific applications of the software (planner, designer, construction, etc.), or use a wizard interface to step through inputs that can be tailored to the user. (L)

2.1.5.7 *Model Improvement Suggestions*

- Add combined curling-axial restraint model. (H)
- Include consolidation/density impacts on stress/strength development model input. (M)
- Add effects of alkali content on the heat of hydration. (M)
- Add a longitudinal early-age cracking prediction. (M)
- Investigate edge restraint due to multipass paving. (L)
- Improve characterization of moisture state with respect to strength and other behaviors. (H)

2.1.5.8 *Other Suggestions*

- Include help screens with measurement guidelines for base temperature, slab-base friction, and other nonstandardized inputs. (H)
- Add additional help screens to describe curing application, moisture loss, and heat retention. (H)
- Add more detailed Microsoft Windows[®] help files to help the user execute the program. (H)
- Add warning/guidance screens with the “do’s” and “don’ts” on the use and interpretation of HIPERPAV. (H)
- Add advanced input screens for inputs like k-value, latitude, and finite-element method (FEM) mesh size, etc. (M)
- Add a smart update feature for easy software updates via the Internet. (M)

- Add command line options for batch processing of input files. (L)

2.1.6 Suggestions Requiring New Major Efforts

The following advancements suggested by the customers would require relatively significant effort:

2.1.6.1 Mix Design Inputs Suggestions

- Add the use of synthetic or steel fibers as an input, and adjust the models accordingly. (H)

2.1.6.2 Other Suggestions

- Develop a construction (real-time) version of HIPERPAV using a weather station and digital satellite weather forecasting. (H)
- Develop a version to model bridge slab decks or deck overlays. (H)
- Add sensitivity analysis options that would run several simulations and compare the results of the runs via plots and tables. (H)
- Convert to a Web-based application. (H)
- Add plot-predicted pavement temperatures vs. time and space. (H)

2.1.6.3 Model Improvement Suggestions

- Develop a version for bridge decks and bridge deck overlays. (H)
- Add a mechanistic moisture model to better predict moisture-related behavior. (H)
- Add fracture mechanics theory to better predict uncontrolled cracking and/or joint popping. (H)
- Conduct a validation study of the effects of chemical and mineral admixtures on the heat of hydration. (H)
- Include early-age PCC durability models as a parallel simulation. (H)
- Develop materials for a National Highway Institute (or other) short course. (H)

2.2 TECHNICAL EXPERT PANEL (TEP)

In recent years, FHWA has begun to specify forming technical expert groups as part of its various research endeavors. The importance of such groups cannot be overstated—this is especially true for projects that require the end result to be ready to implement.

2.2.1 TEP Members Selection Criteria

For the HIPERPAV II project, the following criteria were used to select TEP members:

- The TEP members should be stakeholders in the concrete paving industry.
- The TEP members should have the ability to contribute constructively to help the project team accomplish the objectives of the project.

- The TEP members should be representative of their respective areas of expertise.
- The TEP members should be leaders in their respective areas of expertise.

2.2.2 TEP Members Selected

For this project, a TEP consisting of seven members was formed. The final selection process of the TEP was done in cooperation with FHWA.

2.2.3 Initial Meeting

The initial TEP meeting for this project was held on June 28–29, 2000 at the Turner-Fairbank Highway Research Center in McLean, VA. The primary objectives of this meeting were to:

- Familiarize the TEP members with HIPERPAV.
- Discuss the overall project objectives.
- Discuss the proposed technical approach to the current project.

During this initial meeting, issues were identified and key recommendations to address potential problems during the implementation phase of the project were made. The primary recommendations from the TEP members and key highlights from this initial meeting included:

- Concentrate efforts on strengthening HIPERPAV in its prediction of early-age pavement behavior.
- Keep HIPERPAV user-friendly by ensuring simplicity of the input screens and by possibly creating unique user profiles.
- Optimize the mix design module for materials selection and proportioning, giving the users another reason to open the software.
- Address long-term performance modeling as a means of further optimizing early-age pavement design, materials selection, and construction procedures; looking at relative performance of the aforementioned factors, but not as an independent tool.

2.2.4 Second TEP Meeting

After a draft version of the written guidelines, interim report, and software prototype were developed, a second meeting was held on January 29–30, 2001. The primary objectives for this meeting were to:

- Review project deliverables to date, including software prototype, written guidelines, and modeling.
- Discuss future software development work plan and validation work plan.

The primary recommendations and highlights from this meeting included:

- The draft written guidelines presented to date are clear and understandable.
- Long-term performance models in HIPERPAV II will depend highly on the load transfer efficiency (LTE) model.
- Regarding the field sites, start contacting departments of transportation (DOT) now, if possible, during the bidding process. Involve the American Concrete Pavement Association chapter executives.

- It is important to incorporate the mix design module to attract additional users and to facilitate the use of HIPERPAV's stress analyses techniques.
- FHWA should eventually consider the development of two versions of HIPERPAV—a research grade and a practical grade. In the research grade, include provisions for inputs that are the most sensitive in the models. During the development of this project, the project team should concentrate more on the development of the practical grade version of HIPERPAV.
- The outputs of the models should be evaluated carefully—different scenarios need to be generated, and the results need to be examined from both the absolute and the relative perspective. The TEP should assist in this determination.
- The measurement and inclusion of adiabatic calorimetry for concrete mixes should be a high priority. As a result, HIPERPAV can become a real-time construction tool for quality control.
- If States are interested, additional sites for validation can be funded via a pooled fund project.

2.2.5 Third TEP Meeting

On May 14 and 15, 2002, after the beta version of the computer guidelines was developed, a third TEP meeting was held with the following objectives:

- Present project deliverables to date.
- Discuss specifics of the work plans as executed thus far.
- Understand fully the software layout, menus, and options.
- Accept the technical premise behind the software.
- Develop the ability to work the software and provide advice as to its functionality and ease of operation.

The primary recommendations and highlights from this meeting included:

- HIPERPAV could be seen as a day-to-day quality control tool as well as an analysis tool.
- Recent University of Texas findings on hydration modeling and characterization of admixtures have been incorporated in HIPERPAV II, and should form part of the fundamental training of the software.
- The Total Environmental Management for Pavements (TEMP) System, currently under development, will be a version of HIPERPAV in-place.
- The main focus of the software should still be on early-age behavior of JPCP. The long-term module can be used to reinforce good paving practices.
- The future of HIPERPAV should include mix-related calorimetry for use with specific project materials.

The feedback received from the TEP members during the three meetings held for this project were considered carefully during development of HIPERPAV II, and an extensive number of them were incorporated to ensure a successful implementation.

CHAPTER 3. INFORMATION SEARCH AND MODEL SELECTION

3.1 INTRODUCTION

As was briefly discussed in the introduction to this report, the HIPERPAV system has already proved successful in simulating early-age behavior of JPCP. However, although many of the models incorporated when HIPERPAV was originally developed were considered to be the best options at the time, new developments are now available that could potentially increase the accuracy of prediction. Some examples include the findings from a cement and admixtures characterization study recently conducted by the University of Texas at Austin and improved models for prediction of creep-relaxation in the early-age.^(1,2,3) Furthermore, previous validation and implementation efforts have made it possible to identify areas that may require of model enhancements, such as a better characterization of the concrete creep-relaxation effects at early ages and improved shrinkage models.

In addition, the systems approach used in HIPERPAV makes it ideal for expanding its capabilities to include new modules for prediction of JPCP long-term performance as a function of early-age behavior. Incorporating new modules for predicting early-age behavior of other pavement types such as CRCP is similarly possible.

Finally, a number of studies oriented to enhance the performance of concrete pavements have been identified to be compatible with the function of the HIPERPAV system, and therefore also may be incorporated.

To accomplish the objectives for this project, an information search first was conducted to identify models in each of the above categories. In this chapter, the information review results are described. The chapter is divided into three sections:

1. Literature search (section 3.2).
2. Model identification and selection (section 3.3).
3. Review of FHWA studies for potential incorporation into HIPERPAV II (section 3.4).

3.2 LITERATURE SEARCH

This section describes the literature review efforts made to identify theoretical models developed to date in each of the following four categories:

- Currently available early-age behavior simulation software similar to HIPERPAV.
- General early-age behavior models.
- JPCP performance models.
- CRCP early-age behavior models.

The following sections describe the literature review for each of the above categories. A detailed annotated bibliography on the primary references reviewed during the information search performed in this study is provided in volume III, appendix A of this report series.

3.2.1 Currently Available Early-Age Behavior Simulation Software Similar to HIPERPAV

Besides HIPERPAV, four other software programs that can similarly predict the early-age behavior of concrete have been identified. These include DuCOM[®], HYMOSTRUC[®], Quadrel[®], and 4C Temp & Stress[®]. HYMOSTRUC and Quadrel focus on developing the adiabatic hydration curves for concrete. DuCOM and 4C Temp & Stress are more robust FEM programs that calculate the state of stress in early-age concrete structures. These programs are similar in some aspects to HIPERPAV, but also have differences in theory and application. DuCOM, HYMOSTRUC, Quadrel, and 4C Temp & Stress are summarized in volume III, section A.1 of appendix A in this report series. A review of these models has helped in identifying possible improvements in the HIPERPAV software for characterization of early-age behavior. The section below describes specific models identified for possible incorporation into HIPERPAV.

3.2.2 General Early-Age Behavior Models

The early-age properties of concrete are significantly influenced by the climatic conditions and temperatures, as well as by the concrete mix components. For this purpose, a literature review of early-age concrete properties was completed. The properties that are addressed include:

- Concrete hydration.
- Concrete maturity.
- Drying shrinkage of concrete.
- Moisture transport in concrete.
- Set time of concrete.
- Creep.

A literature search was also performed for concrete thermal properties including: CTE, thermal conductivity, specific heat, thermal diffusivity, convection, surface emissivity, and solar absorptivity.

The literature review on early-age concrete properties is summarized in volume III, section A.2 of appendix A in this report series.

3.2.3 JPCP Performance Models

The literature review of JPCP models contained three categories. The first category was a literature review on pavement structural models for prediction of pavement response as a function of temperature, moisture, and traffic loading. The second category was a literature review on available climatic models that can be used in conjunction with the structural models to account for climatic conditions at the time of pavement curing and also over the years as the pavement is subjected to long-term usage. In the third category, a number of JPCP performance models were investigated. A literature review on faulting, transverse cracking, spalling, and JPCP roughness was conducted for this purpose. In HIPERPAV, it is preferable to use mechanistic models that have been calibrated and validated with actual experimental data. Information on the above three categories is presented in volume III, section A.3 of appendix A in this report series.

3.2.4 CRCP Early-Age Behavior Models

A literature review on CRCP early-age behavior also was conducted. From this effort, a number of references have been compiled, and models were identified describing the early-age behavior of CRCP. An additional effort was made to identify references on CRCP long-term performance. References on

CRCP early-age behavior and CRCP long-term performance are summarized in volume III, section A.4 of appendix A in this report series.

3.2.5 Electronic Database and Search Tool

To help the project team coordinate references, performance data sources, and other aspects of the project, an electronic database and associated search tool were developed.

The search tool, a Microsoft Windows application, allows the user to search by specific categories related to PCC, JPCP, CRCP, and bonded concrete overlays (BCO). A screen capture of the computer program is shown in figure 2. In addition, the user can refine the search by typing title, author, or keywords into the three text boxes just above the results window. If the user does not know the exact spelling of a word, partial entries in these boxes will produce matches that contain the text string somewhere in the reference database entry.

The tool may be of use to those who are interested in learning more about concrete pavements. For this reason, and to enhance the reliability and acceptability of the results of this research project, this database and search tool has been coupled with the final software product from this study.

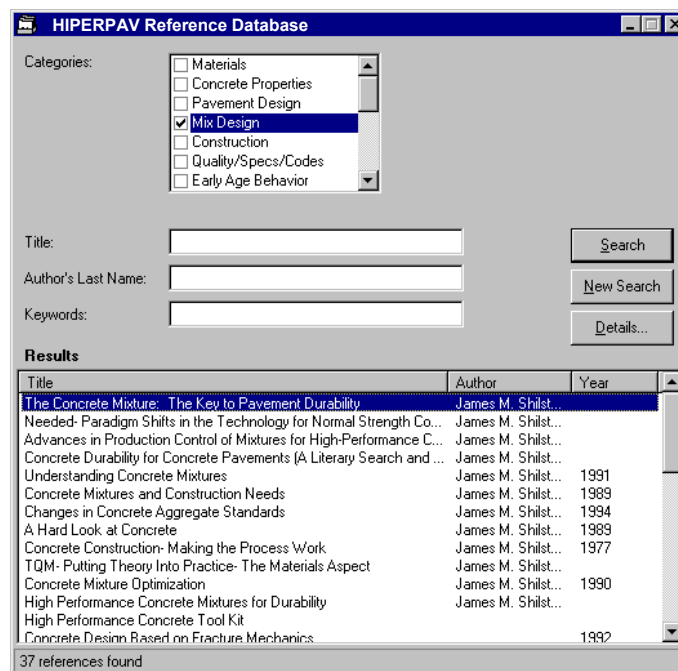


Figure 2. Microsoft Windows screen capture of database search tool.

3.3 MODEL IDENTIFICATION AND SELECTION

This section summarizes the general early-age behavior models, JPCP performance models, and CRCP models identified. A description of model selection is provided, followed by a brief evaluation of each model. The models finally selected for incorporation in the HIPERPAV II system are fully documented in volume III, appendix B of this report series.

3.3.1 Model Approach

In this new set of guidelines, a mechanistic approach is used to describe the existing link between early-age behavior and long-term performance. Traditionally, three classes of theoretical models have been used in the pavement engineering field to predict long-term pavement behavior and performance: empirical, mechanistic, and a hybrid: mechanistic-empirical.

3.3.1.1 *Empirical Models*

Empirical models are based on experimental data collected from field studies. These models are considered valid only within the limited range of data collected. If, for example, the environmental, material, or loading conditions are outside the boundaries of the study, then the model is no longer applicable. A new model will have to be developed for the new conditions. For this reason, empirical models cannot be applied to all situations.

3.3.1.2 *Mechanistic Models*

Mechanistic models do not have the same limitations as empirical models. Mechanistic models are based on the mechanics of the materials and physics behind the problem. With mechanistic models, stress, strain, or resulting deflections are determined to explain the influence of internal or external forces over the pavement system. Using the theoretical mechanistic equations, pavement performance can be predicted.

3.3.1.3 *Mechanistic-Empirical Models*

The empirical approach of pavement performance prediction is a two-step process. From the input parameters, the LTPP (distress) history can be predicted. This process is illustrated in

figure 3. However, this method bypasses four key steps that the mechanistic approach takes into account. The mechanistic method accounts for the material characterization (e.g. strength development of the concrete). Pavement response is then predicted (e.g., stresses development in the slab due to temperature loading). Then, pavement behavior is assessed (e.g., permanent deformation of the pavement slab as a result of curling/warping effects). Finally, the pavement distress is predicted (e.g., transverse cracking). From this, the distress history as a function of time can be generated.

Although mechanistic models more clearly determine the process of pavement behavior and performance, theory, by itself, has not proven sufficient for an accurate analysis of pavements. Therefore, the observed performance must be used with the mechanistic model as part of calibration. Consequently, the models used in pavement performance prediction are commonly termed mechanistic-empirical models. Mechanistic-empirical models are defined as analytical models calibrated with field observations that may be used to predict pavement performance reliably.

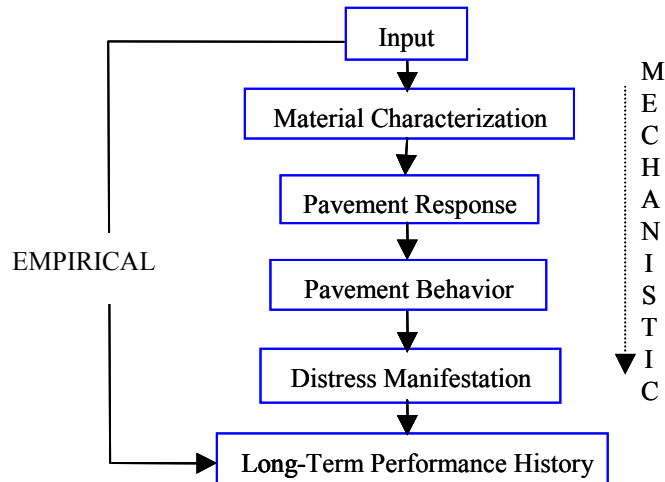


Figure 3. Schematic of empirical and mechanistic solutions for prediction of pavement distress.

There are at least three primary benefits to successfully applying mechanistic-empirical models in design. These are:

- Increased design reliability.
- Ability to predict specific types of distresses.
- Ability to extrapolate from limited sets of field and laboratory results.

Mechanistic-empirical models can be used to provide better pavement performance predictions. With these models, the effect of new parameters can be assessed, such as new loading or materials. Available materials are better utilized, and improved diagnostic techniques are available, leading to an understanding of why a pavement is performing better or worse than expected. Improved modeling of aging distresses, weather, subbase erosion, and the benefits of improved drainage also can be modeled effectively with mechanistic-empirical models.

The concepts behind development of a regression (empirical) model are shown in figure 4. Using the observed points, a regression curve is fit through them. The regression curve can be used to extrapolate beyond the physically measured values for prediction purposes. However, it is this extrapolation that demonstrates the potential for inaccuracy of regression models.

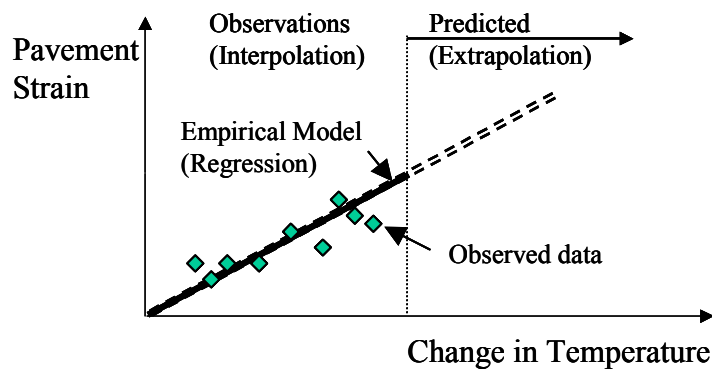


Figure 4. Use of empirical (regression) model for prediction of concrete strains.

In figure 5, an example of the analytical (mechanistic) solution versus the regression solution is shown. The slope of the analytical model is not necessarily the same as that of the regression curve. For this reason, when both are used in the prediction side of the plot, the difference from the regression model is apparent.

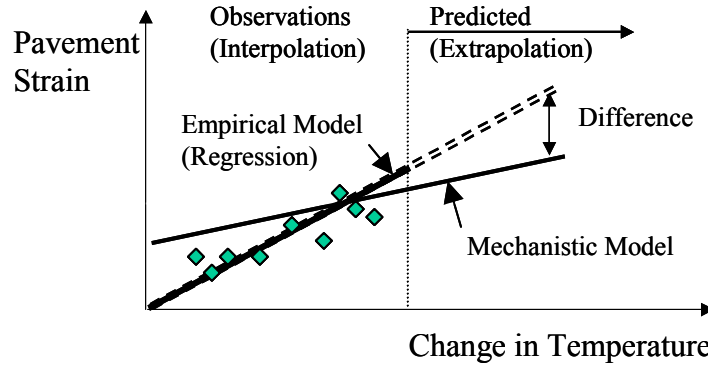


Figure 5. Use of empirical and analytical (mechanistic) model for prediction.

With the collection of additional data, the analytical model can be calibrated for specific sites, resulting in a mechanistic-empirical model. This further increases the accuracy of the analytical model (see figure 6).

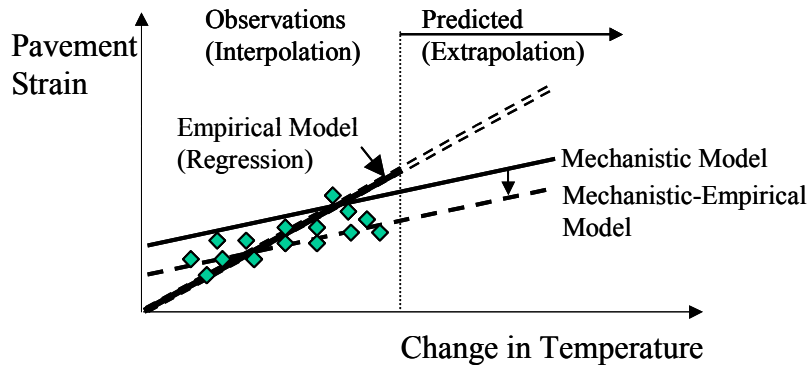


Figure 6. Use of empirical and calibrated analytical (mechanistic-empirical) model for prediction.

In summary, empirical models do not have the same indepth analysis as mechanistic models; instead, they directly relate input to LTPP based on site-specific data. Mechanistic models are the result of a five-step process to relate input to material characterization, pavement response, pavement behavior, distress prediction, and long-term performance history. Without calibration, mechanistic models are not site specific like the empirical models. Instead, these models account for the physical processes behind LTPP. Despite the shortcomings of the empirical data, it is still needed to calibrate the mechanistic models. The use of mechanistic-empirical models is preferred in pavement design and analysis.

3.3.2 Selection Criteria

Five primary factors have been considered in the selection of models for incorporation in HIPERPAV II, namely:

- Type of approach.
- Status of development.
- Calibration/validation.
- Inputs.
- Outputs.

These selection criteria are described below:

1. Type of approach: The HIPERPAV system has been recognized for providing a mechanistic approach to the analysis of early-age behavior of JPCP during the first 72 hours after construction. The advantages of mechanistic models, as compared to empirical models, were provided in section 3.3.1. The selection of models for analysis of JPCP and CRCP should favor mechanistic or mechanistic-empirical models. Also, as stated in the objectives of this project, the most important factor considered when selecting JPCP long-term performance models was the effect that early-age behavior factors had on long-term performance. Section 3.3.4 expands on the importance of early-age behavior factors on long-term performance.
2. Status of development: Some of the identified models may be conceptual, or currently under development. As the scope of this project does not include the resources for developing new models, caution must be used in selecting models that are not fully developed.
3. Calibration and validation: Calibration and validation of the available models was also an important factor to consider in model selection. Some limited validation of the models selected was performed within the scope of this project. However, it was desired that the models selected had undergone at least some calibration to warrant their selection, and to be certain that the model had sound logic in its development.
4. Inputs: One of the objectives of the HIPERPAV system is to be as practical as possible. Models that require inputs that may be difficult to obtain, or not readily available to the average user, were considered undesirable.
5. Outputs: The selection of pavement early-age behavior models will eventually help to assess long-term performance. Therefore, these models should provide the necessary information required by existing long-term performance models.

3.3.3 General Early-Age Behavior Models

The early-age behavior models used in HIPERPAV I for stress and strength prediction are described in detail in previous reports.⁽⁴⁾ The models identified here are improvements to some of those models, which predict:

- Cement hydration.
- Concrete temperature.
- Concrete moisture.
- Shrinkage.
- Concrete creep.
- Subbase restraint.
- Thermal gradients.

3.3.3.1 *Concrete Hydration Models*

From the literature review, several models were identified as candidates to incorporate into HIPERPAV II for expanding and improving the current hydration model. Table 2 lists the identified models, including a summary of advantages and disadvantages for using each of the models. Inputs required, outputs, validation, and need for further development are also identified.

During this project, the research team closely followed the development of hydration models conducted by the University of Texas at Austin under a research project with the Texas DOT.⁽¹⁾ The models developed by Schindler were selected for use in HIPERPAV II, because they could be adapted with relative ease and are practically the only hydration models available validated with U.S. cements. A detailed description of these models is provided in volume III, appendix B of this report series.

3.3.3.2 *HIPERPAV II Finite-Difference Temperature Model*

In HIPERPAV I, a one-dimensional FEM technique was used, but this procedure has proven to be a computational burden and may not be appropriate for the large number of time-steps involved in long-term analyses. The finite-difference method (FDM) is another numerical technique that is available to solve the transient heat transfer problem. In this study, the previous FEM procedure for heat transfer analysis was replaced with an FDM after extensive calibration and validation. The finite-difference model FDM model is used for both early-age and long-term predictions of concrete temperature. A description of this model is provided in volume III, appendix B of this report series.

3.3.3.3 *Models for Characterization of Concrete Moisture*

Many of the models in HIPERPAV I include terms for the moisture state in the PCC. The current moisture model in HIPERPAV I assumes that the moisture gradient varies uniformly from the surface of the pavement to near 100 percent at the center of the slab and below. Although incorporating a mechanistic-based moisture transport model is outside of the scope of this project, an effort was made to improve the moisture characterization. This step included integrating moisture terms into the most sensitive models such as the strength, shrinkage, and warping models.

An improvement to the current model was considered, based on the model proposed by Parrott for PCC slab moisture prediction.⁽⁵⁾ Zollinger has proposed a modification to the Parrot model to account for the effect of curing.⁽⁴⁾ The curing material is assigned an equivalent thickness of concrete. This additional thickness of concrete on top of the slab is assumed to mitigate the moisture loss from the pavement surface. This equivalent thickness was proposed based on an empirical data fit from laboratory data collected to derive the moisture gradient through the slab depth. Rasmussen proposed a modification to the Zollinger model.⁽⁴⁾ Following the same methodology, the revised model increases the depth of the

slab by the equivalent thickness, and derives the resulting moisture gradient. This can be seen graphically in figure 7.

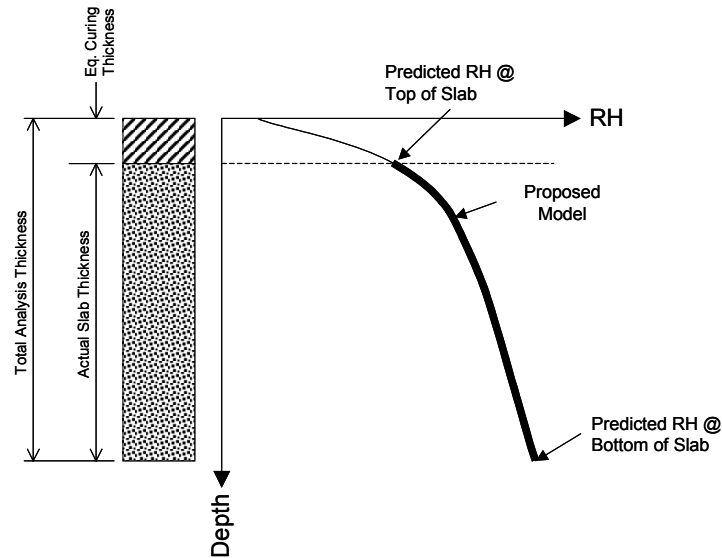


Figure 7. Graphical representation of revised Rasmussen-Zollinger-Parrot model.

Although it is believed that the modified Parrott model would improve the moisture characterization in HIPERPAV, a careful calibration and validation process of the model would have been required before integrating it into the HIPERPAV system. However, validating this model was outside the scope of this project.

3.3.3.4 Shrinkage Models

Two shrinkage models were identified for incorporation into HIPERPAV II: a drying shrinkage model with better materials characterization than the one previously used; and an autogenous shrinkage model for low water-cement ratios.

Although developed later than the previous Reunion Internationale des Laboratoires D'essais et de Recherches sur les Matériaux et les Constructions (RILEM) B₃ model used in HIPERPAV I, the Bazant-Panula (BP) drying shrinkage model incorporates more empirical material dependencies.^(6,7) One of these empirical dependencies is the influence of the aggregate volume fraction on final shrinkage, on which drying shrinkage is believed to be greatly dependent. It accounts for the total aggregate (coarse + fine)-to-cement ratio by weight, the coarse aggregate-to-fine aggregate ratio by weight, and the sand-to-cement ratio by weight. These two models are very similar; however, the B₃ model does not account for these aggregate contributions. Predictions of the BP model and the B₃ model were compared, and it was found that the BP model was better able to predict the shrinkage of concrete specimens of various mix designs. The drying shrinkage model in HIPERPAV II was therefore updated, from the RILEM B₃ model previously used to the BP model. This model is described in volume III, appendix B of this report series.

Table 2. Hydration models identified for possible incorporation in HIPERPAV II.

MODEL	PROS	CONS	VALIDATION	INPUTS	OUTPUTS	DEVELOPMENT
Schindler Hydration Models ⁽¹⁾	-Practical -Can accommodate any cement type -Accounts for fineness	-Empirical -Few tests results on mineral admixtures	Yes, laboratory and limited field conditions	-Cement composition -Water-cement ratio -Mineral admixtures replacement	-Degree of hydration -Activation energy -Set time	Complete
Swedish CCRJ ⁽⁸⁾	-Practical -Well established -Can accommodate any cement type -Data for many mix designs available	-Effect of moisture not modeled -Effect of cement fineness cannot be modeled -Few test results on mineral admixtures	Yes, under laboratory conditions	-Mix proportions -Curing temperature -28-day strengths -Cement type	-Compressive strength -Modulus of elasticity -Poisson's ratio -Creep adjusted modulus -Degree of hydration -Total heat of hydration	Mostly complete Creep models not completed
Dispersion Model ⁽⁹⁾	-Account for cement fineness -Simplicity -Recognized and accepted -ASTM** standard model	-Limited data available on particle size distribution. -Requires conversions from compressive to tensile	Partially	- Mean particle size - Rate constant	-Degree of hydration -Strength vs. maturity	Complete
Hyperbolic Model ⁽¹⁰⁾			Yes	-Final strength -Activation energy -Set time	-Strength gain	Complete
HYMOSTRUC ⁽¹¹⁾	-Accounts for effect of moisture -Accounts for effect of moisture	-Microstructure development is modeled -Effects of mineral and chemical admixtures are not addressed -Large investment in development time	Yes	-Cement composition -Particle size distribution -Water/cement ratio -Initial curing temp -Adiabatic testing -Concrete strength	-Degree of hydration -Temperature -Pore structure -Strength -Stress -Risk of cracking	Complete, but constantly being modified and expanded
DuCOM ⁽¹²⁾	-Accounts for effect of moisture -Modeling of deterioration mechanisms (corrosion and sulfate attack)	-Microstructure development is modeled -Large investment in development time -Moisture model needs improvement	Yes	-Mix proportions -Particle size distribution -Initial curing temperature -Chemical composition -Structural dimensions	-Porosity distribution -Strength -Moisture distribution -Shrinkage, creep -Thermal strains -Concentration of harmful agents	Complete, but constantly being modified and expanded Moisture model in progress
Rahhal and Batic ⁽¹³⁾	-All combinations of mineral admixtures considered	- Argentinian cement types - Empirical model	Yes, empirical	-Mineral admixture replacement level -Cement heat of hydration	-Blended cement total heat of hydration	Complete

*CCRJ = Swedish Cement and Concrete Research Institute

**ASTM = American Society for Testing and Materials

Concrete paving mix designs continually are being developed with lower water-to-cementitious materials ratios (w/cm). It is not uncommon for the w/cm to drop below 0.40. When this occurs, there is not enough water available in the fresh concrete mixture to allow for the complete hydration of the unhydrated cement grains. Two forms of shrinkage are apparent: drying shrinkage (already included in the HIPERPAV I prediction) and autogenous shrinkage. Autogenous shrinkage is a low w/cm phenomenon, and it cannot be ignored in these instances. For example, total shrinkage of a concrete mixture having a w/cm of 0.30 can be 50 percent autogenous shrinkage and 50 percent drying shrinkage. Neglecting autogenous shrinkage would significantly underestimate the concrete's shrinkage in the field; therefore, identifying an autogenous shrinkage model was necessary. The autogenous shrinkage model identified for incorporation in HIPERPAV II is the one developed by Jonasson and Hedlund.⁽¹⁴⁾ A detailed description of this model is presented in volume III, appendix B of this report series.

3.3.3.5 *Concrete Creep and Relaxation*

Efforts were also made to investigate further the extended triple power law creep/relaxation model identified from previous efforts. Although it was anticipated that such a model would require extensive calibration and validation efforts, an initial model evaluation was conducted during this project.

This model is developed from the double power law and the triple power law.^(14,15) The double power law is perhaps the most well known compliance function, and has been used by many authors, because it is based on extensive laboratory test results. The triple power law was developed to more accurately describe the long-term creep. Neither the double nor the triple power laws were calibrated for loading at early ages, and they were not intended to predict creep for young concrete.⁽²⁾ Westman estimated that the double and triple power laws are only valid for loading ages larger than about 2 days.⁽³⁾ Therefore, the triple power law was adjusted first by Emborg, and then by Westman, to account for loading at ages less than about 2 days.^(2,3) The extended triple power law, as documented by Westman, provides good agreement with early-age test data, and accounts for all the factors that could influence the time dependent deformation, such as:

- Concrete age at setting.
- Concrete age at loading (which is most important).
- Applied stress level.
- The influence of varying temperature.

The model definition for the creep/relaxation model based on the extended triple power law is provided in volume III, appendix B of this report series.

3.3.3.6 *Nonlinear Restraint Model*

Recognizing the nonlinear restraint effect imposed by some subbases, such as hot-mix asphalt subbases, a nonlinear model was also included in addition to the current linear one to provide for the characterization of such behavior. The nonlinear restraint model is described in volume III, appendix B of this report series.

3.3.3.7 *Nonlinear Thermal Gradient Model*

Finally, recognizing that thermal gradients through the slab depth are nonlinear for the most part, the model developed by Mohamed and Hansen was included to determine an equivalent linear gradient as a function of a nonlinear one.⁽¹⁶⁾ This model is described in volume III, appendix B of this report series.

3.3.4 **JPCP Performance Models**

To analyze the behavior of JPCP and to predict JPCP distress development as a result of traffic loading, analytical models were selected. As stated in the objectives of this project, the most important factor considered when selecting these analytical models was the effect that early-age behavior factors had on long-term performance. Researchers found the size of the joint opening, curling and warping of the slab, and moisture loss at early ages in JPCP to be some of the primary early-age indicators of the pavement's long-term performance. A brief description of primary early-age behavior factors is given in the following bullets. More detailed information on these factors can be found in volume II of this report series:

- Joint opening controls the LTE across the joint, which controls how well the JPCP will perform over time. Large joint openings may lead to JPCP spalling, faulting, and transverse cracking. The joint opening at early ages is controlled primarily by the effect that temperature and moisture changes have on pavement and subbase properties such as concrete CTE, drying shrinkage, and subbase restraint. Joint opening varies with the daily temperature cycles due to changes in the pavement's thermal conditions. Drying shrinkage, CTE, and pavement length also affect the joint opening. To control the joint opening to acceptable levels, properly curing the pavement at early ages is of paramount importance.
- Evaporation of bleed water at the concrete surface is governed by the concrete temperature and climatic conditions such as windspeed, relative humidity, and air temperature. However, at any point during the early age of the pavement, the loss of moisture in concrete pavements will also be a function of the moisture transport characteristics of the concrete, the water available in the mix, and in particular, the water that has not been used for hydration. Moisture gradients usually develop in concrete pavements due to the loss of moisture to the environment. Under conditions where significant moisture is lost to the environment, critical moisture gradients may develop in the slab, leading to a reduction in the strength of the concrete at the slab surface, plastic shrinkage, and cracking. Moisture loss may later result in delamination and spalling of the concrete surface.
- The temperature gradients during the early age are a function of the environmental conditions and the heat concrete hydration. The initial thermal gradient in the slab at set will influence the curling shape of the slab. Built-in curling is a term used for the curling state that develops at set and that later influences the curled shape of the slab as the thermal gradient is subsequently modified by the hydration process and climatic conditions. In general, when concrete sets, the temperature through the slab is generally not uniform, but rather is a function of the climatic conditions, the heat of hydration, and curing methods. Built-in curling may later translate into faulting and cracking problems as the level of stresses developed in the pavement slabs is increased as a function of traffic loads and long-term daily and seasonal climatic conditions.

A discussion of JPCP performance models that were identified in the literature search of this project is provided in this section, along with a discussion on the models that were finally incorporated in HIPERPAV II. The models are divided into four categories:

1. Environmental.
2. Long-term materials properties models.
3. Structural behavior models.
4. Distress prediction models.

3.3.4.1 *Environmental Models*

Table 3 provides a summary of the climatic models considered, including model basis, advantages, and disadvantages. The models selected for incorporation in HIPERPAV II were the FDM model developed under this study, and the subgrade moisture model by Lytton.⁽²³⁾

The FDM is used to predict long-term concrete temperatures. The selection of this model is previously discussed in section 3.3.3.2. The FDM model is described in detail in volume III, appendix B of this report series.

The moisture model provides a simple method to predict the average monthly moisture content in pavement base materials using site-dependent climate conditions, soil data, and some pavement geometry. This model is described in detail in volume III, appendix B of this report series.

3.3.4.2 *Long-Term Materials Properties Models*

Mechanical properties used for long-term PCC characterization include modulus of elasticity and any of the following three strengths: tensile, flexural (modulus of rupture), or compressive. During the pavement life, the PCC slab is exposed to various stresses, such as curling and warping stresses, thermal axial stresses, and wheel load stresses. In the long term, one of the major failure modes is cracking due to fatigue. This generally has been found to be a function of the tensile stress to strength ratio at the bottom of the layer, implying that tensile strength is a significant characterization property. Unlike most concrete structures, JPCP does not rely on steel to withstand tensile stresses and therefore typically is designed using a specified tensile strength. Because concrete is much weaker in tension than in compression, tensile strength is the most critical strength characteristic.

The elastic modulus is an estimate of the slope of the stress-strain curve in the elastic region and a good indicator of the overall structural stiffness of the concrete. Because stresses and strains are related through the elastic modulus under assumptions of linear elasticity, it is important that this property be characterized.

Although conversion coefficients for the different strength types are user-defined in HIPERPAV II, default conversion models were investigated. The model sources identified are:

- Conversion relationship between third point modulus of rupture (MOR) and splitting tensile strength developed by Melis et al.⁽¹⁷⁾
- Conversion relationship between third point MOR and center point MOR developed by Carrasquillo and Carrasquillo.⁽¹⁸⁾
- Conversion relationship between third point MOR and compressive strength developed by Raphael.⁽¹⁹⁾

- Conversion relationship between compressive strength and modulus of elasticity recommended by the American Concrete Institute (ACI).⁽²⁰⁾

In addition, the long-term strength gain after 28 days was investigated. Long-term strength and stiffness models recommended by the CEB/FIP¹ Model Code 1990 were incorporated.

A detailed description of each of the above models is presented in volume III, appendix B of this report series.

3.3.4.3 *Structural Models (Load Transfer Efficiency, and Midslab Stress and Deflection Models)*

To predict accurately the response of a rigid pavement due to external wheel loads, a model is needed to assess the behavior of the pavement structure in the vicinity of discontinuities such as cracks and joints. Several structural response models based mainly on FEM modeling were identified. A summary of their advantages and limitations is presented in table 4. Initially, a FEM model such as KENSLABS had been proposed to predict slab stresses due to traffic loading for use in the pavement performance cracking models in HIPERPAV II.⁽²¹⁾ However, due to the computational burden of the FEM model and because the cracking models selected are based on stresses predicted with Westergaard formulations, a structural model that accounts for LTE between slabs was developed under this study and was considered more appropriate for this purpose. The LTE, stress, and deflection models selected for incorporation in this study are presented in volume III, appendix B of this report series.

3.3.4.4 *Distress Models*

As previously mentioned in section 3.3.2, several criteria were considered in the selection of each individual JPCP distress model. In selecting long-term distress prediction models, the most important criterion (with respect to this effort) is that the model account for early-age indicators for distress prediction such as joint opening and/or built-in curling. Tables 5 to 9 present the JPCP distress models identified in the literature. For these tables, the “Model Basis” category designates whether the model is mechanistic, empirical, or mechanistic-empirical in nature. Additional fields include the databases used for their development, the quality of data used in their development, model statistics, early-age modeling parameters used, and availability of required model inputs.

3.3.4.4.1 *Faulting*

Table 5 shows the faulting models identified. Models for both doweled and nondoweled pavements were investigated. The models selected are those developed by Smith et al. reported in FHWA-RD-89-137.⁽²²⁾ Selecting the same model source for both doweled and nondoweled pavements was important to avoid inconsistencies in predicting faulting distress under each condition. In addition, these models include an input for joint opening, which is considered an important indicator needed to relate the performance of the pavement to early-age conditions. Selection of these models was also reinforced because they are mechanistic-empirical in nature. Besides joint opening, they account for traffic loading, environmental conditions, support conditions, pavement structure, and the presence of dowels. Finally, these models were developed using the combined Concrete Pavement Evaluation System (COPES) and Performance/Rehabilitation of Rigid Pavements (RIPPER) databases with a large

¹ CEB stands for Euro-International Concrete Committee (Comité Euro-International du Béton), FIB stands for International Concrete Federation (Fédération Internationale du Béton)

data set of pavement sections in a variety of environmental regions (wet-freeze, wet-no freeze, dry-freeze and dry-no freeze) in the United States.⁽²²⁾

These faulting models originally were developed and calibrated based on a unique definition of joint opening. The joint opening prediction made by HIPERPAV II is based on a different approach than the FHWA model. The FHWA model is a closed-form and rather simple prediction, while the model in HIPERPAV II is based on a more sophisticated FDM-based analysis. Therefore, to use the joint prediction made by HIPERPAV II in predicting long-term faulting, a submodel was developed to convert the HIPERPAV II-predicted joint opening to the joint opening parameter used in the FHWA faulting model.

A detailed description of the faulting models and development of the HIPERPAV II joint opening conversion model are presented in volume III, appendix B of this report series.

Table 3. Climatic models.

Model	Model Basis	Pro	Con
HIPERPAV II	M-E*	<ul style="list-style-type: none"> - Able to predict the early-age behavior of PCC 72 hours after construction - Transient FDM temperature core - Accounts for climatic conditions 	<ul style="list-style-type: none"> - Some empirical assumptions
Lytton ⁽²³⁾	E**	<ul style="list-style-type: none"> - Fast run-time - Limited validation 	<ul style="list-style-type: none"> - Simplistic model with empirical assumptions
ICM ⁽²³⁾	M-E	<ul style="list-style-type: none"> - Predicts moisture and temperature profiles in pavement structures 	<ul style="list-style-type: none"> - Moisture model still under development - Slow run-time

*M-E = Mechanistic-Empirical

**E = Empirical

Table 4. Structural behavior models.

Model	Model Basis	Pro	Con
KENSLABS ⁽²¹⁾	M	<ul style="list-style-type: none"> - FEM-based - User-defined dimensions - Two layers (bonded/un) with same/different material properties - Liquid/solid subgrade - Uniform/nonsupport to account for erosion - Multiple slabs with load transfer - Warping/curling with load response - Arbitrary loading conditions—wheel loading - Arbitrary shoulder conditions - Nonuniform slab/shoulder thickness 	<ul style="list-style-type: none"> - Large amounts of computer storage
ILLI-SLAB ⁽²⁴⁾	M	<ul style="list-style-type: none"> - FEM-based - User-defined dimensions, any number of slab arrangements, layer bonding - Two layers (bonded/un) with same/different material properties - Liquid/solid subgrade - Uniform/nonsupport to account for erosion - Multiple slabs with load transfer - Warping/curling with load response - Arbitrary loading conditions, axle configurations - Arbitrary shoulder conditions - Nonuniform slab/shoulder thickness 	<ul style="list-style-type: none"> - Large amounts of computer storage - Poorly conditioned source code
ISLAB 2000 ⁽²⁵⁾	M	<ul style="list-style-type: none"> - Improvement to ILLI-SLAB 	<ul style="list-style-type: none"> - Source code not available
JSLAB ⁽²⁶⁾	M	<ul style="list-style-type: none"> - FE used to compute critical stresses and deflections 	<ul style="list-style-type: none"> - Stiffness matrix reportedly not correct - Based on early version of ILLI-SLAB
LTE, stress, and deflection	M	<ul style="list-style-type: none"> -Fast computations -Predicted stresses compatible with selected midslab cracking model inputs 	<ul style="list-style-type: none"> -Simplistic closed-form solution

3.3.4.4.2 Midslab and Corner Cracking Models

Tables 6 and 7 present the midslab and corner cracking models identified during the literature search respectively. The models selected were those developed by Yu et al. in FHWA-RD-95-111 and the stress adjustment models developed by Lee and Darter and Lee et. al. (See references 27, 28, 29, and 30.) The midslab cracking model is based on Westergaard stresses. Using this model, joint opening, LTE, and built-in curling can be accounted for by using the LTE, stress, and deflection model developed in this study. The accumulated fatigue damage is predicted, as is the percentage of cracked slabs, in both the longitudinal and transverse directions.

These models were selected given the following considerations:

- The model uses mechanistic components.
- The fatigue model is based on Miners Law using the Westergaard edge stress prediction model.
- By incorporating the LTE, stress, and deflection models, stress can be calculated for typical slab configurations, load transfer devices, and joint opening; these can be included as a predictor variable for the stress state at any given time as a function of climatic conditions using the HIPERPAV II joint opening prediction model.
- By employing the stress adjustment factors developed by Lee and Darter, the model can be adapted to use load spectra or 18-kip Equivalent Single Axle Loads (ESAL).
- A relative good fit of a comprehensive database was used for the midslab cracking model validation.

More details on the selection and a detailed description of the midslab cracking models are provided in volume III, appendix B of this report series.

No corner cracking model was selected for incorporation in HIPERPAV II because the LTE model is one-dimensional and could not account for stress transfer efficiency on both directions as a function of joint opening near the corner location. The corner cracking models identified did not account for joint opening or were based on FEM runs impractical for incorporation in HIPERPAV II due to the analysis time required by the FEM.

3.3.4.4.3 Spalling Model

Table 8 shows spalling models identified. Although a number of models were identified, the difficulty to realistically account for all the factors affecting spalling distress was recognized during the TEP meetings. Since developing a new spalling model was out of the scope of this project, it was decided not to include a spalling distress model in HIPERPAV II during this effort.

3.3.4.4.4 Roughness Model

Two common roughness indicators are the Present Serviceability Index (PSI) and the International Roughness Index (IRI). A number of models for both roughness indicators were identified

in this project and are summarized in table 9. A detailed comparison of the models identified is presented in volume III, appendix B of this report series.

Table 5. Faulting models.

Models	Model Source	Model Type	Development Database	Quality of Data Used in Model Development	Model Statistics	Early-Age Modeling Parameter	Availability of Required Model Inputs
Doweled JPCP	Yu et al., 1998 FHWA-RD-95-111 ⁽²⁷⁾	Mechanistic-Empirical	COPEs+ with 208 more sections	Good	N = 146 sections $r^2 = 0.60$ RSE = 0.056 mm	Dowel bearing stress	Sufficient data for 12 of 13 inputs
	Simpson et al., 1994 SHRP P-393 ⁽³¹⁾	Empirical	LTPP GPS-3 and GPS-4	Good	N = 59 sections $r^2 = 0.53$ RMSE = 0.071 mm	None	All six inputs are available in all potential databases
	Smith et al., 1990 FHWA-RD-89-137 ⁽²²⁾	Mechanistic-Empirical	COPEs+	Good	N = 559 sections $r^2 = 0.67$ SEE = 1.27 mm	Dowel bearing stress, Joint opening	Sufficient data for 12 of 14 inputs
Nondoweled JPCP	Yu et al., 1998 FHWA-RD-95-111 ⁽²⁷⁾	Empirical	COPEs+ with 208 more sections	Good	N = 131 sections $r^2 = 0.45$ RSE = 0.86 mm	None	Sufficient data for eight of nine inputs.
	Smith et al., 1990 FHWA-RD-89-137 ⁽²²⁾	Mechanistic-Empirical	COPEs+	Good	N = 398 sections $r^2 = 0.81$ SEE = 0.71 mm	Joint opening, Corner deflection	Sufficient data for 20 of 22 inputs
	Simpson et al., 1994 SHRP P-393 ⁽³¹⁾	Empirical	LTPP GPS-3	Good	N = 25 sections $r^2 = 0.55$ RMSE = 1.19 mm	None	All five inputs are available in all potential databases
Doweled and Nondoweled JPCP	Titus-Glover et al., 1999 FHWA-RD-98-113 ⁽³²⁾	Mechanistic-Empirical	LTPP	Good	N = 120 sections $r^2 = 0.56$ SEE = 0.762 mm	Deflections of unloaded slab	Sufficient data for 9 out of 10 inputs
	Darter et al., 1985 COPEs ⁽³³⁾	Empirical	COPEs	Good	N = 259 sections $r^2 = 0.79$ RMSE = 0.51 mm	None	Sufficient data for all seven inputs

N = number of observations

r^2 = coefficient of determination

RMSE = root mean-square error

RSE = relative standard error

SEE = Standard Error of the Estimate

Table 6. Midpanel cracking models.

Model Source	Model Type	Development Database	Quality of Data Used in Model Development	Model Statistics	Early-Age Modeling Parameter	Availability of Required Model Inputs
Yu et al., 1998 FHWA-RD-95-111 ⁽²⁷⁾	Mechanistic-Empirical	COPEs+ with 208 more sections	Good	N = 465 sections $r^2 = 0.91$ SEE = 6.8%	None	Sufficient data available for 12 of 13 inputs
Titus-Glover et al., 1999 FHWA-RD-98-113 ⁽³²⁾	Mechanistic-Empirical	LTPP	Good	N = 92 sections $r^2 = 0.64$ SEE = 12%	Damage due to temperature stresses	All eight inputs are available in all potential databases
Smith et al., 1990 FHWA-RD-89-137 ⁽²²⁾	Mechanistic-Empirical	COPEs+	Good	-	None	All four inputs are available in all potential databases
Simpson et al., 1994 SHRP P-393 ⁽³¹⁾	Mechanistic-Empirical	LTPP	Good	-	None	Sufficient data available for six of eight inputs
Darter et al., 1985 COPEs ⁽³³⁾	Mechanistic-Empirical	COPEs	Good	N = 303 sections $r^2 = 0.69$ SEE = 33.3 m/km	None	Sufficient data available for all six inputs
Lee and Darter ⁽²⁸⁻³⁰⁾	Mechanistic	n/a*	-	-	Curling	

* FEM model development

N = number of observations

r^2 = coefficient of determination

SEE = Standard Error of the Estimate

Table 7. Corner cracking models.

Model Source	Model Type	Development Database	Quality of Data Used in Model Development	Model Statistics	Early-Age Modeling Parameter	Availability of Required Model Inputs
Lee and Lee ⁽³⁴⁾	Mechanistic	n/a*	-	-	Curling	
Titus-Glover et al., 1999 FHWA-RD-98-113 ⁽³²⁾	Mechanistic-Empirical	LTPP	Good	N = 92 sections $r^2 = 0.69$ SEE = 9%	Damage due to temperature stresses	All eight inputs are available in all potential databases

* FEM model development

N = number of observations

r^2 = coefficient of determination

SEE = Standard Error of the Estimate

Table 8. Spalling models.

Models	Model Source	Model Type	Development Database	Quality of Data Used in Model Development	Model Statistics	Early-Age Modeling Parameter	Availability of Required Model Inputs
Doweled and Nondoweled JPCP	Simpson et al., 1994 SHRP P-393 ⁽³¹⁾	Empirical	LTPP GPS-3	Good	N = 56 sections $r^2 = 0.34$ RMSE = 11.05% joints	None	All two inputs are available in all potential databases
	Titus-Glover et al., 1999 FHWA-RD-98-113 ⁽³²⁾	Mechanistic-Empirical	LTPP	Good	N = 52 Sections $r^2 = 0.61$ RMSE = 12.0% joints	Relative humidity from month of construction, Horizontal movement of slab	Sufficient data available for 11 of 15 inputs
	Senadheera and Zollinger, 1994 ^(35,36)	Mechanistic - Empirical	TTI	Good	-	Moisture loss from concrete surface, joint opening	
	Yu et al., 1998 FHWA-RD-95-111 ⁽²⁷⁾	Empirical	COPEs+ with 208 more sections	Good	N = 163 sections $r^2 = 0.76$ RSE = 5.1% joints	None	Sufficient data available for all 10 inputs
	Smith et al., 1990 FHWA-RD-89-137 ⁽²²⁾	Empirical	COPEs+	Good	N = 262 sections $r^2 = 0.59$ SEE = 9.3 joints/km	None	All five inputs are available in all potential databases

N = number of observations
 r^2 = coefficient of determination
 RMSE = root mean-square error
 RSE = relative standard error
 SEE = Standard error of the estimate

Table 9. Roughness (ride) models.

Pavement Type	Model Source	Model Type	Development Database	Quality of Data Used in Model Development	Model Statistics	Early-Age Modeling Parameter	Availability of Required Model Inputs
Doweled and Nondoweled JPCP	Titus-Glover et al., 1999 FHWA-RD-98-113 ⁽³²⁾	Empirical	LTPP GPS-3	Good	N = 155 sections $r^2 = 0.50$ SEE = 0.33 m/km	Faulting, Transverse cracking*	All eight inputs are available in all potential databases
	Smith et al., 1990 FHWA-RD-89-137 ⁽²²⁾	Empirical	COPEs+	Good	N = 282 sections $r^2 = 0.58$ SEE = 0.31 PSR	Faulting, Transverse cracking*	All four inputs are available in all potential databases
	Darter et al., 1985 COPEs ⁽³³⁾	Mechanistic-Empirical	COPEs	Good	N = 316 sections $r^2 = 0.69$ SEE = 0.25 PSR	None	All six inputs are available in all potential databases
	Perera et al., 1998 FHWA-RD-97-147 ⁽³⁷⁾	Mechanistic-Empirical	LTPP	Good	N = 104 sections $r^2 = 0.79$ SEE = 0.34 m/km	None	Data available for 10 out of 13 inputs
	Yu et al., 1998 FHWA-RD-95-111 ⁽²⁷⁾	Empirical	COPEs+ with 208 more sections	Good	N = 144 sections $r^2 = 0.61$ RMSE = 1.01 m/km	Faulting, Transverse cracking*	All three inputs are available in all potential databases
	Hoerner, 2000 FHWA-RD-00-130 ⁽³⁸⁾	Empirical	LTPP GPS-3	Good	N = 183 sections $r^2 = 0.70$ SEE = 0.35 m/km	Faulting, Transverse cracking*	All seven inputs are available in all potential databases
	Simpson et al., 1994 SHRP P-393 ⁽³¹⁾	Empirical	LTPP GPS-3	Good	N = 21 sections $r^2 = 0.55$ RMSE = 0.30 m/km	None	All five inputs are available in all potential databases
	Simpson et al., 1994 SHRP P-393 ⁽³¹⁾	Empirical	LTPP GPS-3	Good	N = 28 sections $r^2 = 0.64$ RMSE = 0.49 m/km	None	All five inputs are available in all potential databases

* Faulting and transverse cracking models used in HIPERPAV II include early-age parameters.

N = number of observations

r^2 = coefficient of determination

RMSE = root mean-square error

SEE = Standard error of the estimate

The IRI model selected for use in HIPERPAV II is the one developed under FHWA-RD-00-130. Selection of this model was made after a parametric study with other IRI models and is based on a number of considerations, including:

- It accounts for pavement structural distresses including cracking and faulting. Faulting and transverse cracking models used in HIPERPAV II include early-age parameters. Therefore, the model indirectly accounts for early-age parameters.
- Roughness prediction over time is significantly influenced by initial roughness after construction.⁽³⁸⁾ This model includes roughness as an input therefore improving the accuracy of prediction.
- This model was recently developed with data from sections on the LTPP General Pavement Studies (GPS) for JPCP (GPS-3).
- As indicated in table 9, a reasonably good fit was obtained.

The PSI model selected was developed with data from the LTPP GPS-3 sections and is as a function of IRI. The resulting model is also presented in volume III, appendix B of this report series.

A summary list of models that have been identified for incorporation in HIPERPAV II is presented in table 10.

Table 10. JCP selected models.

Model Type	Candidate Model
Environmental	-HIPERPAV FDM Temperature model
	-Subgrade moisture model—Lytton et al., 1990 ⁽²³⁾
Structural Properties	-Conversion relationship between third point modulus of rupture and splitting tensile strength—Melis et. al, 1985 ⁽¹⁷⁾ -Conversion relationship between third point MOR and center point MOR—Carrasquillo and Carrasquillo, 1987 ⁽¹⁸⁾ . -Conversion relationship between third point MOR and compressive strength—Raphael, 1984 ⁽¹⁹⁾ -Conversion relationship between compressive strength and modulus of elasticity—ACI-318-2002 ⁽²⁰⁾
Structural Behavior	-LTE, stress, and deflection models (volume III, appendix B of this report series)
Transverse Cracking	-FHWA-RD-95-111, 1995 ⁽²⁷⁾
	-Stress adjustments—Lee and Darter 1993–1994, Lee et. al, 1997 ^(28,29,30)
Faulting with Dowels	-FHWA-RD-95-111, 1995 ⁽²⁷⁾
Faulting without Dowels	-FHWA-RD-95-111, 1995 ⁽²⁷⁾
Roughness	-FHWA-RD-00-130, 1995 ⁽³⁸⁾

3.3.5 CRCP Models

From the literature review on CRCP (see section 3.2.4), several models were identified as candidates to incorporate in HIPERPAV II for prediction of early-age behavior and long-term performance. In this section, the final CRCP model selected for incorporation in HIPERPAV II is presented, along with an explanation for its selection.

Tables 11 and 12 list the identified models for CRCP early-age behavior and long-term performance prediction, respectively. These tables present a summary of advantages and disadvantages for the use of each one of the models, inputs required, outputs, validation, and need for further development. Early-age behavior models identified include CRCP-8, CRCP-9/10 (also known as CRCPFEM (since it is based on FEM), Texas Transportation Institute (TTI) model TTICRCP, and CTR crack width model. (See references 39, 40, 41, and 42.) A list of advantages and disadvantages for each model is provided in these tables.

Using the selection criteria previously described in section 3.3.2, it is believed that CRCP-8 would best fit all the requirements set for incorporation in HIPERPAV II. Although the CRCPFEM was

extensively evaluated for possible incorporation in HIPERPAV II, it was concluded that calibration and validation was required, and the schedule for those tasks was in conflict with the deadline for this project. As a result, the CRCP-8 model, widely used by the CRCP pavement community, was selected for incorporation in HIPERPAV II. The CRCP-8 model has also undergone extensive field validation and has been used throughout the world. A detailed description of this model is presented in volume III, appendix B of this report series.

3.4 REVIEW OF FHWA STUDIES FOR POTENTIAL INCORPORATION IN HIPERPAV II

One of the objectives under this project is to extend the guidelines to incorporate as many as two FHWA studies compatible with the HIPERPAV system. Six studies were evaluated for possible incorporation in HIPERPAV II: high strength concrete study; dowel bar study; performance-related specifications (PRS) study; curing guidelines study; curling and warping study; and a concrete mix optimization study. In the following sections, these studies are summarized and a framework for their incorporation in HIPERPAV II is presented.

3.4.1 High Strength Study (FHWA-DTFH61-95-C-00108)

A goal of the FHWA high strength study was to determine the effect of higher strength and associated concrete durability properties (permeability) on the long-term performance of pavements. The focus of the study was to examine how to eliminate distresses near joints or free edges. The distresses studied were spalling, faulting, transverse cracking, and corner breaks. Properties of the concrete investigated were tensile, flexural, and compressive strength; shrinkage; elastic modulus; fracture properties; air content; permeability; and thermal expansion.

3.4.1.1 Effect of Concrete Properties on Spalling

There are two types of spalling for concrete pavements: deflection spalling and delamination spalling. These two types of spalling are discussed in detail in volume II, chapter 4 of this report series. Spalling is typically associated with a weakening of the concrete. This weakening of the concrete can take place at early ages due to improper curing, or at later ages due to freeze-thaw cycles. The latter issue is addressed by Hansen et al.⁽⁴³⁾ Petrographic samples of concrete near a spalled joint reveal filling of the air voids with hydration products. The concrete lost its ability to resist freeze-thaw deterioration when this happened. When slabs are placed on top of an impermeable subbase, water can collect between the slab and the base. Subsequent freeze-thaw cycles can also lead to spalling.

Table 11. CRCP models identified for possible incorporation in HIPERPAV II (early-age behavior).

Model	Model Basis*	Pros	Cons	Valid	Inputs	Outputs	Development
CRCP-8 ⁽³⁹⁾	M-E	-Mechanistic-Empirical -Validated	-Crack width predictions are not accurate ⁽⁴⁴⁾ -1D, does not take into account temperature, moisture gradients	Yes	-Temperature drop -Drying shrinkage -Materials properties -Geometry -Strength gain -Friction characteristics	-Crack spacing -Crack width -Steel stress -Bond development length -Steel stress -Crack width	Complete
CRCPFEM ^(40,45)	M	-Mechanistic -2D-FEM (temperature gradient) -Relaxation/creep considered	-Coarse mesh -Requires validation -Requires crack spacing as input	No	-Crack spacing -Bond stress characteristics -Geometry -Materials properties -Concrete temperature gradient -Drying shrinkage gradient -Friction characteristics	-Concrete/steel displacement -Concrete stress -Steel stress -Crack width	Under development
TTICRCP ⁽⁴¹⁾	M-E	-Mechanistic-Empirical -Allows any type of bond-slip relationship -Better prediction of crack width	-Requires crack spacing as input	No	-Crack spacing -Temperature drop -Drying shrinkage -Materials properties -Strength -Geometry -Bond stress characteristics -Friction characteristics	-Concrete/steel displacement -Bond stress -Concrete stress -Steel stress -Crack width	Subject to further modification
CTR** Crack Width Model ⁽⁴²⁾	E	-Validated	-Empirical	Yes	-Residual shrinkage -Materials properties -Temperature difference	-Crack width	Complete

* Model Basis: M – Mechanistic, E – Empirical, M-E – Mechanistic Empirical.

**CTR – Center for Transportation Research

Table 12. CRCP models identified for possible incorporation in HIPERPAV II (long-term performance).

Model	Model Basis*	Pros	Cons	Valid	Inputs	Outputs	Development
FHWA Punchout ⁽⁴⁶⁾	M	-Mechanistic	-Requires validation	No	-Materials properties -Geometry -Crack spacing -Joint stiffness	-Punchout failure	Requires development
CRCP-8 Punchout ⁽³⁹⁾	SM	-Calibrated -Reliability included	- Semi-mechanistic	Calibrated	-Wheel load stress -Materials properties -Geometry -Number of load applications -Fatigue coefficients	-Punchout failure	Complete
Delamination Spalling Model ⁽⁴⁷⁾	M	-Mechanistic -Related to early age	-Requires complex modeling of early-age delamination due to moisture loss	No	-Delamination depth -Tire pressure -Tire shear stress -Materials properties -Bond friction	-Spalling failure	Complete
Performance Models ⁽⁴⁸⁾	E	-Simple	-Empirical	No	-Geometry -Materials properties -ESALs -Subbase type	-Failures per mile	Complete
CTR** TxDOT Performance Models ⁽⁴⁹⁾	E	-Simple	-Empirical	No	-Geometry -ESALs -Support -Distress index	-Distress index	Complete
Blowup Model ⁽⁵⁰⁾	M	-Mechanistic	Requires validation	No	-Temperature increase -Materials properties -Geometry	-Blowup failure	Complete

* Model Basis: M – Mechanistic, E – Empirical, M-E – Mechanistic Empirical, SM – Semi-Mechanistic

**CTR = Center for Transportation Research

3.4.1.2 *Effect of Concrete Properties on Faulting*

Faulting of pavements is believed to be a two-step process. First, the joint opens and water penetrates into the joint, causing erosion of the subbase/subgrade. PCC material properties, such as its CTE, and shrinkage, (in addition to slab-subbase interaction) control the size of the joint opening. If the opening is large, water penetration into the joint is likely to occur, and faulting will begin. However, if the joint does not open to a critical level, then faulting can be delayed. If the joint opening can be kept smaller than 0.6 to 0.75 millimeters (mm), aggregate interlock will provide load transfer, and this will keep the joint tight.

After water has penetrated the joint, faulting is controlled primarily by the behavior of the material under the concrete slab. If the material is granular, erosion of the subbase at the leave edge of the slab and its subsequent accumulation under the approach edge of a JPCP slab will cause faulting. If the material is a cement-treated base (CTB), pumping erodable subgrade materials under the slab will lift the slab and cause faulting. Curling of the slab can contribute to an increased amount of faulting.

3.4.1.3 *Effect of Concrete Properties on Transverse Cracking and Corner Breaks*

To prevent transverse cracking and corner breaks, one possibility is to increase the strength of the concrete, that is, its tensile strength. In pavements, concrete fails in tension, and very rarely in compression. Because compressive strength of concrete is one of the properties commonly measured, relations between compressive strength and tensile strength were generated. However, increasing the compressive strength from 33 to 75 MPa only increases the tensile strength by 50 percent. Tensile strength of concrete is influenced by the aggregate-matrix bond. The bond does not affect the compressive strength to the same degree. Likewise, increasing the compressive strength of the concrete increases the concrete's modulus of elasticity. This also increases the curling and warping stresses. Because fatigue of the concrete is believed to control transverse cracking and corner breaks, the stress-to-strength ratio is important. This ratio is used in the theoretical equations to predict the number of loads the concrete can sustain before cracking. Because an increase in concrete strength causes a similar increase in concrete stresses, it is unlikely that increasing the concrete's strength will also increase pavement life.

Decreasing the water-to-cement ratio is known to increase concrete's tensile strength. Increasing cement content can also increase concrete strength, but this is not desirable because thermal expansion and contraction increase, as does the concrete's shrinkage. The aggregate used in the concrete must be sound (not reactive or influenced by freezing and thawing) and have good fracture properties if the tensile strength is to increase. From a fracture perspective, to increase the tensile strength of the concrete, the resistance to crack initiation (fracture toughness) and crack propagation (fracture energy) has to be increased. Fracture toughness has been found to correlate positively to concrete tensile strength. Using hard coarse aggregate will increase the toughness of the concrete and also lead to a tougher failure. Larger sized aggregate will also make the concrete tougher, provided the aggregate is not susceptible to durability problems.

Faulting of the concrete pavement can also lead to transverse cracking. Pumping and erosion of the soil beneath the slab when supported by a CTB can cause cracking; this results from traffic loading and curling stresses. Increasing slab thickness has been found to decrease the degree of transverse cracking in this scenario.

3.4.1.4 Concrete Durability Issues

In pavements, it is not desirable for the strength of the concrete to decrease with time due to weathering. This will cause increased spalling and as well as cracking. Therefore, concrete should be designed to have good durability properties, such as resistance to freeze-thaw cycles and to air and water permeability. Low permeability will prevent freeze-thaw damage, as will a good air void system.

3.4.1.5 Concrete Mix Proportions

The concrete mix proportions are the key to obtaining the required concrete properties, whether they are for increasing the strength or for increasing the concrete durability. The primary variables affecting PCC properties are shown below in table 13. Coarse aggregate characteristics and water-to-cement ratio are important in determining the properties of the concrete.

Table 13. Primary variables affecting PCC properties.

PCC Property	Coarse Aggregate Characteristics	w/c Ratio	Cement Type and Content	Mineral Additives	Air Entrainer
PCC strength	•	•	•	•	•
Elastic modulus	•	•			
Fracture energy	•	•			
Permeability		•	•	•	
CTE	•		•		
Air void system			•		•

NOTE: Coarse aggregate characteristics refer to size, type, gradation, hardness and angularity.

3.4.1.6 Potential HIPERPAV II Module Based on the High Strength Study

If included in HIPERPAV II, a module can be developed to relate the PCC properties to the distresses quantitatively as well as a qualitatively. The primary PCC properties that influence the JPCP distresses are shown in table 14.

Table 14. Primary PCC properties that influence JPCP distresses.

PCC Property	Joint Faulting	Joint Spalling	Transverse Cracking	Corner Breaks
PCC strength	•	•	•	•
Elastic modulus	•	•	•	
CTE	•		•	
Shrinkage	•			
Fracture energy			•	•
Permeability		•		
Air void system		•		

3.4.2 Dowel Bar Study⁽⁵¹⁾

One of the possible improvements to HIPERPAV is the addition of a dowel bar module. Dowel bars are subjected to combined environmental loading and dynamic traffic loading at the joint during the pavement's lifetime. This module can assess how dowel bars affect the early-age performance of the joint in JCPs (e.g., how the bearing stress of the dowel on the concrete changes as a function of temperature and time will be calculated). If the bearing stress is greater than the concrete's early-age bearing strength, then it is probable that the dowel will loosen in the pavement at a faster rate than if the bearing stress was designed to be less than the concrete's bearing strength. Cyclic loadings commonly cause crushing of the concrete at the dowel interface due to the high stresses at those locations. Voids at the dowel-concrete interface will eventually cause the dowel to provide reduced LTE.

This section is divided into two parts. The first part provides background information on experimental instrumentation of dowels in a test section in Ohio, and the second section describes the input and potential output from the HIPERPAV II dowel analysis module. The data from the experimental study can be used to validate theoretical models that will possibly be used in the HIPERPAV II dowel analysis module.

3.4.2.1 *Experimental Study of Dowel Bars in Rigid Pavement*

An experimental study on the performance of dowel bars in rigid pavements was recently completed by Sargand at Ohio University.⁽⁵¹⁾ One of the major rehabilitation costs for pavements is repairing prematurely deteriorated transverse contraction joints. Sawed joints are the primary location of premature distress. Joint performance is influenced mainly by temperature and moisture distributions through the pavement and the subgrade. Physical properties of the base and subgrade, and dowel bar type, size, and spacing are also factors. Typically, circular steel dowel bars are used to transfer vertical shear and horizontal bending moments between adjacent slabs. Construction methods used in placing these dowels are critical to their performance. For the bars to successfully transfer load, they must be aligned properly along their longitudinal axis and be lubricated over half their length before they are placed in the concrete.

The purpose of the Ohio experimental study was to evaluate dowel bar response under field traffic loads and environmental conditions. The performance of steel and fiberglass dowel bars was also compared. The dowel bars were instrumented with strain gages so that the effect of traffic loading and environmental conditions on dowel-concrete bearing stress could be obtained.

A typical Ohio PCC mix design was used. The PCC pavement is placed over a nonstabilized aggregate drainage base (100 mm thick). This layer is over a 150-mm-thick dense-graded aggregate base. A bituminous prime coat is applied between the two base materials. The steel dowel bars are 38.1 mm in diameter and 457 mm long with modulus of elasticity (E) of 200 gigapascals (GPa) and shear modulus (G) of 78 GPa. The fiberglass dowel bars are transversely isotropic; their properties parallel and perpendicular to the longitudinal axis of the bar are: $E_{\text{long}} = 5,516$ GPa, $E_{\text{trans}} = 13.8$ GPa, $G_{\text{trans}} = 2.8$ GPa, Poisson's ratio $\nu_{\text{long}} = 0.071$ and $\nu_{\text{trans}} = 0.42$. The dowel bars are instrumented with two uniaxial strain gages and one rosette strain gage. The strain gages are epoxied to the center of the bar to coincide with the location of future joint sawing in the pavement.

The dowels act to resist the temperature and moisture-induced pavement shapes. For example, if the slabs curl upward (as in figure 8), then the dowels bend negatively to resist slab deformation.

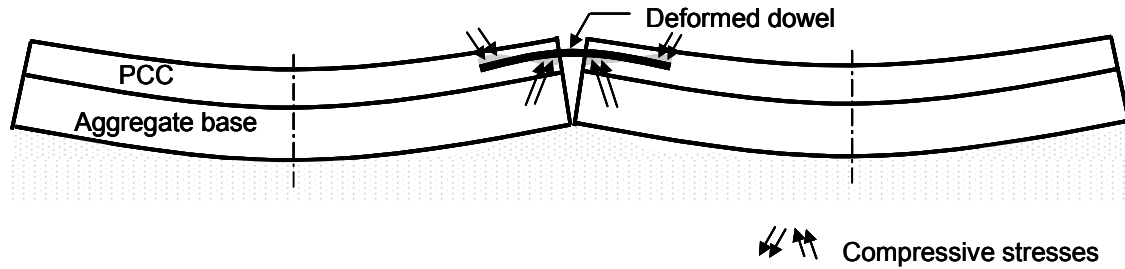


Figure 8. Schematic of dowel bar deformation due to slab curling.

The opposite happens for slab warping, where the dowels bend positively (upward) to resist deformation. The stiffer the dowel, the more it is able to resist deformation. However, the resultant stresses in the dowel and at the dowel-concrete bearing location are higher.

In this analysis, equations are provided to determine:

1. Strain as a function of gage voltage for the uniaxial strain gages.
2. Dowel bar bending moment as a function of strain.
3. Dowel bar bending stress as a function of bending moment.

Vertical shear force and shear stress in the dowel can be determined based on the results obtained with the rosette strain gages. Finally, the measured bearing stress on the concrete due to the dowel bar is calculated, as is the allowable theoretical bearing stress (using an empirical equation).

As shown in figure 9, the bending moments measured in the steel and fiberglass dowel bars are dependent upon the cyclic daily temperatures.

The bending moments in the steel dowel bar were found to be three to four times greater than in the fiberglass dowel bars; this was due to the greater stiffness of the steel bars. Some of the measurements indicated that the calculated steel dowel bar bearing stress is greater than the early-age compressive strength of the concrete (during hydration), depending on dowel bar location. The stresses on the dowel were found to be 17.9 MPa at the pavement edge, 16.5 MPa at the wheel path, and 15.3 MPa at the pavement center. It is highly probable that the dowel will loosen and reduce its efficiency in transferring loads across the joint if the dowel bearing stress is greater than the concrete's compressive strength. The fiberglass dowels did not induce a bearing stress comparable to the concrete's compressive strength.

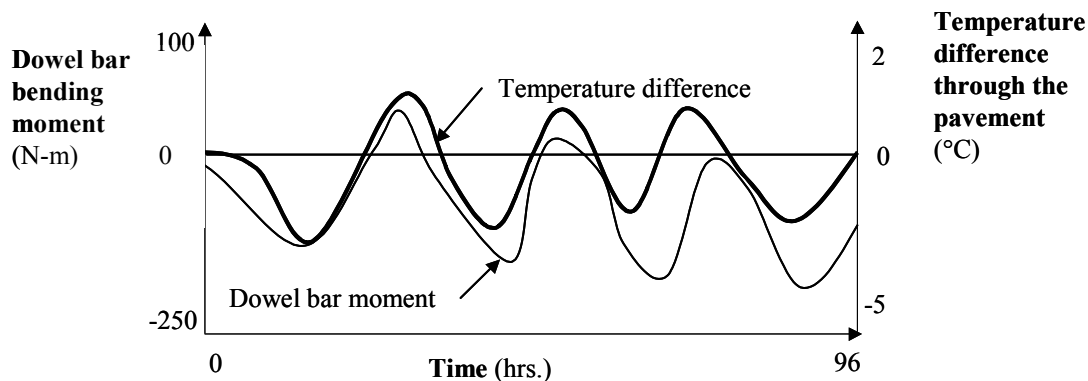


Figure 9. Conceptual schematic of dowel bar bending moment and its correlation to the temperature difference in the slab.

To simulate the effect of wheel loads on the pavement joint, the Falling Weight Deflectometer (FWD) test was used. FWD is one of the most popular nondestructive dynamic testing devices in the pavement industry. The results show, as expected, that the joint did not crack where the strain gages are. Moments in the steel dowel bars were much higher than for the fiberglass bars. Vertical shear in the dowel bars was also calculated at the approach, joint, and leave sections. Again, the vertical shear is greater in the steel dowel bars than in the fiberglass bars.

The addition of a dowel analysis module in HIPERPAV II is feasible. This module could be used to predict the long-term performance of the dowels based on their early-age behavior. If the dowel bearing stress on the concrete is greater than the concrete's bearing strength during the first 72 hours after pavement construction, it is likely that the dowel will loosen from the concrete under additional loading, and its LTE would be reduced. This module could be used to reduce expensive and time-consuming pavement rehabilitation costs, because deterioration of the JCP's transverse joint is one of the most common distresses.

3.4.3 Performance-Related Specifications Study (See references 52, 53, 54, and 55.)

Adding a PRS module to HIPERPAV II for JPCP is a possibility. This section summarizes past work on PRS and describes how a module can be incorporated in HIPERPAV II.

3.4.3.1 Performance-Related Specifications

Acceptance quality characteristics (AQC) are pavement properties that can be measured immediately after construction, such as concrete strength, slab thickness, and initial smoothness, and can be controlled directly by the contractor. PRS is the method that can directly relate these early-age pavement properties directly to pavement performance (distresses), maintenance and rehabilitation (M&R) costs, and finally to the pavement's life cycle costs (LCC). The result of this analysis is the pay adjustment factor for the contractor. Pay adjustment is based on the comparison between the pavement's "As-Designed" LCC (LCC_{DES}) and the "As-Constructed" LCC (LCC_{CON}). If LCC_{CON} is less than LCC_{DES} because of the high quality of the product delivered by the contractor, then the contractor will receive a pay increase. However, if the opposite occurs, then the contractor will receive a pay decrease. PRS allows for a rational determination of pay adjustment factors. It also can be used to determine the optimal values of the AQC (mean and standard deviation) for the optimal financial return for the contractor and

for the State highway agency (SHA). PRS links materials and construction practices directly to pavement performance.

A simplified schematic showing how PRS works is provided in figure 10. PRS are similar to quality assurance (QA) specifications. However, QA specifications only specify the quality of the product and not the desired performance of the pavement. QA specifications address only item 1 in figure 10, while PRS address all 5 items.

- 1. Select desired AQC (acceptance quality characteristics)**
- 2. Quantify relationships (models) for distress prediction**
- 3. Predict pavement performance**
- 4. Calculate life cycle costs (LCC)**
for 'as-designed' LCC_{DES} and 'as-constructed' pavements LCC_{CON}
- 5. Calculate pay factor for contractor**
If $LCC_{DES} > LCC_{CON}$, pay decrease
If $LCC_{DES} < LCC_{CON}$, pay increase

Figure 10. Simple schematic outlining PRS.

First, the SHA should identify the distresses that should be controlled by the specifications. The distresses selected are function of the aspects of pavement performance that the SHA wants to improve.

Second, the desired AQC are selected. These are properties of the pavement that the contractor controls, and are properties that impact the long-term performance of the pavement. At the lowest level of PRS, typical AQC are concrete strength, concrete thickness, air content of the concrete, and initial roughness of the pavement. Other AQC that are being considered for inclusion in the future include percent consolidation around dowels, tie bar depth, and sawcut depth. The mean values and standard deviations of these properties impact the final pay adjustment. Therefore, it is important to adopt an acceptance sampling and testing plan for the determination of these properties. Because the AQC should be obtained immediately after construction, it is necessary to have models that can predict the long-term properties based on the early-age properties.

Third, the pavement distress models are selected. For JPCP, typical distress models selected are indicators of faulting, transverse cracking, transverse spalling, and present serviceability rating (PSR). The models are chosen because they relate the AQC to the distress type. However, AQC are not the only input to these models. In addition, constant values are input to the model, for example climate, traffic, and project location. However, the contractor does not have control over all these properties.

After relating AQC to pavement distresses, pavement performance can be predicted. Figure 11-14 illustrate that PRS quantify the change in the distresses with time.

The fourth step is calculating LCC. LCC takes into account the M&R plan and the unit costs for M&R. M&R costs can be divided into SHA costs and user costs. The SHA costs are day-to-day maintenance, localized rehabilitation (individual slabs and joints), and global rehabilitation (pavement replacement). In the FHWA PaveSpec software, local rehabilitation is considered on a subplot basis and global rehabilitation on a lot basis. Typical costs to the user are travel time, vehicle operation, accident costs, and discomfort costs.

The final step is to calculate pay factors. Different methods are used to calculate pay factors dependent on the level of PRS selected. If a Level A PRS is chosen, then an independent pay factor is calculated for each AQC. Finally, a composite pay factor is calculated which is a mathematical function of each independent AQC. However, if a Level B PRS is selected, the interactions between the AQC are accounted for (e.g., how concrete strength affects pavement thickness). Computer simulation (i.e., using the FHWA PaveSpec software) is necessary to calculate the pay factor.

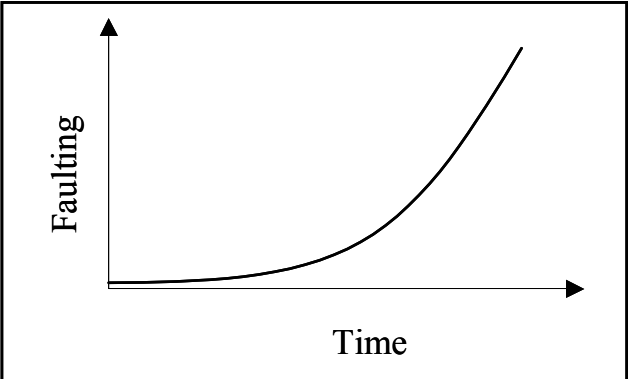


Figure 11. JPCP pavement performance in terms of faulting.

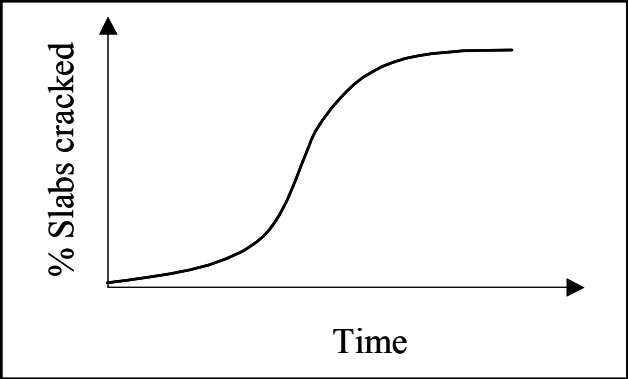


Figure 12. JPCP pavement performance in terms of transverse cracking.

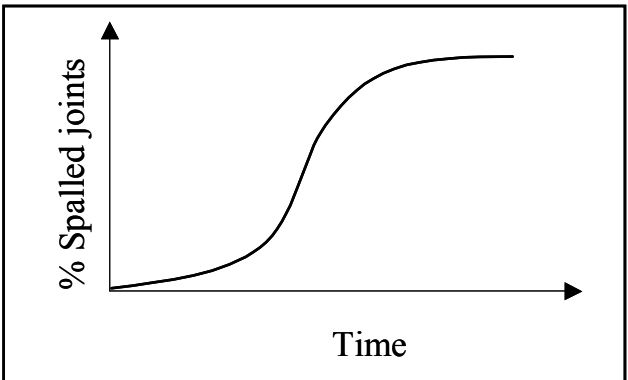


Figure 13. JPCP pavement performance in terms of spalled joints.

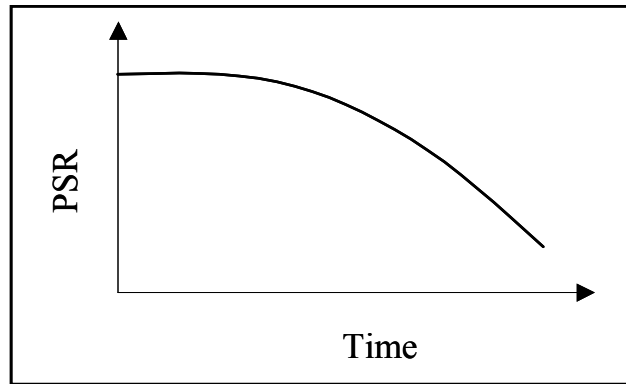


Figure 14. JPCP pavement performance in terms of initial pavement roughness.

3.4.3.2 *PRS Benefits*

Four benefits of PRS design for SHAs are:⁽⁵²⁾

- PRS provides well-defined AQC target values (mean and standard deviation). A particular pavement quality can be reached if the target AQC is achieved.
- PRS provides a rational means to determine pay adjustments.
- PRS relates construction properties to pavement performance and LCC.
- Pavement costs will decrease once a rational PRS plan has been implemented. This is because both the SHA and the contractor strive to minimize LCC.

3.4.3.3 *PRS Levels*

There are three discrete levels of PRS implementation.⁽⁵²⁾ Level A is the simplest and most readily implementable PRS. Complexity increases from Level B to Level C. Three factors comprise the PRS levels.

- Methods of acceptance testing (tests currently in use by the SHA).
- Pay adjustment method (with more tests in situ, such as cores, air content, etc.).
- Use of nondestructive tests.

The Level A method of acceptance testing involves in situ sampling and testing from sublots of the constructed concrete pavement. A pavement lot is “a discrete quantity of constructed pavement to which an acceptance procedure (and corresponding pay adjustment) is applied. All pavement placed within a lot should consist of the same mix design and material sources, should be subjected to the same support conditions, and should consist of the same design characteristics.”⁽⁵²⁾ For Level B, sampling and testing should include additional in situ testing in addition to nondestructive testing. For Level C, nondestructive testing to determine concrete properties primarily should be used. Level C is typically described as a futuristic PRS level.

3.4.3.4 *Prospective PRS Module in HIPERPAV II*

PRS and HIPERPAV systems can be thought of as truly complementary. PRS are a means to directly address the impacts of various design and construction features on the resulting pavement performance. On the other hand, HIPERPAV is able to verify the impacts that these design and construction features may have with respect to the potential for early-age damage. For example, if strength is selected as an AQC in the PRS system, then the contractor may have an incentive to increase

the strength. Often, a higher cement factor is selected to achieve the higher strength. Although the payment under the PRS system could serve to benefit the contractor, the performance may not necessarily improve. Although higher strength will increase the predicted fatigue life of the pavement, the higher cement factor could also lead to early-age problems. The interaction of the advantages and disadvantages of the strength gain are not easy to quantify. The problem is compounded with separate programs (PaveSpec used for PRS, and HIPERPAV used for early-age, damage-related specifications), since the user would need to run both systems independently, requiring manual interpretation from both systems. However, if brought together, the components of the PaveSpec and HIPERPAV predictive capabilities can present the user with this information in a straightforward and easy-to-understand fashion.

To incorporate early-age damage related specification concepts into HIPERPAV, a substantial amount of additional work would have to be performed. As a start point, the lowest equivalent PRS Level A could be added. AQC would have to be designated in the software, and their standard deviations would be included. An additional module would be required so that the lots and sublots could be defined for all sampling and testing. Likewise a pay factor module, an LCC analysis module, and an M&R costs module would need to be added. As new models that are able to predict interactions between concrete properties of interest and innovative test procedures become available, Levels B and C could be incorporated later.

In general, three unique ways of integrating HIPERPAV with standard specifications are possible:

1. Merging standard specifications into HIPERPAV: This method consists of incorporating the text of standard specifications into HIPERPAV through a knowledge base. It would provide recommendations and warnings during the HIPERPAV runs that relate to items considered in the standard specifications, tying them to the inputs in the software.
2. Merging HIPERPAV into standard specifications: In this method, standard specifications could be written to require the use of a temperature management software such as HIPERPAV, further assuring that uncontrolled cracking is avoided.
3. Integrating HIPERPAV and PaveSpec: This method involves combining HIPERPAV and PaveSpec together as described in the above paragraphs, and would be ideal for highway agencies currently considering PRS.

The best option from the above three would depend on the current specifications being used by any individual SHA. It is believed that the first method—merging standard specifications into HIPERPAV—would be the most readily implementable, because it involves less risk to the highway agency in terms of liability. On the other hand, following the current trend of highway agencies shifting to PRS, integrating HIPERPAV and PaveSpec would provide an ideal tool for implementing such a specification.

3.4.4 Curing Study

One FHWA contract currently underway is intended to provide guidelines for curing of PCC pavements (PCCP).⁽⁵⁶⁾ This section describes briefly the objectives of that study, and evaluates the possibility of including the resulting PCCP curing guidelines in HIPERPAV II.

3.4.4.1 PCCP Curing Guidelines

The initial efforts under the FHWA curing study have been compiled into an interim report.⁽⁵⁶⁾ That interim report is the primary source of information in evaluating the guidelines that are expected to be available in the near future.

The primary project objectives identified on the FHWA curing study are:

- Develop a summary of curing standards, current practice, new technologies, and published research.
- Compile gathered information into a guide on curing practices for PCCP.
- Identify deficiencies in the current practice.
- Develop a plan for correcting deficiencies of the current practice.

Based on the information search on PCCP curing, a number of guidelines on curing methods and procedures are recommended in the report. These recommendations are outlined in figure 15. These guidelines primarily address the selection of curing methods, duration of curing, and temperature management during placement.

Selection of Curing Methods. The curing methods section in the guidelines is divided into curing compound methods, water-added methods, and water-retention methods. The selection of curing compounds is primarily based in economic and practical considerations rather than quality or performance.

Selection of the curing compound method is recommended primarily for large placement areas such as highway applications, where the curing compound is the only practical option. Curing compounds are also recommended when other curing materials are unavailable.

Selection of water-added versus water-retention methods is based primarily on the availability of water for hydration. Because water-cement ratios lower than 0.40 lead to insufficient hydration of the cement paste, this threshold is used for selecting curing methods. Water-added methods are recommended whenever the water-cement ratio is equal or less than 0.40, or when expansive cement is used. For water-cement ratios greater than 0.40, the risk of damage to the concrete is lower, and water-retention methods are considered a more viable option. Water-retention methods are also recommended whenever curing compound methods are not suitable, and when no risk on excessive evaporation is present.

For each of the curing methods, additional guidelines on material selection, application rate, time of application, inspection, and curing verification are also presented. The selection is based primarily on select standards, climatic conditions (evaporation rate), mix design and materials (bleeding rate), and recommended practice.

Duration of Curing. Initial guidelines on duration of curing are also presented based on strength-gain rate criteria. However, additional work is required to develop guidelines on the duration of curing based on concrete durability.

Temperature Management. Temperature management is addressed in terms of cold weather concreting and hot weather concreting. For temperature management under hot weather, initial

recommendations are made in terms of preventive measures and adjustments to the curing methods (e.g., application rate). Procedures to determine the expected temperature drop in the concrete, and calculation of thermal stresses using software programs such as HIPERPAV, are also considered. In addition, estimating potential risk in concrete strength reduction for high temperature curing is mentioned. Additional work to address this issue is expected. Time of day of construction is also addressed, and recommendations in scheduling construction are made to avoid coincidence of the heat of hydration peak and the maximum temperature of the concrete due to solar radiation.

For temperature management during cold weather, precautions and recommendations are given to protect concrete from freezing, and to maintain a uniform concrete temperature. Primary measures mentioned in the guidelines include: insulation, heated enclosures, and need for moisture retention. More work is expected for developing cold weather concreting guidelines.

3.4.4.2 Benefits of Incorporating the Curing Study in HIPERPAV II

Incorporating the curing guidelines in HIPERPAV II is considered beneficial, as it would complement the software with useful recommendations on improving the performance of concrete pavements through appropriate selection of curing methods, as well as guidelines on the application and duration of curing procedures.

Provided that the curing guidelines address the effect of moisture loss on strength gain, the accuracy of the strength gain prediction with HIPERPAV for different curing methods would also be enhanced.

Finally, it is believed that since HIPERPAV predicts the temperature development in the concrete during the early age, incorporating curing guidelines in HIPERPAV would help users address temperature management-related issues such as thermal stress development, potential of strength reduction (high temperature), strength development during cold weather concreting, and freezing risk.

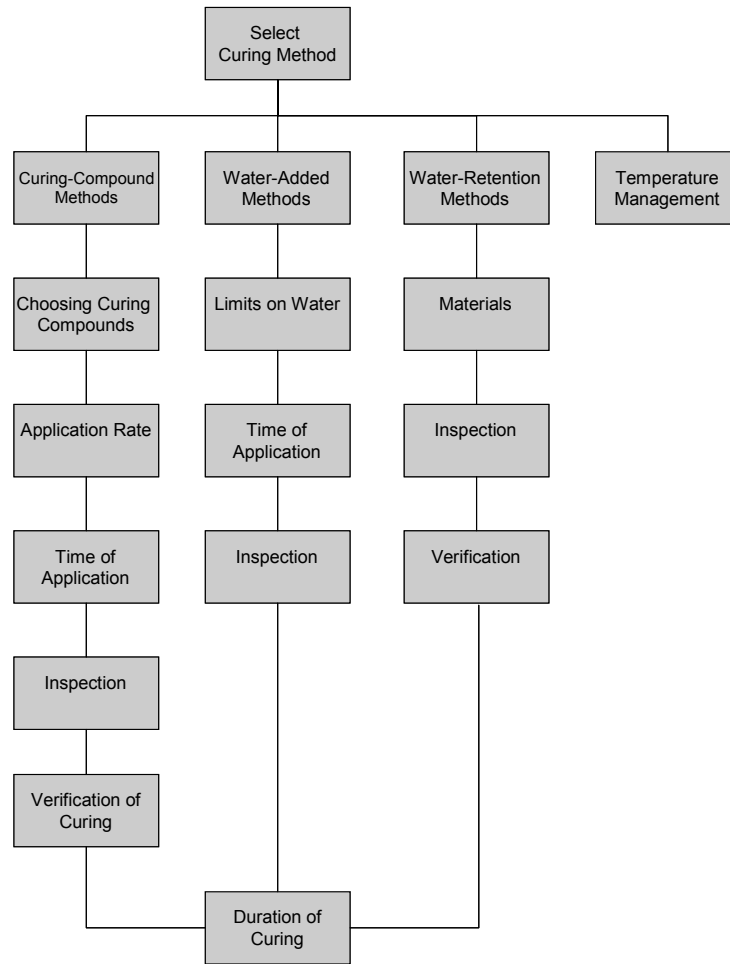


Figure 15. General outline of the FHWA curing guide.⁽⁵⁶⁾

3.4.5 Curling/Warping Study

An FHWA study on the modeling of curling and warping behavior of PCCP (Early and Long-Term Effects of Curling and Warping on Jointed Concrete Pavement—DTFH61-95-C-00021) was under development at the time of writing this report. Although not enough information on the curling/warping study could be obtained at the time of writing this report, the results of this study will include new and improved models for predicting the curling and warping response. Since curling and warping are already an integral part of the HIPERPAV system, these models would be a natural extension to the overall total systems approach in HIPERPAV II.

3.4.6 Mix Optimization Study

Under a research project, “Concrete Mixture Optimization Using Statistical Methods,” of the FHWA Concrete Pavement Technology Program (CPTP), a straightforward but powerful approach to select mixture proportions based on a number of performance criteria was developed.^(57,58) The technique had been used previously by the petrochemical and food industries, among others, and was adapted for use on concrete mixes in that project. It employs the use of statistical techniques for optimization of given performance criteria (i.e., slump, strength, cost) based on results from experimental batches. This

methodology provides the flexibility for optimizing virtually any combination of performance criteria defined by the user.

Over the past 5 years, FHWA and the National Institute of Standards and Technology (NIST) have further developed this optimization approach, and have recently completed a Web-based application named COST (Concrete Optimization Software Tool).⁽⁵⁹⁾

The mix optimization procedure used in COST is summarized below:

1. Responses to be measured are specified by the user (i.e., slump, strength, cost).
2. The mixture components considered for optimization and proportioning limits for each component are specified.
3. Based on the above information, an experimental design is developed to produce a factorial of mixes for laboratory testing.
4. Trial batches are run and the responses of interests are measured.
5. With the results from laboratory testing, polynomial models are developed and calibrated to predict the performance results as a function of the mix proportions.
6. Weight (desirability) functions are assigned to the various performance measures (i.e., minimum cost, maximum strength, target slump).
7. Statistical tools and plots are used for data analysis and interpretation.
8. Mix designs are scored based on the weight functions assigned for each individual response.
9. Numerical optimization techniques are used to identify optimum mixture proportions.

3.4.6.1 *COMET*

A simplified concrete mix optimization module named Concrete Optimization, Management, Engineering, and Testing (COMET) is proposed for incorporation in HIPERPAV II. COMET would be based on the same principles used in developing COST. A schematic of COMET is envisioned in figure 16. As seen in this figure, COMET follows the same general logic as previously described, but with some notable modifications. The mix optimization procedure in COMET illustrated in figure 16 is described below:

1. To ensure the greatest potential for implementation (requiring minimal training), mix constituents are limited to cement, pozzolan, water, coarse aggregate, and fine aggregate. Variables that the user can optimize are limited to coarse aggregate fraction, cementitious content, pozzolan substitution, and water-cementitious materials ratio (box 1).
2. Optimization ranges are provided by the user for every variable, and a total of 29 mixes are developed for the experimental program (box 2).

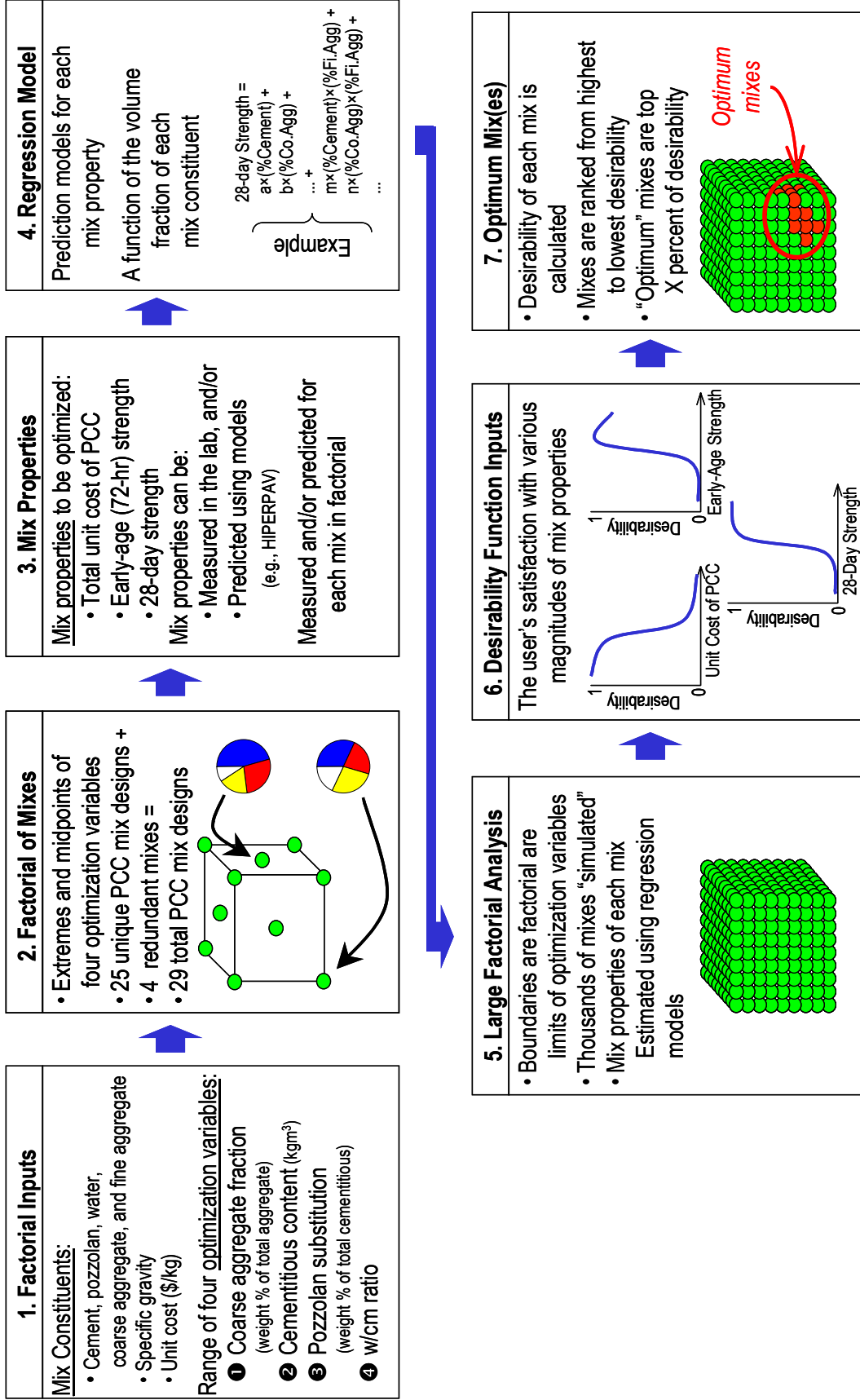


Figure 16. Conceptual representation of the COMET module in HIPERPAV II.

3. Optimization responses are fixed to early-age strength, long-term strength, and cost per cubic yard. A unique addition to the process is made here, whereas the COST system simply prompted the user to enter lab-measured properties. HIPERPAV II optionally utilizes analytical models to predict the same properties. This addition allows the optimization tool to be used in a planning stage, where the mix constituents may not be readily known or available for testing (box 3).
4. Regression models based on the results from the experimental program or from the predicted responses are developed and calibrated to predict the performance results as a function of the mix proportions (box 4).
5. With the models developed, thousands of mixes are simulated, and the responses for every mix computed (box 5).
6. The user has the flexibility to assign desirability functions to the various optimization responses (box 6).
7. Finally, optimum mixes are identified in terms of the individual desirability for every response and in terms of the maximum overall desirability for all responses (box 7).

3.4.7 FHWA Studies Selected for Incorporation

Although all FHWA studies reviewed have a potential for successful implementation in HIPERPAV II, only two of these studies had to be selected. Several factors were considered for this selection, including the status of completion, level of difficulty required for incorporation, easiness of implementation, and usability by the pavement community. Table 15 presents a discussion of the pros and cons considered during the selection process. Based on the advantages and disadvantages identified on each study, the dowel bar study and the mix optimization study were identified as the best candidates for incorporation in HIPERPAV II.

Table 15. Pros and cons of the FHWA studies identified for incorporation in HIPERPAV II.

FHWA Study	Pros	Cons
The Effects of Higher Strength and Associated Concrete Properties on Pavement Performance (FHWA-RD-00-161) ⁽⁴¹⁾	<ul style="list-style-type: none"> • Examines the effect of higher strength and durability properties of concrete on long-term performance and is inline with the objectives of the long-term JPCP module in HIPERPAV II. • This study had been completed at the time of this selection. 	<ul style="list-style-type: none"> • Although guidelines are provided, no specific models are identified for performance prediction.
Performance of Dowel Bars and Rigid Pavement ⁽⁵¹⁾	<ul style="list-style-type: none"> • Examines the effect of bearing stress at the dowel locations as a result of environmental and traffic loading. • Models for prediction of dowel stresses coupled with HIPERPAV predictions are readily available. • This study had been completed at the time of this selection. 	<ul style="list-style-type: none"> • Simulation of dowel bearing stress for traffic loading may require further development.
Guide to Developing Performance-Related Specifications for PCC Pavements ⁽⁵²⁻⁵⁵⁾	<ul style="list-style-type: none"> • PRS and HIPERPAV can be used as complimentary tools for identifying desirable acceptance quality characteristics. • This study had been completed at the time of this selection. 	<ul style="list-style-type: none"> • A substantial amount of additional work would be required for incorporation of this module. • Only a small portion of the PRS study could be realistically added within the time constraints for this project.
Curing of Portland Cement Concrete Pavements ⁽⁵⁶⁾	<ul style="list-style-type: none"> • This study would complement HIPERPAV with useful recommendations for selection of curing methods. • Provided that the curing guidelines address the effect of moisture loss on strength gain, the accuracy of the strength gain prediction with HIPERPAV for different curing methods would be enhanced. • The temperature management concepts in the curing guidelines could be complemented with HIPERPAV predictions. 	<p style="text-align: center;">*</p>
Early and Long-Term Effects of Curling and Warping on Jointed Concrete Pavement FHWA contract No. DTFH61-95-C-00021	<ul style="list-style-type: none"> • Models developed for prediction of curling and warping response are directly applicable to HIPERPAV and could be used to enhance prediction of pavement behavior. 	<p style="text-align: center;">*</p>
Concrete Mixture Optimization Using Statistical Methods ^(57,58)	<ul style="list-style-type: none"> • The concepts in the mix optimization study are easily implementable in HIPERPAV. • Incorporation of this module in HIPERPAV would address the request from many users during previous implementation efforts. • This study had been completed at the time of this selection. 	<ul style="list-style-type: none"> • No particular drawbacks for incorporating this module in HIPERPAV were noticed.

* At the time of this selection process, this study was still in progress.

CHAPTER 4. GUIDELINE ENHANCEMENTS AND EVALUATION

4.1 APPROACH

The total systems approach that the project team has adopted served as the common methodology and the general philosophy throughout the enhancement of the software guidelines. This unique approach allows for the integration of a number of disconnected concepts into a unified, interconnected entity.

As discussed in chapter 1, the total systems approach allows the various components of the current HIPERPAV system to be integrated easily to work in conjunction with the proposed modules to be developed in this phase. This chapter addresses the technical approach that was taken to enhance the guidelines by incorporating the JPCP long-term module and the CRCP early-age module. In addition, the design of the software user interface and development approach for incorporation of each of the individual modules in HIPERPAV II is described.

4.1.1 CRCP Early-Age Behavior

The approach in developing the CRCP module for early-age behavior is similar to the current HIPERPAV I system for JPCP. The framework for the CRCP module is illustrated in figure 17. This figure presents the interactions of the models used to predict the development of strength and stresses in the pavement and the resulting cracking behavior.

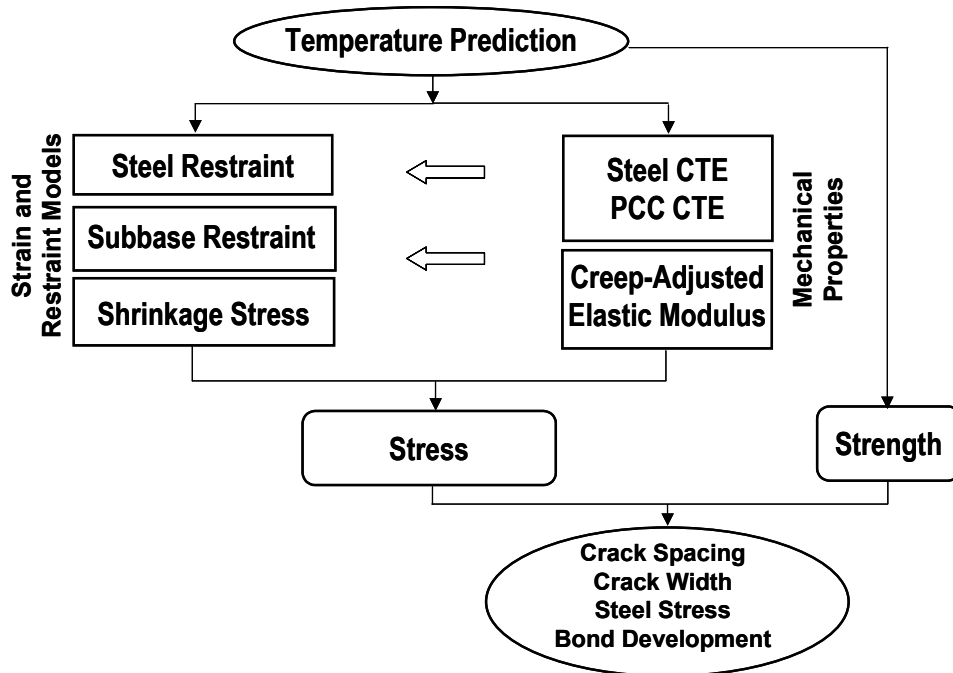


Figure 17. CRCP early-age module.

Like the early-age JPCP module, the CRCP module uses the HIPERPAV core for temperature prediction. The HIPERPAV I core is a two-dimensional FEM model that governs the heat transport in the concrete pavement. HIPERPAV II has been upgraded with a FDM-based model. With the concrete

temperature as predicted by the HIPERPAV temperature core, coupled with the maturity model (based on the Arrhenius method), the development of the strength and modulus of elasticity are predicted.

Concrete and steel stresses are predicted in terms of the volumetric changes that accompany the predicted change in concrete temperature under the defined restraint conditions. One of the mechanical properties required for determining stresses is the CTE of both concrete and steel.

Volumetric changes in the concrete are influenced largely by temperature and moisture changes. As these changes are restrained due to steel restraint, friction with the subbase, and the weight of the slab, stresses develop in the concrete. In addition to predicting mechanical properties and concrete temperature, the slab behavior in terms of stress development also is predicted. Modeling the CRCP early-age behavior characterizes the interaction between the steel and the concrete subjected to the various loads and restraints. By computing the stresses and strength along the pavement, the final crack spacings, widths, and steel stresses are solved.

“Early age” in HIPERPAV II includes the first 72 hours after construction for both JPCP and CRCP. However, in the case of CRCP, the cracking behavior continues to change until approximately 1 year after construction. After 1 year, cracking commonly remains constant. HIPERPAV II predicts the cracking behavior of CRCP during the early age and also during the early life (up to 1 year) to realistically assess the behavior of CRCP in service.

4.1.2 JCP Long-Term Performance

This section describes the overall functionality of the JCP long-term performance module. Figure 18 illustrates how each one of the different models is assembled in the HIPERPAV II system. The process is divided in nine different steps:

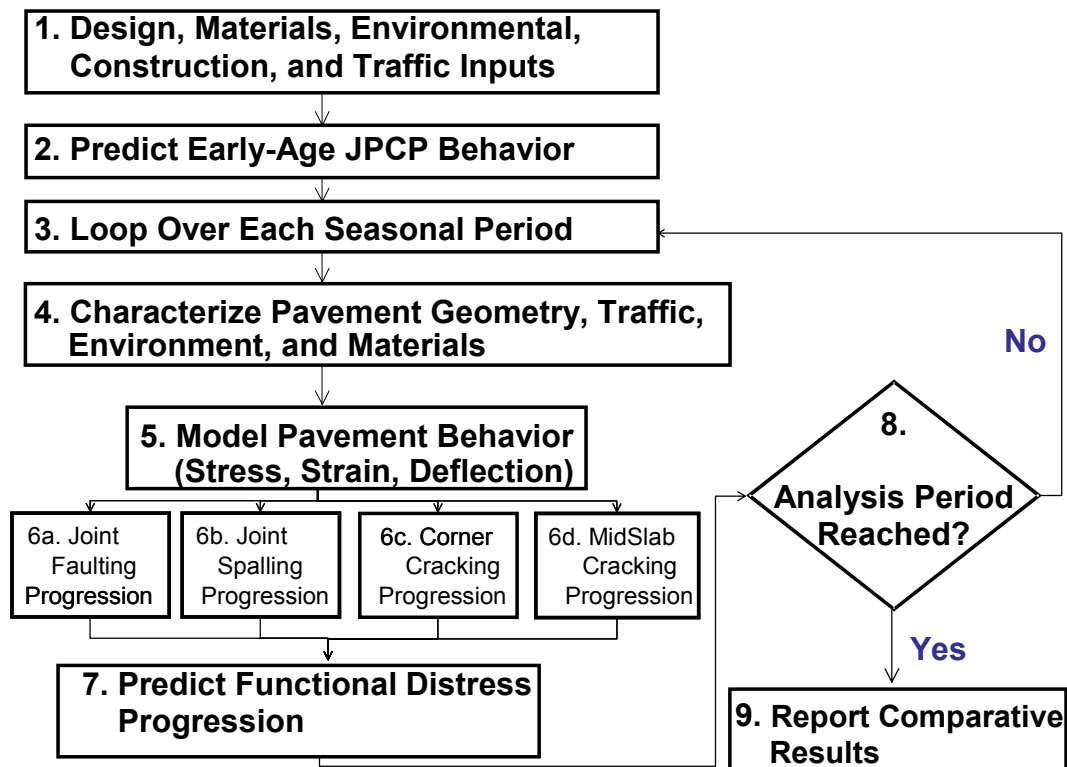


Figure 18. JCP long-term performance modeling.

Step 1—User Inputs

The user inputs for the long-term JCP models generally can be grouped into five categories:

1. Pavement design.
2. Materials and mix design.
3. Environment.
4. Construction.
5. Traffic.

Each of these categories contains a number of variables that can be defined by the user. Due to the number of inputs, guidance is provided in HIPERPAV II via default values, warnings, and tool tips. This also was accomplished by careful and practical engineering of the graphical user interface. As mentioned in chapter 2, the TEP members reviewed the product at various stages of completion to ensure its practicality.

Based on interaction with the TEP, great care was employed in this step. It was recognized that if the software was too data or labor intensive, most practitioners would not use it. However, if it was too simple, it might lack the accuracy for a reliable analysis. Therefore, a balance was made between the accuracy of the software and the complexity of the inputs.

Step 2—Early-Age Behavior

Early-age behavior of the pavement is required to be characterized for the long-term analysis, because it will provide initial information to feed the performance models. For example, initial temperature, moisture conditions, and joint opening are key early-age indicators (box 2 in figure 18). The enhanced early-age behavior models in HIPERPAV II are used for this purpose.

Step 3—Loop Over Each Seasonal Period

The essence of a systems analysis tool is to predict the various paving strategies as realistically as possible. This simulation is done chronologically by looping over each season from the initial construction season up to the last season of the user-defined analysis period.

Step 4—Characterize Pavement Geometry, Traffic, Environment, and Materials

After each seasonal period, the current conditions for the long-term pavement analysis are defined in terms of pavement geometry, traffic, environment, and materials.

a) Characterizing Pavement Geometry

The pavement geometry is characterized in terms of the layer thicknesses, slab configuration, and support conditions.

b) Characterizing Traffic

The traffic for the current period is defined as follows:

- Axle-load spectra—the simulation is performed over the full range of anticipated axle load spectra. An integration of the number of axles by the distress due to each axle load is made to predict the overall incremental distress.

- Growth—the traffic level generally will increase with time. An adjustment is made to reflect the growth function as defined by the user. Three growth functions are provided—linear, exponential, and logistic (s-shaped) growth.
- Time of day—the simulation loops over the time of day. This effect is important because the deflected shape of the pavement will differ from day to night, and therefore will impact in the predicted stresses.

To be as compatible as possible with the new guide for pavement structures, which was under development at the time of this writing (National Cooperative Highway Research Program (NCHRP) Project 1-37A), every attempt was made to develop the traffic module using similar logic.⁽⁶⁰⁾

c) Characterizing Environment

Various user inputs are needed to characterize the environmental conditions at the specified location for the design. To minimize the burden to the user, these inputs are extracted using a sophisticated GIS-based interface. When a location for the design is selected using the GIS system, an extensive environmental database is queried for weather data from weather stations in the vicinity of the specified location.

Using an intelligent algorithm, the most relevant weather stations are selected, and the weather information for the specified location is calculated based on a weighted interpolation scheme. The database actually contains mean hourly readings for the entire year (based on 30 years of data) for each of the specified stations. For simplicity, these values are the reduced seasonal means. In addition, the database contains the variances for each of these factors to better characterize the stochastic nature of weather phenomena.

Using the environmental inputs and the materials inputs, the temperature profiles in the pavement system are predicted using the FDM algorithm, similar to that of the integrated climate model (ICM) developed for FHWA.⁽²³⁾ The remaining characterization, behavior, and distress models in HIPERPAV II, in turn, use these profiles.

d) Characterizing Materials

HIPERPAV II uses dynamic values of variables such as temperature, moisture, cumulative damage, and time.

HIPERPAV II uses two unique models to predict the PCC strength and modulus. The first models are based on maturity methods and are used during the early-age analysis (step 2). The second are based on a more general form, and are used for subsequent analysis periods (step 4).

Step 5—Model Pavement Behavior

For each time step, the pavement behavior is evaluated as a function of the early-age conditions and conditions at the current time step to determine the stress, strain, and deflection of the pavement system.

Step 6—Distress Progression

After the pavement behavior is analyzed for the current conditions, individual models are used to predict distress progression. Two key structural distresses are evaluated. These include joint faulting and midslab cracking.

Other distress types, such as materials related distresses, are covered in the written design and construction guidelines (volume II of this report series), but due to the lack of reliable models, are not included in HIPERPAV II.

Step 7—Predict Functional Distress Progression

Functional distresses are a function of the structural distresses and are computed next.

Step 8—Check Analysis Period and Distress Thresholds

This step evaluates the current state of the pavement in the analysis loop. If the simulation has predicted a level of distress that the user denotes as being “terminating” in nature, HIPERPAV II reports it as the end of the service life for that analysis. However, the analysis continues until the analysis period is reached. It is also at this point that the loop advances to the next season to be simulated.

Step 9—Report Results

Depending on the analysis period selected, the long-term performance module in HIPERPAV II proceeds to the next environmental and traffic loop (step 3), or proceeds to report the results of the analysis (step 9).

As the TEP strongly recommends, long-term performance modeling should be used as a means to further optimize early-age pavement design, materials selection, and construction procedures. Long-term performance modeling should examine a relative (strategy comparison), rather than an absolute performance, based on the aforementioned factors. It must not be used for pavement (structural) design purposes.

4.2 SOFTWARE DEVELOPMENT

The software product is a stand-alone Microsoft Windows application. It contains code written in Microsoft Visual Basic[®] and Compaq[®] Visual Fortran[®]. The software displays numerical and graphical outputs for each analysis. The software saves, opens, and prints all inputs and outputs. The software also contains an add-in system to allow simple interoperability with current and future modules.

This section will present the components that make up the HIPERPAV II software in a top-down approach. The remainder of this section is divided into four subsections: Section 4.2.1 contains a list of feature set of HIPERPAV II; section 4.2.2 is an overview of the components that make up the system architecture and the relationships between these components, including the add-in system; section 4.2.3 is an overview of the components of the graphical user interface (GUI) with screenshots; section 4.2.4 will cover the document object model (DOM); section 4.2.5 describes the technical code that implements the models for HIPERPAV II; section 4.2.6 is an indepth look at the steps involved in the process of the software validation and verification; and section 4.2.7 summarizes the overall software project.

4.2.1 Features

The following feature set has been implemented into the GUI.

4.2.1.1 *File Management*

- The software allows the user to open and save files, using standard file dialogs. For example, File → New, Open, Save, Save As.
- The software allows for standard Microsoft Windows interoperability with both the local and network file systems, including drag-and-drop, most recently used (MRU) files, and file association.
- HIPERPAV II can import files from previous versions (extensions hpv and h25).

4.2.1.2 *Inputs*

- Only inputs necessary for the current analysis are shown to the user.
- All inputs contain default values and do not require adjustment to be able to run the analysis.
- The user is given the ability to select measurement units for inputs when applicable (for individual units just by clicking on the unit label or for the overall project by going to Tools → Options: Program Settings\General: Metric System).
- The product validates all inputs necessary for an analysis to run. Inputs that are questionable are displayed along with an explanation: Strategy → Validate.
- The product provides a graphical representation of inputs, where possible, to provide the user with a highly cognitive method of instant error checking.

4.2.1.3 *Outputs*

- The user may run the analysis for multiple strategies, and each set of outputs is available so that various alternatives can be analyzed and compared within a single project.
- The software also displays the input set that is associated with the current strategy selected.
- The user is given the ability to select measurement units for outputs when applicable.

4.2.1.4 *Printing*

- The software allows the complete set of inputs and outputs to be printed as a report.

4.2.1.5 *Troubleshooting*

- The product displays and saves any errors that have occurred: Tools → Event Log.
- The product is able to perform a self-diagnostic to determine if any installation files are outdated or missing: Tools → File Checker.

4.2.1.6 *Strategy Comparison*

- The product allows for comparison of multiple strategies for the same type of analysis to determine the difference between the strategies.

4.2.2 **System Architecture and Communication**

4.2.2.1 *Overview of Components*

The flowchart in figure 19 presents a top-level view of the system architecture. All modules use “Errors and Diagnostics.” The “Add-In System” is integrated into the system as a whole and is not considered a module.

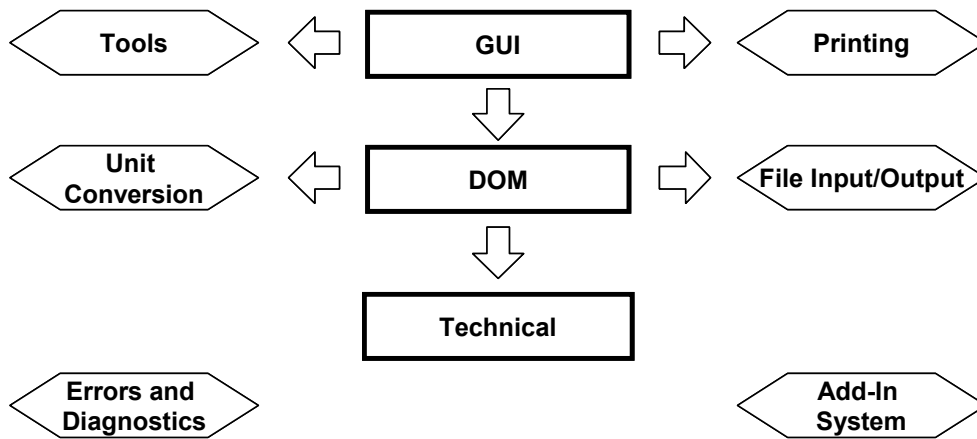


Figure 19. System architecture flowchart.

4.2.2.2 *Description of Primary Components*

The primary components for this project are highlighted in bold boxes in figure 19. These three components contain subcomponents and are examined in table 16.

Table 16. Primary system architecture components.

GUI	Graphical User Interface (GUI) The GUI component contains the code for the user display and presentation, as well as some validation and preprocessing logic.
DOM	Document Object Model (DOM) The DOM component contains the code for logic and processing. The DOM is responsible for tying all the components together.
Technical	Technical Code Module The technical code module contains the code for the engineering models and calculations that are used in processing the analysis.

4.2.2.3 Description of Secondary Components

The secondary components for this project are hexagonal shapes in figure 19. Table 17 identifies those components that are shared libraries, as well as other components that are needed to accomplish secondary functions of the software.

Table 17. Secondary system architecture components.

Tools	Tools The tools component is a collection of several modules. These additional modules are not necessary to run an analysis, but provide additional features that complement the main software functions, such as input validation.
Printing	Print Engine The print engine provides encapsulated functionality for report generation, previewing, and printing.
Unit Conversion	Unit Conversion System The unit conversion system consists of several modules that control all measurement unit conversion and storage that takes place in the software.
File I/O	File Input and Output (I/O) System The file I/O system is composed of several modules that provide easy and fast access to database functions, importing and exporting data, file conversions, and saving and opening data.
Errors and Diagnostics	Error Log and File Checker These two components make up the bulk of the troubleshooting system. They are responsible for logging and viewing errors and ensuring that all of the files that HIPERPAV II requires are present.

4.2.2.4 System Communication

The majority of the communications between the components in the system involve the component object model (COM) and the extensible markup language (XML). All of the components “talk” to each other using COM. Most of the data transfer between components use COM directly or XML. However, Microsoft ActiveX[®] Data Objects (ADO) is used to load data from the environmental databases.

4.2.2.5 Add-In System

As stated in the total systems approach, HIPERPAV II is composed of several different modules. It is desirable to possibly add or remove modules after the software is designed and/or produced. To accommodate this, HIPERPAV II was designed with an add-in system. The system defines a standard interface through which modules can define themselves. This eased the development on a module basis. Finally, the add-in system allows for more customization of the software for each subsequent version of HIPERPAV II.

4.2.3 Graphical User Interface

The GUI is the means through which the user will interact with the HIPERPAV II code. Therefore, it was essential to develop a clear, concise, and uncluttered interface. Based on these premises and the feature set that needs to be implemented, the development team designed an interface centered around the idea of a strategy. The GUI is based on forms. A different form is used for each screen of inputs, outputs, tools, etc. Most, if not all, forms are independent of each other, so work can be done on one without affecting the others. The GUI also uses some support classes and modules.

Figure 20 shows the interface for HIPERPAV II. The circled numbers identify key features of the interface and are described below:

1. This is the analysis type dropdown menu. Each project (file) contains only one type of analysis except for long-term JPCP projects, which also contain early-age analyses. This dropdown identifies the type of analysis for the current project. For long-term JPCP projects, there will be two options: early-age JPCP and long-term JPCP. This allows the user to switch between the two analysis types.
2. This is the strategy list. HIPERPAV II is strategy-based. All of the strategies are listed here. The highlighted strategy will have its data shown in the right panel (number 5). The user can rename the strategies, as well.
3. The TreeView displays all of the sections or components that make up each strategy (inputs and analyses). Three different input categories are differentiated with icons for graphical recognition.
4. The location bar shows where the user is located. In this case, strategy information is shown, which is the same as the highlighted item in the TreeView.
5. The data panel displays the inputs or outputs for the current strategy.

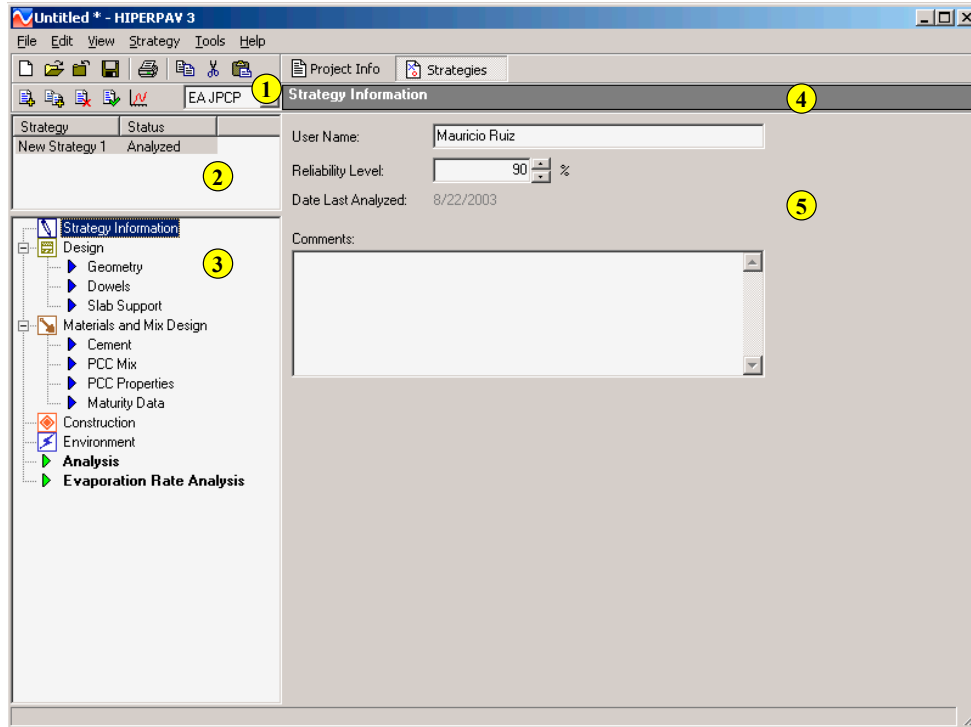


Figure 20. Screenshot of interface for HIPERPAV II.

The user's manual contained in volume II of this report series provides a more detailed description of the HIPERPAV II graphical user interface.

4.2.4 Document Object Model (DOM)

4.2.4.1 Introduction

The DOM is the component that handles most of the interactions between components and most of the functions involving the data except for technical analyses. The DOM has many responsibilities, including:

- Temporary and permanent storage of the input and output data.
- Handling requests for unit conversion.
- Input validation.
- Business rules (e.g., calculating the effects of one input on another input).

4.2.4.2 Architecture

The DOM is a class-based hierarchy. The strategy class is the focus of most of the activity in the DOM. It consists of the following classes: general, design, materials, environment, construction, traffic, and outputs. Not every strategy will make use of all the available classes.

There is also a set of global objects that all classes are able to access. Currently, these objects contain routines for printing, file I/O, strategy comparison, the error log, units' conversion functions, definitions for standards, input validation, and any other support function necessary for the classes.

4.2.5 Technical Code

The objective of this section is to provide a high-level design for the HIPERPAV II software components. This high-level design served as a guideline for the programming of the HIPERPAV II technical code. This section details the structure of each component and interaction among those components. The goal of this guideline was to build a sound base for modularization of the HIPERPAV II software components to facilitate the subsequent software integration.

4.2.5.1 Algorithm Development and Technical Coding

The algorithm for each technical component (theoretical model) was developed based on its corresponding theoretical background. Calibration and verification of each algorithm was implemented using available data sources. Then, the technical specification for each component was developed based on the calibrated/verified algorithm.

The technical coding followed the technical specifications. Each technical component is a self-contained module. Each module contains the following routines:

- Driver Routine—a communication interface to setup an I/O for solving a specific analysis.
- Computing Routine—the actual routine to perform the computation for a specific analysis.
- Supporting Routine(s)—low-level routine(s) to perform a specific mathematical maneuvering.
- Type Module—a facility to define variable “types.”
- Error Handler—a routine to handle errors if they occur in executing the component.

Software testing was performed at the technical component level, and overall system testing was conducted after integration of technical components.

4.2.5.2 Overall Structure

As seen in table 18, 6 components were formed for HIPERPAV II. The interaction among the components is illustrated in figure 21. HP_CORE serves as the core program to feed its output to HP_MECH. Then, HP_MECH feeds data to either HP_JCP, HP_BCO, or HP_CRCP for early-age analyses. The HP_JCPLON takes output and interacts with HP_JCP and HP_MECH to perform long-term JCP analysis.

Table 18. List of HIPERPAV II tech components.

No.	Name	Description
1	HP_CORE	Predict pavement temperatures, PCC equivalent age, and moisture contents
2	HP_MECH	Predict fundamental concrete properties such as: modulus, CTE, shrinkage, strength, friction, curling, and warping
3	HP_JCP	Predict JCP concrete stress and joint width/opening
4	HP_BCO	Predict BCO delamination (not bundled with HIPERPAV II)
5	HP_CRCP	Predict crack width, crack spacing, and steel stress for CRCP
6	HP_JCPLON	Predict JCP long-term performance

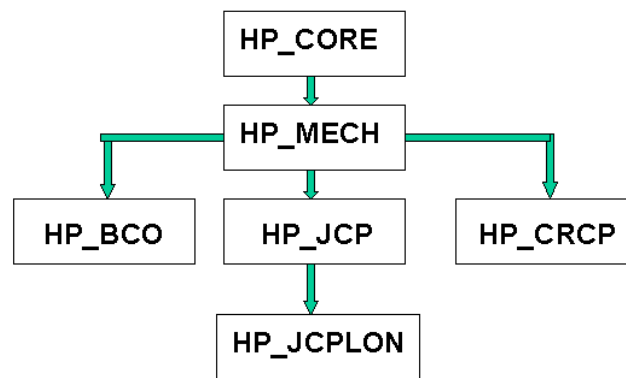


Figure 21. Structure of HIPERPAV II tech components.

4.2.5.3 Component 1—HP_CORE

The HP_CORE is the core component for the HIPERPAV II technical codes. The component is used to predict pavement temperatures, PCC equivalent age, and moisture profile. The structure of this component is illustrated in figure 22, and each subcomponent is described in table 19.

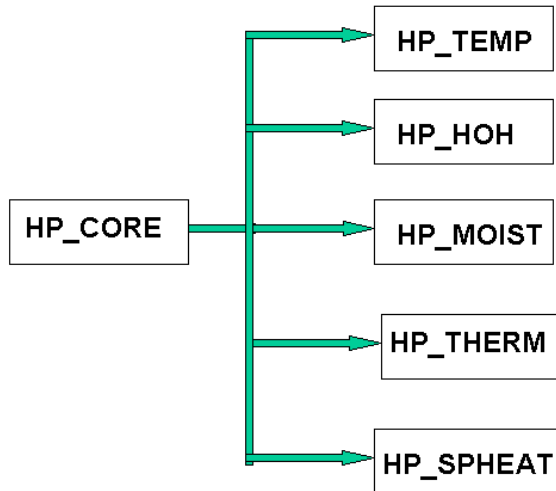


Figure 22. Subcomponents of module HP_CORE.

Table 19. List of HP_CORE subcomponents.

No.	Name	Description
1	HP_THERM	Predict thermal conductivity of pavement materials
2	HP_SPHEAT	Predict specific heat of pavement materials
3	HP_HOH	Predict heat of hydration of concrete
4	HP_TEMP	Predict temperature profile through the pavement structure
5	HP_MOIST	Predict moisture profile through the pavement structure

4.2.5.4 Component 2—HP_MECH

The HP_MECH is a supporting component to provide computed/predicted mechanical properties of pavement materials. Its structure is illustrated in figure 23, and a description of each subcomponent is listed in table 20.

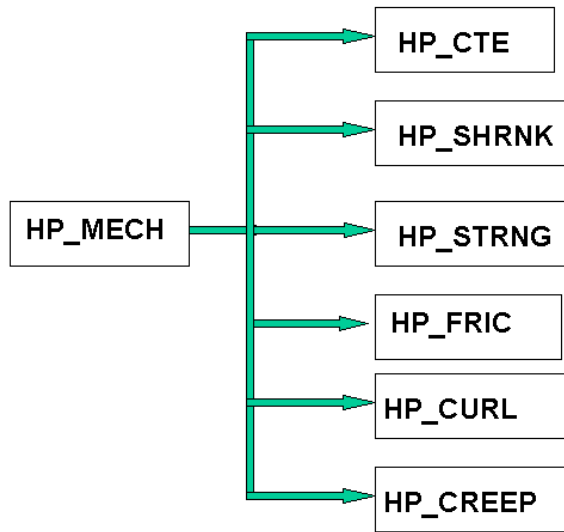


Figure 23. Subcomponents of module HP_MECH.

Table 20. List of HP_MECH subcomponents.

No.	Name	Description
1	HP_CTE	Predict CTE of pavement materials
2	HP_SHRNK	Predict shrinkage of concrete
3	HP_STRNG	Predict strength of concrete
4	HP_FRIC	Predict slab-base friction
5	HP_CURL	Predict curling/warping
6	HP_CREEP	Predict creep effect of concrete

4.2.5.5 Component 3—HP_JCP

The HP_JCP component, as its name implies, is used to perform JCP analysis. The structure of HP_JCP is illustrated in figure 24, and the description of each subcomponent is listed in table 21.

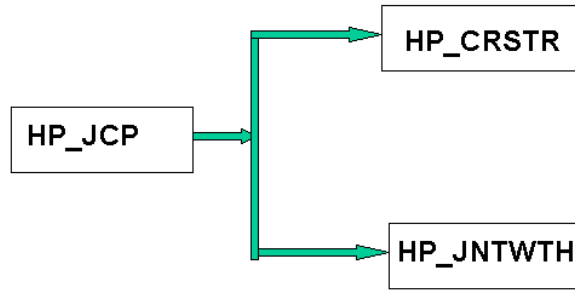


Figure 24. Subcomponents of module HP_JCP.

Table 21. List of HP_JCP subcomponents.

No.	Name	Description
1	HP_CRSTRS	Predict critical stress in concrete slab
2	HP_JNTWTH	Predict JCP joint width

4.2.5.6 Component 4—HP_BCO

The HP_BCO component is used to perform BCO analysis. The HP_BCO component consists of the subcomponent in table 22. This component is included to provide compatibility with the HIPERBOND module developed under a separate effort, but is not included in the HIPERPAV II system at this time.

Table 22. List of HP_BCO subcomponents.

No.	Name	Description
1	HP_DELAM	Predict delamination

4.2.5.7 Component 5—HP_CRCP

The HP_CRCP component is used to perform CRCP analysis. Its structure is illustrated in figure 25.

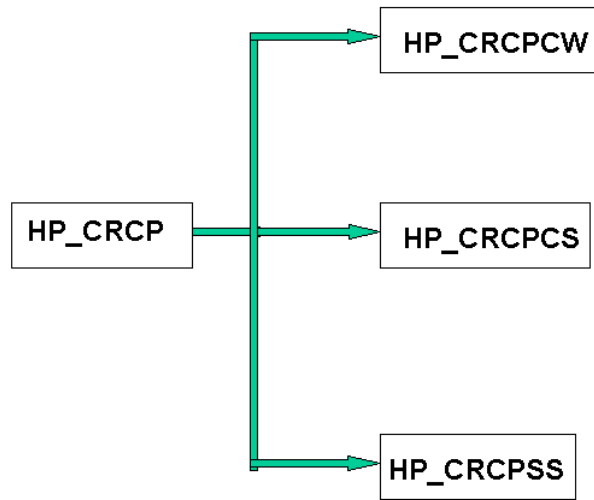


Figure 25. Subcomponents of module HP_CRCP.

The HP_CRCP component consists of the following subcomponents listed in table 23 below:

Table 23. List of HP_CRCP subcomponents.

No.	Name	Description
1	HP_CRCPCW	Predict CRCP crack width
2	HP_CRCPCS	Predict CRCP crack spacing
3	HP_CRCPSS	Predict steel stress in CRCP

4.2.5.8 Tech Component 6—HP_JCPLON

The HP_JCPLON component is used to compare alternatives of JCP pavements for their long-term performance, as seen in figure 26.

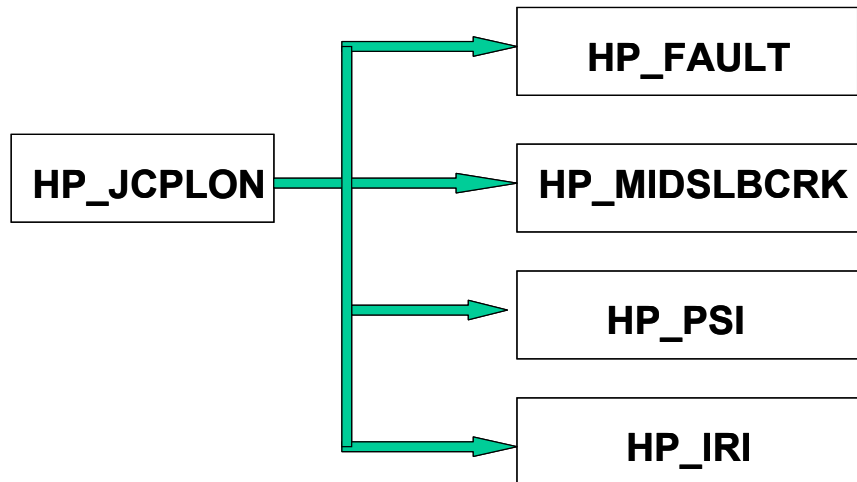


Figure 26. Subcomponents of module HP_JCPLON.

The subcomponents of HP_JCPLON are listed in table 24:

Table 24. List of HP_CRCP subcomponents.

No.	Name	Description
1	HP_FAULT	Predict long-term faulting of JCP
2	HP_MIDSLBCRK	Predict long-term midslab cracking of JCP
3	HP_PSI	Predict long-term PSI of JCP
4	HP_IRI	Predict long-term IRI of JCP

4.2.6 Verification and Validation

4.2.6.1 Models

Each technical model was developed in Microsoft Excel or Mathsoft MathCAD[®]. Calibration and verification of each algorithm was implemented using available data sources.

4.2.6.2 Software

The software was integrated one component at a time. For each integration, the components were checked to ensure that they were communicating and functioning correctly with all other modules. The first integration included the GUI and DOM. The file I/O was then checked so that test data files could be loaded for system-level testing of the models. Next, the DOM was connected to the technical code, and I/O communications were tested strenuously to ensure models robustness. The remaining feature development and testing occurred concurrently with the model testing.

4.2.7 Implementation

The implementation plan included an overall software development plan, development of the software requirement specification, development of the software design specification, coding, and release and debugging. Each of these stages is described in the following sections.

4.2.7.1 Overall Software Plan

The overall software plan included the software project life cycle illustrated in figure 27. This plan involved the following four steps implemented during execution of the work plan:

1. Development of the software requirement specification (SRS).
2. Development of the software design specification (SDS).
3. Implementation (coding).
4. Release and debugging.

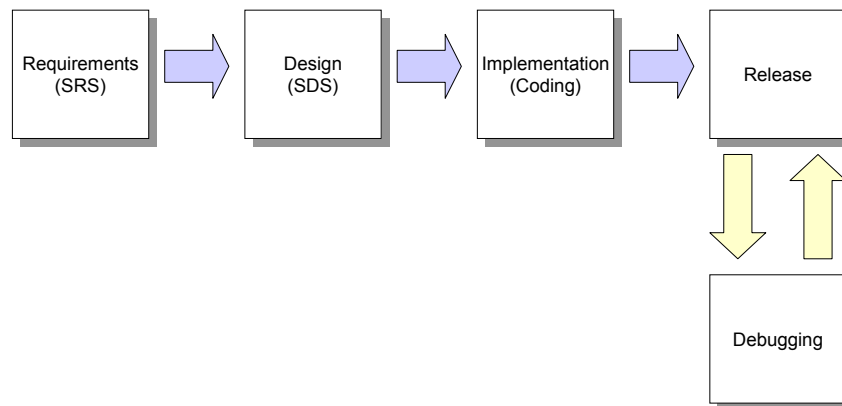


Figure 27. Software project life cycle.

4.2.7.2 Development of the SRS

The SRS was based on the requirements that are defined in previous sections in this chapter. The SRS specifies the software requirements (such as features) in general terms, with no discussion of how the features will be implemented. For the technical code, the SRS includes a high-level description of the integration of technical models. Iterations of review/modification are needed to reach the final, well-defined scope.

4.2.7.3 Development of the SDS

The SDS is an extension and detailed design based on the SRS documentation. The SDS includes low-level designs (such as properties and functions for each component class) in tables and flowcharts. Iterations of review/modification are needed to reach the final, well-checked design.

During this phase, a nonfunctional prototype of the GUI was developed. This prototype allowed basic navigation among the screens that compose a strategy. This was essentially a proof-of-concept

prototype for presentation and obtaining feedback concerning the layout of the GUI. This feedback was used during the iteration process of the SDS for the GUI to better define the specifications.

For the technical code, algorithms for each technical model were developed in technical memorandums, and prototyped in Microsoft Excel/MathCAD files. These prototypes were then calibrated and validated using field data. Sensitivity analyses were performed to check the engineering reasonableness.

4.2.7.4 Implementation (Coding)

The actual coding for the GUI, DOM and technical code were implemented based on the SDS. The coding followed the Microsoft Visual Basic and Fortran coding guidelines to maximize robustness, modularization, reusability, and interoperability.

4.2.7.5 Release and Debugging

Upon completing the coding phase, the project team developed an initial beta version of the software for review by the TEP members. Feedback from the TEP on the software was included to enhance its development. Several beta versions of the HIPERPAV II software were then released after the verification and validation. Debugging and enhancement was performed based on the user feedback and the available resources.

4.2.8 Modifications to the Software Development Plan

During the various TEP meetings for this project, a number of comments and feedback from the FHWA Contracting Officer's Technical Representative (COTR) and TEP members were received. These comments required modifications to the work plan for developing the HIPERPAV II software and are addressed in this section.

4.2.8.1 HIPERPAV Practical Grade and Research Grade Versions

It was recognized that, because of the diversity of users, two different versions of HIPERPAV should be developed: a "practical grade" version and a "research grade" version. The practical grade version would be geared toward users that require practical and easy-to-use tools for their application in real construction projects in a regular basis. For this version, the inputs required would be simplified as much as possible without compromising the accuracy of the results. A research grade version would include advanced screens with more detailed inputs. This version would be tailored for academic and experimental applications.

Since the aim of this project is to develop practical tools for use by the engineering community, the emphasis was on developing a practical grade version of HIPERPAV. Before releasing the software, a final assessment of the product should be made to determine if additional simplification is necessary to improve the success of the implementation process.

4.2.8.2 *Relative Versus Absolute Software Values*

The panel members' comments were split on the desire for relative versus absolute software value outputs for the long-term performance JCP module. The project team made both options available in the software.

4.2.8.3 *Software Prototype: Comments on Materials and Mix Design Inputs*

The possibility of obtaining adiabatic calorimeter data for different cement types and compiling it in the technical code of the software was discussed. During the previous HIPERPAV I validation effort, researchers found that the prediction of the pavement temperature relies heavily on the hydration characteristics for the specific mixture in evaluation. It is believed that, although information on the total heat of hydration of the cement (and admixtures) obtained with American Society for Testing and Materials (ASTM) test method ASTM C 186 would be helpful, this information would still have to be complemented with the shape of the hydration curve obtainable only through calorimetry tests. Volume III, appendix B of this report series expands on the database of cements evaluated and hydration models included in HIPERPAV II.

To compare strength types and complement the available information on concrete strength relationships, the research team evaluated a report on modulus of rupture conversion relationships.⁽⁶¹⁾

It was agreed that incorporating a mix design module in the software would benefit engineers who would be interested in mix design, particularly contractors. This module would facilitate its acceptability and implementation in the future. Incorporation of the COMET module for mix optimization was pursued after this recommendation.

4.2.8.4 *Comments on Construction Inputs*

For skip sawing, the preferred approach from FHWA's standpoint was to have the operator "fool" the program, as with HIPERPAV I, by putting in a longer joint spacing as the input. However, after further discussions with the TEP members, it was agreed to provide a skip sawing option and include a comment stating that this is not a recommended practice; however, it can be used to assist the contractor to avoid undesirable situations.

4.2.8.5 *CRCP Steel Design*

The need to model the use of a double layer of steel as an input option (top and bottom mats) was discussed. As new models that consider the effects on shrinkage and other behaviors as a function of the steel depth and number of bar mats become available, they may be included in subsequent generations of HIPERPAV.

4.2.8.6 *Long-Term Performance Models*

Spalling distress prediction as a function of early-age behavior was very difficult to model due to a number of factors, including lack of data required for model calibration and validation. Since development of a new spalling model was out of the scope of this project, a spalling distress model was not included in HIPERPAV II during this effort.

4.2.8.7 *Additional Modules*

FHWA suggested incorporating information from the joint FHWA/NIST mixture optimization study, and the COMET module based on this study was incorporated successfully. In addition, at the time of writing this report, a new project under FHWA CPTP Task 64 is further investigating concrete mixture optimization procedures based on the work developed under the FHWA concrete mixture optimization study.⁽⁶²⁾

4.3 **VALIDATION OF THE ENHANCED GUIDELINES**

Although the CRCP early-age behavior models and long-term JPCP models selected for use in this project (see table 10 and section 3.3.5) have already undergone extensive validation efforts, modification to some of the models to reflect specific early-age conditions and integrate effectively with the overall system warranted further validation.

Validation focused on determining the reliability of the models. Model reliability determines if the model is a good one or a poor one. If there is significant scatter in the data compared to the prediction, then the model is possibly poor. Less scatter implies that the model is reliable. The reliability of the individual models in the long-term JPCP and early-age CRCP modules in HIPERPAV II was assessed under this concept.

Two levels of validation were undertaken for both the long-term JPCP and early-age CRCP models incorporated into HIPERPAV II. The first level of validation was performed with using databases. The second level of validation consisted of evaluating the accuracy of prediction with information collected from a field investigation performed on select pavement sites. Additional validation was also performed for general early-age behavior enhanced models such as the FDM temperature prediction model and the improved drying shrinkage model. A summary of the validation efforts and findings is presented in the following paragraphs. A detailed description of the field investigation, laboratory testing, and validation efforts is presented in volume III, appendixes C through F of this report series.

4.3.1 **Database Validation**

The primary databases used for this purpose were the database maintained by LTPP and the CRCP database maintained by the Texas DOT. (See references 63, 64, and 65.) The wider geographical distribution and variety of pavement sections in the LTPP database was a determining factor for its use, while the extensive amount of early-age data for CRCP in the Texas rigid pavement database was a major factor for its selection. Other databases such as the COPES and the RIPPER databases were also investigated.^(33, 27) However, lack of early-age information and monitoring records made validation with these databases difficult.

4.3.1.1 *Validation of JPCP Structural Response Models with LTPP Data*

Database validation efforts within this project were limited due to the lack of extensive early-age information on current databases. Information required for validation of JPCP long-term performance prediction includes mix design information, early-age climatic data, construction times and dates, early-age material characterization, initial construction smoothness, history of structural pavement response, and distress information.

Information in the Seasonal Monitoring Program (SMP) pavement database maintained by LTPP was used exclusively to validate the JPCP structural response models. Provided the LTE model has not been previously calibrated as a whole, pavement sections in the LTPP-SMP database were also used for model calibration. The LTPP-SMP program includes monitoring of JPCP sections to observe the effects of temperature and moisture on the pavement structure and pavement's response to loads. It was found during the verification process that, although the LTE model predictions follow the general trends of LTE as computed from FWD tests, further investigation of a number of factors is necessary to be able to predict LTE with more accuracy. For the doweled sections evaluated, it was difficult to determine the level of dowel looseness, because LTE appears to be provided by aggregate interlock with some dowel looseness present for half of the sections, while the remaining sections appear to have very little or no dowel looseness. Therefore, further work is required to verify the dowel looseness models presented. It is recommended that factors such as aggregate characteristics, dowel coatings, and compressive stresses at the dowel location due to curling stresses in the early age be investigated.

4.3.1.2 *Validation of CRCP Early-Age Behavior Models*

Validation of the CRCP early-age behavior models had two objectives: validation of cracking behavior during the early age, and validation of cracking behavior in the long term. Although, as its name implies, the CRCP module in HIPERPAV II should predict cracking behavior at early ages, long-term performance can be estimated better based on the cracking characteristics after the lowest temperature (typically after 1 year). Therefore, validation also was performed on existing CRCP sections with crack spacing information. In addition to information on cracking behavior, information on characterization of the concrete materials used, climatic data, and construction times and dates were needed. This information was available in the Texas rigid pavement database and CRCP field sites investigated.

With the above information, each section was analyzed with the CRCP module in HIPERPAV II to compare the measured crack spacings to the predicted values. Although a slight overprediction of crack spacing was observed, a reasonably good fit of predicted versus measured crack spacing with respect to the 45° line was obtained ($r^2=0.82$).

For the early age, a generally poor prediction of crack spacings was observed. However, similarly poor results had been observed in previous validation efforts with this dataset. Suh et al. had found good predictions for the first few months after construction; however, significant deviations were observed for the first 5 to 10 days.⁽⁶⁵⁾ This poor prediction was attributed to the inability to accurately predict early-age temperatures due to lack of curing information. It was also suggested that because the sections were relatively short (70 meters (m) long), and the crack spacings relatively large, it is possible that the data points generated were not sufficient to predict crack spacing with accuracy.

Otero et al. reported crack width measurements 2 years after placement for the SH-6 test sections.⁽⁶⁶⁾ The CRCP module in HIPERPAV II was used to predict crack widths at the temperature observed in the concrete during the crack width measurements. Although a positive trend in crack width prediction was observed, all crack widths were largely overpredicted. This overprediction in crack widths had been observed in previous validation efforts.⁽⁶⁶⁾ Although Otero et al. proposed a new model for crack width prediction, using this model in this study did not give reasonable results. The overprediction was attributed to the fact that the CRCP-8 model does not account for the time when the crack forms, but it is rather dependent on the predicted crack spacing, PCC thermal properties, and total shrinkage. It is believed that the residual drying shrinkage after the crack forms has a large effect on crack width. In addition, the CRCP-8 model includes a fixed model for the concrete-steel interaction. Later studies have shown crack widths to be very sensitive to this characterization.⁽⁶⁷⁾

4.3.2 Field Validation

Four field sites were investigated for validation of the HIPERPAV II system:

- Two in-service JPCP sections were evaluated to validate the long-term performance models in the JPCP module.
- Two newly constructed CRCP sections were instrumented to validate the CRCP early-age behavior module.

It is believed that the number of field sites evaluated provides the minimum level of information necessary to meet the objectives of this effort successfully. However, additional data from field sites in the future could be used for local customization.

4.3.2.1 *Validation of Long-Term Performance Models with In-Service JPCP Sites*

JPCP sites investigated include a section on U.S. 50 in Illinois and a bypass section of a farm-to-market road near Ticuman, Mexico. The selection of both sites was heavily weighted on the fact that extensive early-age and performance information is available for both of these sections. A field investigation and monitoring of both JPCP test sections was performed in the summer of 2001. Extensive information on design, construction, and previous monitoring activities for both pavement sites was collected.

During the current field investigation, the monitoring activities included:

- Installation of a weather station to collect ambient temperature, relative humidity, and solar radiation.
- Visual inspection of each JPCP section.
- Deflection measurements at transverse contraction joints and at midslab.
- Demountable mechanical gagee caliper measurements of joint movement.
- Profile measurement.
- Coring to determine depths and obtain specimens for laboratory testing.

The data collected from these sites was used with early-age information available to validate the long-term JPCP performance models in HIPERPAV II.

The reliability of prediction for these two sites was evaluated. Several factors were considered in validating the long-term JPCP module in HIPERPAV II for each field site. This validation included comparing measured and predicted mechanical properties, LTE, and long-term distresses.

In summary, it can be concluded that reasonable predictions were obtained in terms of long-term performance for both field sites. Although limited, this validation was done with quality data on pavement design, materials, climatic, and construction inputs. Validation of the models should continue, as more information about materials characterization and construction information becomes available for sites.

4.3.2.2 *Validation of Early-Age Behavior Models with Newly Constructed CRCP Sites*

Besides database validation, the CRCP model in HIPERPAV II was validated with two CRCP construction sites. The first CRCP section instrumented was part of an access road to the Interstate

highway (IH)-35/IH-30 interchange located in Fort Worth, TX. The second CRCP section was located on IH-29 near Sioux Falls, SD.

Model inputs were collected for prediction of crack spacing, crack width, steel stress, and bond development length. Information collected included all necessary inputs to feed the prediction model, such as structural design, mix design, slab/subbase restraint, concrete strains, steel strains, and climatic conditions during the first 72 hours after placement. In addition, laboratory testing was performed for material characterization, including splitting tensile strength, elastic modulus, CTE, drying shrinkage, and concrete set time.

The instrumentation procedures consisted in installing embedment gages at midslab, edge, and corner at three different depths. Thermocouples also were installed at seven different depths throughout the slab depth. Resistance type strain gages were also installed on the steel rebar at different distances from the crack. In addition, similar procedures were used to monitor climatic conditions; CTE and free drying shrinkage; slab curling and warping; and cracking behavior in the field. A summary of the validation results is discussed below:

- Variable results were obtained for bond development length. The bond development length predicted with HIPERPAV II for the Fort Worth, TX site varied from 560 to 790 mm for the first 3 days of age. This prediction is significantly higher than the measured one of approximately 280 mm. However, the bond development length predicted with HIPERPAV II for the CRCP section in South Dakota closely matched the bond development length obtained from field measurements, varying from 480 to 660 mm. The difference in predicted and measured bond development length for the Fort Worth, TX site was attributed to the limitations in the bond-slip relationships assumed in the CRCP-8 model; Palmer et al. previously identified these limitations.⁽⁴¹⁾
- Similar to the bond development length results, variable results in steel stresses were observed. While a large overprediction was observed for the Fort Worth, TX site, a rather good prediction of stresses at the steel was observed for the South Dakota section. The difference in predicted and measured steel stress for the Fort Worth, TX site was also attributed to the limitations in the bond-slip relationships assumed in the CRCP-8 model.
- As had been reported in previous validation efforts of crack width in the CRCP-8 model, a large discrepancy in measured and predicted crack widths was observed for both CRCP sections. The predicted crack width is overpredicted by a factor of 3, compared to the average crack width measured at middepth for the CRCP section in South Dakota, and by a factor of 10 for the CRCP section in Fort Worth, TX. The limitations in crack width prediction are attributed to the fact that the CRCP-8 model incorporated in HIPERPAV does not take into account the time when the crack forms, but it is rather dependent on the predicted crack spacing, PCC thermal properties, and total shrinkage. The drying shrinkage after crack formation depends on the concrete age when the crack occurs. It is believed that the residual drying shrinkage after the crack forms has a large effect on crack width. The differences in steel stress and bond development length found in this analysis are believed to also contribute to overpredicting crack widths.
- The average crack spacing predicted for both CRCP sites matches the measured average crack spacing at 3 days of age very closely.

This analysis concludes that reasonably good predictions for the crack spacings observed after 3 days are achieved for both sites. However, further investigation of the bond slip relationships in the CRCP-8 program is recommended to accurately predict steel stresses and crack widths.

4.3.3 Validation of General Early-Age Behavior Models

In addition to the validation of JPCP long-term performance and CRCP early-age behavior models, improvements to the concrete pavement temperature prediction, drying shrinkage, and creep-relaxation models were also investigated in this study.

4.3.3.1 FDM Temperature Prediction Model

Over the course of its development, HIPERPAV has employed two different temperature prediction models (see section 3.3.3.2). Originally, the temperature prediction model was a transient two-dimensional FEM model. However, this procedure had proven to require excessive solution times. The model has since been replaced by a one-dimensional FDM approach, which allows quicker execution without a compromise in accuracy. However, the accuracy of the FDM model needed to be verified by comparison with field data. Verification of the temperature predictions with the improved model is presented in volume III, appendix F of this report series.

4.3.3.2 Drying Shrinkage Prediction Model

Using the field data collected from the five early-age HIPERPAV I field sites, the calibration factor (D_{eff}) for the Bazant-Panula shrinkage model could be determined.⁽⁶⁸⁾

To calibrate the size factor D_{eff} for CRCP, 28-day drying shrinkage predictions from the Bazant-Panula model were matched to the experimentally measured drying shrinkage values taken in concrete placed on State Highway 6 in winter and summer.⁽⁶⁵⁾ At 28 days, the drying shrinkage was 171 $\mu\epsilon$ in the summer and 165 $\mu\epsilon$ in the winter. These values were matched using a D_{eff} of 0.2.

4.3.3.3 Relaxation-Creep Model

Attempts were made to validate the creep model based on the extended triple power law presented in volume III, appendix B of this report series. However, preliminary sensitivity analyses showed that in some instances, tensile stresses were being significantly overpredicted as compared to results from the previous validation efforts of the current prediction models in HIPERPAV I. Possible reasons for inaccuracy:

- In an attempt to incorporate this model in HIPERPAV II, it was assumed that creep in compression is equivalent to creep in tension. Due to the cyclic stress state in the pavement between tension and compression, if this assumption does not hold true, it is possible that compressive stresses may be underpredicted while tensile stresses are overpredicted or vice versa.
- In implementing the creep compliance formulation, there are two possible approaches as outlined in volume III, appendix B: (1) with numerical integration, and (2) with the use of a Maxwell chain model for conversion of creep compliance into relaxation values. In this effort, both methods were explored. However, the required user intervention in the second method made it inappropriate for this effort. The first method was investigated

further, however, the large matrix array required to store the stress history limited the minimum time step that could be implemented to 1 hour. Such a large time step possibly contributed to the observed overpredictions of tensile stresses.

Further work is required to validate this method properly. It is believed that, once calibrated and validated, this relaxation-creep model will prove helpful in properly determining creep and relaxation effects for stress prediction, built-in curling prediction, and possibly the curled slab shape.

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Significant findings and recommendations for enhancing the guidelines in the future are outlined in this chapter.

5.1 SUMMARY

This report documents enhancements incorporated in the HIPERPAV II system. These enhancements include the addition of two major modules: a module to predict the performance of JPCP as affected by early-age factors, and a module to predict the early-age behavior (first 72 hours) and early life (up to 1 year) of CRCP. Two additional FHWA studies were also incorporated: one that predicts dowel bearing stresses as a function of environmental loading during the early age, and a module for optimization of concrete paving mixes as a function of 3-day strength, 28-day strength, and cost.

Additional software functionality was incorporated by reviewing and prioritizing the feedback provided by HIPERPAV I system users. The following is a short list of the many features incorporated:

- A new graphical user's interface accommodating the different analysis types and options while keeping the simplicity and user friendliness of the previous version.
- A geographical weather database system that contains historical averages of weather data from weather stations located throughout the United States. Climatic information includes air temperatures, windspeed, relative humidity, cloudiness, and annual rainfall conditions.
- Analysis of multiple strategies: The new HIPERPAV II system is capable of analyzing multiple strategies for one specific project. This allows for evaluating "what if" scenarios within the same project file and facilitates comparison between strategies.
- A routine to perform consistency of inputs (input range validation).
- A reference database that includes the primary references used during the HIPERPAV II development.
- Improved cement and admixtures characterization with recently developed models.
- A strength conversion tool with default and user-defined conversion factors.
- An option for user-defined equivalent age maturity in addition to the Nurse-Saul maturity option previously incorporated.
- Inputs for user-defined nonlinear slab support characterization.
- Optimum sawcutting, skip sawcutting, and no sawcutting options.
- Concrete CTE and ultimate shrinkage inputs.
- Enhanced input capability with tabular and graphic options.

To ensure a successful implementation of the HIPERPAV II system, a TEP was formed, which consisted of stakeholders in the paving industry. Throughout the project's development, the project team followed recommendations from the TEP, and numerous feedback items were incorporated to facilitate software implementation.

To incorporate the new modules, an exhaustive literature search was performed, and the pertinent models were identified and selected after evaluating the advantages and disadvantages of each of them. Special emphasis was placed in selecting models developed with a mechanistic or mechanistic-empirical approach that took early-age factors into account. Model selection was followed by a plan for model integration. This integration was achieved by following a systems approach methodology that built on the concrete temperature and early-age behavior prediction core modules within HIPERPAV I. Model integration included developing a new graphical user interface and extensive model coding. This phase was followed by extensive software debugging and testing.

Although the CRCP behavior models and long-term JPCP models selected for use in this project had already undergone extensive calibration and validation efforts, further modification to some of the models to reflect specific early-age conditions and to integrate well with the overall system warranted further validation during this effort. Validation focused on determining the reliability of model prediction. Two levels of validation were undertaken. The first level of validation was performed with databases. The SMP pavement database maintained by LTPP and the Texas rigid pavement database were used to validate the JPCP LTE response and early-age behavior prediction, respectively. The second level of validation consisted of evaluating the accuracy of prediction with information collected from a field investigation performed on select pavement sites. Two JPCP sections were investigated to evaluate distress prediction, and two CRCP sections were investigated to evaluate early-age CRCP behavior. Additional validation also was performed for general early-age behavior enhanced models, such as a FDM temperature prediction model and an improved drying shrinkage model.

5.2 CONCLUSIONS

The objectives for this study were accomplished successfully. The module for JPCP long-term performance prediction as a function of early-age factors and the module for prediction of CRCP early-age behavior were successfully incorporated by employing available models in the literature from recognized sources. Because developing new models was outside the scope of this project, available models were adapted for integration into the HIPERPAV II system.

Overall, the results from the validation efforts for both long-term performance of JPCP and early-age CRCP behavior models were positive. A summary of the findings obtained during the validation phase of this project is summarized below:

- It was found during the verification process that although the JPCP LTE model predictions follow the general trends of LTE as computed from FWD tests, further investigation of a number of factors are necessary to predict LTE with improved accuracy.
- Reasonable predictions were obtained in terms of long-term performance for the JPCP field sites evaluated; these follow logical trends. Although limited, this validation was done with quality data on pavement design, materials, climatic, and construction inputs.
- For the validation of the CRCP models, variable results were obtained for bond development length and steel stress prediction. This difference in prediction was attributed to the limitations in the bond-slip relationships assumed in the CRCP-8 model.
- A large overprediction of CRCP crack widths was also observed with both pavement databases and field sites investigated. The overprediction was attributed to the fact that the CRCP-8 model does not take into account the time when the crack forms, but rather is

dependent on the predicted crack spacing, PCC thermal properties, and total shrinkage. It is believed that the residual drying shrinkage after the crack forms has a large effect on crack width. It is also believed that the limitations in bond-slip characterization in the CRCP-8 model contributed to the overprediction in crack width.

- Despite the expected overpredictions in crack width, a reasonably good prediction of CRCP average crack spacing was observed with both the pavement databases and the field sites investigated.

The long-term JPCP module of the HIPERPAV II system was developed to optimize early-age strategies based on how they perform in the long term. With this objective in mind, two early-age strategies can be analyzed in the long term under the same long-term environmental and traffic conditions. Accurate predictions of long-term performance require accurate and detailed information on pavement structural factors, materials characterization, environmental conditions, and traffic data. Because the long-term module in HIPERPAV II is intended to help the user optimize early-age strategies rather than serve as a tool for pavement design, a number of considerations were made to simplify the data entry and improve user-friendliness. Long-term models assumptions and limitations are described in volume III, appendix B of this report series. Despite the model limitations, significant efforts were made to include mechanistic or mechanistic-empirical models. The advantage of taking a more mechanistic approach is that new developments and model improvements can be incorporated gradually in the future.

Regarding the CRCP models, it is believed that despite the observed overprediction in bond development length, steel stress, and crack width, the CRCP model provides a good foundation for comparing alternatives. With relatively moderate effort, the crack width model could be improved to account for drying shrinkage effects and time of crack formation. Furthermore, the CRCP-8 model could be replaced with relative ease with the newer CRCP-9/10 model which validation is currently in progress.⁽⁶⁷⁾ The CRCP-9/10 model may provide improved predictions.

Regarding the additional FHWA studies evaluated, although all FHWA studies reviewed potentially could have been implemented successfully in HIPERPAV II, only two of these studies had to be selected. Several factors were considered for study selection, including the status of completion, level of difficulty required for incorporation, easiness of implementation, and usability by the pavement community. Based on the advantages and disadvantages identified on each study, the dowel bar study and the mix optimization study were incorporated in HIPERPAV II.

5.3 RECOMMENDATIONS

5.3.1 Model Improvements

Based on the findings from the model validation, a number of key recommendations are provided below; these would greatly enhance the prediction capabilities of the HIPERPAV II system.

- To improve the prediction of LTE, further investigation of the slab support conditions, aggregate interlock, dowel looseness, and aggregate wearout, among other factors, is recommended, both in the early age and throughout the pavement's long-term performance.
- A limited validation with good quality early-age information available for two field sites was performed; however, the long-term module requires further validation with

numerous other sites. Database validation efforts within this project were limited due to the lack of extensive early-age information on current databases required for validation. Required information includes mix design information, climatic data, construction times and dates, early-age material characterization, initial construction smoothness, history of structural pavement response, and distress information.

- Because of the model limitations and assumptions made, predictions will not be comparable with the NCHRP 1-37A product result. Furthermore, HIPERPAV II must never be used for pavement structural design, since it was not validated for this purpose. Instead, the results of long-term performance comparisons should be used for further optimization of early-age strategies examining the effect of early-age environment, materials, and construction factors. The inputs for pavement structural design should already have been performed using a design procedure such as the American Association of State Highway and Transportation Officials (AASHTO) method.⁽⁶⁹⁾
- Continued validation of the long-term JPCP models is recommended as more sites become available with enough information on materials characterization and construction information.

The PRS module based on the FHWA PaveSpec study was not incorporated in HIPERPAV. However, three unique ways of integrating HIPERPAV with standard specifications were identified:

1. Merging standard specifications into HIPERPAV: This method consists of incorporating the text of standard specifications into HIPERPAV through a knowledge base. It would provide recommendations and warnings during the HIPERPAV runs that relate to items considered in the standard specifications, tying them to the inputs in the software.
2. Merging HIPERPAV into standard specifications: In this method, standard specifications could be written to require the use of temperature management software such as HIPERPAV, further assuring that uncontrolled cracking is avoided.
3. Integrating HIPERPAV and PaveSpec: This method involves combining HIPERPAV and PaveSpec together as described in the above paragraphs, and would be ideal for highway agencies currently considering PRS.

The best option from the above three would depend on the current specifications being used by any individual SHA. It is believed that the first method, merging standard specifications into HIPERPAV, would be the most readily implementable, since it involves less risk to the highway agency in terms of liability. On the other hand, following the current trend of highway agencies shifting to PRS, an integration of HIPERPAV and PaveSpec would provide an ideal tool for implementing such a specification.

5.3.2 The Future of HIPERPAV

When HIPERPAV was first developed in 1996, a new approach was born: a total systems approach to concrete paving. In this simple to use yet technically complex piece of software, the power to simulate problems before they happen is now a reality. Since its development, the HIPERPAV concept has expanded into a usable and reliable tool for concrete pavement design and construction. Demand for HIPERPAV has spread throughout the industry. Contractors, suppliers, agencies, and academics all realize the power in this approach. In the future, it is only logical to further advance the total systems

approach concepts inherent in HIPERPAV by incorporating additional modules. The following sections briefly identify some of the possible future trends that have been recognized by the users of the HIPERPAV system.

5.3.2.1 Bridge Deck Application

Users have asked at nearly every HIPERPAV presentation: “Can I use this software for my concrete bridge decks?” The answer at this time is: “Not without proper modification of the models for this application.” However, there is high demand for this application. A bridge deck (or bridge deck overlay) application of HIPERPAV would allow a user to predict the potential for uncontrolled cracking just as it does currently for pavements. In truth, because the majority of the models inherent in the HIPERPAV system are based on structural engineering models for concrete, industry acceptability of this could be achieved with minimal validation.

5.3.2.2 Real-Time HIPERPAV Application

Another concept that is often discussed involves the development of a real-time version of HIPERPAV. As with the current version of HIPERPAV, the real-time version would provide a means to predict the behavior of a concrete pavement during the first few critical hours after construction. The difference would be in the methods in which the inputs to the program are determined. In the current version, the user enters the various inputs and a number of assumptions are made as a result. A real-time version would use a weather station and pavement instrumentation to, in essence, calibrate the models in the HIPERPAV system in real time. As a result, the reliability of the HIPERPAV solution is increased substantially, and more informed decisions could be made.

5.3.2.3 Fiber-Reinforced Concrete Application

Fibers, both synthetic and steel, are being used more often in today’s concrete pavements. Although common in other concrete flatwork construction, such as industrial floors, the use of fibers in concrete paving has been slow to evolve. However, in many instances, fibers can contribute to the durability and overall performance of concrete pavements. HIPERPAV currently does not use models that would predict the difference in concrete behavior as a result of fiber use. However, using more sophisticated materials characterization models, such as fracture mechanics, would allow for the HIPERPAV system to objectively assess the impact of fibers in the mix.

5.3.2.4 Internet (Web)-Based Application

Although slow to respond at first, the paving industry is now realizing the potential of the Internet in improving efficiency in day-to-day operations. One possible future direction for HIPERPAV would be to deploy the software in an Internet-based mode. By developing a Web-based HIPERPAV application, the customer base of the HIPERPAV systems would expand. In addition, the resulting client server-based system would allow HIPERPAV system use to be evaluated. Trends could be tracked, and modifications to the system made more effective.

5.3.2.5 Concrete Durability Predictive Application

One final application that could be developed, based on the current HIPERPAV system, is an application to better predict the potential durability of concrete used in paving operations. There are a

number of ongoing research efforts that aim to better predict the durability of paving concrete as a function of the mix and the surrounding conditions. A future version of HIPERPAV could be developed that can use these models to predict the potential for durability-related issues in a practical manner. With the current trend toward longer life pavements, the durability of the materials used in concrete is becoming more prevalent. In the future, HIPERPAV can be used to make more informed decisions objectively and practically with respect to this important criterion.

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VOLUME I: PROJECT SUMMARY

