

DEVELOPMENT AND CALIBRATION OF A MECHANISTIC DESIGN PROCEDURE FOR JOINTED PLAIN CONCRETE PAVEMENTS

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ABSTRACT

The development of a mechanistic-based design procedure is currently underway in the United States. This development is being conducted under the National Cooperative Highway Research Program (NCHRP) under sponsorship by the AASHTO. This paper addresses the key aspects of the design procedure for jointed plain concrete pavements (JPCP).

Design inputs include traffic (full load spectra for single, tandem, tridem, and quad axles), material and subgrade characterization, climatic factors, performance criteria, shoulders, subdrainage, joint details, and others. One of the most interesting aspects of the design procedure is the consideration of different levels of inputs. Level 1 requires the engineer to obtain the most accurate design inputs (e.g., direct testing of the materials, on-site WIM and AVC, etc.). Level 2 requires testing, but the use of correlations is allowed (for example, subgrade modulus estimated through correlation with another test), and Level 3 generally uses estimated values. Thus, Level 1 has the least possible error associated with inputs, Level 2 has more and Level 3 has the most. The effect of potential error on design reliability is directly considered in design.

The basic assumptions used to structurally model the PCC slab, the base, the subbase and the subgrade along with joints are described in the paper. The primary finite element model used was the new finite element program, ISLAB2000. Factorials of ISLAB2000 runs were performed to train neural networks for rapid prediction of critical distresses.

The key distress types include joint faulting, top-down slab cracking, and bottom-up slab cracking. Each was modeled using mechanistic principles and damage accumulated over the design life. Smoothness is characterized by the International Roughness Index (IRI) and is dependent on initial as-constructed IRI, the above distresses, and site conditions of subgrade and climate.

The incremental damage approach used is perhaps the most significant aspect of the design procedure in that it allows for the direct consideration of changes in many factors throughout the entire design period, including material properties (PCC strength and modulus, erosion of base), seasonal climatic conditions, traffic loadings, joint load transfer, subgrade support, and others. Each analysis increment represents a specific combination of the preceding factors over a distinct period of time (i.e., month, season).

Reliability is directly considered through realistic simulation of the project design process and construction considering variabilities and uncertainties of each design factor and potential errors in models. Input estimation errors for Levels 1, 2, and 3 are directly considered. Monte Carlo simulation is used to develop probable distributions of each distress and IRI over the design period. Reliability is then defined as the probability that a given distress type or IRI will not exceed a critical limiting value.

One of the most important aspects of the design procedure is the use of many pavement sections located throughout North America (various databases including LTPP) for calibration purposes. This process will reduce the distress and IRI prediction bias associated with the models.

INTRODUCTION

The development of a mechanistic based design procedure is currently underway in the United States by the National Cooperative Highway Research Program (NCHRP). The work is intended to replace the empirical procedure currently used for many years by the American Association of State Highway and Transportation Officials (AASHTO). Significant progress has been made and the new pavement design procedure is scheduled for completion in 2001.

This paper presents the concepts and approach used to develop a mechanistic based design procedure for jointed plain concrete pavements (JPCP). The paper addresses the key aspects of the design procedure including: brief design overview, design inputs, structural response model, prediction of pavement deterioration, incremental damage analysis, reliability of design, and calibration of design. Details of the models are presented elsewhere.⁽¹⁾

BRIEF DESIGN OVERVIEW

The overall design process for JPCP is illustrated in figure 1. The process involves raw inputs including the trial design, selection of damage increments, level of design reliability and stochastic inputs, prediction of each distress type (structural response using finite element based models, damage accumulation, and calibrated model distress prediction), prediction of smoothness, and finally checking to see if the distress and smoothness predictions meet selected criteria at the desired level of reliability.

An initial trial design is first selected that includes many important design details of the pavement. Guidance is provided on all values required for the trial design. The trial design is then analyzed in detail to determine if it meets all performance criteria (i.e., joint faulting, slab cracking, punchouts, IRI) over the design analysis period. If the trial design does not meet the performance criteria at the design reliability level, it is modified and reanalyzed. This process continues until the design does meet the criteria. The design is then considered feasible from a structural and functional viewpoint and can be further considered for life cycle cost analysis. Thus, the procedure is iterative and requires hands on interaction by the design engineer.

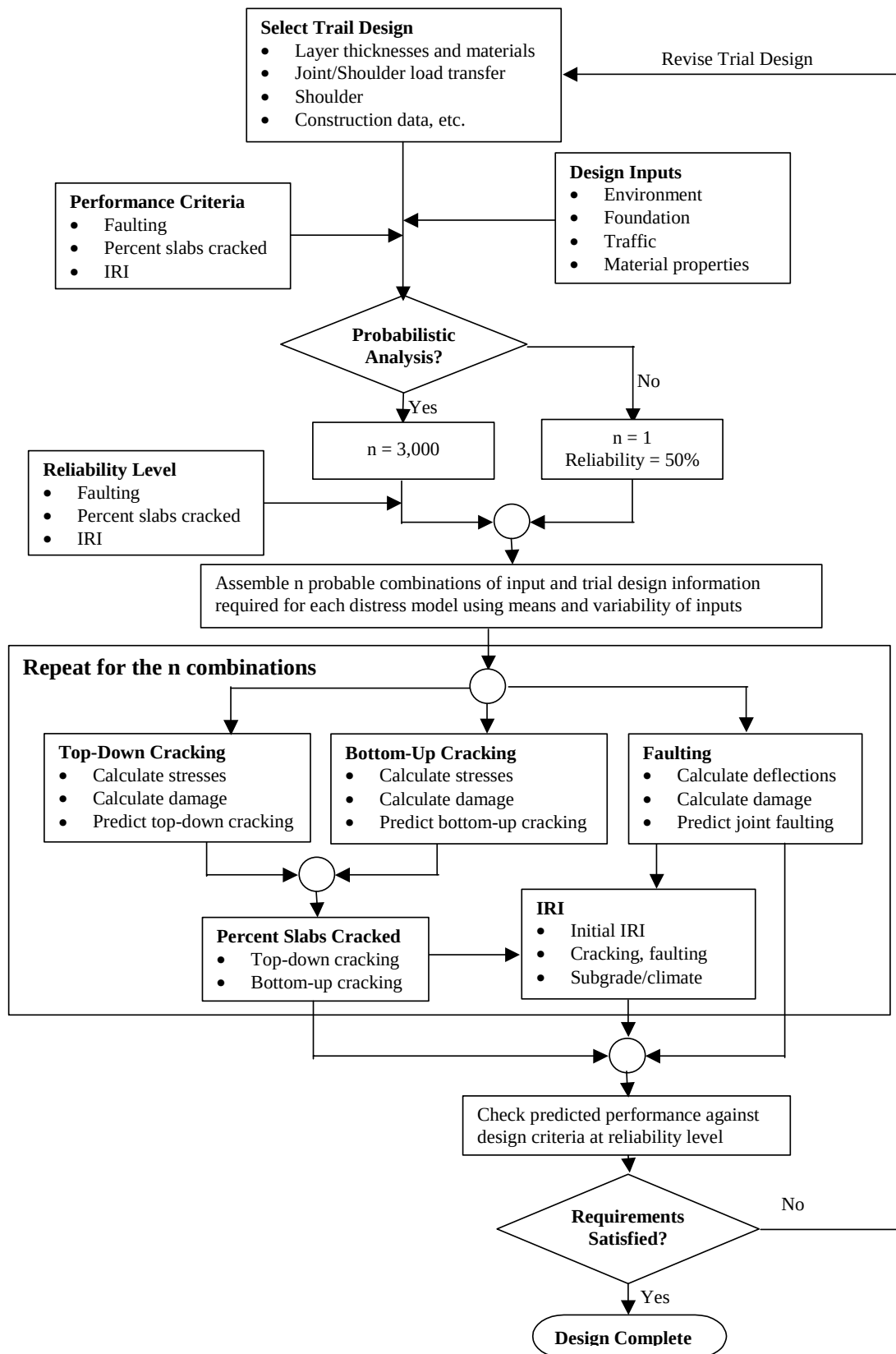


Figure 1. Overall design process for JPCP.

DESIGN INPUTS

Inputs for JPCP design include traffic (full load spectra for single, tandem, tridem, and quad axles), material and subgrade characterization, climatic factors, performance criteria, shoulders, subdrainage, joint details, and others. One of the most interesting aspects of the design is the consideration of different levels of inputs.

- Level 1 requires the engineer to obtain the most accurate design inputs (direct testing of the materials, on-site WIM and AVC, FWD testing, etc.).
- Level 2 requires testing but use of correlations is allowed (subgrade modulus estimated through correlation with another test, see figure 2 for an example of level 2 input, where user enters mean PCC compressive strength and the flexural strength and elastic moduli are calculated internally based on correlations).
- Level 3 is generally estimated or default values.

The screenshot shows the 'PCC Materials Module' window. At the top left, a 'Level' dropdown is set to '2'. Below it is a table with four columns: 'Time Period', 'Mean PCC Compressive Strength (psi)', 'Mean PCC Modulus of Rupture (psi)', and 'Mean PCC Modulus (million psi)'. The rows represent curing times: 7 day, 14 day, 28 day, 90 day, and 20 year*. The 20 year* row is highlighted. To the right of the table, there are input fields for 'Poisson's Ratio' (set to 0.20) and 'CRCP' (28-day Mean PCC Tensile Strength (psi)). Below the table, there is a 'Level' dropdown set to '2' and a 'Mean Coefficient of Thermal Expansion' input field set to 5.3 X 10⁻⁶ in/in/°F. At the bottom, there is a section for 'Other PCC Information' with various input fields: Unit Weight (145 pcf), Curing Method (Moist), Cement Type (Type I), Aggregate Type (Gravel), Max. Aggregate Size (1.5 in), Air Content (5.5 %), Water-Cement Ratio (0.52), Cement Content (690 lbs/yd³), Fine Aggregate Content (1240 lbs/yd³), and Dry Coarse Aggregate Content (1670 lbs/yd³). The 'Cancel' and 'OK' buttons are at the bottom right.

Time Period	Mean PCC Compressive Strength (psi)	Mean PCC Modulus of Rupture (psi)	Mean PCC Modulus (million psi)
7 day	2,600	483	2.93
14 day	3,920	595	3.28
28 day	4,325	660	3.76
90 day	5,760	721	4.11
20 year*	6,950	792	4.50

*Estimated

Figure 2. Level 2 Concrete materials input.

Thus, Level 1 has the least error associated with inputs and Level 2 more and Level 3 the most. The uncertainty of design inputs will be directly considered in design through assignment of different levels of variability to each level. The design of the pavement and thus its construction cost will therefore be a function of the design inputs which will provide economic incentive to obtain Level 1 inputs.

INCREMENTAL DAMAGE ACCUMULATION

The trial design is analyzed for adequacy by dividing the design period into time increments. The shortest increment is one month and the longest is two or more years.

- Each increment represents a period of time wherein some parameters are held constant (i.e., PCC strength, subgrade modulus, joint load transfer) and damage is accumulated over the axle load distributions and temperature gradient distributions specific to that increment.
- Some factors vary over the entire design period (PCC strength, truck volumes), while others vary within a year only (relative humidity, temperature gradients, subgrade modulus). The shortest time increment is 1 month of daytime conditions or 1 month of nighttime conditions.
- The increments are automatically selected and are typically shorter time periods in the first year due to PCC strength gain. After the first year, longer time periods may be selected. The more increments selected, the more damage computations are necessary and the longer computer time required for prediction of a distress over the design period. Table 1 is a summary of the design factors and the increments for which they will be required in design.

Table 1. Summary of design factors and increments for which they will be required.

Design Factors	Increments
PCC strength	Increases continuously over design period (selected such that strength gain does not exceed 5 percent)
PCC shrinkage strain (top of slab)	Changes with season (humidity)
PCC thermal gradient (throughout slab)	Changes with season, distribution within season
Base/subbase erodibility	Base erosion index/loss of support, changes with time (for CRCP)
Joint load transfer	Changes with season, deteriorates over time
Subgrade modulus	Changes with season

STRUCTURAL RESPONSE MODEL

The critical stresses and deflections in the pavement under traffic and climatic loadings are computed using rapid solution models (neural networks) that are based on a finite element (FE) structural model. Finite element analysis has been proven to be a reliable tool for solving many engineering problems, including prediction of pavement responses, such as stresses, strains, and deflections, under traffic and environmental loading. The following groups of FE models for rigid pavements are available for pavement engineers:

- Models based on general-purpose three-dimensional (3D) finite element packages—e.g., ABAQUS, ANSYS, and DYNA3D.^(2,3,4)
- Models based on 3D finite element code specifically developed for rigid pavement analysis—e.g., EVERFE.⁽⁵⁾
- The two-dimensional (2D) finite element programs specifically developed for rigid pavement analysis—e.g., ILLISLAB, WESLIWID, J-SLAB, KENSLAB.^(6,7,8,9,10)

The models from the first group are generally the most powerful, with the capability to model the most complex pavement systems. However, they demand large computational resources and in-depth knowledge and experience to utilize.

EVERFE is a rigid pavement 3D finite element analysis tool developed at the University of Washington in cooperation with Washington Department of Transportation. At the present time, EVERFE is the most sophisticated and user-friendly 3D finite element program specifically developed for rigid pavement analysis. EVERFE incorporates a novel technique for modeling aggregate interlock joint shear transfer and rationally incorporates nonlinearities, as well as a new method for modeling dowel joint shear transfer. Nevertheless, EVERFE has significant limitations. The computation time of the program is still substantial – about an hour for a single run with a fine mesh on a PC with a Pentium III 450 MHz processor. The current version of the program can analyze only one slab in transverse direction and, therefore, cannot analyze the effect of tied PCC shoulder.

Using a 2D finite element code specifically developed for rigid pavement analysis is therefore more practical at this time because hundreds of thousands of computations are required to train the neural networks. Also, there are no significant differences in results from the general-purpose and rigid pavement design 2D FE codes. Numerous rigid pavement specific 2D FE programs are available to pavement engineers for use in design. They include:

- ILLISLAB.
- WESLIWID.
- J-SLAB.
- KENSLAB.

FE Model Used

Any of the FE programs can be used for design and, for basic loading situations, all provide about the same responses. For this design guide, ISLAB2000—the latest version of ILLI-SLAB—was used for calibration and the development of rapid solutions.⁽¹¹⁾ It is a 2D FE program with the capability to analyze two-layered multislabs pavement systems subjected to the combined effect of multi-wheel traffic loading and stresses from nonlinear temperature gradient within the PCC slab. ISLAB2000 was developed by ERES Consultants in cooperation with the Michigan and Minnesota Departments of Transportation, Michigan Technical University, University of Michigan, and Michigan State University. ISLAB2000 retains the well-tested and proven aspects of the original ILLI-SLAB FE program and also has the new features added to enhance the capabilities of ILLI-SLAB:

- The ability to analyze the effect of separation between the pavement layers.
- Capability to analyze the effects of nonlinear temperature distribution in PCC layers.
- Inclusion of a capability to model pavement joints, including the ability to analyze rigid pavements with different joint properties (e.g., the load transfer efficiency between traffic lane slabs can be different than load transfer between the traffic lane and a shoulder).
 - ISLAB2000 can analyze an unlimited number of nodes (this may be limited by available hard drive space), pavement layers, and wheel loads. It also has the ability to analyze mismatched joints and cracks.

This incremental design procedure requires thousands of stress and deflection calculations to compute damage monthly over a long design period of many years. Thus, it is not practical to include a finite element program with the design guide software. To reduce computer time to a practical level, neural networks (NNs) have been developed to compute critical stresses and deflections virtually instantaneously. This makes it possible to conduct detailed incremental analysis (month by month) to sum damage over time in a realistic way. The NNs reproduce the same critical stress and deflection very accurately given a set of design inputs. NNs were developed separately for single, tandem, and tridem axles.

To determine critical responses required as input parameters to performance prediction models, the neural networks (NN) developed were based on factorials of SLAB2000 runs for single, tandem, tridem or quad axle loadings. For nonstandard axle loading, a user has the following options:

1. Use ISLAB2000 directly to compare critical stresses
2. Use ILLISLAB or any other 2D finite element program direction to compare critical stresses
3. Use any other finite element tool directly to compare critical stresses

Although the mechanistic based distress models are calibrated using the ISLAB2000 program, another finite element model may be used to determine mechanistic response if the following conditions are satisfied:

1. The model should describe the pavement structure (constructed layers and subgrade) in a manner that is consistent with SLAB2000.
2. The model should satisfy finite element mesh convergence requirements be finite element mesh insensitive (i.e., the solution should not depend on the finite element mesh selected within tolerance limits).
3. The model should characterize applied loading (both traffic and environmental) in a manner consistent with ISLAB2000.

PCC Material Modeling

PCC layers are modeled as medium-thick plates, with cracks and joints modeled using shear spring elements. The following material properties need to be assigned for each finite element run:

- PCC modulus of elasticity, assigned in accordance with the PCC age over the design analysis period.
- Poisson's ratio.
- Coefficient of thermal expansion.
- Unit weight.

Structural Modeling of JPCP

To predict the performance using the mechanistic-empirical models, the means of determining the following structural responses are needed:

- Maximum bending stress at the bottom surface (JPCP bottom to top cracking).
- Maximum bending stress at the top surface (JPCP top to bottom cracking).
- Maximum corner deflection and differential deflection across the joint at the corner (JPCP faulting).

PCC Response Model Configuration

Five PCC slabs were modeled in the longitudinal direction. Depending on the response of interest and shoulder type, one or two slabs were modeled in the transverse direction for analysis of a truck lane.

Thermal Gradients and Other Climatic Parameters

Thermal gradients through the JPCP slab are the most critical climatic input. Thermal gradients affect greatly the critical stresses in the slab that contribute to cracking. Distributions of thermal gradients are required over each month throughout the year (both day and night). The designer executes the Enhanced Integrated Climatic Model (EICM) using the trial design before performing damage computation. Historical (24 to 51 months) of hourly weather data for hundreds of weather stations across the U.S. are included with the software. By providing the latitude, longitude, and altitude of the design project, a list of nearby weather stations in the database is displayed. The designer can select a weather station or can create a virtual weather station by combining one or more weather stations that are in the vicinity of the project.

The layer properties entered by the designer in the trial design and the selected weather station are used in the EICM execution. The output of the EICM execution is a temperature file that includes historical hourly temperature profile in the PCC slab. For example, if the weather station selected has 4 years of historical weather data, then the temperature file will include approximately 35,000 (4 years * 365 days * 24 hours) hourly nonlinear temperature profiles in the PCC slab.

Each hourly nonlinear temperature profile is converted to effective linear thermal gradient (difference) for computational efficiency and more realistic stress predictions. For daytime conditions, the bottom-up cracking neural network is used to calculate the total stress corresponding to the nonlinear temperature distribution for 18,000 lb single axles, 36,000 lb tandem axles, and 54,000 lb tridem axles. This stress is compared with the total stress due to a

linear temperature gradient in the slab with the same support condition. The linear temperature gradient that produces the same stress as the nonlinear temperature gradient is then the effective linear temperature gradient for that axle type. A similar procedure is followed for nighttime conditions.

Figure 3 shows a typical nighttime distribution of thermal gradients at a site. Top-down cracking and joint faulting models consider nighttime (negative) gradients and the bottom-up cracking model considers daytime (positive) gradients. Other temperature and moisture factors include mean monthly slab temperatures and seasonal moisture variations in an unbound aggregate base or subbase and the subgrade, which are also generated using the EICM module.

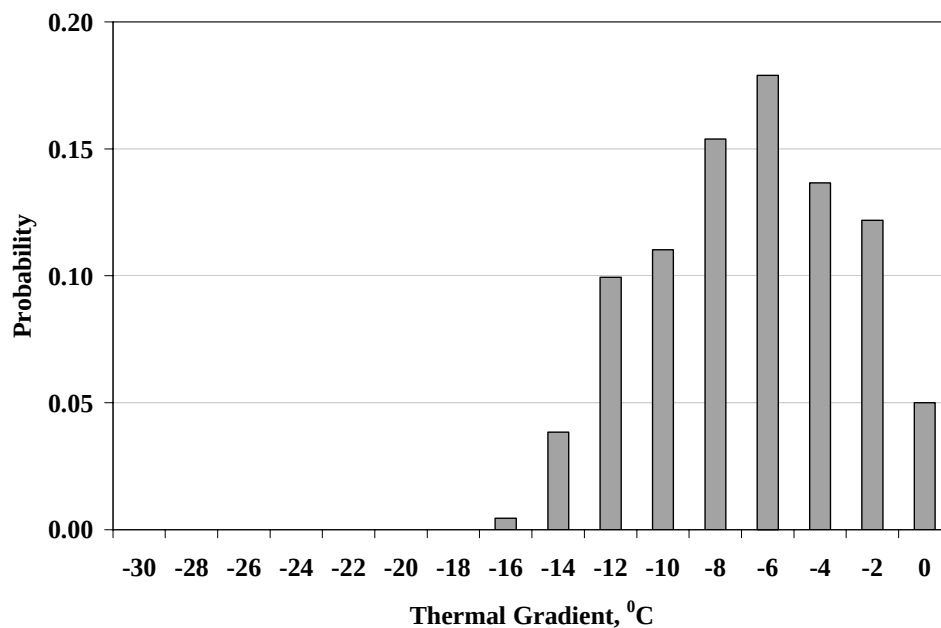


Figure 3. Example of nighttime critical thermal gradient distribution plot.

Base Modeling

To account for structural contribution of the base layer(s), at least one base layer should be modeled as a medium-thick plate bonded or unbonded with the PCC slab. If the pavement structure employs at least one stabilized layer, then all unbound layers placed beneath the lowest stabilized layer may be included in the foundation model. If the pavement structure contains more than one stabilized base layer, they can be combined into one layer with an equivalent thickness.

Presence of the base layer also increase load transfer efficiency of the transverse joint. Currently, there is no widely accepted methodology that accounts for this effect directly. It is recommended to assign a certain level of the load transfer efficiency (LTE) for the base layer as one of the components of the total load transfer efficiencies. Table 2 presents recommended

LTE values for different base types for flat slab condition (no PCC slab curling occurs). These values should be adjusted for local conditions.

Table 2. Recommended transverse joint load transfer efficiencies for base and subgrade contributions (user may modify).

Base type	LTE_{Base}
Aggregate base	20%
Asphalt treated or cement treated base	30%-40%
Lean concrete base	40%-50%

Subgrade Modeling

The unbound subbase and subgrade layers are modeled as a Winkler (or dense liquid [DL]) foundation and characterized by the coefficient of subgrade reaction, k-value.⁽¹²⁾ The coefficient of subgrade reaction is defined as that measured or estimated on top of the finished roadbed soil or unbound subbase upon which base and PCC layers are constructed. The design software internally backcalculates an appropriate coefficient of subgrade reaction, k-value, of the subgrade using the deflected profile at the top of the PCC slab computed for an elastic layer pavement with the appropriate resilient modulus.^(13,14) Thus, the subgrade modulus for rigid pavements is directly related to the resilient modulus of the soil.

Loss of Support Modeling

Two types of loss of support are considered in the design process: temporary loss of support due to PCC slab curling and permanent loss of support due to erosion. The effect of loss of support due to slab curling is included in all analysis of all types of responses. The effect of permanent loss of support due to erosion is included in analysis of CRCP responses only. Permanent loss of support should be modeled using either gap elements or springs elements with zero stiffness. Loss of support of 0 to 0.45 m (0 to 18 in) from the edge should be considered in the CRCP analysis.

Joints

The joints can be modeled using vertical shear spring finite elements. The equivalent stiffness of the spring element, AGG-factor, should be selected to provide appropriate deflection load transfer efficiency, LTE^* for flat slab (no curling) conditions. For transverse joints, the total deflection load transfer efficiency should consider contribution of three major mechanisms of load transfer: load transfer by PCC aggregates, load transfer by joint dowels (if applicable), and joint transfer by the base/subgrade. The combined load transfer efficiency can be determined from the following equation:

$$LTE_{joint} = 100 * (1 - (1 - LTE_{dowel} / 100) * (1 - LTE_{AGG} / 100) (1 - LTE_{base} / 100)) \quad (1)$$

LTE_{joint} = total joint LTE, percent

LTE_{dowel} = joint LTE if dowels are the only mechanism of load transfer, percent

LTE_{base} = joint LTE if the base is the only mechanism of load transfer, percent

LTE_{AGG} = joint LTE if aggregate interlock is the only mechanism of load transfer, percent

LTE_{base} can be determined from table 3.

LTE_{AGG} depends on joint/crack opening and joint/crack deterioration and described in the chapters related to JPCP faulting. Long term load transfer contribution of a dowel joint can be estimated based on the following relationship if no other information is available:

$$LTE_{dowel} = 100 * (1 - \text{Exp}(-0.7D^3)) \quad (2)$$

where

LTE_{dowel} = joint LTE if dowels are the only mechanism of load transfer, percent

D = dowel diameter, in

Table 3 presents recommended load transfer efficiencies for longitudinal joints.

Table 3 Recommended load transfer efficiencies for longitudinal joints.

Joint	LTE*, percent
Longitudinal tied lane to lane joint	50-70
Monolithically built tied PCC shoulder	50-70
Tied PCC shoulder (separately connected)	40-50
AC shoulder	20-30

From known load transfer efficiency, the joint stiffness (or AGG-factor) can be estimated from Croveti's equation:⁽¹⁵⁾

$$LTE = \frac{1}{0.01 + 0.012 * \left(\frac{AGG}{k \ell} \right)^{-0.849}} \quad (3)$$

where,

k = coefficient of subgrade reaction

l = radius of relative stiffness.

AGG-factor can be also estimated from figure 4.

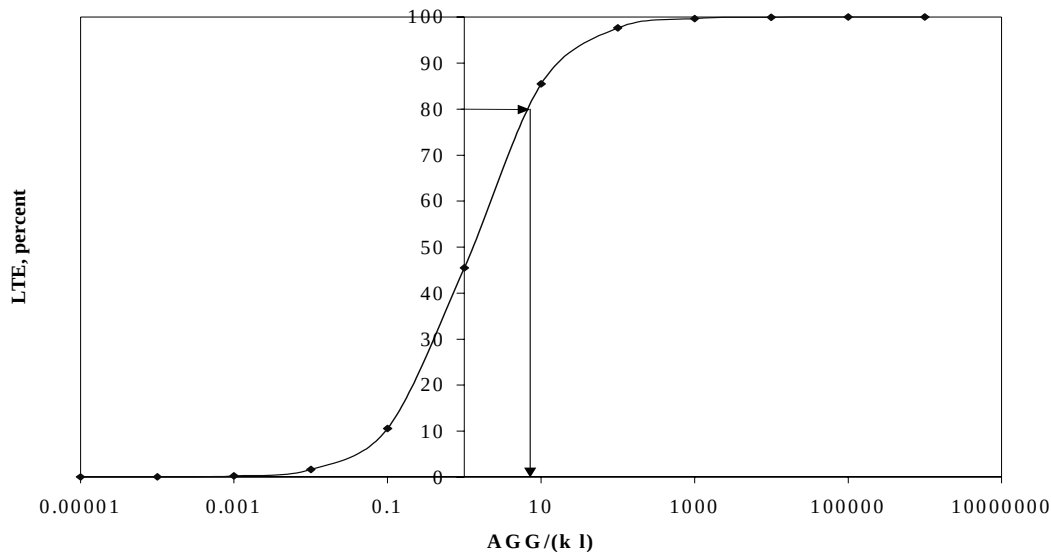


Figure 4. Estimation of AGG parameter from the deflection load transfer efficiency.

KEY MECHANISTIC BASED DISTRESS MODELS

Three types of JPCP distresses were modeled mechanistically: joint faulting, top-down fatigue cracking, and bottom-up fatigue cracking.

Transverse Cracking (Bottom-Up) Damage Accumulation

When the truck axles are near the longitudinal edge of the slab midway between the transverse joints, a critical tensile bending stress occurs at the bottom of the slab, as shown in figure 5.⁽¹⁶⁾ This stress increases greatly when there is a high positive temperature gradient through the slab. Repeated loadings of heavy axles result in fatigue damage along the edge of the slab that eventually results in micro-cracks that propagate to the slab surface and transversely across the slab. These cracks in JPCP eventually deteriorate and cause roughness and require repairs. The cracking model accumulates the amount of fatigue damage caused by every truck axle load, time increment by increment (i.e., month by month), over the entire design period. The appropriate distribution of temperature gradients and lateral distribution are directly considered within each time increment.

Transverse Cracking (Top-Down) Damage Accumulation

When the truck steering axle is near the transverse joint and the drive axle is within 10 to 20 feet away and still on the same slab, a high tensile stress occurs at the top of the slab between the axles, some distance from the joint, as shown in figure 6.^(16,17) This stress increases greatly when there is a negative temperature gradient through the slab, a built-in negative gradient from construction, or significant drying shrinkage at the top of the slab (all of these are common).

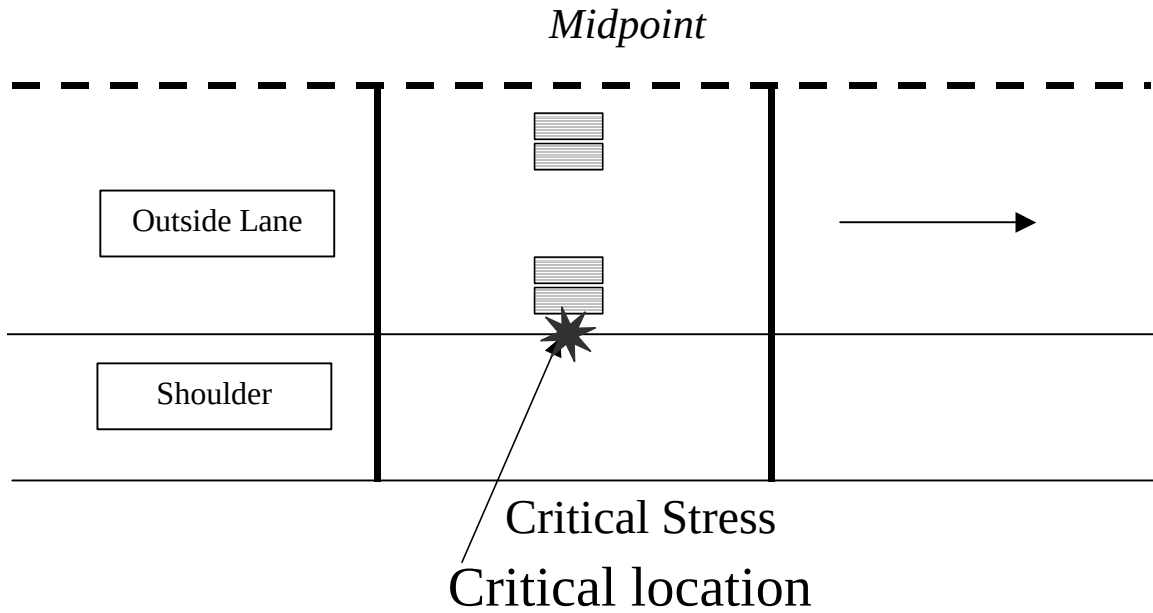


Figure 5. Critical loading and structural response location for JPCP bottom-to-top transverse cracking.

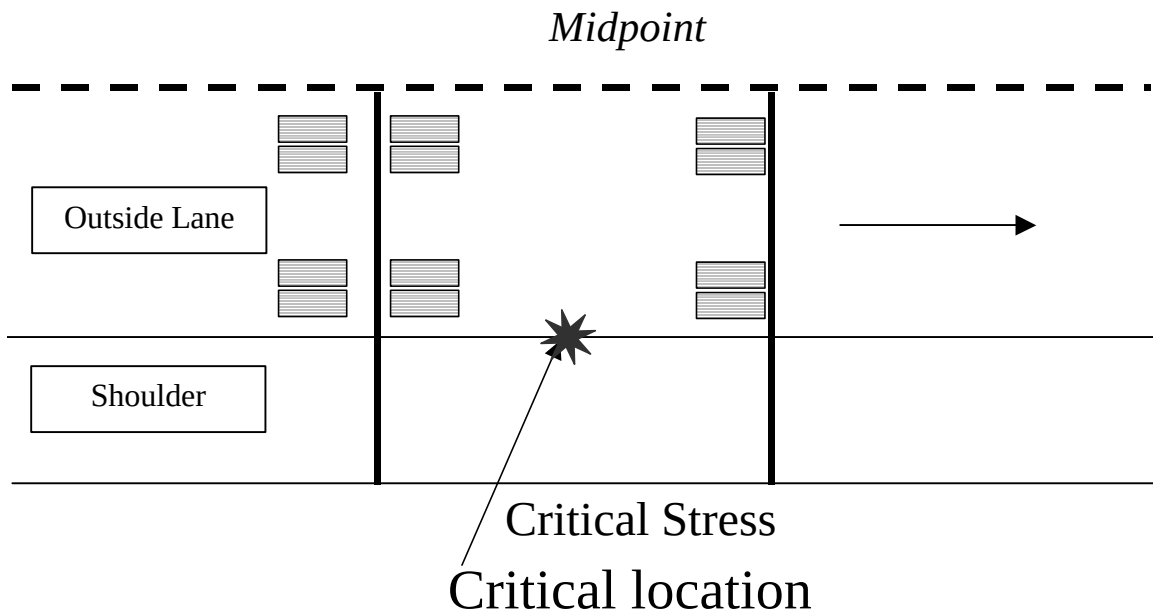


Figure 6. Critical loading and structural response location for JPCP top-to-bottom transverse cracking.

Repeated loading of heavy axles result in fatigue damage at the top of the slab, which eventually results in micro-cracks that propagate downward through the slab and transversely or diagonally across the slab. The cracking model accumulates the amount of fatigue damage caused by every truck axle load, time increment by increment, over the design period. The appropriate distribution of temperature gradients is directly considered within each time increment.

Joint Faulting Damage Accumulation

Repeated heavy axle loading crossing transverse joints creates the potential for joint faulting to occur, as shown in figure 7.⁽¹⁸⁾ If any of the following conditions occurs:

- less than 80-100 percent load transfer efficiency,
- an erodible base, subbase, shoulder, or subgrade,
- free moisture beneath the slab, and
- heavy traffic

then faulting can become severe and cause loss of ride quality and early rehabilitation. The faulting model accumulates the amount of faulting damage caused by every truck axle load, time increment by increment, over the design period. The appropriate distribution of temperature gradients is directly considered within each time increment.

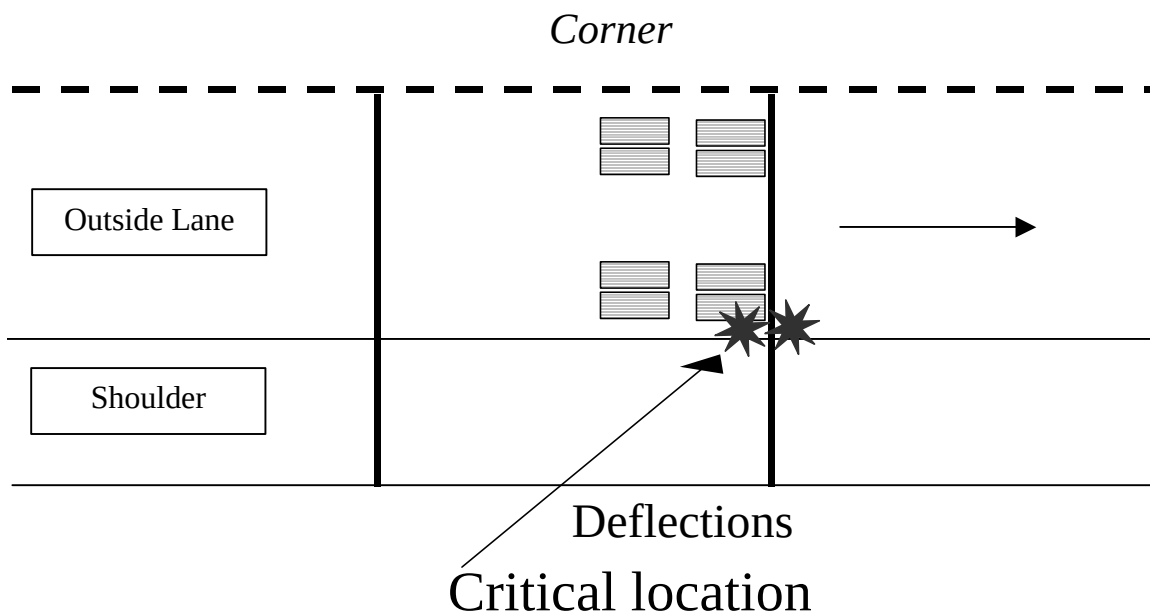


Figure 7. Critical loading and structural response location for JPCP faulting analysis.

SMOOTHNESS (IRI) PREDICTION

The IRI over the design period depends upon the initial as-constructed profile of the pavement from which the initial IRI is computed, the subsequent development of distresses such as joint faulting and slab cracking, and any future settlement of the slab that affects longitudinal profile

over time.⁽¹⁹⁾ A model was developed for JPCP that relates the IRI at any time to the as-constructed initial IRI and to the occurrence of the previously described distresses. The model also includes subgrade and climatic calibration factors. IRI is estimated for each time increment throughout the design period. The functional IRI model for JPCP is given as follows:

$$S(t) = S_0 + a_1 D(t)_1 + a_2 D(t)_2 + \dots + a_n D(t)_n + b_j M_j$$

where

$S(t)$ = pavement smoothness over time (IRI, m/km)

S_0 = initial smoothness (IRI, m/km)

a_i, b_j = regression constants

$D(t)_i$ = i^{th} distress at a given time

M_j = repair activities that significantly influence smoothness

ASSESSMENT OF PERFORMANCE AND DESIGN MODIFICATIONS

The design software computes the amount of joint faulting, transverse cracking, and IRI for JPCP for each time increment over the design period. These curves are plotted and the data are summarized in tables. This performance is compared to the critical levels selected by the designer at the desired level of reliability, and the trial design is deemed either acceptable or unacceptable, depending on the magnitude of distress and IRI predicted. If unacceptable, the trial design is modified to reduce the extent of deterioration.

DESIGN RELIABILITY

A large amount of uncertainty and variability exists in pavement design and construction, as well as in the application of traffic loads and climatic factors over the design life. The design reliability is established through the simulation of many of these uncertainties and variabilities by establishing the potential errors of each design input and various models in the design procedure. Thus, the designer must decide what limiting amount of distress can occur for a given level of design reliability. For example, one criterion might be to limit percent slabs cracked to 8 percent at a design reliability of 90 percent. Thus, if a designer designed 100 projects, 90 of these projects would exhibit slab cracking less than 8 percent. If the simulation process shows the trial design to be excessive (say, 15 percent), then the trial design must be modified to reduce the amount of distress.

SUMMARY OF SITE CONDITIONS

Site conditions for a new or reconstructed rigid pavement are defined by the subgrade support, climatic conditions, and traffic loadings at the project site, similar to that of flexible pavements. These site conditions are defined by a number of specific inputs. This section briefly summarizes these site conditions specifically related to rigid pavements.

Subgrade

The subgrade is characterized by a resilient modulus determined through direct laboratory testing, correlations from other test sites, or estimation (depending on the level of input selected by the designer). The subgrade resilient modulus is adjusted to reflect the low deviator stress that typically exists under a concrete slab and base course. The design software internally backcalculates an appropriate k-value of the subgrade using the deflected profile at the top of the PCC slab computed for an elastic layer pavement with the appropriate resilient modulus. Since the subgrade support varies considerably along a typical highway project, the mean and standard deviation of moduli are required as inputs to the design procedure.

Traffic

The axle load spectra is required to design a new or reconstructed rigid pavement. Axle types include singles, tandems, and tridem. The number of these axles (over a range of weights), month by month, is required over the design period. Lateral distribution of trucks in the design lane is also considered.

Climate

Thermal gradients through the JPCP slab is the most critical climatic input. Thermal gradients affect greatly the critical stresses in the slab that contribute to cracking. Distributions of thermal gradients are required over each month throughout the year (both day and night). These are generated using the EICM (Enhanced Integrated Climatic Model) module. Other factors include mean monthly slab temperatures and seasonal moisture variations in an unbound aggregate base or subbase and the subgrade, which are also generated using the EICM module.

CALIBRATION OF MECHANISTIC BASED MODELS

The mechanistic based distress models for joint faulting, top-down cracking, and bottom-up cracking must be calibrated to actual field data. Extensive field data was obtained from two sources:

1. Long-Term Pavement Performance (LTPP) national database of JPCP (GPS-3, SPS-2, GPS-9, and others)
2. FHWA JPCP database established in 1992 includes data from a number of states experimental projects

The design, climatic, and performance data from the LTPP and the FHWA databases were combined into a large database and later reduced to individual databases (one for each distress type). Table 4 shows the distribution of the sections in the cracking database by climatic regions and design features. The databases cover a wide variety of designs and site conditions and will provide useful calibrations in various regions and for various designs. Actual calibration of the cracking and faulting models has shown reasonable predictions thus far. This work will be completed by April 2001.

Table 4. Distribution of sections in the PCC cracking database.

Climate:				Dry				Wet			
				Nonfreez e		Freeze		Nonfreez e		Freeze	
Base Type:				Gran.	Stab.	Gran.	Stab.	Gran.	Stab.	Gran.	Stab.
	Slab Thickness	Doweled	Edge Support								
Low	Low	No	No	0	3	2	1	1	1	0	1
			Yes	0	0	1	1	1	1	2	0
		Yes	No	1	2	4	4	3	2	3	6
			Yes	1	2	2	4	0	1	1	2
	High	No	No	0	0	3	1	1	9	1	0
			Yes	0	2	0	1	0	3	0	0
		Yes	No	1	2	3	4	1	3	3	7
			Yes	1	2	2	6	1	2	2	1
High	Low	No	No	0	19	3	2	2	19	6	13
			Yes	0	2	0	0	0	4	5	7
		Yes	No	0	0	2	0	2	7	9	4
			Yes	0	0	3	0	0	2	7	2
	High	No	No	0	3	0	1	1	1	6	0
			Yes	4	0	0	0	0	1	14	3
		Yes	No	0	1	0	0	0	6	2	3
			Yes	0	1	0	1	2	2	4	4

- Cutoffs for Slab Length (Cracking model only): ≤ 15 ft = low, > 15 ft = high
- Cutoffs for Slab Thickness: ≤ 9 in = low, > 9 in = high
- Cutoffs for Dowel Diameter (Faulting only): ≤ 1.25 in = small, ≥ 1.375 in = large
- Basetype was broken down as follows:

Cracking Model	
Granular	Stabilized
GB	TB
	PATB

Faulting Model		
Granular	Stabilized	Permeable
GB	TB	PATB

SUMMARY

The mechanistic based design procedure for JPCP has put together existing technology into a working design procedure. Some of its most interesting characteristics are the following:

- Design input levels can vary in terms of their accuracy (from testing to estimating). The level used will, however, affect the resulting design, reliability, and the cost of the pavement.
- The finite element structural model has the capabilities to structurally model the key design features, traffic loadings, climatic conditions, and subgrade support.
- The incremental damage approach makes the design procedure extremely flexible and robust since material properties, traffic levels, seasonal climatic conditions, and joint load transfer can vary throughout the life of the pavement.
- The direct consideration of key distress types of joint faulting, top-down transverse cracking, and bottom-up transverse cracking provides a way to reduce them.
- Estimation of smoothness (IRI) over time based on initial smoothness and future development of distress and site factors.
- Direct calibration of each distress model to region or State to ensure accuracy.
- Direct consideration of variations and uncertainties in the design process (from inputs, to construction, to prediction models) to develop JPCP designs with specified reliability.

A complete software package is under development that can be utilized to conduct the iterative design process is under development and will be available in the fall of 2001.

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