Computer-Based Guidelines for Concrete Pavements, Volume II: Design and Construction Guidelines and HIPERPAV® II User's Manual

U.S. Department of Transportation
Federal Highway Administration

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 II of a three-volume set, is the Construction and Design Guidelines and HIPERPAV II User's Manual, which provides general instructions on the use and application of the HIPERPAV II. Volume I is the Project Summary documenting the efforts undertaken for the development of the guidelines. Volume III is the Technical Appendices, 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 Federal Highway Administration (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.

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 Research and Development

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15. Supplementary Notes

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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 also was incorporated by reviewing and prioritizing the feedback provided by users of the first generation of the software, HIPERPAV I.

This volume provides a comprehensive set of guidelines useful in designing and constructing both JPCP and CRCP concrete pavements. In addition, this document also provides sample case studies that illustrate the proper use of HIPERPAV II to optimize concrete pavement behavior and contains a user's manual for HIPERPAV II. This is the second volume in a series of three volumes that document the different tasks carried out in accomplishing the objectives for this project.

FHWA No.	Vol. No.	Short Title
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 Appendices

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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)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
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)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
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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CHAPTER 1.   INTRODUCTION

The HIPERPAV® II system was developed as a tool for predicting the early-age behavior of both Jointed Plain Concrete Pavements (JPCP) and Continuously Reinforced Concrete Pavements (CRCP). In addition, the effect of early-age behavior factors on JPCP long-term performance has been addressed. It is expected that the above predictive capabilities will help designers, contractors, and concrete suppliers identify factors that can contribute to achieving good performing pavements. Similarly, it is expected that factors that could potentially put the pavement's long-term performance at risk also can be identified.

It is important to recognize the numerous factors affecting the performance of a concrete pavement, and furthermore, when and how these factors come into play during the various stages of a pavement project. For example, planners may use HIPERPAV II to develop quality control specifications for projects based on the available materials and climatic conditions in the region of construction. For designers, HIPERPAV II may be used to optimize pavement designs so that an improved long-term pavement performance is achieved. For contractors, HIPERPAV II may be used to prevent expensive pavement repairs. Higher potentials of cracking due to unexpected changes in the weather can be predicted and avoided. Using HIPERPAV II, the impact of these changes on the pavement is quantified, and an alternative construction time or method can be developed to reduce or altogether prevent pavement damage. Suppliers may use HIPERPAV II to assess the performance of a given mix design under various climatic conditions. Finally, HIPERPAV II may be used as a forensic analysis tool for pavements. For example, engineers can better pinpoint the reasons behind pavement damage and/or poor pavement performance.

With these considerations in mind, this document aims to provide theoretical concepts on early-age behavior and long-term pavement performance, providing a basis for understanding the numerous models in HIPERPAV II. Ultimately, understanding the above concepts will help guideline users select from the wide range of design and construction alternatives available. Finally, a user's guide for the HIPERPAV II system is presented at the end of this document.

1.1   BACKGROUND

The original HIPERPAV I system provided design and construction guidelines for JPCP. This set of guidelines provided recommendations for selecting primary inputs that influence the early-age behavior of JPCP.[1] In this document, the guidelines are extended to cover the design and construction of CRCP. In addition, the JPCP guidelines are extended to consider the inputs of various early-age parameters on long-term performance.

If well designed and constructed, CRCP is one of the best alternatives for heavily trafficked roads. This is especially true when minimizing user delays due to maintenance, providing long-lasting smoothness, and minimizing user costs are important considerations. Identifying factors that influence the early-age behavior of CRCP will therefore provide the basis for developing adequate guidelines to improve current design and construction practices.

Several investigations have addressed the importance of early-age behavior on long-term performance of concrete pavements.[1,2,3] Most of the factors that influence the early-age behavior of concrete pavements can be classified into four different categories: pavement design, materials and mix design, environmental, and construction operations. Based on these factors, initial conditions have been

identified that are known to influence the performance of the pavement in the long term. Such initial conditions or early-age indicators of long-term performance include joint/crack opening, built-in curling, and surface delamination due to moisture loss. This document identifies the primary early-age indicators influencing the long-term performance of the pavement. To understand their progression with time, the effects of traffic and long-term environmental factors are also discussed.

1.2   OBJECTIVES

The primary objective of this volume is to serve as a stand-alone document covering a comprehensive set of guidelines useful in the design and construction of both JPCP and CRCP concrete pavements. Good design and construction practices not only will help prevent immediate (early-age) problems from occurring, but also may improve performance in the long term. To accomplish this, this document will cover guidelines on the following topics:

1. Early-age behavior of JPCP and CRCP pavements.

2. Early-age distresses that may result from poor design or construction practices.

3. Early-age indicators that can influence long-term pavement performance (e.g., joint opening, crack spacing).

4. Long-term pavement distresses that relate to early-age factors (e.g., cracking, punchouts, faulting).

In addition, this document also provides sample case studies that illustrate the proper use of HIPERPAV II to optimize concrete pavement behavior and contains a user's manual.

1.3   SCOPE AND FORMAT

Chapter 2 presents a brief description of early-age concrete pavement behavior. "Early age" in these guidelines is defined as the first 72 hours after pavement construction for both JPCP and CRCP. According to experience, the potential for damage to the pavement structure due to excessive thermal and moisture related stresses is significant during this time. 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 inservice. Primary early-age indicators influencing long-term pavement performance for JPCP and CRCP are also discussed in this section.

In chapter 3, early-age concrete pavement distresses such as plastic shrinkage cracking and thermal shock are discussed. Considerations are made for both JPCP and CRCP.

Chapter 4 presents a mechanistic approach to the impact of early-age behavior on long-term performance. The influence of early-age indicators on each individual distress type will be discussed. Primary distress types associated with early-age pavement behavior addressed include faulting, spalling, transverse cracking, corner cracking, spalling, and punchouts.

Chapter 5 provides recommendations and guidelines for inputs selected from five unique categories: pavement design, materials and mix design, environment, construction, and traffic inputs.

Sample case studies are presented in chapter 6, with design and construction scenarios to illustrate the proper use of the guidelines. The guidelines have been developed with two possible scenarios in consideration: a proactive scenario, and a post-mortem scenario.

The proactive scenario is one that may occur anytime during the planning, design, or construction stages of a project. Under this scenario, the guidelines user may refer directly to chapter 5—HIPERPAV II Input Parameters—for the proper selection of HIPERPAV II inputs under the five categories of pavement design, materials and mix design, environment, construction, and traffic. Because these guidelines provide only general guidance with the selection of the input parameters in these categories, it is the user's responsibility to use engineering judgment in the final selection of the inputs.

For the case of the post-mortem scenario, the guidelines user may be experiencing a particular problem either occurring in the early age or during the long term. For this particular case, the user may refer to chapter 3, Early-Age Pavement Distresses, or chapter 4, Impact of Early-Age Behavior on Long-Term Performance, according to the nature and timeframe of the specific problem.

Under both scenarios, the user may refer to chapter 2, Early-Age Pavement Behavior, for a detailed understanding of the mechanisms occurring during the early age that influence the performance of the pavement in the long term.

Finally, chapter 7 is a user's guide for the HIPERPAV II system.

CHAPTER 2.   EARLY-AGE PAVEMENT BEHAVIOR

2.1   GENERAL

The behavior of concrete pavements at early ages is influenced by a number of factors including, but not limited to:

- Generated heat from hydration of the cement.

- Climatic conditions such as air temperature, solar radiation, relative humidity of the air, and windspeed.

- Concrete temperature and subbase temperature during placement.

- The concrete coefficient of thermal expansion (CTE).

- Slab-subbase interface restraint.

- Concrete shrinkage as a result of the drying process.

- Curling and warping of the concrete slab as a result of temperature gradients.

- Creep/relaxation phenomena.

- Construction procedures.

During the first hours after construction, the interactions of these factors result in volume changes in the concrete, primarily due to changes in temperature and moisture. During the hardening state, stresses in the concrete start to buildup due, in part, to slab curling and warping and restraint to axial movements at the slab-subbase interface. As concrete is weak in tension, undesirable situations may occur if the stresses in the concrete exceed the developing strength.

In this context, early age is understood as the first 72 hours after pavement placement. Experience demonstrates that significant stresses in the pavement develop during this curing period. These stresses may lead to undesirable situations if not properly controlled.

2.1.1   Temperature and Moisture Changes

The following sections describe the various factors that influence the temperature and moisture state of early-age concrete.

2.1.1.1   Heat of Hydration

A number of properties of concrete are governed by the heat of hydration of the cementitious materials. These properties include concrete set time, strength development, and modulus of elasticity development. In addition, the heat of hydration contributes to the temperature increase in the concrete during the first hours after placement.

The combination of cementitious materials and water results in a variety of chemical reactions in which hydration products are formed. The hydration of the cementitious materials is exothermic, and the degree of hydration is related to the amount of heat liberated at any point during the hydration stage. The

rate of hydration and total heat liberated during hydration depends on factors such as the type of cement, admixtures, water-to-cementitious materials ratio (w/cm), fineness of the cement, and curing temperature.

2.1.1.2   Concrete Temperature

In the early ages, concrete temperature is a function of the heat of hydration and climatic conditions. The heat generated due to hydration results in a temperature rise in the concrete as a function of the thermal conductivity and specific heat of the paste and aggregate. On the other hand, climatic conditions such as air temperature, solar radiation, cloud cover, and convection due to windspeed affect the amount of heat lost or gained through the surface of the pavement. This heat loss or gain is transported through the depth of the slab, as a function of the concrete thermal conductivity and specific heat. Heat conduction to or from the subbase also affects the temperature of the concrete.

An intrinsic relationship exists between heat of hydration and concrete temperature. Because the heat of hydration has a direct correlation with the development of mechanical properties such as strength and modulus of elasticity, the temperature at which the concrete is cured will affect its mechanical properties.

2.1.1.3   Moisture in Concrete

Moisture in the concrete may be classified into two types. The first type is structural water, chemically bound within the cement paste. The second type is water contained in the pore structure. The sum of these portions equals the total water content in the paste. In addition to temperature development, the moisture state in the pore structure of hydrating concrete is another important factor affecting its early-age behavior. It has been recognized that the level of moisture at which a concrete structure is cured can have a significant effect on its strength, and also on the stress development due to shrinkage.

The moisture profile in a pavement structure is a function of climatic conditions such as relative humidity, temperature, and precipitation. The moisture state of the underlying subbase also affects this moisture profile. In addition to the external moisture conditions at which the pavement structure is exposed, the moisture gradients in the pavement are also a function of the thermodynamic equilibrium conditions of moisture flow and the random geometrical nature of the pores in the concrete structure. In general, differences of energy due to capillary forces, gravity, and thermal gradients are the primary factors governing the moisture transport in concrete. The flow of moisture is also a function of the concrete moisture diffusivity and the characteristics of the porous media.[4]

2.1.2   Development of Concrete Properties

This section describes the development of various early-age concrete properties.

2.1.2.1   Concrete Set

Concrete set is defined as the transition of concrete from a plastic to a solid state. Concrete set also marks the start of development of significant mechanical properties. It also is common to associate the set time with the moment where the stresses in the slab begin to develop due to volumetric changes coupled with various restraints.

2.1.2.2   Strength and Modulus of Elasticity Development

Tensile strength development in concrete begins to increase after the concrete sets. It develops primarily as a function of the water-to-cement (w/c) ratio, cement, admixtures, and aggregate characteristics and content. It is also a function of the energy of compaction (consolidation), the curing temperature, and moisture state. The strength of the concrete depends on the strength of the cement paste, the strength of the aggregates, and the bond strength of the cement/aggregate interface. The rate of strength development will be a function of the cement properties such as the cement fineness, cement compounds, and admixtures used.

Cements with a higher fineness commonly will hydrate faster, developing a high early strength, although the strength development at later ages may be lower as compared to coarser cements. Furthermore, it has been observed that fine ground cements are associated with durability problems.[5] A similar effect on the strength development occurs when the concrete is cured at high temperatures. A rapid strength increase is observed at early ages, and a less steep strength increase is noted with the long-term strength.

The effect of moisture on concrete strength also should be emphasized. In concrete pavements, pronounced moisture profiles may occur as a consequence of climatic conditions. It has been observed that whenever the internal relative humidity in the concrete drops below 80 percent, the development of strength can be significantly affected.[6] Similar to strength, the hardening process of concrete also contributes to its stiffness or modulus of elasticity. The concrete modulus of elasticity is directly related to the concrete strength, and also depends on the type of aggregates and its volume in the concrete mix.

2.1.3   Development of Stresses

Stresses in concrete pavements develop due to a number of factors. The following sections discuss some of these.

2.1.3.1   Axial Expansion and Contraction

As the temperature changes after set, the concrete tends to expand or contract as a function of its CTE. The concrete CTE is a function of the CTE of the paste and the CTE of the aggregates. Depending on the concrete-making materials and specifically on the type of coarse aggregate selected, the concrete CTE may be higher or lower. Typically, calcareous aggregates such as limestone and dolomite have a low CTE (4 to 9×10^{-6} m/m/°C) while siliceous aggregates, such as quartzite, possess a high CTE (10 to 12.5×10^{-6} m/m/°C). Also, because the CTE of the hardened cement paste is greater than that of the aggregate, as the percentage of aggregate increases, the overall concrete CTE decreases. CTE has been found to be one of the most influential factors on the performance of concrete pavements. Stresses in the concrete also develop due to restraints imposed at the slab-subbase interface that resist the expansion and contraction of the slab. Stresses develop in the concrete due to this restraint coupled with the temperature changes from day to night. Expansive movements will lead to compressive stresses, while contractive movements will lead to tensile stresses.

2.1.3.2   Plastic Shrinkage

As the name implies, plastic shrinkage occurs in the plastic state of concrete, before it sets. Plastic shrinkage is a function of the evaporation of water from the surface of the concrete. Evaporation is a function of air temperature, windspeed, ambient relative humidity, concrete temperature, and many

other factors. If the water at the surface evaporates faster than the water that migrates from the interior of the slab, plastic shrinkage can occur. Plastic shrinkage can also occur at the bottom of the slab by suction due to a dry subbase.[7] Plastic shrinkage commonly takes the form of random cracks at the surface of the concrete.

2.1.3.3   *Autogenous Shrinkage*

Autogenous shrinkage is related to the reduction in volume of the cement paste as a result of self-desiccation. Self-desiccation is a process where physical and chemical changes in the cement components during hydration lead to drying of the capillary pores in the concrete. This reduction in volume is significant after initial setting and is more pronounced in the case of high-strength concrete where low w/c ratios are used. Autogenous shrinkage has been observed to be less significant for high w/c ratios.[8]

Autogenous shrinkage is not associated with moisture transport, temperature changes, or external restraints. Shrinkage reducing admixtures are available to minimize autogenous shrinkage. However, autogenous shrinkage can also be minimized or avoided by maintaining water available during the cement hydration. This can be accomplished by water curing or by including saturated porous aggregate in the mix (commonly termed internal curing).[8] When enough water is available during hydration, self-desiccation is avoided, and some minor swelling of the concrete may occur instead.[9]

2.1.3.4   *Drying Shrinkage*

Drying shrinkage of concrete occurs due to drying when concrete is exposed to unsaturated air. The normal wetting and drying cycles to which the concrete is subjected lead to changes in the moisture state of the concrete. Although some of the water movement may be replaced by subsequent wetting periods, some of the water lost to the environment is irreversible and leads to permanent concrete shrinkage. Drying shrinkage is a function of a number of factors, including the w/c ratio, cement type, cement content, admixtures used, type and amount of aggregates, and climatic conditions.

2.1.3.5   *Curling and Warping*

Temperature and moisture transport in the concrete result in gradients that can lead to curling and warping movements and stresses. The concrete slab will curl up or down depending on whether the top of the slab is cooler or warmer than the bottom. If the top of the slab is cooler than the bottom, the upper surface will tend to contract, and the bottom will tend to expand, causing the slab to curl up. A downward curling usually is observed if the opposite temperature differential occurs. Due to its exposure to the environment, the top of the slab typically experiences higher drying shrinkage than the bottom. This can cause an upward curvature of the slab, commonly known as warping. Warping has been observed to change as a function of the climate, including the relative humidity and rainfall. Slab curling and warping are, in turn, restrained by the weight of the slab as well as subbase restraints. Compressive and tensile stresses are generated in the pavement as a function of this restrained movement.

2.1.3.6   *Creep/Relaxation*

It has been observed that creep and relaxation effects can be significant during the early age of concrete.[10] When concrete is subjected to a constant load, both an instantaneous and a delayed elastic strain occur. Strain due to plastic deformation of the concrete develops and increases during the loading period. If the load is removed, the elastic strain is totally recovered, while the strain due to plastic

deformation is not. This viscous behavior is commonly known as creep. Conversely, when concrete is subjected to a constant strain level, relaxation of stresses occurs.

During the early age, concrete behaves more like a viscoelastic material than it does later in its hardened state, when its behavior is more purely elastic. During this early-age period, concrete is more susceptible to creep and relaxation effects. Because most of the axial, shrinkage, and curling movements in the pavement are restrained by external factors (such as the slab weight and subbase restraints), the pavement is constantly subjected to tensile and compressive strains. The corresponding level of stress that develops is a function of the creep-relaxation characteristics of the concrete.

Figures 1 and 2 illustrate the typical relaxation effects in concrete as a consequence of temperature loading. After the concrete is placed, the concrete temperature increases due to the heat of hydration (figure 1). Immediately after the concrete sets, strength begins to develop. As the concrete is restrained to move in the axial direction, the concrete tries to expand due to the temperature increase, and compressive stresses develop (figure 2). Because of the creep characteristics of the concrete at such an early age, the compressive stresses are relaxed significantly. After the maximum temperature is reached and the concrete starts a cooling period, the concrete begins to contract. Due to the continued relaxation, the concrete is subjected to tensile stresses even before it cools down to the set temperature at which the compressive stresses initially started. Eventually, as the concrete keeps contracting, increased tensile stresses are generated. When the concrete stresses exceed the tensile strength of the concrete, cracks form. The creep and relaxation properties of concrete are a function of a number of factors, including the moisture state, temperature, concrete properties, stress level, duration of load, and concrete age.[10]
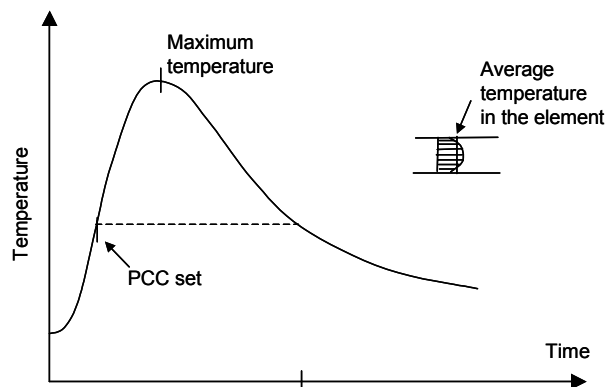
Figure 1. Conceptual representation of temperature development in a concrete element with time.
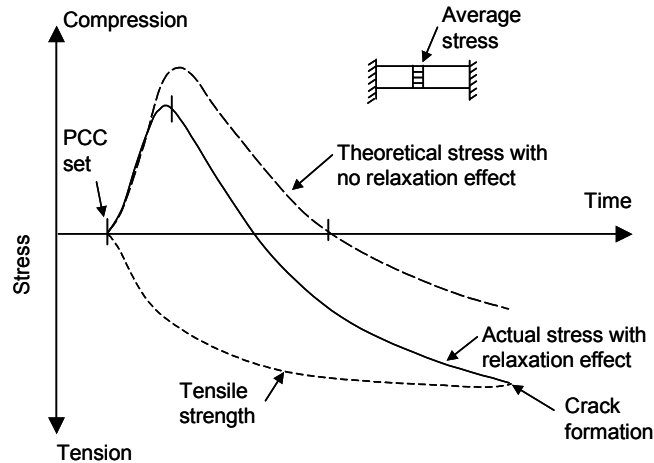
Figure 2. Conceptual effect of creep/relaxation on concrete stresses.[11]

2.1.4 Thermal Cracking

The combination of axial and curling thermal stresses commonly leads to the development of significant compressive and tensile stresses. Because the concrete is weaker in tension than in compression, any condition leading to a decrease in concrete temperature, thermal gradients in the slab, and/or the continued drying shrinkage originated from moisture changes may result in thermal cracking whenever the stresses that develop exceed the tensile strength of the concrete.

2.2 EARLY-AGE INDICATORS OF LONG-TERM PERFORMANCE OF JPCP

The size of the joint opening in JPCP is one of the primary early-age indicators of the pavement's long-term performance. This opening controls the load transfer efficiency across the joint, which controls how well the JPCP will perform over time. JPCP can either have doweled or nondoweled joints. In this section, the physical mechanisms that influence joint movement are described. In addition, the influence of joint opening on pavement distresses is discussed.

2.2.1 Physical Mechanisms Governing Joint Opening at Early Ages

The joint opening at early ages is primarily controlled by the effects of temperature and moisture changes on pavement and subbase properties such as concrete CTE, drying shrinkage, and subbase restraint. Before the concrete's final set, a common assumption is that the pavement is free of stress and strain. After this time, stress develops in the pavement due to phenomena such as climatic conditions, hydration, creep, and shrinkage.

As an example, if the pavement is subjected to an increase in temperature ($+\Delta T$), the pavement will expand about its centerline, and the joint will close. During a decrease in temperature ($-\Delta T$), the pavement will contract about its centerline, and the joint will open (see figure 3).

10
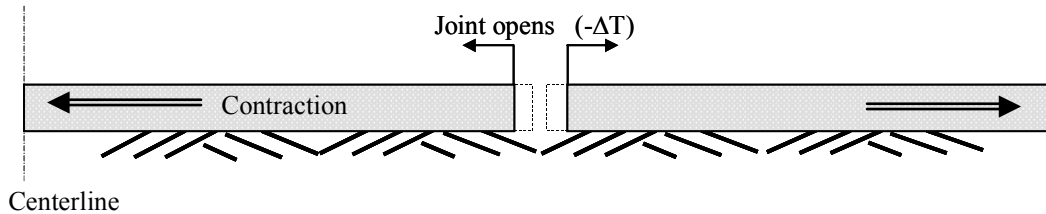
Figure 3. Schematic of joint opening due to temperature drop (–ΔT).

It has been observed experimentally that a change in temperature is the most influential parameter affecting joint opening. Joint opening varies with the daily temperature cycles due to changes in the pavement's thermal conditions.[12] CTE, drying shrinkage, and pavement length also affect the joint opening. To control the joint opening to acceptable levels, proper curing of the pavement at the time of placement is of paramount importance. If the concrete's temperature differential can be minimized, the size of the joint opening will decrease as a result. Likewise, drying shrinkage should also be minimized if the joint opening is to stay tight. This can also be accomplished with adequate curing methods.

2.2.2   Effect of Joint Opening on Load Transfer Efficiency—JPCP without Dowels

In JPCP without dowels at the joints, the size of the joint opening governs the load transfer efficiency across the joint (see figure 4). The aggregate interlock transfers the load, and its efficiency is a function of factors such as aggregate type, aggregate size, angularity, and abrasion characteristics.[13] However, if the joint opening is too wide (0.6 millimeters (mm) or greater), the aggregate cannot provide load transfer.[14] In addition, because of the wide opening, water can infiltrate the subbase from the surface of the pavement. The water will infiltrate faster as the joint opening increases. The size of the joint opening also determines how quickly incompressibles can fill the joint over time. Incompressibles apply pressure on the pavement edges and can cause spalling, as described in section 2.2.4.
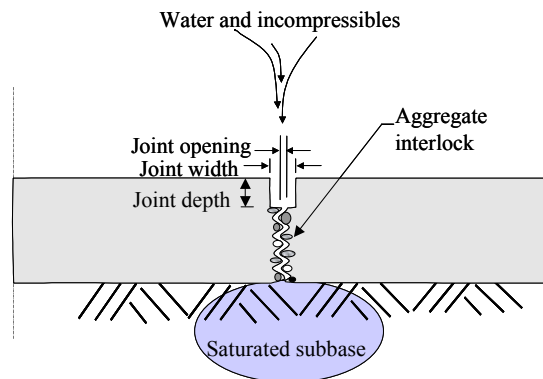
Figure 4. Schematic of joint in JPCP without dowels.

The loss of load transfer across the joint can result in the development of significant deflections, particularly for the case of granular subbases, as shown in figure 5. This eventually can lead to faulting and transverse cracks, so it is desired that the pavement maintain good load transfer efficiency. This phenomenon will be discussed in more detail in section 2.2.4.
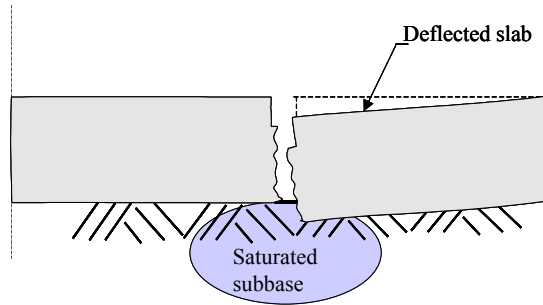
Figure 5. Schematic of JPCP after loss of aggregate interlock/load transfer at the joint.

2.2.3   Effect of Joint Opening on Load Transfer Efficiency—JPCP with Dowels

For JPCP with dowels across the joint, the dowels act to partially restrain vertical movement. As figure 6 illustrates, the adjoining slabs deflect a similar amount. This minimizes faulting, while still allowing horizontal movement due to temperature fluctuations. The size of the joint opening does not significantly affect the load transfer efficiency component due to the dowels.
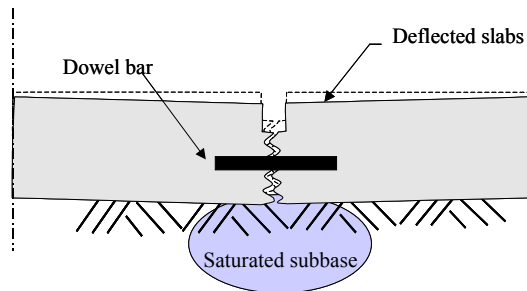
Figure 6. Schematic of doweled joint in JPCP.

2.2.4   Distresses Influenced by Joint Opening—JPCP without Dowels

As described in the previous sections, the size of the joint opening can impact significantly the behavior of the pavement in the long term. Three possible pavement distresses that can result due to adverse behavior are spalling, faulting, and transverse cracking.

Spalling. Spalling is one of the pavement distresses that can occur at a concrete pavement joint. Incompressibles that enter the joint exert pressure on the pavement edges. This pressure can induce significant stresses in the concrete that can eventually cause the concrete to spall. This form of distress may be delayed or prevented if the joint opening is tight enough to prevent infilling of incompressibles. More details on spalling are provided in sections 4.5 and 4.6.

Faulting. When aggregate interlock at the joint does not provide adequate load transfer, the pavement profile will not be continuous (section 2.2.1). Faulting can occur due to this mismatch in slab deflections at the joint. A larger joint opening can also increase the amount of water infiltration into the joint. Faulting can initiate when aggregate interlock at the joint is no longer effective. More details on faulting are provided in sections 4.1 and 4.2.

Transverse Cracking. Transverse cracks can form in JPCP due to a number of different mechanisms. The two mechanisms discussed here are both the result of a large joint opening. The first form of

transverse cracking is termed top-down cracking; it is caused by the erosion of the subbase support. Severe erosion of the granular subbase material from under the leading edge of the pavement can cause tensile stresses to form at the pavement surface. This extreme loss of support can cause a top-down transverse crack to form. For a nonerodable stabilized subbase, transverse cracking can still occur, but the mechanism is different. Incompressibles can become trapped beneath the pavement and the subbase. This leads to a slab lift-up, and a bottom-up transverse crack can result. Both bottom-up and top-down transverse cracking can be avoided or delayed if water seepage into the pavement joint is prevented. This is possible if a tight joint opening can be maintained. Transverse cracking is discussed in greater detail in section 4.3.

2.2.5   Distresses Influenced by Joint Opening—JPCP with Dowels

In doweled JPCP, pavement distresses are related predominately to the bearing stress placed on the concrete at the dowel-concrete interface. If this pressure is too great, spalling of the overlying concrete is possible. Likewise, faulting is possible if the bearing stress is excessive. The dowels will lose their ability to transfer load if their bearing stress causes the concrete around them to fail. Over time, faulting will be apparent. Yet, if the bearing stress is kept below the crushing strength of the concrete, faulting can be maintained at an acceptable level.[15] Dowel looseness also is possible if the dowel-concrete stress is very high. The concrete near the dowel can crush, and voids can develop underneath as the crushed concrete particles are removed. For more detail on dowel looseness, refer to section 5.1.7.

2.3   EARLY-AGE INDICATORS OF LONG-TERM PERFORMANCE OF CRCP

As its name implies, CRCP refers to concrete pavement constructed with no transverse contraction joints, and is reinforced with steel. For this type of pavement, concrete is allowed to crack randomly as a consequence of volume changes resulting from temperature and moisture variations that are restrained by steel and subbase friction.

Concrete and steel tend to contract and expand with changes in temperature. Because the CTE of steel and concrete are usually different, the expansion and contraction movements are not uniform, and stresses can develop in both elements. Concrete drying shrinkage, slab curling and warping, and subbase restraint each contribute uniquely to stress development. Since concrete is weak in tension, whenever the stresses that develop are higher than the tensile strength of the concrete, transverse cracks form to relieve the stresses. Because the steel has a high yield strength, it keeps cracks together. Keeping the cracks tight is essential in maintaining load transfer through aggregate interlock, and to avoid water infiltration and intrusion of incompressibles through the cracks. Subsequent drops in temperature and loss of moisture in the concrete can reduce the transverse crack spacing further. Later in the life of the pavement, externally induced stresses due to wheel loads and seasonal changes in climatic conditions can reduce the initial crack spacing even further. It has been observed that the crack spacing decreases rapidly during the early age of the pavement, then remains fairly constant from the initial year until pavement wearout, as illustrated in figure 7.[16]
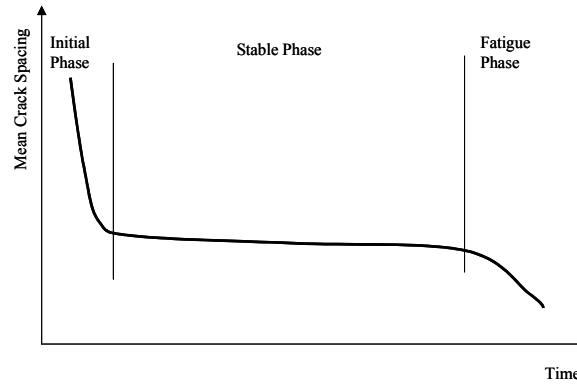
Figure 7. Conceptual reduction in mean crack spacing over time.[16]

The crack spacing typically is greater near the ends of the pavement than at the central section. This is because the pavement is more restrained to movement at the center of the slab than at the ends. Therefore, most of the longitudinal movement due to volume changes occurs at the ends of the slab, and higher stresses are generated at the central section of the pavement.

Previous experience has shown that primary early-age pavement indicators of performance on CRCP include crack spacing, crack width, and steel stress. The following sections describe these behavioral indicators in more detail.

2.3.1   Crack Spacing

CRCP slabs usually distribute traffic loads in both the longitudinal and transverse directions. However, in the case of short crack spacings, the slab acts more as a beam, with its longer dimension on the transverse direction. As a result, the load is distributed primarily in the transverse direction, and significant transverse tensile stresses may develop. Due to this condition, longitudinal cracks may form as a function of the magnitude of the stresses, tensile strength, fatigue characteristics of the concrete, and cumulative load applications. The longitudinal cracks lead to a distress condition that is commonly known as a punchout. Punchouts are a typical distress manifestation in CRCP where a block of the concrete slab is separated from the rest of the pavement by cracks in the transverse and longitudinal directions. The severity and progression of punchout distresses is a function of the traffic loads, support conditions, and load transfer between cracks. On the other hand, larger crack spacings commonly result in wider cracks that may lead to spalling problems.

McCullough et al. demonstrated that the crack spacing could be properly controlled to fall within certain limits to minimize such undesirable conditions. He proposed a crack spacing of 1.7 to 2.4 meters (m) for this purpose.[2] The American Association of State Highway and Transportation Officials (AASHTO) guidelines later recommended a similar crack spacing of 1.1 to 2.4 m,[17] although, in some instances, crack spacings of less than 0.6 m have performed well under very good soil-support conditions.[18] Crack spacing in CRCP is also affected due to the variability of materials and construction procedures. Therefore, it is a recommended practice to evaluate crack spacing in terms of its average value as well as in terms of its distribution. For a given crack spacing distribution, the percentage of crack spacings that do not fall within the recommended range of 1.1 to 2.4 m will lead more likely to distress during the life of the pavement.

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2.3.2   Crack Width

Crack widths affect CRCP performance in several ways. For example, excessive crack widths may lead to undesirable conditions (such as infiltration of water) that later result in corrosion of the reinforcing steel. Incompressibles can also enter the cracks. Because the pavement is subject to contraction and expansion movements as well as deflections due to traffic loadings, this can lead to excessive stresses at the cracks that eventually lead to spalling. In addition, for wider cracks, there is less contact between the surfaces of the cracks, resulting in poor aggregate interlock. This results in increased slab deflections and stresses. Higher stresses in the concrete, in turn, lead to spalling, faulting, additional cracking, and punchouts.

Recent investigations have found that cracks that form within the first few days after pavement construction tend to be wider than cracks that form later during the life of the pavement.[16,19] One possible explanation for this behavior is due to the bond strength development at the concrete-steel interface. At earlier ages, the bond strength is weaker than at a later age. Therefore, the bond strength does not restrain the movement of the crack at earlier ages as it does later when this bond is stronger, and the restraint to movement is higher. This phenomenon results in tighter cracks. Furthermore, concrete drying shrinkage also increases with time after placement. Because drying shrinkage is one of the factors that govern the contraction of the concrete, the increase of drying shrinkage with time will also affect crack width. It has been observed that cracks that develop during the first few days are more affected by the remaining drying shrinkage than cracks that occur later when the remaining drying shrinkage is not as large.

A crack width of 0.6 mm has been found to be effective in reducing water percolation.[2] The AASHTO guidelines limit the crack width to 1 mm to avoid spalling and to limit water penetration.[17] For temperatures below freezing, crack width is not as much of a consideration, because frozen conditions do not permit the penetration of water.[16] A strong correlation between crack spacing and crack width has been found in some references.[2] It is believed that this correlation is due primarily to the fact that many of the mechanisms that influence crack spacing also influence crack width.[2,19]

2.3.3   Steel Stress

The level of stress at which the concrete and the steel are subjected in a CRCP will influence its performance in the long term. As stated before, due to volume changes in the concrete, the reinforcement acts as a restraining system to keep cracks together. Consequently, significant stresses develop in the steel at the crack locations. The design of the steel reinforcement must consider the possible steel fracture and/or excessive plastic deformation. Usually, the stress at which the steel is subjected is limited to a reasonable percentage of the ultimate tensile strength to avoid steel fracture, and allowing only a small amount of plastic deformation.[17,20]

2.3.4   Factors Affecting Crack Spacing, Crack Width, and Steel Stress

It has been shown that crack spacing, crack width, and steel stress on CRCP are a function of the concrete tensile strength and the level of stresses that result due to the restraint to volume changes. Therefore, any factor affecting the concrete tensile strength, the pavement restraint, or factors contributing to volume changes will affect the cracking characteristics of CRCP, and therefore can influence its long-term performance.

Primary factors known to affect crack spacing and crack width in the early age include:

- Coarse aggregate type (see section 5.2.1).

- Steel reinforcement (see section 5.1.8).

- Placement temperature (see section 5.4.3).

- Time of the day of placement (see section 5.4.2).

- Curing procedures (see section 5.4.1).

- Slab thickness (see section 5.1.2).

- Subbase type (see section 5.1.6).

2.4 EARLY-AGE INDICATORS OF LONG-TERM PERFORMANCE COMMON TO JPCP AND CRCP

The early-age behavior of JPCP and CRCP is different in many respects. However, because both pavement types are made with portland cement concrete (PCC), they share some mechanisms that later lead to long-term distresses. Some of the primary common phenomena occurring in the early age of the pavement include pavement delamination and built-in curling. These two conditions are known to be early-age indicators of the future performance of the pavement in the long term, and are presented in the following section.

2.4.1 Delamination

2.4.1.1 Moisture Loss

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. Typical moisture gradients resulting from excessive moisture loss usually present a sharp drop in moisture close to the pavement surface, as illustrated in figure below.
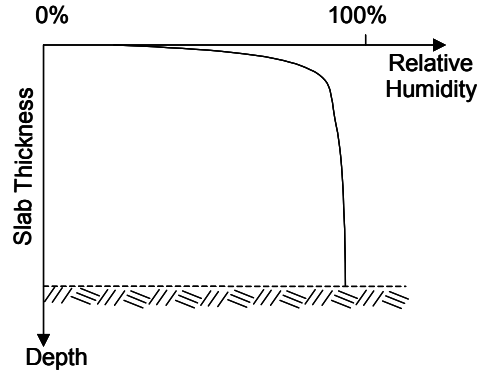
Figure 8. Moisture gradient resulting from excessive moisture loss.

2.4.1.2   Strength Development

Because water available in the concrete mix is a determinant factor for the continuing hydration of the concrete, this hydration may be affected if excessive loss of moisture occurs. In addition, since the strength development is a function of hydration, the strength of the cement paste also may be affected due to moisture loss. Previous experience has indicated that the loss in moisture leads to reduced concrete strength, specifically at the surface. This reduction in concrete strength occurs because of the loss of strength gain in the cement paste, and in particular, at the interface between the paste and the aggregate. This interruption is due to the lack of water available for hydration.

2.4.1.3   Vertical Stress Development

Undesirable situations resulting from moisture loss are typically observed in the form of plastic shrinkage cracking, but also and most importantly, due to a radical change in the gradient of the moisture profile. Vertical tensile stresses and shear stresses develop as a consequence of the difference in shrinkage at different depths of the slab, as well as the pavement restraint to movement.

2.4.1.4   Formation of Delamination

In theory, whenever the tensile or shear stresses exceed the concrete strength, horizontal cracks tend to develop. The horizontal cracking that usually occurs close to joints or cracks and has typical depths of 13 to 76 mm is known commonly as delamination.[16] The depth of the delamination will be primarily a function of the evaporation rate, the type of curing, and the time to application of curing. Climatic conditions leading to high evaporation rates and poor curing procedures will also lead to significant reduction in strength and increased tensile and shear stresses in the concrete, producing deeper delaminations. On the other hand, climatic conditions leading to low evaporation rates and/or good curing procedures will typically result in shallower delaminations, and may even prevent delamination from occurring.

Other concrete delamination mechanisms commonly are cited in the literature. Delaminations at the steel depth have been observed in some CRCP in the past. This type of delamination is attributed to several factors. Some projects were paved in a two-stage construction process, placing steel on top of the first layer of concrete in plastic state, then constructing the second layer immediately following this. In

some cases, delamination was observed due to a delay in placement of the second layer.[21] However, delamination of plain concrete pavements with no reinforcement also has occurred at middepth. In these cases, concrete placement has occurred during cold temperatures. This type of delamination has been attributed to sharp temperature drops, leading to excessive temperatures gradients in the slab, compounded with the restraint imposed by reinforcement/dowels at that location and traffic loads.

2.4.1.5   *Spalling*

Usually, the formation of delaminations is not evident in the early age; this depends on the subsequent climatic conditions, traffic loading, and depth. Delaminations may result in spalling distresses that will influence the performance of the pavement in the long term (see section 4.5). Delamination spalling is characterized by small pieces of concrete near cracks or joints that become loose from the pavement as a result of shear forces imposed by traffic loads, temperature fluctuations, and concrete fatigue characteristics. The amount of spalling distress and severity usually increases with time.

2.4.2   Built-In Curling

2.4.2.1   *Temperature Gradients at Set*

The temperature gradients during the early age are a function of the environmental conditions and the heat of hydration of the concrete. The initial thermal gradient in the slab at set will influence the curling shape of the slab.

2.4.2.2   *Built-In Curling*

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.[22] The time-dependant relaxation properties of the concrete also affect the curled shape of the slab. As illustrated in figure 9, if the temperature throughout the slab depth was constant (thermal gradient at set = 0), the curling and warping state of the slab would be a function of the subsequent thermal gradient and the drying shrinkage of the slab. If the thermal gradient at time *t* is zero, the shape of the slab will only be a function of the drying shrinkage and the restraint conditions of the slab as imposed by its own weight and the subbase (figure 9). For this case, the slab would tend to warp up slightly due to the drying shrinkage. However, if the thermal gradient is positive (hotter at the top than at the bottom), then the curling of that positive thermal gradient would tend to counteract the warping due to the drying shrinkage (figure 10), possibly resulting in a flat shape. On the other hand, if the thermal gradient is negative, then the curling of the slab toward the top will be increased by the drying shrinkage (figure 11), resulting in a moderately upward shape.
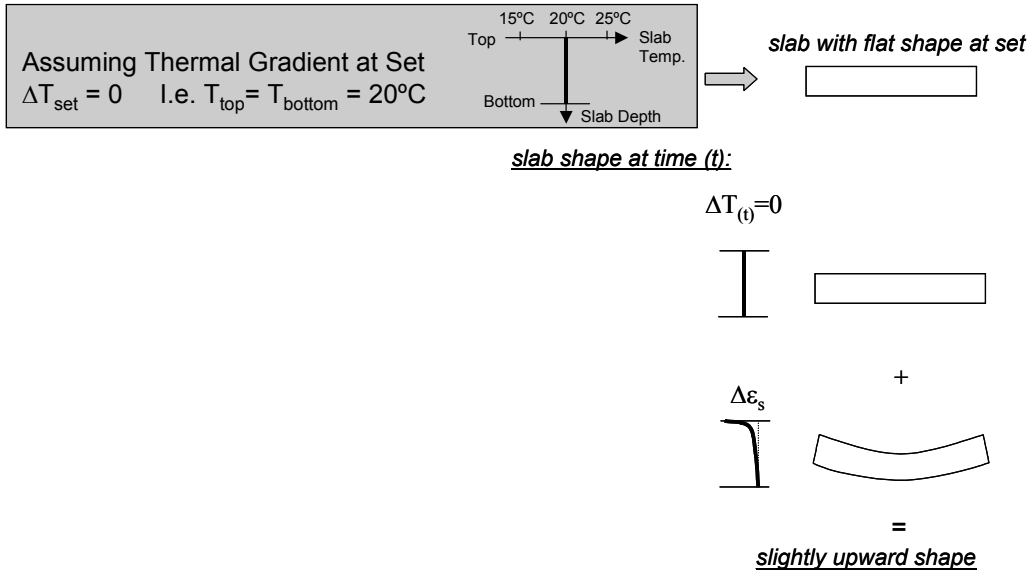
Figure 9. Effect of drying shrinkage and thermal gradient on curling and warping
(thermal gradient at set = 0 and thermal gradient at time t = 0).
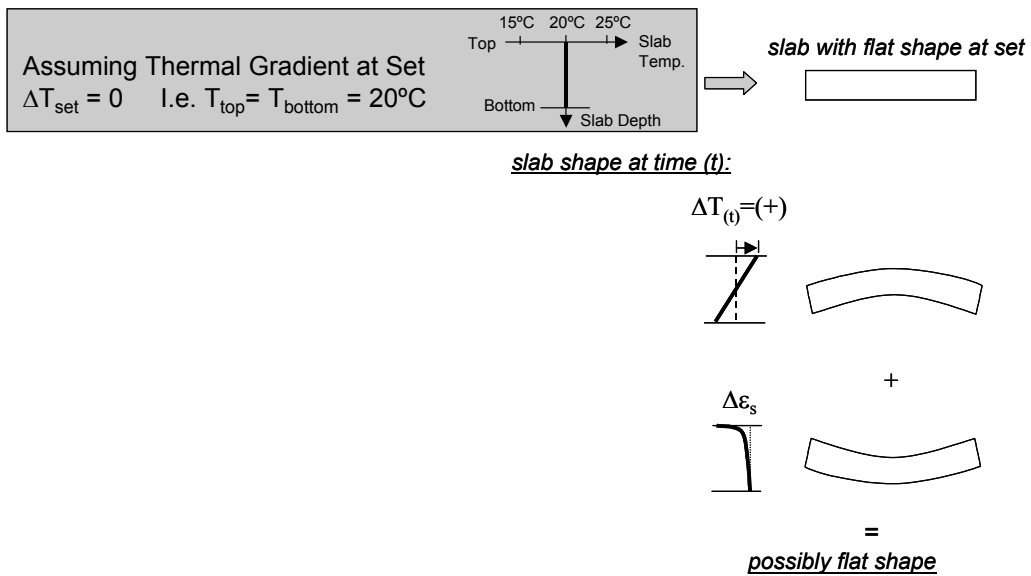
Figure 10. Effect of drying shrinkage and thermal gradient on curling and warping
(thermal gradient at set = 0 and thermal gradient at time t is positive).
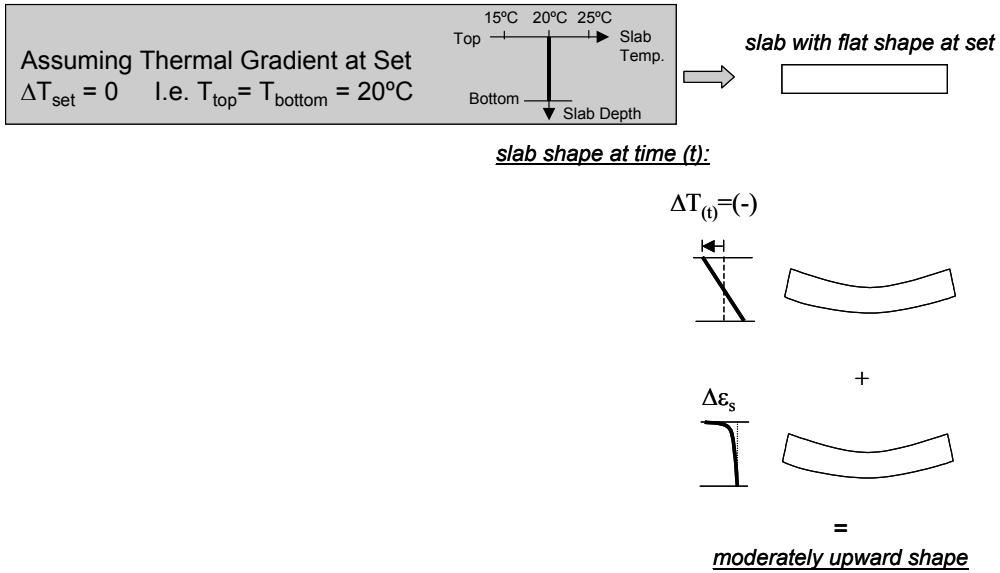
Figure 11. Effect of drying shrinkage and thermal gradient on curling and warping (thermal gradient at set = 0 and thermal gradient at time *t* is negative).

In general, when concrete sets, the temperature through the slab generally is not uniform, but rather is a function of the climatic conditions, the heat of hydration, and curing methods. Because there is a thermal gradient at set, the curling and warping of the slab at any time will be a function of that initial thermal gradient, the drying shrinkage, and the current thermal gradient of the slab. This is illustrated in figures 12–14 for a positive thermal gradient at set and in figures 15–17 for a negative thermal gradient at set.
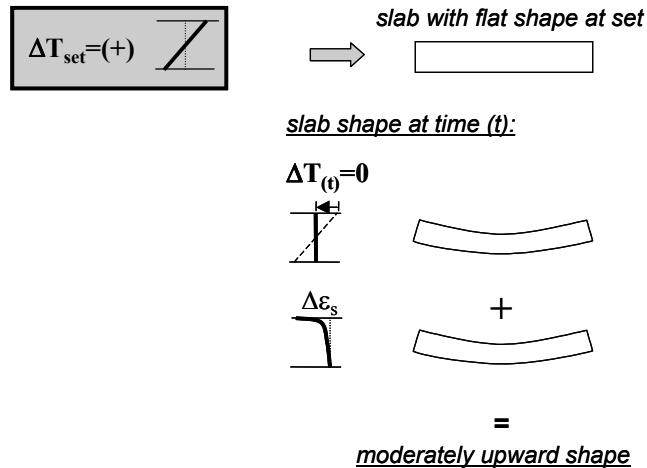
Figure 12. Effect of positive thermal gradient at set on curling and warping (thermal gradient at set is positive and thermal gradient at time *t* = 0).

slab with flat shape at set

slab shape at time (t):

$\Delta T_{(t)}$=(+)

$\Delta \varepsilon_s$ +

=
slightly upward shape
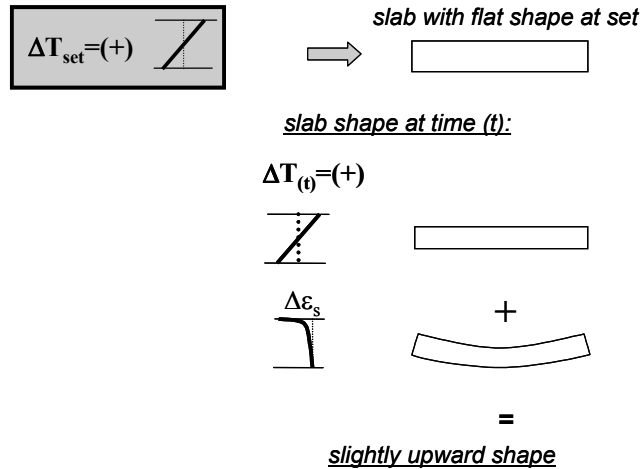
Figure 13. Effect of positive thermal gradient at set on curling and warping (thermal gradient at set is positive and thermal gradient at time *t* is positive).

slab with flat shape at set

slab shape at time (t):

$\Delta T_{(t)}$=(-)

$\Delta \varepsilon_s$ +

=
significant upward shape
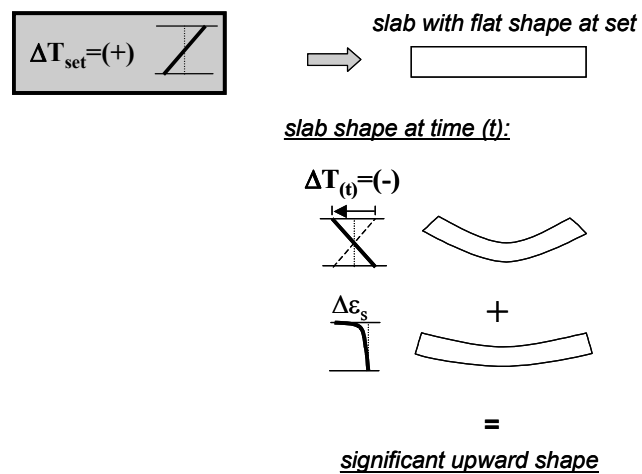
Figure 14. Effect of positive thermal gradient at set on curling and warping (thermal gradient at set is positive and thermal gradient at time *t* is negative).

For a positive thermal gradient, considering average temperature equal to the average temperature at set, whenever the subsequent thermal gradient becomes zero (figure 12), the pavement will tend to curl up due to the initial thermal gradient at set. This occurs due to the fact that the top fibers cool down from the initial temperature at set, and the bottom concrete fibers will warm up. This effect is accentuated by the warping generated due to the drying shrinkage. However, no curling is observed if the current thermal gradient is positive and similar to the thermal gradient generated at set (figure 13). For this case, the shape of the slab will only be a function of the drying shrinkage. The most critical case would be observed if the thermal gradient of the slab is negative, as illustrated in figure 14. For this case, the difference in temperature from the positive gradient at set will generate a significant amount of upward curling of the slab, which will be further accentuated by drying shrinkage.

A similar situation would occur for the case of negative thermal gradient at set as illustrated in figures 15–17. For a negative thermal gradient, the worst case would occur with a positive thermal gradient at time t as represented in figure 16.
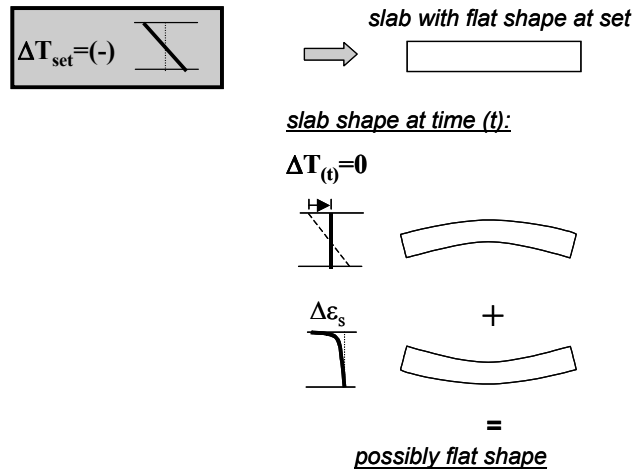
Figure 15. Effect of negative thermal gradient at set on curling and warping (thermal gradient at set is negative and thermal gradient at time $t = 0$).
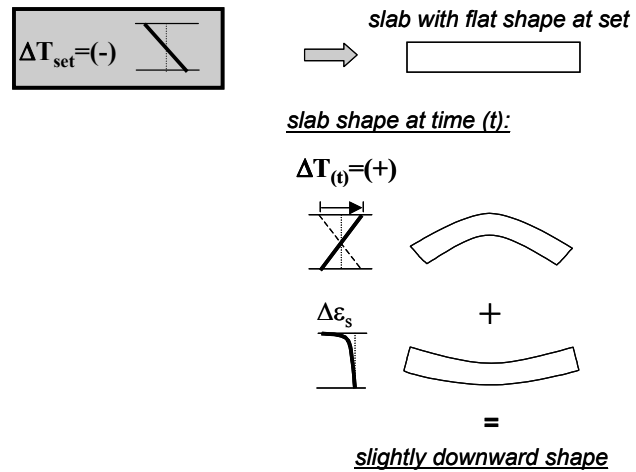
Figure 16. Effect of negative thermal gradient at set on curling and warping (thermal gradient at set is negative and thermal gradient at time t is positive).

slab with flat shape at set

slab shape at time (t):

$\Delta T_{(t)}=(-)$

$\Delta \varepsilon_s$ +

=

slightly upward shape
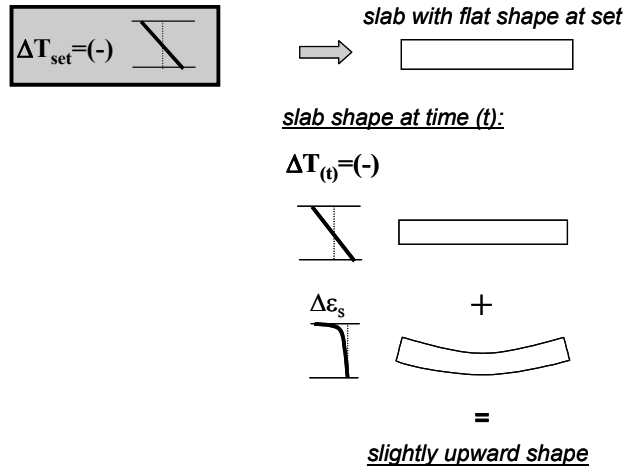
Figure 17. Effect of negative thermal gradient at set on curling and warping (thermal gradient at set is negative and thermal gradient at time *t* is negative).

2.4.2.3   *Pavement Smoothness, Faulting, and Cracking*

It has been observed that built-in curling may translate later 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. This will affect further the curling shape and the support conditions under the pavement. For positive thermal gradient at set, it is believed that the pavement is more susceptible to corner cracks (figure 14), while for negative thermal gradient at set, the pavement would be more susceptible to midslab cracking (figure 16). The effect of drying shrinkage suggests that built-in curling would be more critical for stresses due to corner cracking than for midslab cracking. In addition, under certain circumstances, built-in curling could lead to a more pronounced curling shape of the slab, which may influence the initial pavement smoothness and, therefore, its riding quality during the service life.

CHAPTER 3.   EARLY-AGE PAVEMENT DISTRESSES

3.1   PLASTIC SHRINKAGE CRACKING

Plastic shrinkage cracking is an early-age pavement distress that forms before the set of a freshly placed concrete pavement. Plastic shrinkage cracks are the short irregular cracks that form on the fresh surfaces of concrete (see figure 18). They can be from few centimeters to just under 1 m long. The crack spacing is irregular, varying from a few centimeters to 0.6 m apart. Plastic shrinkage cracking is caused by the rapid loss of water from the surfaces of the fresh concrete. The cracks form when the rate of evaporation is greater than the concrete's bleeding rate. According to experience and previous research, conditions where the evaporation rate of a pan of water in excess of 1.0 kg/m^2/hr will cause cracks to form in concrete of the same temperature.[6] Caution should be exercised when the evaporation rate exceeds 0.5 kg/m^2/hr.

Figure 18. Plastic shrinkage cracking in concrete pavement.

With the loss of water from the pavement surface, there is a volumetric contraction of the fresh concrete. The shrinkage occurs primarily in the paste, with the aggregate acting only as restraint. These differential volume changes can induce tensile stresses in the pavement, and can subsequently cause cracks to form. The fresh concrete does not have sufficient strength to resist these capillary stresses within the fresh paste. There is currently no way to predict with certainty when plastic shrinkage cracks will form.

The method currently used to predict evaporation rate was developed by C. Menzel in 1954. It uses air temperature, relative humidity, concrete temperature, and wind velocity to determine if the evaporation rate is high enough for plastic shrinkage cracks to form. When the rate of evaporation is 0.5 kg/m^2/hr, cracks can occur. When the rate exceeds 1.0 kg/m^2/hr, precautionary measures are mandatory. This procedure originally was developed based on the rate of water evaporated from a standing pan of water.

Evaporation of water from the surface of freshly placed concrete is primarily due to climatic conditions. Typically, plastic shrinkage cracking occurs when construction takes place in hot weather. The climatic conditions that are suitable for their formation are:

- High concrete temperatures.

- Low ambient relative humidity.

- High wind velocities.

These three conditions increase the rate of evaporation from the surface of the concrete pavement. Water also can be extracted from the slab by absorption or suction into the subbase and/or formwork. This can aggravate the water loss and promote additional cracking.

Plastic shrinkage cracks do not always form during the hot weather months. Other factors in addition to climate can influence the behavior of the fresh concrete. Some cracks are caused by incorporating new materials into the concrete, such as excessive fines, admixtures, and fiber reinforcement. Fines have a greater water demand and can affect the bleed water rate. Admixtures, such as superplasticizers and retarders, also affect the plastic state of the concrete by making the concrete experience less bleeding, and delay the set. Polypropylene fibers have been effective in delaying plastic shrinkage cracking. Similarly, the size of the concrete structure influences plastic shrinkage, since the slab depth is related to bleed rate.[23] These factors influence plastic shrinkage cracking, and the method to predict crack formation should account for these different material constituents and size considerations.

The loss of water from the surface of the concrete must be minimized to prevent plastic shrinkage cracking. One option is to moist cure the surface of the concrete immediately after placement, and to continue to do so for at least 24 hours. The most effective method is to keep the surface of the pavement wet. Other options are to erect wind barriers around the pavement or to erect sunshades to protect the surface from heat.

To improve current curing practices, the Federal Highway Administration (FHWA) recently sponsored a research project intended to provide guidelines for curing of PCC pavements (PCCP).[24] These guidelines include recommendations on selecting curing methods, curing application, curing duration, and temperature management issues.

Another ongoing FHWA project aims to develop a Microsoft® Pocket personal computer (PC)-based system with guidelines on curing of PCCP using concepts in the FHWA curing guidelines study and in HIPERPAV II. In addition to guidelines on selecting, applying, and timing curing methods, the Pocket PC system will have the capability to monitor real-time concrete temperature for determining concrete maturity and predicting concrete strength, among other features.

3.2   CRACKING DUE TO THERMAL SHOCK

Placement of concrete pavements during hot weather conditions when the temperature of the air exceeds 32 ºC, may be undesirable with respect to pavement behavior. During hot weather concreting, the cement hydration is accelerated by the temperature of the air and the initial high temperature of the mix components. Depending on the cement composition, cement fineness, and admixtures used, the accelerated cement hydration may result in significantly higher heat development during the first hours after placement. This increased hydration also reduces the set time and complicates the paving operations, delaying the time for proper curing. The higher heat development in the concrete mix increases the loss of moisture in the concrete, increasing drying shrinkage. Undesirable hot weather conditions can be compounded further with the use of high heat cements, high cement contents, and

certain admixtures. In addition, drastic temperature drops during the first days after concrete placement may significantly increase the tensile stresses in the pavement. If precautions are not taken to minimize the above situation, excessive stresses in the concrete pavement may develop that can result in what is commonly known as thermal shock, or random, uncontrolled cracking.

Although the strength of the concrete develops faster due to the higher hydration rate, the long-term strength is usually lower than that of concrete hydrating at a lower temperature. After the first 72-hour period, it has been found that the early-age effects (accelerated hydration and rapid strength gain) become minimal.

3.2.1   Distress Manifestation on JPCP

For the case of JPCP, thermal shock may occur in the form of random cracking before, or even after, the time when joints are sawed. Although these cracks may be tight initially, they may extend to full depth, affecting the structural integrity of the pavement. Traffic loads and subsequent temperature fluctuations usually will increase the extent and deterioration of the pavement, providing poor performance in the long term.

3.2.2   Distress Manifestation on CRCP

As figure 19 illustrates, thermal shock may be observed in CRCP in the form of very closely spaced cracks. In addition, the cracks tend to meander more than cracks developed during placements at lower temperatures. Also, cracks occurring during the first few hours tend to be wider than those occurring at later ages. The formation of longitudinal cracks is another typical distress associated with high temperature placement (see figure 20). According to experience, closely spaced transverse cracks and longitudinal cracks due to thermal shock are more prone to develop into spalling and punchout distresses in the long term as a consequence of traffic loadings and climate.

Figure 19. Closely spaced cracks resulting from thermal shock in CRCP.

3.2.3 Recommended Precautions against Thermal Shock

When significant changes in temperature are expected during the construction of concrete pavements, it is important to assess the risk of damage to the pavement, as well as measures that would keep the stresses in the concrete at an acceptable level. Alternatives such as modifying the temperature of the mix or curing methods to insulate the pavement from the environment may be used to control the pavement temperature and excessive moisture loss.

The initial temperature of the mix can be reduced in several ways, such as cooling down the mixing water, sprinkling or fog spraying the aggregates, or maintaining the aggregates in shade storage. In addition, minimizing the concrete hauling time will reduce the time that the concrete mix is exposed to hot weather before placement. Scheduling placing operations during times of the day, when climatic conditions are not as critical, will also minimize the risk of developing extremely high temperatures in the concrete mix.

Protecting concrete against moisture loss during the curing period to avoid excessive drying shrinkage can be accomplished by increasing the application rate of the curing compound, or by using curing methods that provide moisture insulation such as polyethylene sheeting. If drastic temperature drops are expected, a combination of curing methods such as polyethylene sheeting and cotton mats may be necessary to keep moisture in the concrete, and to provide a more uniform curing temperature. If curing procedures are not performed on time, excessive moisture loss in the pavement may not be avoided.

Recommended precautions to avoid thermal shock could also include the use of low heat cements and supplementary cementitious materials (SCM) such as fly ash. Retarding admixtures also may be used to help minimize the water demand during hot weather concreting. Some retarding admixtures possess water-reducing and set-retarding properties. Other types of admixtures may help prevent drying of the surface by increasing early bleeding. However, caution must be taken that the admixtures do not reduce the tensile strength or tensile strain capacity of the concrete.[25]

Figure 20. Longitudinal crack in CRCP due to thermal shock. Crack is enhanced for clarity.

An important factor that can determine the potential for early-age cracking in newly constructed JPCP is the timing of the joint sawing operations. The purpose of joints in a jointed concrete pavement is to control the location of the cracking that will naturally occur during the life of the pavement. The majority of this cracking will occur during the early-age period as a result of restraint to volumetric changes. If the joints are not sawed early enough, uncontrolled cracking can result. This may lead to undesirable long-term performance due to poor load transfer and spalling. Therefore, sawcutting operations should be performed as soon as possible following construction to minimize the potential for uncontrolled cracking. However, when sawcutting begins is also constrained by the time required to gain sufficient PCC strength to support the weight of the equipment (and operator), as well as the forces introduced by the cutting blade during the cutting operations.

CHAPTER 4. IMPACT OF EARLY-AGE BEHAVIOR ON LONG-TERM PERFORMANCE

Early-age behavior may impact the long-term performance of concrete pavements leading to a number of distresses. These guidelines discuss the impact that early-age behavior may have on JPCP faulting and cracking, CRCP punchouts, and the impact on spalling distress, which is common to both JPCP and CRCP. While JPCP faulting and cracking are modeled in HIPERPAV II, a spalling model was not included in the long-term prediction module because of the complexity required to account for all possible factors that affect spalling distress. Likewise, since CRCP long-term performance was out of the scope of the HIPERPAV II project, no punchout models were included in HIPERPAV II. It is important, however, that users of these guidelines understand the factors influencing spalling and punchout distresses and the design and construction factors that should be considered to minimize their occurrence.

4.1 FAULTING OF JPCP WITHOUT DOWELS

Faulting of pavements is the most predominant factor contributing to pavement roughness. Faulting is the difference in elevation of adjoining slabs at the joint. In JPCP without dowels at the joints, faulting is caused by the buildup of loose material. The location of the buildup is most commonly under the approach edge of the slab, hypothetically due to the erosion of subbase material from under the leave edge of the slab. The magnitude of faulting is affected significantly by heavy traffic loads, the type of subbase material, and climatic conditions that the pavement is subjected to over the course of its lifetime.

This section outlines how early-age parameters at the time of pavement construction influence the long-term faulting performance of JPCP without dowels. The damage progression, initiating at early age, is described in the flowchart in figure 21. The early-age input (step 1) controls the concrete's material properties (step 2) and the pavement's early-age response (step 3). Material characterization describes the change of PCC properties, such as strength and stiffness. Early-age response describes the stresses, strains, and deflections that form within the pavement. With time and daily cyclic temperature changes, the pavement's behavior (step 4) is apparent. Pavement behavior covers visible phenomena such as joint opening and curling and warping. Steps 1–4 outline the sequence of early-age processes that occur before distress formation. After the pavement is subjected to traffic loading and changing climatic conditions, the pavement behavior may lead to distress. The long-term inputs that are influential in causing faulting are listed in step 5. Repeated loading of the pavement will eventually cause the distress to form (step 6). After the distress first forms, repeated loading cycles will increase the severity of the distress. How this distress changes with time (long-term pavement performance) is provided in step 7. These seven steps, from early age to long term, are described here in greater detail.

4.1.1 Early-Age Inputs

The early-age inputs that govern faulting in nondoweled JPCP are listed in step 1 of figure 21. Faulting is caused by slab deflection at the joint. Load transfer through aggregate interlock is lost as the joint opens, and the pavement deflects downward due to continued mechanical and environmental loading. During the design stage, preventive measures should be taken to limit slab deflection. This is possible by constructing shoulder support or by widening the lanes. Widened lanes reduce the stresses at the slab edge.[26] Proper pavement curing also can help reduce the severity of built-in curling (see section 2.4.2), which is affected by temperature and moisture. Built-in curling may contribute to faulting of the pavement even before traffic loads are applied.

To prevent excessive opening of the joints, joint design should be carefully evaluated. Short joint spacings usually translate to narrower joint openings, and larger joint spacings translate to wider joint openings. If the joint spacing is large, more material is available for contraction during temperature drops. The slab-subbase friction resists this movement, which affects the joint opening. To prevent the loss of aggregate interlock, a good bond between the aggregate and concrete is necessary if suitable load transfer is to be provided for a significant period of time.

4.1.2 Materials Characterization

The strength and stiffness of PCC is determined primarily by the mix design, material properties, construction curing practices, and climatic conditions at the time of placement. PCC mix design also determines the effectiveness of the aggregate interlock at the joint. Larger aggregates have been found to be more effective in transferring load, and therefore lead to decreased faulting.[26] PCC material properties also influence the early-age responses of the pavement, namely the stresses, strains, and deflections that develop.
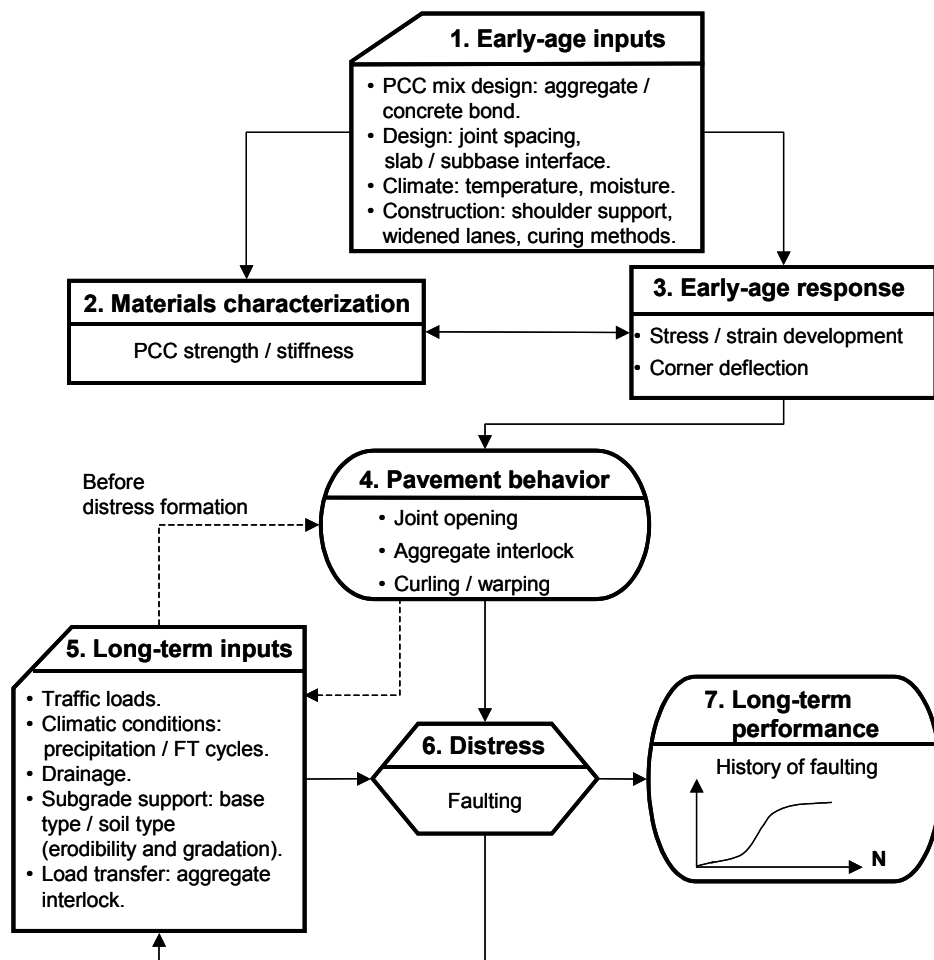
Figure 21. Flowchart outlining impact of early-age input on long-term faulting performance of JPCP without dowels.

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4.1.3   Early-Age Response

For JPCP to fault, loading one of the adjoining slabs results in deflection greater than the adjacent slab. It commonly is assumed that faulting initiates at a slab corner, because deflection is typically the greatest there. The difference in slab deflections is the result of a loss of load transfer at the joint due to large joint openings. Since it is necessary to maintain good load transfer at the joint, the size of the joint opening should be minimized. Joint opening is controlled by the stresses and strains in the pavement. Therefore, the internal stresses in the pavement must be controlled for optimal joint opening and reduced faulting in the long term.

4.1.4   Pavement Behavior

As mentioned previously, the size of the joint opening determines how efficient the aggregate interlock is in transferring load across the joint. Experimental studies have shown that a joint opening of 0.6 mm or greater can translate to total loss of load transfer by aggregate interlock.[14] This was discussed in greater detail in section 2.2. Slab deflection is the other component required if a pavement is to develop faulting. Curling or warping is another form of slab deflection. Figure 22 illustrates how a deformed pavement shape promotes the ingress of water into the pavement subbase and subgrade layers. Pumping is more severe when the pavement is curled up or has built-in curling.[27]
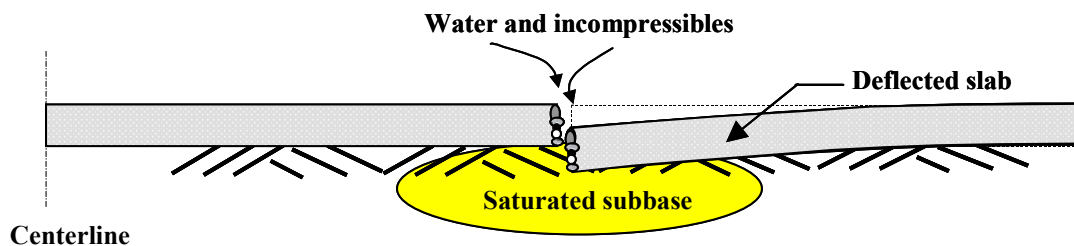
Figure 22. Deflected pavement shape.

4.1.5   Long-Term Inputs

As the size of the joint opening increases and curling and warping become more apparent, faulting commonly will develop over time. This section identifies the long-term inputs that control the rate of faulting. Opening of the joint promotes water infiltration into the pavement's underlying layers. Water softens the subbase and subgrade, and increases the stresses and deflections in the pavement. Faulting is a common distress associated with poor drainage. However, if a pavement's drainage capacity is improved, faulting can be reduced effectively, especially for nondoweled JPCP.[28]

Heavy traffic loads and climatic factors such as precipitation significantly contribute to the amount of faulting at a pavement joint. The repeated loading of pavement joints causes erosion of the subbase from under the leave edge of the slab and its buildup under the approach slab. Figures 23–25 depict faulting in pavements with erodable base material. As the wheel load deflects the approach side of the concrete pavement, material is pushed toward the leave side (figure 23). This frictional erosion and pore water pressure generates loose fine materials. Coarse-grained soils are able to withstand the effects of traffic better than fine-grained ones. Then, as the wheel passes to the leave slab, the water is pushed back to the approach side, and the fines are deposited (figure 24). A void forms on the leave side (figure 25), and faulting is apparent. The degree of faulting increases on sections with longer slabs.[26] The slabs also can rotate as a result of this mechanism.[14] Faulting sometimes can be reduced if shorter slabs are used.
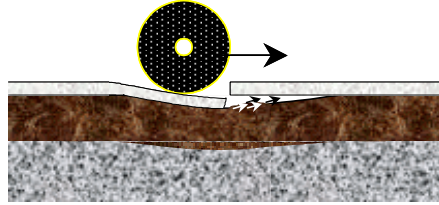
Figure 23. Schematic of faulting progression in JPCP without dowels, wheel on leave edge of slab (exaggerated to show mechanism).
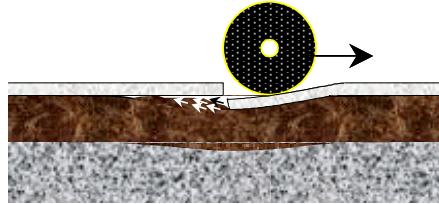
Figure 24. Schematic of faulting progression in JPCP without dowels, wheel on approach edge of slab.
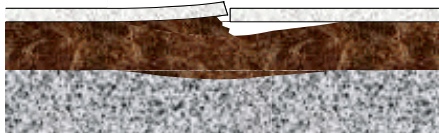
Figure 25. Schematic of faulting progression in JPCP without dowels, resultant behavior at the JPCP joint that causes faulting.

The amount of faulting commonly correlates with the properties of the subbase materials. Subbase materials that are able to resist a shear stress of 25–50 pascals (Pa) do not erode for the life of the pavement. Weaker subbase materials will typically experience high erosion.[29] Pavements constructed with cement-stabilized subbase materials, such as lean concrete bases, typically experience less faulting, and their corner deflections generally are reduced.[26]

Freeze-thaw cycles also influence the magnitude of faulting. When the pavement system freezes during the winter months, the pavement system is stiff. However, during the winter thaw, the pavement is highly susceptible to traffic loadings. At this time, the subbase is saturated, causing a marked decrease in its strength. Pumping and erosion of the subbase accelerates. Faulting damage can increase significantly during this period.[15]

4.1.6   Distress Prediction

The three major factors that cause faulting are repeated heavy traffic loads at the joint, differential deflection at the joint, and thermal and moisture gradients in the slab and subbase that cause curling of the pavement and subbase erosion.[30] Water in the pavement subbase and subgrade layers increases the amount of pumping, and thereby increases the degree of faulting. Figure 26 shows evidence of faulting at a typical contraction joint. Faulting is determined in the field by measuring the difference in adjoining slab elevations 0.3 m from the pavement edge.[15]

Figure 26. Photograph of faulting in JPCP.

4.1.7 Long-Term Performance

Faulting increases with time as the pavement is subjected to more traffic loads and climatic fluctuations. As figure 27 illustrates, faulting initially grows linearly up to a point, and then grows nonlinearly as loading continues.[31] Faulting is commonly found to be objectionable when it exceeds 3.3 mm.[26]
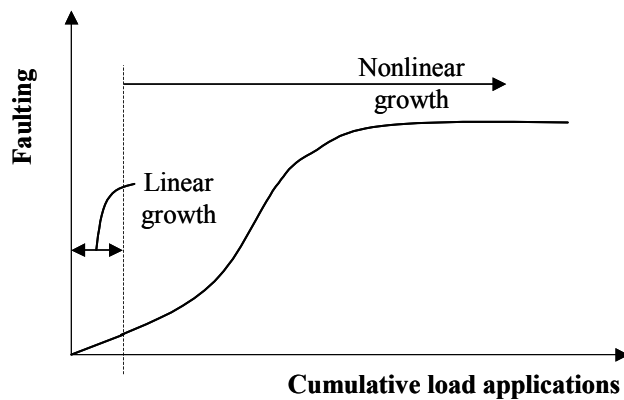
Figure 27. Schematic of time growth of faulting for JPCP without dowels.

The climatic conditions at the pavement's location greatly influence the magnitude of faulting. Analysis of the Long-Term Pavement Performance database revealed that faulting is lowest in the dry-no freeze region, as compared to dry freeze, wet-no freeze, and wet freeze regions.[32] This result demonstrates the importance of water to the faulting mechanism. Temperature fluctuations also influence faulting. Daily expansion and contraction cycles have been found to cause up to 0.5 mm of faulting per year.[27]

4.2 FAULTING OF JPCP WITH DOWELS

Faulting of pavements was discussed in section 4.1 for JPCP without dowels at the joints. This section discusses faulting of JPCP with dowels. Dowels at the joints effectively reduce JPCP faulting.[33] They commonly are used today on most high-volume roadways.[26]

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In reference to figure 28, this section will describe the early-age inputs (step 1), material property development (step 2), and the pavement's early-age response (step 3). Dowel-concrete bearing stress significantly influences faulting.[15,34] These responses are included in the pavement behavior (step 4), which includes joint opening, dowel looseness, and curling and warping of the pavement. Over time, as the pavement is subjected to traffic loading and changing climatic conditions (step 5), faulting can develop (step 6). Finally, the long-term faulting performance of JPCP with dowels is discussed (step 7).
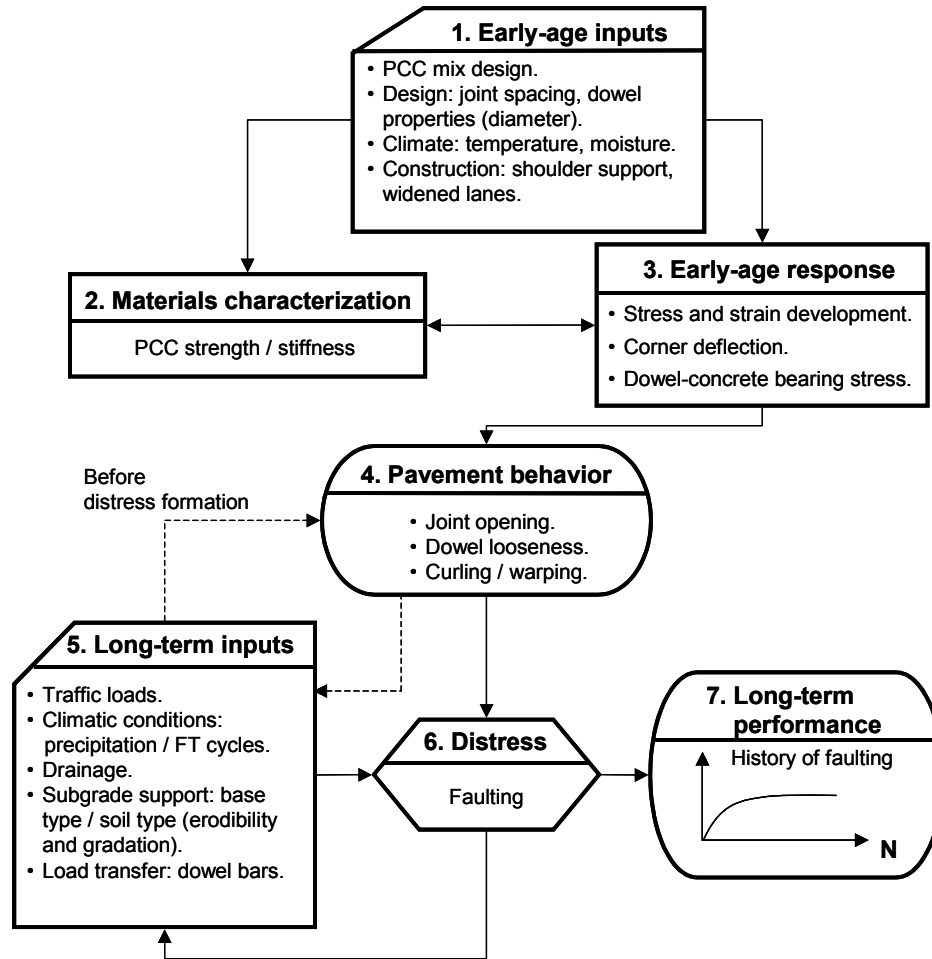
Figure 28. Flowchart outlining the influence of early-age properties on long-term faulting performance of JPCP with dowels.

4.2.1   Early-Age Inputs

Early-age inputs impact the long-term faulting performance of doweled JPCP. The parameters with the greatest influence are listed here. Because the dowels and the concrete interact, the concrete mix should be tailored for strength and durability. Likewise, the dowels should be designed for reduced faulting. Larger dowel bars (28.7 to 38 mm in diameter) are more effective in reducing faulting than smaller 25.4-mm diameter bars.[26] Similarly, decreasing the joint spacing often reduces faulting. Climatic conditions are important, since they determine the built-in curling at set.

Design features are also an important consideration. Shoulder support and widened lanes can minimize slab deflection, especially at the corners. It is assumed that, since loaded corner deflections are often the largest, faulting commences here.[30] Faulting is caused by the mismatch of adjoining slab

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deflections. Tied shoulders have been shown to reduce faulting by 50 percent.[35] Likewise, construction methods used in placing these dowels are critical to their performance, as these methods may contribute to dowel misalignment. Circular steel dowel bars are used to transfer vertical shear and horizontal bending moments between adjacent slabs. To successfully transfer load, the bars must be properly aligned along their longitudinal axis and must be lubricated over half their length before placement.[36] Dowel bar coatings are commonly used to prevent corrosion. Preventing dowel deterioration also translates to reduced dowel lockup.[37]

4.2.2   Materials Characterization

Development of the concrete's tensile and compressive strength and stiffness significantly influences the behavior of doweled JPCP. Strength and stiffness determine the magnitude of pavement stresses, strains, and deflections. They relate step 2 in figure 28 directly to the pavement's early-age response in step 3. The concrete also must interact with the dowels immediately after construction by resisting the dowel bearing stress. This early-age interaction means that care should be taken when curing the concrete to maximize its early-age strength. The concrete can be damaged if the stress exceeds its early-age strength.

4.2.3   Early-Age Response

Faulting is directly related to the bearing stress at the dowel-concrete interface. If the dowel bearing stress can be kept below the crushing strength of the concrete, faulting can be maintained at an acceptable level.[15] The early-age behavior of the concrete at set determines the magnitude of bearing stress. Ideally, the pavement should cure without any curling or warping, as shown in figure 29. The dowel is straight and does not exert any stresses on the surrounding concrete.
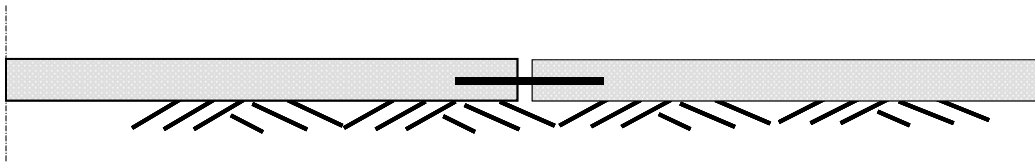
Figure 29. Schematic of ideal JPCP at set (dowel bar straight).

However, as the pavement undergoes daily temperature and moisture changes, the pavement will curl up and down. The dowel resists this movement and, as a result, subjects the concrete to a bearing stress. If the slabs curl upward, as shown in figure 30, the dowel will bend negatively (downward) to resist slab deformation. The concrete above the dowel is put into compression. The opposite happens when the slab curls down; the dowels bend positively (upward) to resist deformation. The stiffer dowels are more able to resist deformation, yet the resultant stresses in the dowel and at the dowel-concrete bearing location are higher. Fiberglass dowels have lower stiffness than steel dowels. The longitudinal stiffness of fiber dowels is approximately 55 gigapascals (GPa), compared to 207 GPa for steel dowels. The bearing stress for fiber dowels at the dowel-concrete interface is also lower than for steel.[36] At early ages, the concrete has not yet reached its full compressive strength, so a higher bearing stress is more prone to causing damage. Early-age damage to the concrete will greatly reduce the pavement's long-term performance.
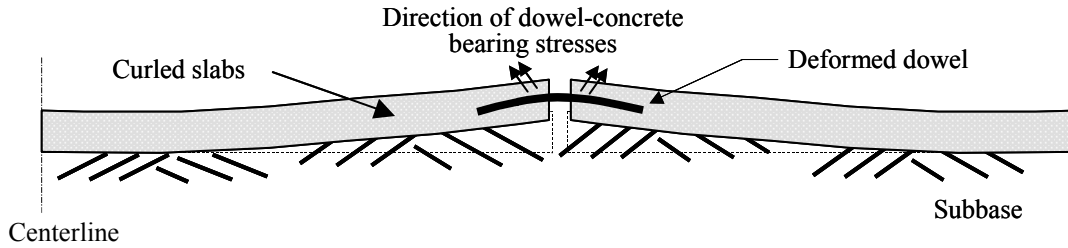
Figure 30. Schematic of curled JPCP connected by a dowel in bending (enlarged to show mechanism).

4.2.4   Pavement Behavior

The stresses, strains, and deflections that develop in the pavement at an early age influence joint opening and pavement curling and warping. The repeated temperature cycles may loosen the dowel-concrete interface, and therefore reduce the load transfer efficiency. Traffic loadings aggravate this condition, as is discussed in the next section.

4.2.5   Long-Term Inputs

Long-term inputs affect the doweled and nondoweled pavements similarly (section 4.1). Faulting increases as traffic and precipitation increase. Good drainage and a stabilized subbase can reduce faulting. Climatic conditions also influence faulting of the doweled pavements, but not as significantly.[35]

Over time, the number of thermal and moisture cycles a pavement experiences accumulates. The joints open and close as the pavement expands, contracts, curls, and warps.[30] Similarly, the dowel continues to subject the concrete to compressive stresses. High bearing stresses are commonly found at the dowel-concrete interface due to this cyclic loading. Traffic loading also increases the bearing stresses, as shown in figure 31. In this figure, the dowel-induced stresses are on the upper half of the pavement's approach slab and on the lower half of its leave slab. This can cause crushing of the concrete in adjoining pavements over time.[36] This loss of concrete forms voids at the dowel-concrete interface and reduces load transfer efficiency.
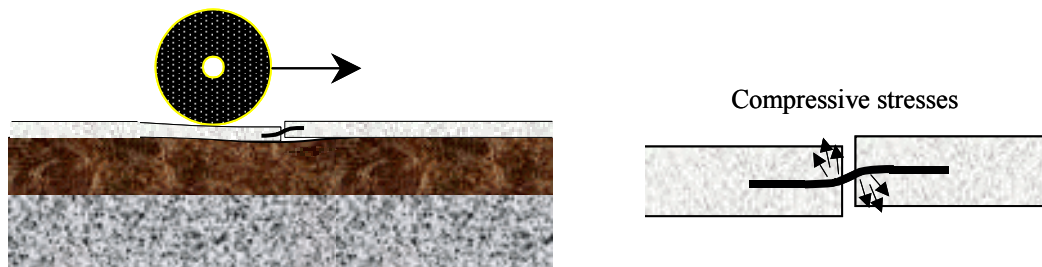
Figure 31. Schematic of wheel load on JPCP with dowels (dowel enlarged to show bearing stresses).

4.2.6   Distress Prediction

Faulting in doweled JPCP is caused, in part, by dowel loosening and enlargement of the dowel socket. The reasons for doweled pavement faulting are similar to those for nondoweled pavements. They include heavy traffic loading, differential deflection at the joint, and thermal and moisture gradients that cause slab curling and subbase erosion. In the case of doweled pavements, these three mechanisms

loosen the dowel, reducing the load transfer efficiency and causing concrete crushing at the dowel-concrete interface. A photograph of faulting distress was shown in figure 26.

4.2.7   Long-Term Performance

The relationship of faulting versus traffic is shown in figure 32 for JPCP with dowels at the joints.[35] Initially, faulting increases rapidly. Then, with time and increased traffic, the faulting levels off. Dowels can significantly reduce faulting, when compared to JPCP without dowels. See section 4.1 for more details on faulting of JPCP without dowels.

Faulting of doweled pavements can also lead to other distresses, such as spalling and transverse cracking. If the dowel bearing stresses are too severe, concrete above the dowels can break off to form a spall. This is discussed in more detail in sections 4.5 and 4.6. Transverse cracking is also possible if the doweled joints are improperly constructed. Dowel misalignment can cause a transverse crack to form near the joint. For more details on this distress, see section 4.3.
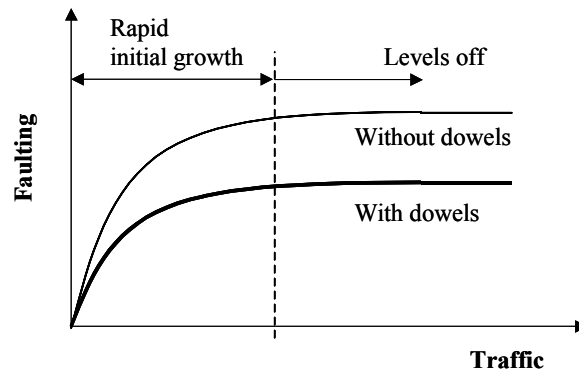
Figure 32. Schematic of time and traffic growth of faulting for JPCP with doweled joints.

4.3   JPCP TRANSVERSE CRACKING

Transverse cracking of JPCP can develop at early ages immediately after construction, or it can form years later due to fatigue. However, the mechanisms that cause these cracks to form are different. At early ages, transverse cracks form because of restrained volume changes. Concrete tends to expand and contract due to changing climatic conditions. When these internal deformations are restrained by external slab-subbase restraint and self-weight, early-age transverse cracking is possible.[2] Because young concrete has not yet reached its full mature strength, it is more susceptible to tensile damage. More detail on this type of cracking is provided in section 3.2.

When transverse cracks form after years of pavement use, the most common cause of cracking is fatigue. Over time, the cumulative number of traffic loadings increase, as do the number of seasonal climatic cycles. Stresses are generated in the concrete, and eventually a transverse crack can form. Transverse cracks can either propagate from the top of the pavement down (top-down cracking), or they can propagate from the bottom of the pavement up (bottom-up cracking). The difference between these two cracking mechanisms is discussed in the following sections.

This section examines how early-age inputs influence transverse cracking in JPCP over the long term. A flowchart connecting early-age input to the long-term performance of JPCP is shown in figure 33. The six fields presented in that figure are discussed in greater detail in the following sections.

4.3.1   Early-Age Inputs

Early-age inputs that have a significant influence on transverse crack formation are listed in step 1 of figure 33. The concrete mix design will determine the strength and fracture properties of the concrete at early ages and in the long term. The coarse and fine aggregate percentages also can influence the amount of transverse cracking to the level aggregate gradation affects drying shrinkage.[35] Pavement design also controls the stresses generated in the pavement. Widened pavements can significantly decrease the pavement edge stresses that cause transverse cracking. Joints alleviate tensile stresses that occur in the pavement at early ages. Shorter joints decrease frictional stresses at the slab-subbase interface and decrease the severity of transverse cracking in the long term. Slab thickness also has a significant influence on transverse cracking.[38] Thicker slabs are better able to resist deformation, and they are better able to carry mechanical and environmental loading.[26]

Climatic conditions at the time of pavement construction have a marked influence on long-term pavement performance. The temperature gradient at the time of set determines the amount the pavement curls up or down, and the moisture gradient controls the amount of warping. This built-in curling is discussed in section 2.4.2. Climatic conditions influence the set time and thermal gradient at set, and therefore significantly influence the magnitude of stresses generated over the long term. Finally, construction methods are critical in controlling transverse cracking. Time of joint sawing is important to control, since the joints are designed to alleviate internal pavement stresses and control where the cracks form. Both of these construction methods can improve the pavement's long-term performance.
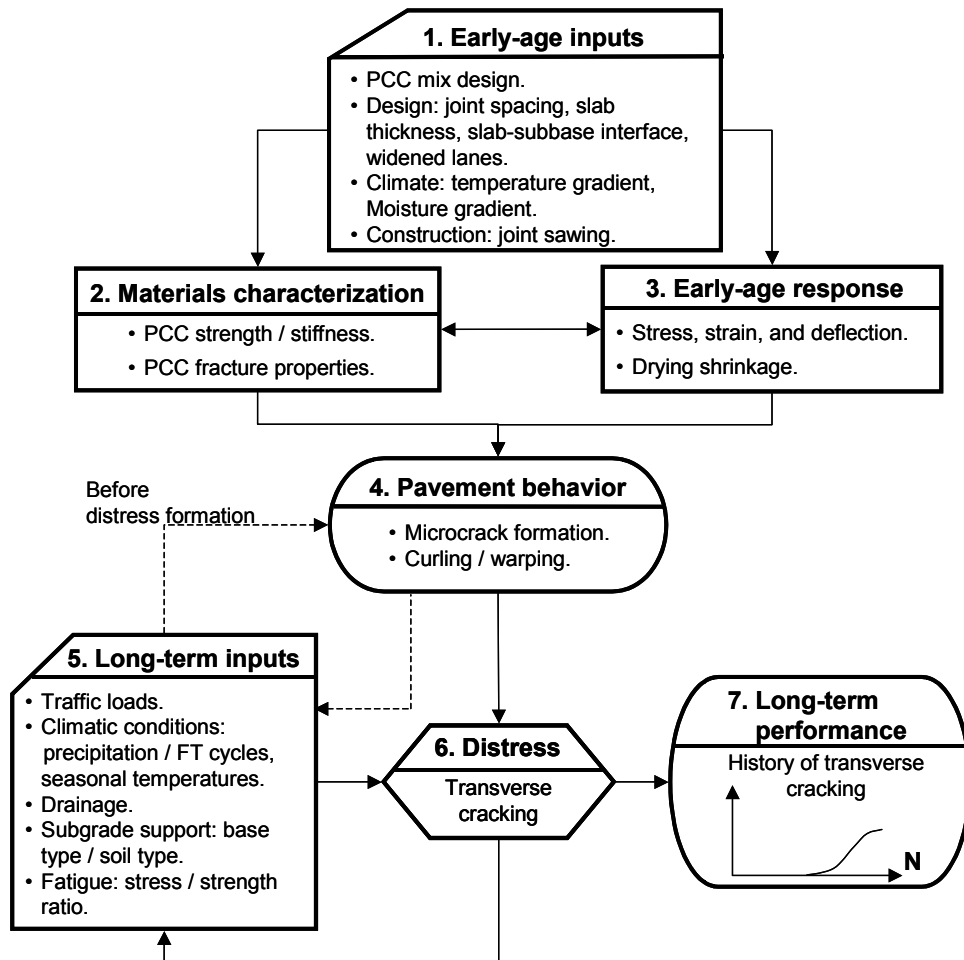
Figure 33. Flowchart outlining impact of early-age input on long-term transverse cracking performance of JPCP.

4.3.2   Materials Characterization

The strength and fracture properties of concrete have a significant impact on transverse cracking. The stiffness of the concrete determines the magnitude of induced stresses and deflections. The strength and fracture properties control when the concrete cracks.

Fatigue of concrete has been shown to be a function of the stress-to-strength ratio.[39] A high-strength concrete will commonly have a greater fatigue life than a low-strength concrete. However, high-strength concrete also can have higher stress concentrations at flaws or microcracks, making it brittle. Pavements constructed of concrete with high flexural strength typically fracture more easily.[35] For this reason, it is recommended that concrete strength be kept within a midrange from 4.5 to 4.8 megapascals (MPa).

4.3.3 Early-Age Response

The pavement's critical stresses can either occur at the bottom of the pavement (bottom-up cracking) or at the top of the pavement (top-down cracking). The mode of failure depends, in part, on the pavement's "built-in" temperature gradient. The term "built-in" is in quotes because it is not really a fixed property. However, for simplicity, it is commonly assumed to be the temperature gradient at final set. To better explain some of the more fundamental concepts, it will be defined in this manner for the discussion to follow. However, this gradient truly is not fixed, but will instead change with time as the stresses in the slab relax.

As figure 34 illustrates, when there is a positive temperature gradient at set, the pavement sets with its top surface hotter than its bottom one. Typically, this happens when the pavement is constructed in the morning or afternoon. Eventually, when the slab cools, it will curl up.
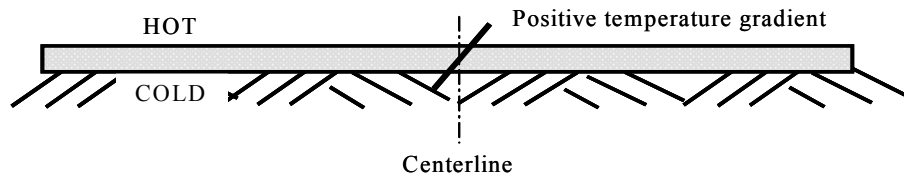
Figure 34. Schematic of JPCP with a positive temperature gradient at set.

Figure 35 illustrates that if a pavement has a negative temperature gradient at the time of set, the slab surface will be cooler than the slab bottom. This scenario is possible for night paving. If the pavement's surface is hotter than the bottom during subsequent seasonal temperature changes, the pavement may curl downward.
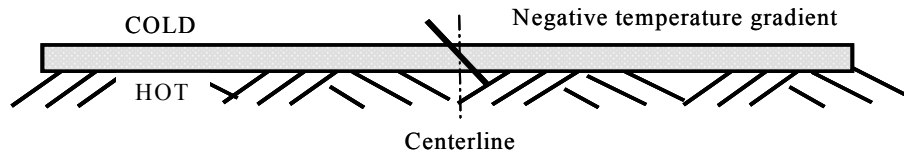
Figure 35. Schematic of JPCP with a negative temperature gradient at set.

Upward curling is less restrained than downward curling because only the corners of the slab lift. Downward curling requires that the slab joints bear down on the subbase (see figure 36). This downward curling requires more force than the upward curling.[22] Drying shrinkage most commonly increases the tensile stresses at the pavement surface due to an increase in the degree of upward slab curling.[39] For the first 72 hours after construction, the pavement's expansion and contraction stresses are partially restrained by the slab-subbase friction. If the internal stresses are greater than the strength of the concrete, transverse cracks may form. If the joints are sawed at the optimal time, early-age uncontrolled transverse cracking can be prevented. If dowels are used at the pavement joint and are significantly misaligned, transverse cracks can form at the joint. Care must be taken to construct and maintain the pavement properly to prevent dowel bar corrosion. Dowel bar corrosion may lead to a locked transverse joint, which may cause additional transverse cracks to form.[40] Even if no transverse cracks form in the pavement at early ages, they may still form in the long term due to fatigue. The upward and downward

built-in set conditions increase the likelihood of midslab crack formation due to subsequent mechanical and environmental loading. This is discussed in section 4.3.5.

4.3.4   Pavement Behavior

Repeated tensile stresses in the pavements initially can damage the concrete at the microscopic level. Eventually, microcracks form that act as stress concentrators. After these microcracks have lengthened and connected, a macroscopic crack will form.

Curling and warping stresses subject the pavement to tensile damage, and help generate transverse cracks. As mentioned in section 2.4.2, built-in downward curling at set due to negative thermal temperature gradients increases the tensile stresses at midslab. The combination of thermal gradients and traffic loading assist in transverse crack formation.
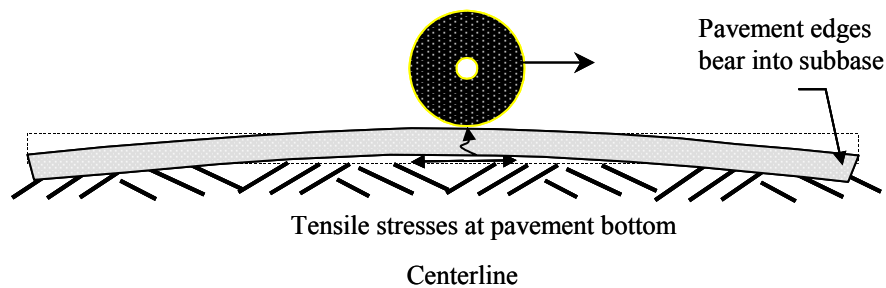
Figure 36. Schematic of curled-down JPCP. Note the pavement lifts off the subbase at midslab, and its edges bear on the subbase.

4.3.5   Long-Term Inputs

Even though the pavement may resist transverse crack formation at early ages, cracks may still form in the long term due to fatigue. Fatigue loading causes any flaws in the concrete to lengthen. Repeated loads cause the microscopic flaws to blunt and resharpen until they form into a visible crack.[41] Fatigue depends primarily on the ratio of induced stresses to the concrete's strength. Miner's damage law typically is used to calculate the amount of damage a pavement sustains over its lifetime.

The two most significant factors affecting long-term fatigue are the combined effects of traffic and environmental loading.[26] Traffic loads increase the stresses to which the pavements are subjected. They contribute considerably to bottom-up and top-down transverse crack formation. As figure 37 demonstrates, for bottom-up cracking, the critical stresses that cause transverse cracking are at the pavement's midslab edges.[15]
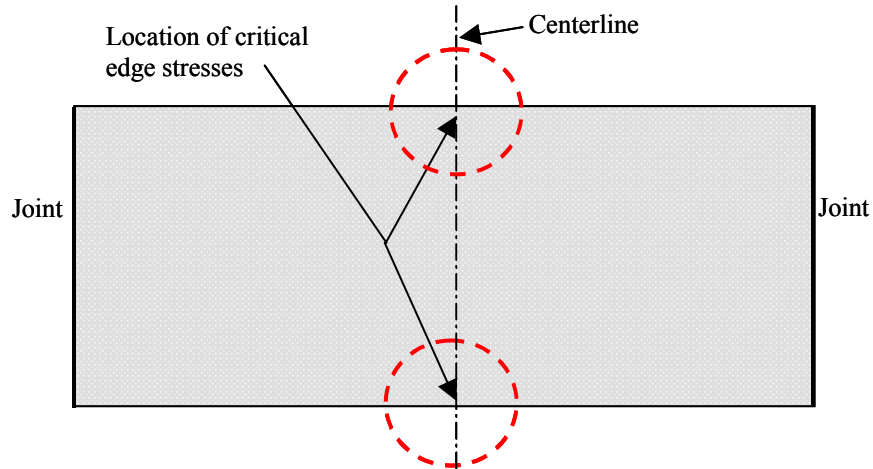
Figure 37. Plan view of JPCP slab showing location of critical edge stresses that cause transverse cracking at midslab.

Figure 38 demonstrates how wheel loading during the service life causes the pavement to deflect downward, putting the bottom of the pavement in tension. Traditionally, transverse cracking is assumed to initiate at the bottom of the pavement.
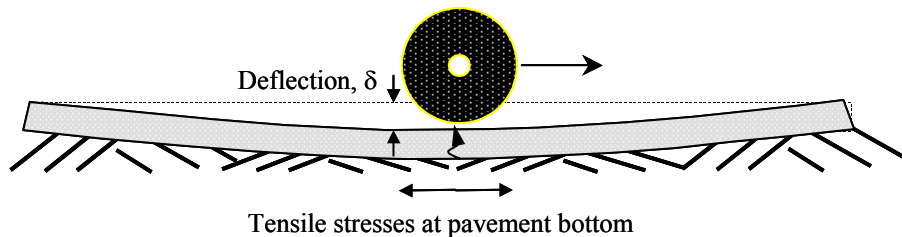
Figure 38. Schematic of curled-up JPCP.

Similarly, wheel loading can put the bottom of the slab in tension when it is curled down. The interior of the slab may not have contact with the subbase when it is curled down.[15] This loss of support increases the likelihood of midslab transverse cracking.

Environmental loading changes subbase support. The subbase sometimes erodes, settles, pumps, or heaves, all of which negatively impact pavement performance.[38] The development of these subbase phenomena is often directly related to precipitation amounts. Figure 38 demonstrates that, for a curled-up pavement, the water softens the subbase, therefore increasing midslab deflection and, consequently, the tensile stresses at the bottom. For this scenario, the potential of bottom-up cracking is increased. For a curled-down pavement, loss of subbase support, coupled with traffic loading close to the joint, put the surface of the curled-down pavement in tension, increasing the potential for top-down cracking. This can be seen in figure 39.

Tensile stress

Severe erosion
of subbase
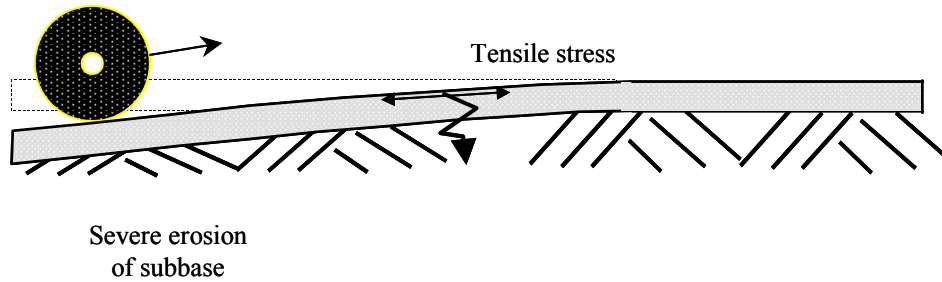
Figure 39. Schematic of top-down JPCP transverse cracking due to severe erosion of subbase.

Seasonal freeze-thaw cycles further aggravate the effect of water. Freezing can stiffen the subbase and the subgrade during the winter months. During the subsequent thaw cycle, the pavement is most susceptible to damage. The subbase soils cannot sustain the loading, so they erode and pump at a faster rate. This increases the pavement damage.[17] As shown in figure 39, severe erosion of the subbase under the pavement makes transverse cracking due to top-down cracking possible, because the loss of support puts the pavement surface in tension.

While erodable subbases often are not desirable, the use of cement-treated or lean concrete bases also can lead to problems. Pavements built on these bases can also have significant amounts of transverse cracking. Since these impermeable subbases lack flexibility, water can trap beneath the slab and the subbase to form voids. Fines that buildup under the slab create areas of high stress, and transverse cracking can result.[38] Lean concrete bases also cause the pavements to develop large curling and warping stresses, increasing transverse cracking potential.[33]

Pavement system drainage is one of the most significant factors governing long-term pavement performance. Pavements in extreme climates (wet and freezing) sometimes perform badly.[33] The presence of water in the pavement system and subbase and subgrade layers leads to premature pavement damage. Coarser subgrades typically have better drainage than fine grained ones, resulting in better performance when they are used.[39]

Seasonal temperature changes are another environmental factor that can lead to pavement damage. Temperature changes can induce large thermal changes in the pavements. For example, pavements constructed in hot and dry climates have been found to have more transverse cracks than those constructed in milder climates.[33]

4.3.6   Distress Prediction

Figure 40 shows a transverse crack that formed due to fatigue. As mentioned in the above sections, transverse cracks are the result of early-age factors such as concrete strength and fracture properties, pavement geometry, and climatic conditions. Early-age conditions due to these factors result in curling and warping shapes and bending stresses that, when combined subsequently with traffic loads, climate, and level of subgrade support, cumulatively damage the pavement structure. According to the level of bending stresses and concrete fatigue characteristics, the pavement may eventually crack.

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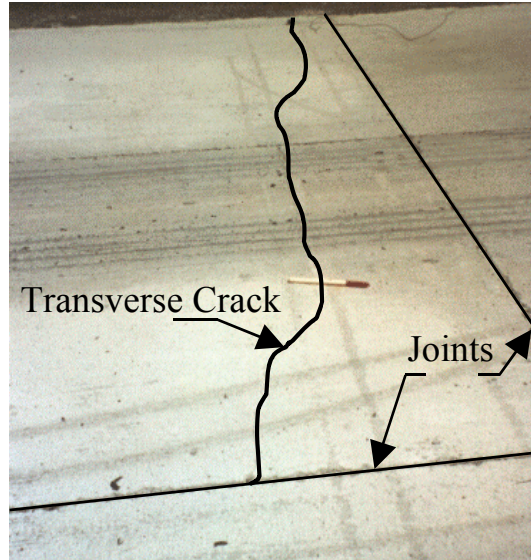
Figure 40. Photograph of transverse crack. Transverse crack and joints enhanced for clarity.

4.3.7 Long-Term Performance

Figure 41 shows how the percent of cracked slabs in a pavement versus time follows an S-shaped curve.[38] Initially, pavement fatigue is low, so transverse cracks are not likely to form. However, after the pavement has sustained a critical number of loads, the number of cracked slabs increases significantly. Over time, the number of transverse cracks commonly levels off. The critical level of cracked slabs in JPCP associated with pavement failure is commonly reported as 10 percent.[26]
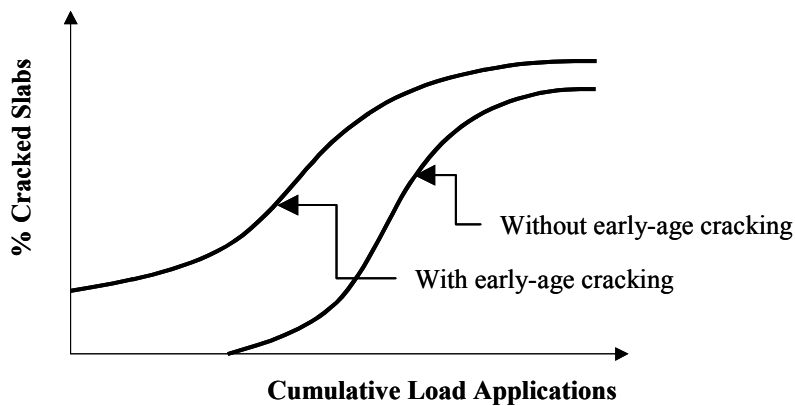
Figure 41. Schematic of long-term performance of JPCP: Percent cracked slabs vs. time.

The formation of transverse cracks can increase other pavement distresses. Because water can infiltrate the cracks and weaken the subbase below, the pavement deflection will increase. As a result, increased faulting is possible.[35] The concrete also may deteriorate at this joint, resulting in increased spalling.

4.4 JPCP CORNER CRACKING

This section highlights the influence of early-age inputs on the long-term performance of JPCP with respect to corner breaks. Corner breaks are more likely to form in the long term if certain early-age phenomena occur. These phenomena depend on design and construction parameters.

For example, the probability that corner breaks will form increases if the pavement has built-in upward curling. Built-in upward curling was discussed in detail in section 2.4.2. In simple terms, it is the result of a positive temperature gradient (the temperature at the slab surface is greater than at the bottom). This typically occurs when the pavement is placed during the summer in the morning or afternoon. A decrease in the temperature gradient through the pavement causes the slab to curl up. Drying shrinkage at the surface of the pavement enhances the slab's curled-up shape.

Over time, the deformed shape accelerates the deterioration of the pavement. Subbase support is more likely to erode from under the pavement, as water infiltrates at a faster rate. Load transfer at the joint will also decrease. Heavy traffic loadings and seasonal temperature changes will induce high tensile stresses on the pavement surface, increasing the potential for development of corner breaks.

A flowchart indicating the early-age mechanisms influencing corner cracking distress of JPCP is shown in figure 42.

4.4.1 Early-Age Inputs

Material, design, and construction procedures all influence the long-term corner cracking performance of JPCP. The mix design controls the strength and stiffness development of the concrete, as well as its fracture properties. The pavement design also affects the magnitude of stresses in the pavement. For example, skewed joints have been found to increase the number of corner breaks.[26] Thick slabs are able to sustain mechanical and environmental loadings better than thin ones.

Climatic conditions determine the shape of the pavement at set by defining the temperature and moisture gradients. Set conditions determine how the pavement will deform as it undergoes climatic changes throughout its lifetime. A positive temperature gradient at set commonly translates to a pavement with a predominately curled-up shape, except when the surface is heated to a higher temperature than it was at set. However, a pavement with a negative temperature gradient at set can transition from a curled-up shape to a downward curled pavement. Built-in curling determines the location of the critical tensile stresses in the pavement and the likely long-term pavement distresses.

Finally, construction practices and design features can influence the stress state of the pavement, from the early ages throughout its lifetime. Shoulder support can reduce slab deflection at the corners, while widened lanes reduce the pavement's edge stresses. The wheel loading on widened pavements no longer occurs at the pavement's edge. Instead, the loading occurs closer to the pavements interior. These construction methods may extend the pavement's life by several years.

1. Early-age inputs
- PCC mix design.
- Design: joint spacing, slab thickness.
- Climate: temperature gradient, moisture gradient.
- Construction: shoulder support, widened lanes.

2. Materials characterization
- PCC strength / stiffness.
- PCC fracture properties.

3. Early-age response
- Stress. strain, and deflection.
- Drying shrinkage.

Before distress formation

4. Pavement behavior
- Microcrack formation.
- Curling / warping.

5. Long-term Inputs
- Traffic loads.
- Climatic conditions: precipitation / FT cycles, seasonal temperatures.
- Drainage.
- Subgrade support: base type / soil type (erodibility & gradation).
- Load transfer.
- Fatigue: stress / strength ratio.

6. Distress
Corner breaks

7. Long-term performance
History of corner cracking

N

Figure 42. Flowchart outlining the influence of early-age properties on long-term JPCP corner breaks.

4.4.2 Materials Characterization

Concrete material properties can influence the long-term performance of the pavement significantly with regard to corner cracking. The stiffness of the concrete governs the magnitude of the stresses within the pavement. This determines how severely the concrete will curl at the pavement edges due to mechanical wheel and environmental loading. Fracture properties and strength of the concrete are also important, because they determine the pavement's resistance to cracking. To reduce the severity of corner breaks, a lower stiffness material with high fracture resistance (strength) is needed. However, because these two requirements are commonly contradictory for concrete materials, a compromise should be made at the time of design.

4.4.3 Early-Age Response

The early-age factors mentioned previously influence the pavement response, including the early-age stresses, strains, and deflections. Their magnitude will influence the pavement performance significantly over its lifetime. The early-age stresses govern the degree of built-in curling. Upward curling causes the slab corners to lift. Downward curling requires that the slab joints bear down into the subbase. The slab length is stressed against its self-weight. This requires more force than upward

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curling.[39] Over the lifetime of the pavement, the curling can transition from upward to downward, or vice versa. However, drying shrinkage nearly always acts to curl the slab upward, placing the surface in tension.

4.4.4 Pavement Behavior

During the early-age period, upward built-in curling and drying shrinkage are the primary conditions for the development of corner breaks. As figure 43 illustrates, microcracks later form because the tensile stresses placed on the pavement induce damage as the corners deflect. Over time, these microcracks, not visible to the naked eye, will lengthen and form a visible crack as a result of fatigue loading.
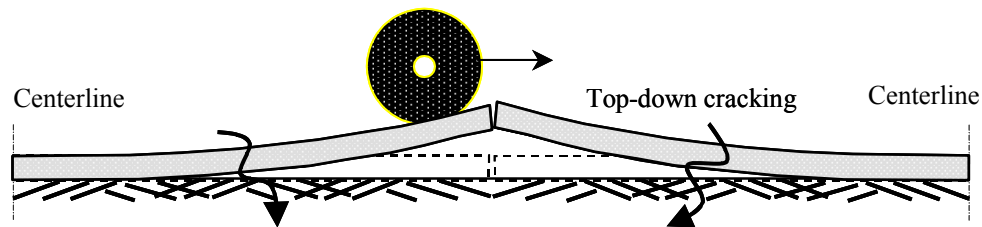
Figure 43. Schematic of top-down JPCP corner cracking in pavements with built-in curling and reduced subbase support and load transfer. Wheel loading results in top-down cracking.

4.4.5 Long-Term Inputs

With the initial microcrack formation and the pavement's built-in curling, it is more likely that corner breaks will form in the long term due to heavy traffic loading and the changing climatic conditions. However, if the pavement maintains suitable load transfer across the joints, fatigue damage can be delayed, reducing the number of corner breaks. However, when load transfer is lost, the joint allows water to infiltrate the pavement system. For a granular subbase, the annual precipitation and freeze-thaw cycles cause it to erode. If the pavement has adequate drainage, then the rate of erosion will not be as severe. For stabilized bases, corner cracking is still possible, because the pavement loses support when it lifts off the stiff subbase.

The loss of subbase support due to built-in curling or subbase erosion is aggravated by heavy traffic loading. When loaded, the pavement surface is in tension, so top-down corner cracking is the mode of failure as shown in figure 43. Traffic is one of the major factors that influence the pavement surface's state of stress, but thermal gradients caused by seasonal temperature changes can have a similar effect. At a certain temperature or time of day, the curling stresses can equal or exceed the wheel stresses.[39] This demonstrates the importance of thermal gradients on pavement performance.

4.4.6 Distress Prediction

A photograph of two corner breaks is provided in figure 44.
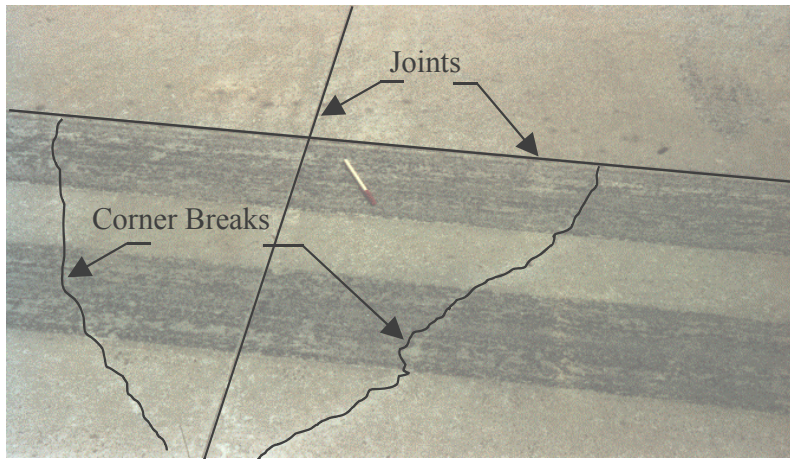
Figure 44. Photograph of corner breaks. Joints and corner breaks are enhanced for clarity.

Several criteria must be met for a crack to be classified as a corner break. The crack must extend vertically through the thickness of the slab. Also, as figure 45 shows, the crack must intersect both the transverse joint and the longitudinal joint at less than 1.8 m from the slab corner.[15]
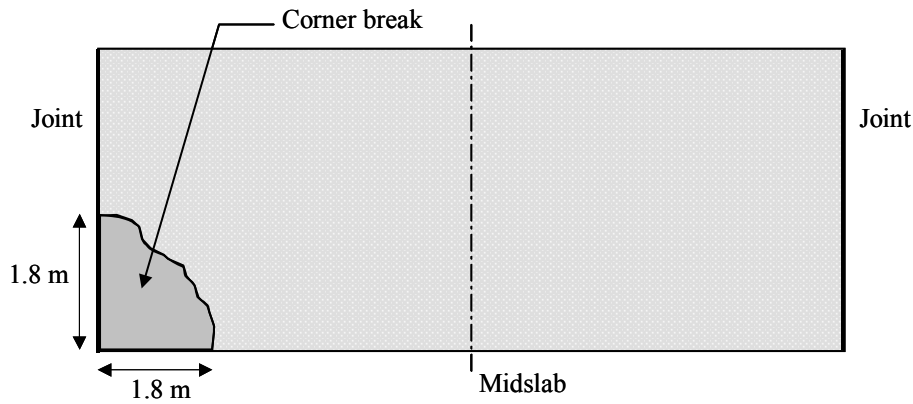
Figure 45. Plan view of JPCP showing a corner break.

4.4.7 Long-Term Performance

A typical curve showing the growth of corner breaks as a function of cumulative load applications is given in figure 46. The shape of this curve is similar to the one for transverse cracking (section 4.3). Initially, the percentage of corner breaks is relatively minor when the pavement is first loaded. But as climatic cycles and wheel loadings increase, the number of corner breaks rises sharply. After this rapid period of growth, the cracking damage typically levels off.
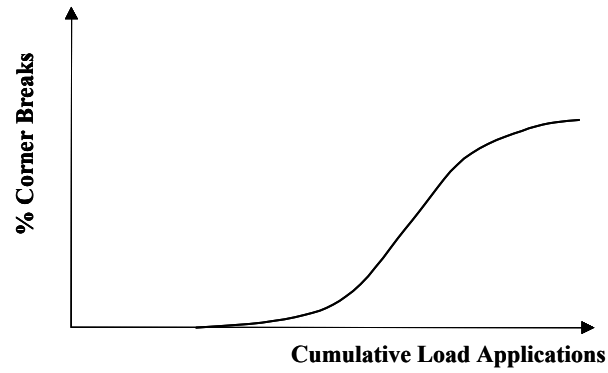
Figure 46. History of JPCP corner breaks.

4.5   DELAMINATION SPALLING

Spalling distress is the cracking, breaking, or chipping of the slab edges within 0.6 m of the joint or crack.[15] Several factors have been found to contribute to development of spalling in concrete pavements. Some of the most common factors include: moisture loss at the pavement surface, presence of incompressibles at the joint, freeze-thaw action, traffic loads, mix proportioning, weak concrete at the surface due to poor finishing techniques, aggregate type used, width of the crack, type of joint sealant, and poorly designed or constructed load transfer devices. (See references 15, 16, 42, and 43.)

This section describes the mechanisms involved in developing spalling distress primarily due to moisture loss at the surface. A schematic representation of these mechanisms, and the processes involved, is presented in figure 47.
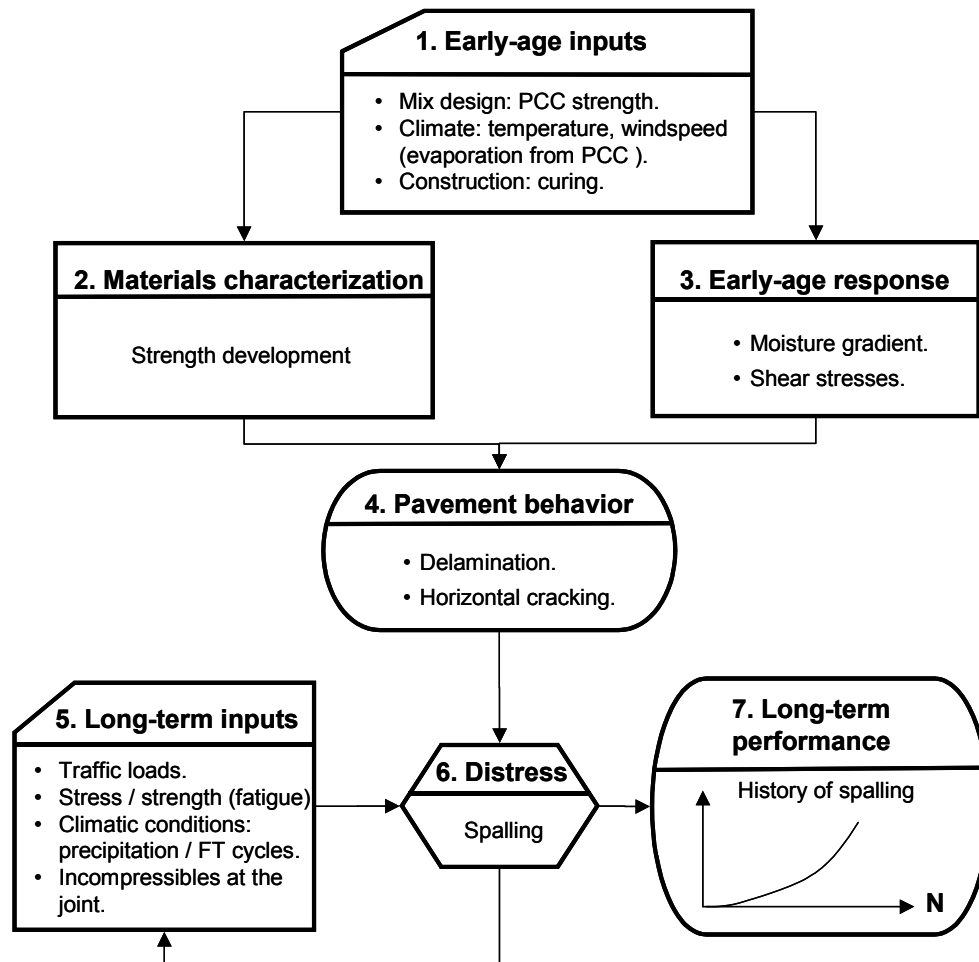
Figure 47. Flowchart outlining impact of early-age input on long-term delamination spalling distress for JPCP and CRCP.

During pavement construction, early-age inputs such as materials, climate, and construction procedures affect the strength and stress development in the pavement. During this early-age period, development of stresses exceeding the strength of the concrete may result in delamination areas near cracks or joints. These delaminated areas later interact with long-term variables such as traffic, climate, and other factors that contribute to spalling distress. In the long term, during the service life of the pavement, the distress progression is a result of the initial pavement behavior and the long-term inputs. A more detailed discussion about each one of the processes contributing to spalling development is provided in the following sections.

4.5.1   Early-Age Inputs

As discussed in section 2.4.1, potential for delamination is a function of the strength development and shear stresses produced by the drying shrinkage differential throughout the slab depth.

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Primary factors that contribute to strength development and to the level of shearing stresses in the slab are:

- Mix proportioning characteristics (such as amount and type of coarse aggregate, w/c ratio, cement content, and admixtures used).

- Climatic conditions (such as temperature of the air, relative humidity and windspeed).

- Construction procedures (such as curing methods and curing timing).

4.5.2 Material Characterization

The factors affecting the strength development in the concrete are discussed in section 5.2.6. For delamination spalling, the strength of the concrete is primarily affected by loss of moisture at the surface. Moisture loss at the surface results in a moisture gradient in the slab, as shown in figure 48. Due to the moisture gradient, the rate of strength development will decrease for the concrete at the surface. Therefore, the concrete strength will not be uniform throughout the pavement depth as shown on figure 49. It is important to note that the concrete strength throughout the pavement depth also will be a function of the temperature gradient, and the moisture loss at the bottom of the pavement as affected by moisture conditions at the subbase.
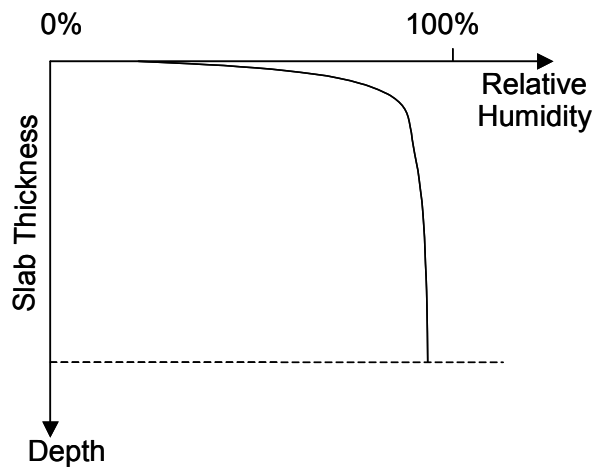
Figure 48. Relative humidity as a function of slab depth.
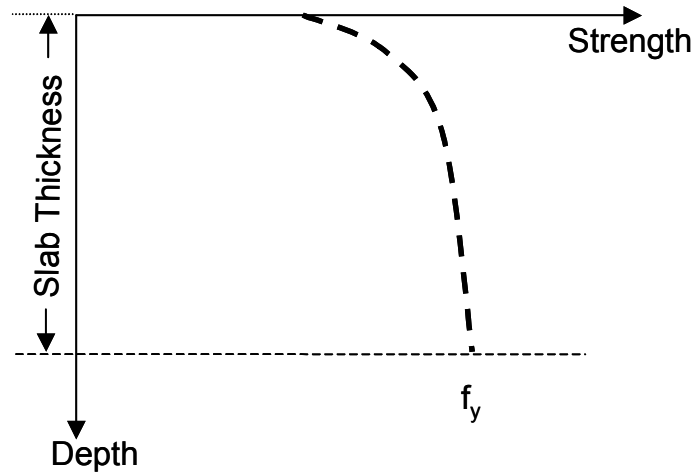
Figure 49. Strength development as a function of slab depth.

Reduced strength of the concrete at the surface also has been attributed to problems with inadequate mix proportioning combined with poor finishing practices. Mixes with high contents of fine aggregate and cement often result in segregation problems that can result in weak concrete at the surface, especially if overworked. Other contributing factors include poor consolidation (high entrapped air) and lack of entrained air when concrete resistant to freezing and thawing is required.[42]

4.5.3   Pavement Response

The moisture gradient also can produce a drying shrinkage differential in the slab. Because the pavement is restrained by its own weight, the subbase, and reinforcement in the case of doweled pavement or CRCP, shear stresses tend to develop throughout the slab depth, as shown in figure 50.
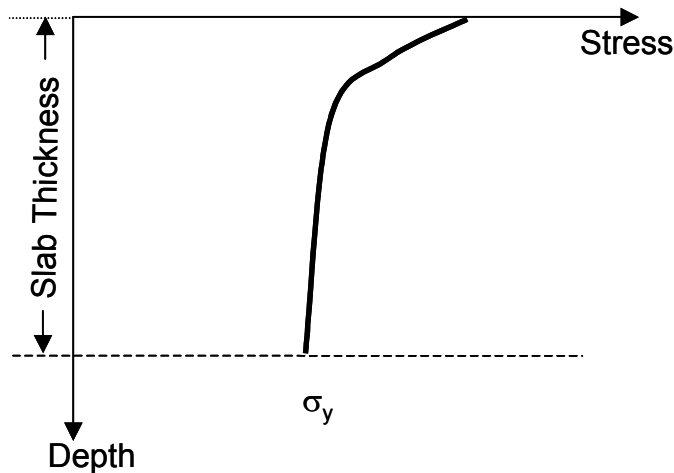
Figure 50. Shear stresses as a function of slab depth.

4.5.4   Pavement Behavior

In theory, whenever the tensile or shear stresses exceed the concrete strength, cracking in a horizontal plane parallel to the pavement surface will tend to develop, as illustrated in figure 51. These

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horizontal cracks usually occur close to joints or crack, and have typical depths of 13 to 75 mm. These cracks are commonly known as delamination.[16]

The depth of the delamination will be primarily a function of the evaporation rate, the type of curing, and the time to application of curing.
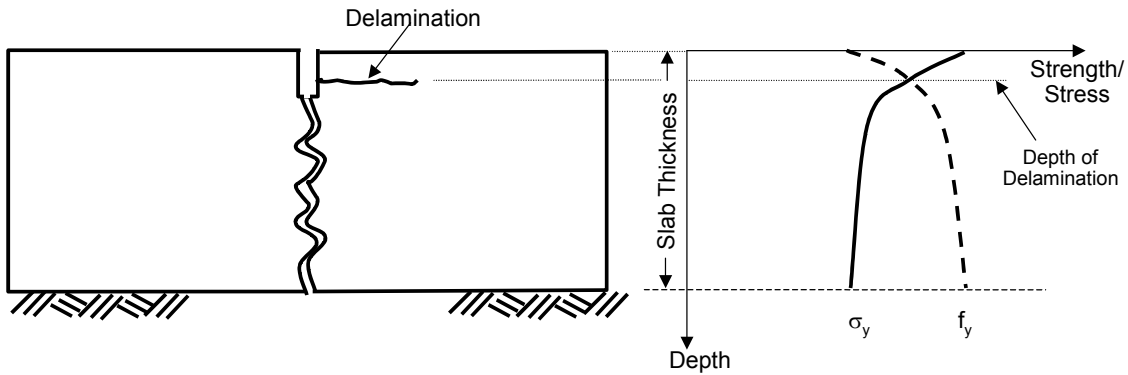
Figure 51. Delamination mechanism.

4.5.5   Long-Term Inputs

Although the formation of delamination planes may not be evident in the early age, subsequent climatic fluctuations, coupled with traffic loading, will induce tensile stresses at the area of the delaminated concrete that eventually break continuity with the pavement. Depending on the shape and depth of the delamination, concrete strength, level of stresses that develop, and the fatigue properties of the concrete, vertical cracks may form at those locations, as illustrated in figure 52.
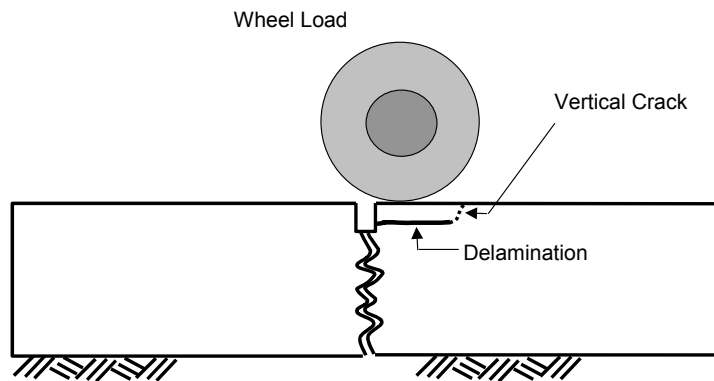
Figure 52. Vertical cracks at delaminated areas leading to spalling distress.

As mentioned in section 2.3.3, other concrete delamination mechanisms include delamination at the steel depth in CRCP due to steel corrosion, two-layer concrete construction, excessive temperatures gradients in the slab, and restraint imposed by dowels.

4.5.6   Distress Prediction

Depending on the magnitude of traffic loads, temperature fluctuations, and concrete fatigue characteristics, the vertical cracks formed at the delaminated areas eventually translate into spalling

distresses. Delamination spalling is characterized by small pieces of concrete near cracks or joints that come apart from the pavement as a result of traffic and environmental forces. Spalling distresses affect the riding quality and the structural integrity of the pavement, and therefore affect the performance of the pavement in the long term. Spalling also reduces the pavement cross section, and therefore the load transfer efficiency is reduced across joints or cracks.[44] Typical cases of delamination spalling are presented in figures 53 and 54.

Figure 53. Delamination spalling at a CRCP crack.

Figure 54. Round-shaped aggregates at a spalled CRCP crack.

4.5.7 Pavement Long-Term Performance History

The depth of the delamination correlates with the evaporation rate occurring in the early age. According to experience, high evaporation rates in the early age lead to higher depths of delamination. In the long term, as observed in figure 55, low evaporation rates usually produce a greater rate of spalling than high evaporation rates in the first few years. However, the spalling rate tends to flatten out faster, as opposed to high evaporation rates, where the spalling development keeps increasing. This phenomena is attributed to the fact that low evaporation rates produce shallower delamination depths than high evaporation rates. Due to the proximity to the surface, delaminations with shallower depths are more prone to being affected by traffic loads than delamination of greater depths. Depending on the fatigue characteristics of the concrete, deeper delaminations will start to be affected later and usually will result in a higher severity spalling. In some cases, the development of spalling distress may occur during construction operations or early in the life of the pavement.
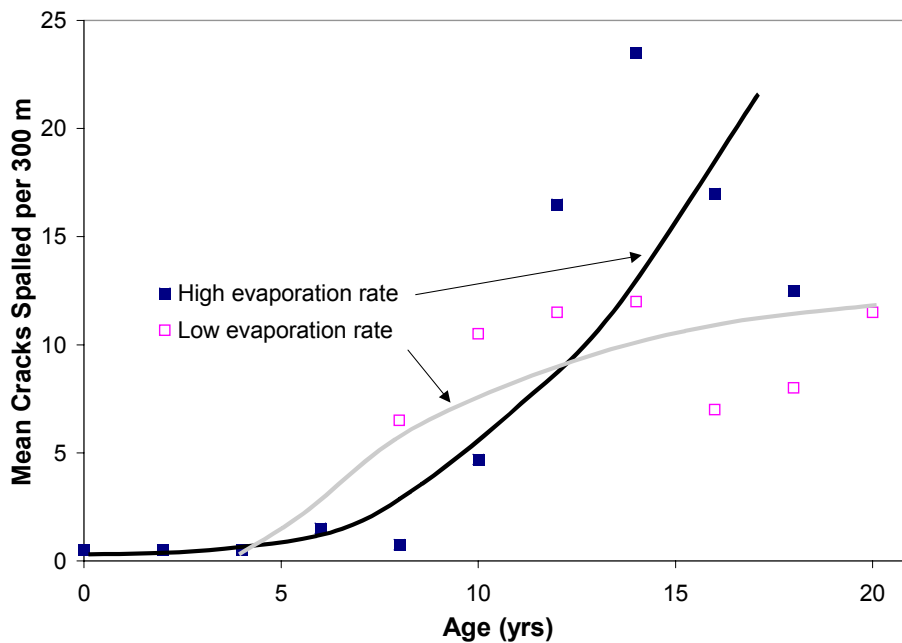
Figure 55. Spalling progression as a function of evaporation rate.[16]

4.6   DEFLECTION SPALLING

Deflection spalling generally is found on airport pavements or on very thin slabs. On airport pavements, spalling is caused by heavy aircraft loads. The heavy vertical loadings deflect the concrete pavements significantly at the joints and/or cracks. If the joint or crack is tight, or if incompressibles are present, the tops of the adjoining slabs bear on each other, and the concrete crushes. The breaking and chipping of the concrete is termed a deflection spall. Deflection spalls also form in thin slabs, such as ultrathin whitetopping, because the thin slabs also experience high deflection. Deflection spalls are not commonly found on interstate highway pavements thicker than 200 mm. The flowchart connecting early-age mechanisms to deflection spalling is shown in figure 56. Each of the seven sections are discussed in greater detail below. Deflection spalls can form in both CRCP and JPCP pavements.
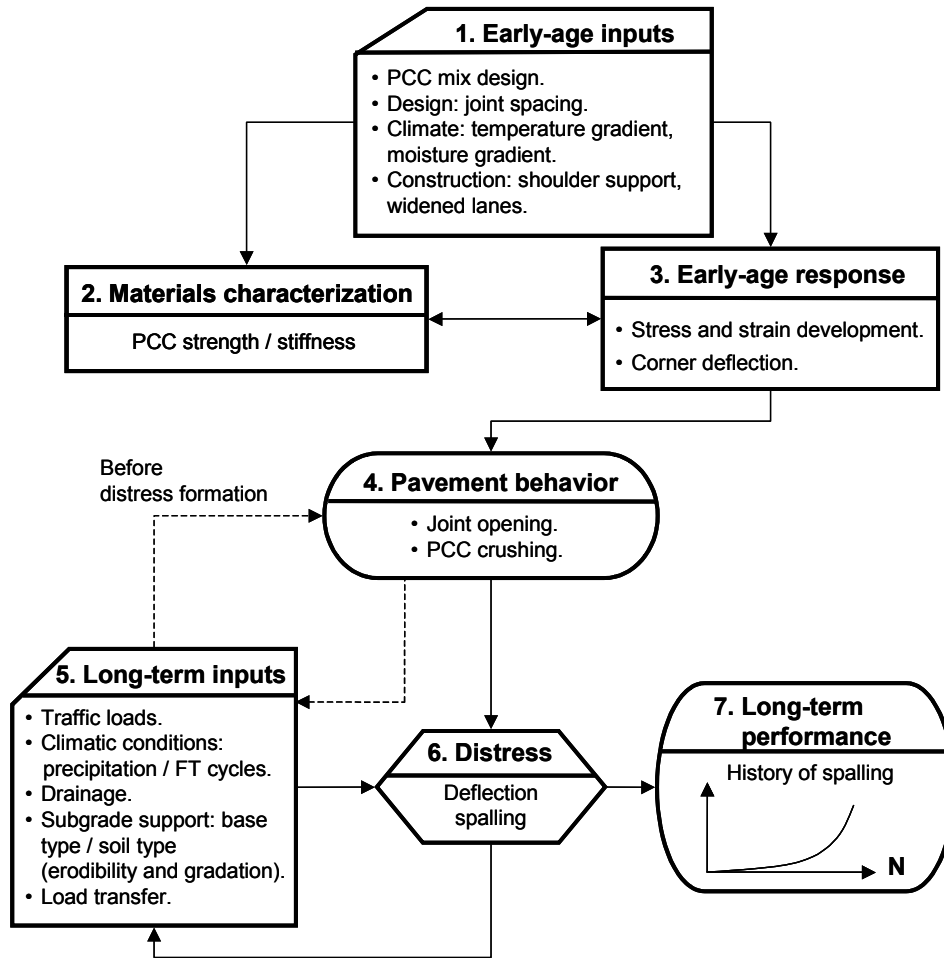
Figure 56. Flowchart outlining the impact of early-age input on long-term deflection spalling performance for JPCP and CRCP.

4.6.1 Early-Age Inputs

The early-age inputs that impact deflection spalling are listed in step 1 of figure 56. The inputs address concrete mix design, pavement design, climatic conditions, and construction practices. The concrete mix should be tailored for optimal concrete strength. The joint/crack spacing in the pavement should be designed to keep the joint/crack openings tight, even when the pavement is subjected to climatic temperature and moisture changes. Construction practices should aim to reduce corner deflections. Similarly, the fresh concrete should not be overworked at the pavement's surface during construction because this weakens its strength.

4.6.2 Materials Characterization

The concrete's strength and stiffness development is important. Concrete strength at the edges of the adjoining pavements needs to be maintained to prevent crushing of the concrete.

4.6.3 Early-Age Response

The stresses and strains generated in the early-age pavement control the size of the joint opening. Likewise, the corner deflection of the pavement will later control the degree of deflection spalling.

4.6.4 Pavement Behavior

The size of the joint opening controls the efficiency of load transfer. Loss of load transfer means that joint deflection will increase. Similarly, the pressure on the concrete at the joint increases when loaded vertically.

4.6.5 Long-Term Inputs

As figure 57 illustrates, deflection spalling of the pavement is caused primarily by heavy wheel loading (with respect to the structural capacity of the pavement). These wheel loads cause the pavement joints/cracks to deflect and the top edges of the adjacent slabs to press together, thus producing significant compressive stresses causing crushing in the top layer of the slab.
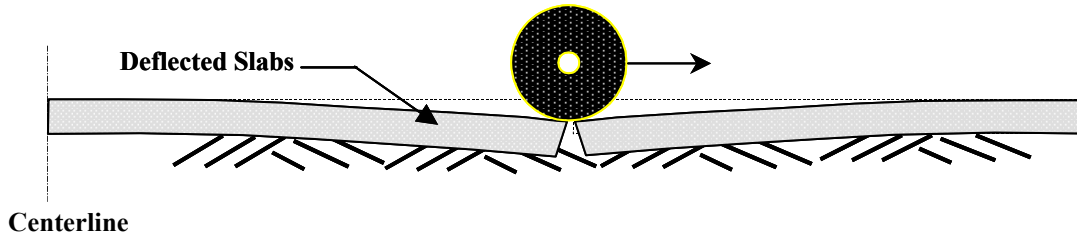
Figure 57. Schematic of deflection spalling mechanism.

The mechanism behind deflection spalling is shown more clearly in figure 58. The compressive stresses crush the concrete at the joint/crack. The severity of the distress is controlled by the pavement's deflection at the joint/crack (δ).
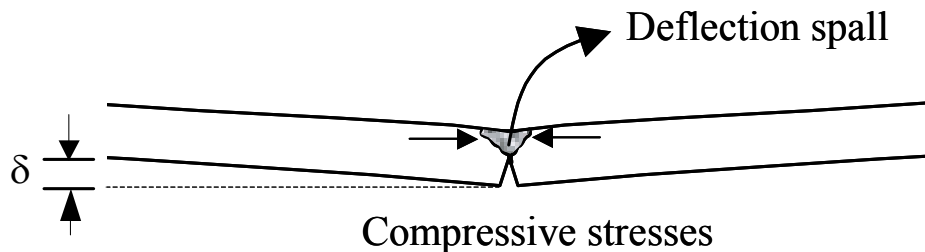
Figure 58. Schematic of deflection spalling mechanism.

If the joint/crack width is kept tight and incompressibles kept out, deflection spalling can be minimized. The tight joint/crack will maintain the load transfer, and the deflection will be reduced. Another way to alleviate the severity of deflection spalling is to use a subbase with low deformation properties, such as a stabilized subbase. Heavy wheel loads would not have as great an impact with tight joints/cracks and stiffer subbases.

4.6.6   Distress Prediction

A photograph of deflection spalling is shown in figure 59. It can be seen that the top layer of concrete on both sides of the adjoining slab edges has spalled off. These spalls are deep, sometimes 76 mm or deeper. In this case, aircraft have generated the heavy loads required for deflection spalling to occur.

Figure 59. Photograph of deflection spalling on a CRCP.

4.6.7   Long-Term Performance

The rate of spalling increases with time, as shown in figure 60. Over time, and with increased traffic loadings, microcracks form in the concrete to reduce its strength and durability. After the critical number of loads has been reached, the concrete will crush and deflection spalls will form.
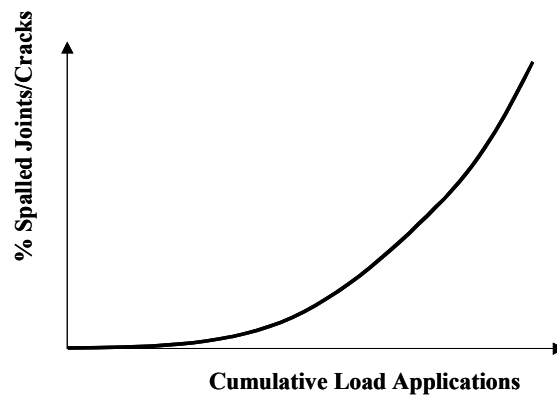
Figure 60. Schematic of percent JPCP spalled joints/cracks vs. time.

4.7   PUNCHOUTS

Punchout distress is a condition that usually occurs in CRCP pavements between closely spaced cracks. Loss of aggregate interlock at the cracks, a function of crack width and traffic loads, can cause the slab to act as a cantilever beam, inducing high transverse (perpendicular to the direction of traffic) tensile stresses at the surface. Depending on the magnitude of the tensile stresses, strength and fatigue characteristics of the concrete, and traffic load applications, a longitudinal crack may eventually form between transverse cracks (CRCP transverse crack development is described in section 2.3). The result is a punchout. Progression of the punchout distress continues with traffic loads and climate cycles that induce spalling at the cracks, further loss of support, pumping, reduced subgrade support, and increased severity of the punchout distress.[15]

This section describes the mechanisms involved in the development of punchout distress, primarily early-age factors such as crack spacing and crack width. A schematic representation of these mechanisms and the processes involved is presented in figure 61.
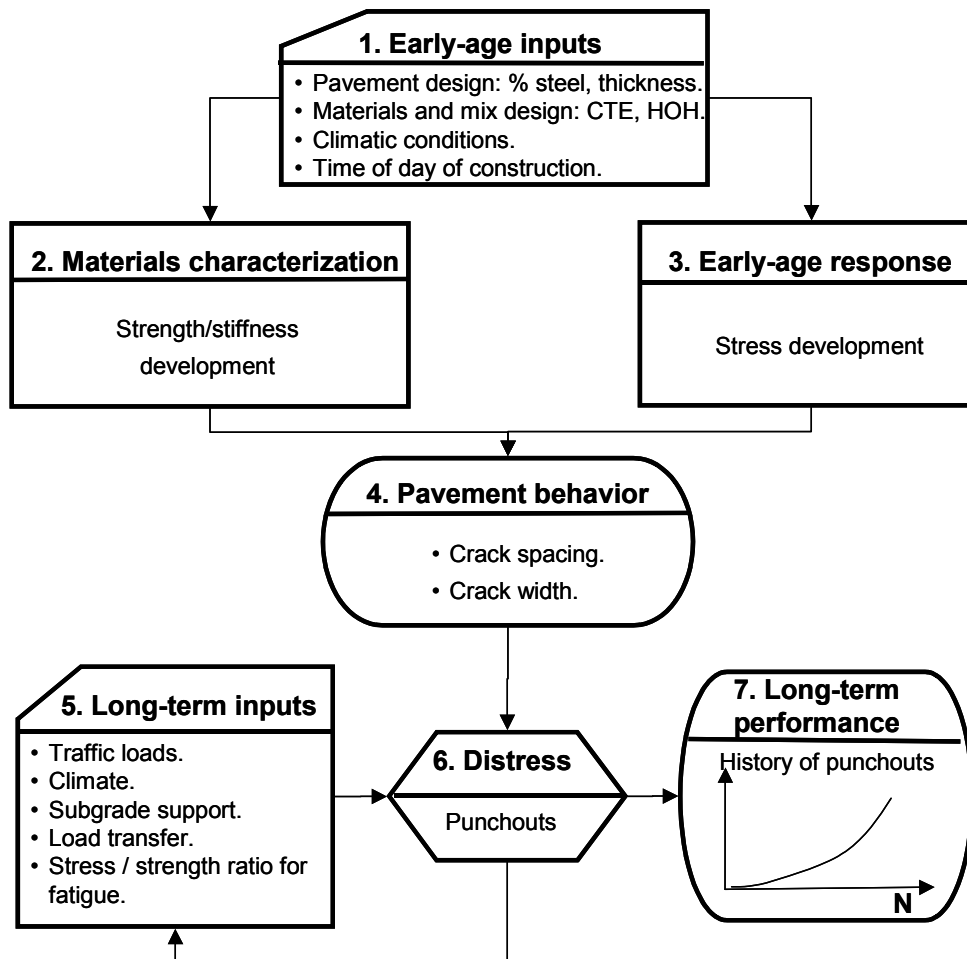
Figure 61. Flowchart outlining impact of early-age input on long-term punchout distress of CRCP.

Initially, during pavement construction, early-age inputs such as materials, climate, and construction procedures (step 1) affect the strength, stiffness (step 2), and stress development in the pavement (step 3). The interaction of strength, stiffness, and stress development will lead to formation of cracking patterns (step 4) that will vary according to materials properties, climate, and design factors. The spacing and width of the cracks that form are determining factors in the magnitude of the stresses that later generate as a function of traffic loads, climatic cycles, load transfer, subgrade support, and concrete fatigue characteristics (step 5). Eventually, longitudinal cracks may form that will create an isolated piece of slab commonly referred to as a punchout (step 6). Progression of punchout distresses with time will be a function of the evolution of the cracking patterns and long-term inputs with time (step 7). A more detailed discussion about each one of the processes contributing to punchout development is provided in the following sections.

4.7.1   Early-Age Inputs

Early-age inputs that contribute to punchout formation are typically those inputs that affect the crack spacing, crack width, and steel stress during the early age. These factors include coarse aggregate type, steel reinforcement details, placement temperature, placement season, curing procedures, time when crack occurs, slab thickness, and subbase type.

4.7.2   Material Characterization

The strength development in the concrete is important in preventing punchout distresses. The strength at the cement-aggregate interface directly influences the load transfer achieved through aggregate interlock. On the other hand, the strength of the concrete will govern the formation of cracks due to tensile stresses. In the same manner, the elastic modulus or stiffness of the concrete will directly affect the level of stresses that develop.

4.7.3   Pavement Response

As described in chapter 2, volume changes resulting from temperature and moisture variations induce significant stresses in the concrete primarily as a function of the difference in the CTE of steel and concrete, the concrete drying shrinkage, the slab curling and warping, and the restraints imposed by the steel and the subbase.

4.7.4   Pavement Behavior

As a consequence of the tensile stresses that develop in the concrete, transverse cracks tend to form to relieve the stresses. Important characteristics of these cracks are the crack spacing and crack width, because they govern the stresses that develop in the long term as a function of traffic loads and climatic conditions.

4.7.5   Long-Term Inputs

In the long term, factors such as joint load transfer, traffic loads, climatic cycles, and subgrade support interact with the initial crack spacing and crack width to determine the level of stresses that develop in the CRCP. With time, the initial crack spacing will continue to change as a function of the combined effect of temperature fluctuations, drying shrinkage, and traffic loads. The crack width that initially may govern the load transfer through aggregate interlock also will change with time as a function of drying shrinkage, temperature fluctuations, and newly formed cracks.

As figure 62 conceptually demonstrates, the interaction of crack spacing and crack width with long-term factors will govern the level of tensile stresses that develop. For long crack spacings, the bending stresses that generate at the edge due to wheel loads are higher than for short crack spacings. However, the stress tends to reach a maximum at a relatively long crack spacing, and it remains at that level even for longer crack spacings, if all factors are the same (see figure 63). On the other hand, short crack spacings generate significant bending stresses in the transverse direction. The load transferred in the longitudinal direction across transverse cracks will depend on the moment transfer and aggregate interlock that, in turn, are a function of crack width as well as the dowel action produced by the reinforcing steel.[20]
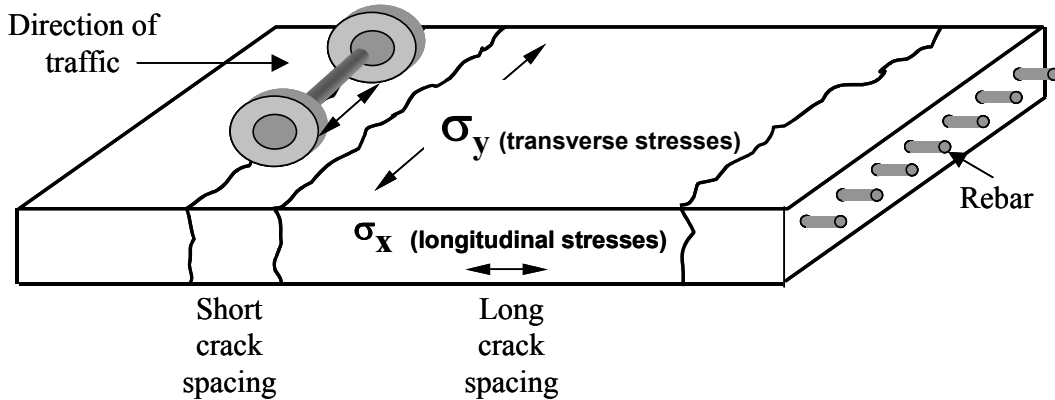
Figure 62. Schematic of position of tensile stresses in CRCP.
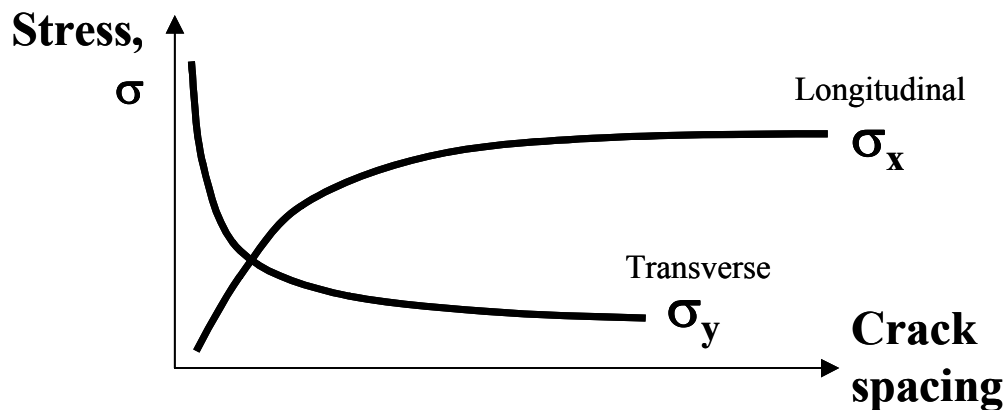
Figure 63. CRCP longitudinal and transverse stresses in CRCP as a function of crack spacing.

4.7.6 Distress Prediction

Eventually, load transfer at transverse cracks is reduced due to traffic and temperature fluctuations. That is, the loss of load transfer reduces the capacity of the pavement to distribute load across transverse cracks (longitudinal direction). As a result, the slab between short cracks will tend to act as a beam with the longer dimension in the transverse direction, producing high bending stresses in the slab. The deflection produced by wheel loads thus tends to increase, aggravating the loss of aggregate interlock. In addition, the repeated action of traffic and precipitation, combined with subbases prone to erosion, may weaken the support provided by the subgrade. Depending on the strength and fatigue

characteristics of the concrete, subgrade support, loss of load transfer, and load applications, longitudinal cracks interconnecting closely spaced transverse cracks form and lead to what is commonly known as a punchout distress. This is illustrated in figure 64.

4.7.7 Pavement Long-Term Performance History

At every individual punchout location, the isolated piece of slab between transverse and longitudinal cracks will eventually continue to deteriorate, inducing spalling at the cracks. Reduced subgrade support and loss of load transfer may also result. In advanced stages of punchout distress, the traffic applications, combined with loss of support, load transfer, and pavement stiffness, rupture the steel reinforcement. Corrosion also causes steel rupturing, which can contribute to a significant reduction in the cross-sectional area of the reinforcement.[18]

The number of punchout distresses commonly increases with time. Faulting progression for a typical CRCP section is shown in figure 65. Faulting progression is a function of the continuing pumping of the subbase materials, loss of aggregate interlock, concrete strength and fatigue characteristics, traffic applications, and climatic conditions.

Figure 64. Typical CRCP punchout distress.
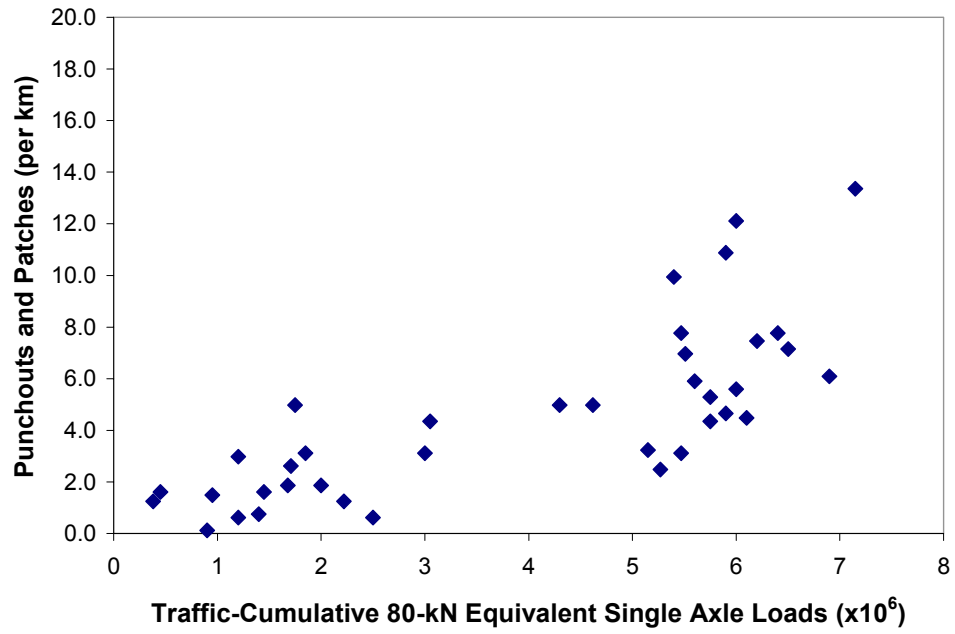
Figure 65. CRCP punchout progression with time.

CHAPTER 5.   HIPERPAV II INPUT PARAMETERS

This section discusses input parameters that influence the early-age behavior of JPCP and CRCP. This section will also outline general guidelines for designing and constructing these pavement types. Inputs to these guidelines are divided into the following five basic categories; these are discussed in the following sections.

1. **Pavement Design**—These inputs often are selected in the preconstruction phase based on factors such as structural capacity. However, some of these inputs can be adjusted, possibly up to the day of construction.

2. **Materials and Mix Design**—PCC is a combination of aggregate, cement, water, and other additives. To achieve the desired concrete performance, the type and proportioning of these components can be modified. This section discusses how these factors control concrete behavior.

3. **Climate**—Climatic conditions are often the most unpredictable and uncontrollable inputs that affect pavement performance. The user must consider the high variability of climatic conditions and understand the sensitivities of the results as a function of these factors.

4. **Construction**—Construction inputs sometimes can be specified to meet the specific needs of the project. Typically, modifying these are less expensive than modifying other nonconstruction-related variables. Construction practices can affect the long-term performance of the pavement significantly.

5. **Traffic Loading**—Over time, pavements are subjected to increased traffic loading. The pavement should withstand the designed traffic loading. These guidelines discuss how traffic loading is considered in long-term pavement performance.

The following sections detail the specific recommendations and guidelines for input selection in each of the five categories. Because these guidelines provide only general guidance for selecting the input parameters, the user must exercise sound judgment when selecting the final input parameters. To make the final decision, other factors such as economics, material availability, and ease of construction also should be considered. These guidelines are not intended to optimize the decision process, but they do provide a means by which to predict the success or failure of a particular combination of inputs to the overall performance of a JPCP or CRCP.

5.1   DESIGN INPUTS

Pavement design parameters typically are selected before construction based on the project site location. Factors such as type of subbase to be used can significantly impact both the early-age and long-term performance of the JPCP and CRCP. Other design parameters, such as thickness, drainage, and joint spacing (if applicable) also have an influence on the pavement's long-term behavior.

5.1.1 Pavement Type

Four general types of PCCP are constructed today. JPCP is the most common. Its transverse joint spacings are typically 4.5 to 6 m, and it contains no slab reinforcement. If a crack occurs at midslab, only the aggregate interlock will transfer load across the joint. Jointed reinforced concrete pavement (JRCP) is another type of pavement. Its transverse joints are longer, with spacings typically between 12 to 30 m. This pavement is reinforced at midslab, allowing for the longer joint spacing. Cracks can occur midslab where the reinforcement holds the pavement together, providing load transfer efficiency. CRCP does not have transverse contraction joints. It is heavily reinforced, and this reinforcement holds the cracks closed that do form. The last type of pavement is prestressed concrete pavement (PCP). It is constructed using the prestressed concrete girder ideology—by applying a compressive stress via post-tensioned cables to the pavement, it can resist greater loads, and thus may be constructed with a smaller cross-sectional area and longer spans. FHWA and the Texas Department of Transportation (DOT) recently have sponsored some recent pilot sections in Georgetown, TX, for using precast PCP in rapid construction projects, and additional work is underway for implementation of this technology in other States.[45]

Of these four pavement types, JPCP comprise the greatest number of new and existing concrete pavements. CRCP is increasingly popular due to the minimum maintenance required, but only accounts for a small fraction of the lane-miles of concrete pavement. PCP and JRCP are not as commonly used as the other types. Only JPCP and CRCP will be discussed further in these guidelines.

5.1.2 Thickness

Thickness design of JPCP or CRCP usually is based on long-term pavement performance requirements. Traffic-induced loading can lead to fatigue and other forms of cracking, spalling, and faulting. Each of these distress types can be controlled to different degrees by specifying a thicker cross section. In general, a thicker pavement will lead to a lower potential for early-age and long-term damage.

For CRCP, the thickness of the slab is believed to affect crack width. Thicker pavements tend to result in smaller crack widths. A possible explanation for this behavior may be that thicker pavements have less exposed surface in relation to their volume than thinner pavements. As a result, thicker pavements are less affected by drying shrinkage.[16,19] With respect to crack spacing, thicker slabs provide a higher stiffness to the pavement, thus reducing the level of deflections at which the pavement is subjected due to wheel loads. Thinner slabs, on the contrary, are subjected to larger deflections, and therefore higher stresses develop, contributing to the development of additional transverse cracks, thus reducing the crack spacing.

5.1.3 Joint Spacing

In these guidelines, joint spacing is a design input only for JPCP. At early ages, joint spacing controls the amount of stresses that accumulate in the pavement. The joints relieve the thermal and frictional interface stresses by allowing controlled cracks to form. Joint spacing is also a significant factor that influences the joint opening size. At later ages, joint opening determines the load transfer efficiency of the aggregate interlock across the joint. Joint sawing (and dowels, if used) are costly, so a tradeoff between cost and allowable stress level usually occurs in the selection of the optimal joint spacing.

5.1.4   Reliability

Reliability is a measure of design (or system) effectiveness based on the variability of each individual component. Each of the input parameters identified in this study has a different degree of variability associated with it. Reliability concepts are used to reduce the individual variabilities to a system reliability. By selecting a certain level of reliability, the user is, in essence, selecting the confidence level of the analysis and an acceptable level of risk. For example, if a reliability of 95 percent is selected, the user is willing to accept a 1 in 20 chance (5 percent) that the results obtained using these guidelines will be outside the bounds of what is predicted (unconservative). By selecting a higher level of reliability, the odds decrease. However, the higher the reliability, the more conservative the design may become, making it cost prohibitive.

The user should select the optimum reliability level based on the function and importance of the facility. For low-end facilities, such as streets or local roads, a lower degree of reliability may be chosen (50 to 85 percent). For primary or interstate highways, a higher degree of reliability should be selected (90 to 95 percent).

5.1.5   Drainage

Water drainage from pavement layers is extremely important if the pavement is to provide suitable long-term performance. Excess water, in combination with heavy traffic loads, can lead to early distress of the pavement structure, such as faulting, transverse cracking, and corrosion of steel elements (dowels and steel reinforcement). Water can also reduce the strength of unbound granular subbases and subgrade soils. Water causes pumping and erosion of material from under the slab, and results in loss of pavement support. For CRCP, crack widths should be kept less than 0.5 mm to prevent water infiltration.[2] Pooling of the water between the slab and the subbase also can cause concrete deterioration that leads to spalling, especially in frost-susceptible regions. The effect of water on pavement properties, and its affect on the structural capacity of the pavement, must be considered when predicting the long-term behavior of JPCP and CRCP.

For pavements, three different drainage systems are commonly used: 1) surface drainage; 2) groundwater drainage; and 3) structural drainage. These drainage systems are designed to drain water as quickly as possible away from the pavement system. The design of all important highways should consider the use of a drainage layer in the pavement structure.

5.1.6   Support Layers

There is commonly an engineered subbase course beneath JPCP and CRCP pavements. A subbase is typically a layer of granular or stabilized material. The subbase layer imposes restraint to volume changes occurring in concrete pavement during the early age. The restraint is the result of friction, adhesion, and bearing stresses that develop as a function of the subbase materials and construction procedures. For CRCP during the early age, the bond strength of the concrete to the steel is still weak, and the frictional restraint plays a more significant role in the pavement. After the bond strength increases with time, the subbase restraint is more negligible compared to the restraint imposed by the steel.[46]

By selecting a subbase with minimum frictional resistance at the slab-subbase interface, restraint can be minimized. This reduces the stress development in the pavement at early ages. A bond breaker can minimize slab restraint as well as reduce the possibility for reflective cracking from high frictional

subbases such as cement stabilized or hot-mix asphalt (HMA) subbases. Typical values of slab-subbase friction for various subbase types can be found in the HIPERPAV II software.

The type of subbase used has been found to influence the long-term performance of the pavement significantly. The subbase should be chosen to allow for optimal water drainage away from the slab. If water cannot drain, the concrete at the joint can deteriorate, and spalling damage is more likely in the long term. The amount of faulting is also related to the ability of the subbase to drain. In the presence of water, fines can pump underneath the slab, increasing the potential for faulting. On an impermeable subbase, such as cement-treated base, the pumping of fines underneath the slab on one end and the erosion of fines at the end of the other slab can lead to a loss of support, which can result in transverse cracking. These distresses can be prevented or delayed if the subbase provides good drainage. Good drainage is one of the most efficient ways to prevent pumping.[15]

The properties of the subgrade influence the long-term behavior of the pavement, especially in seasonal frost areas (see section 5.3.2). In these regions, the subgrade's resilient modulus varies significantly with changing seasons. Different subgrades are affected differently by effects such as thaw-weakening. Well-drained sandy soils tend to have a higher bearing strength, while clayey soils are generally weaker.[17]

5.1.7   Load Transfer

Load transfer commonly is understood as the ability of a pavement to transfer loads across a joint or crack, from one slab to another. Load transfer at joints or cracks in a concrete pavement can be provided by aggregate interlock and mechanical devices such as dowels. When loads are applied near a joint or crack for a pavement with poor load transfer efficiency, significant deflections often develop. Good load transfer efficiency between joints or cracks greatly reduces the level of these deflections and stresses. The deflection and stress is reduced because the adjacent slab helps support the load. Primary factors known to affect load transfer efficiency include load magnitude, number of applications, slab thickness, joint opening, subgrade support, and aggregate characteristics.[47]

5.1.7.1   Joint Design

JPCP pavements are susceptible to cracking due to restraint to expansion and contraction movements with changes in temperature and moisture. Transverse and longitudinal joints commonly are sawed or formed at regular intervals to control the spacing of the cracks and provide a uniform shape that is easier to seal against infiltration of water or incompressibles. The joint depth must be designed to create a weakened plane that intensifies the stresses at the joint location and therefore induces the crack to occur at that point. However, the depth of the joint also affects the load transfer, because the area of aggregate interlock through the thickness of the slab is reduced.

5.1.7.2   Load Transfer through Mechanical Devices

Application of loads, either by temperature or wheel loading, can be transmitted from one slab to the other by using dowels with JPCP or steel rebars with CRCP. Dowels in JPCP allow slabs to expand and contract while restraining the vertical movement from one slab to the other to avoid faulting. With CRCP, the expansion and contraction of the slabs is restrained by the steel to keep the cracks tight. Although steel is not designed for load transfer, the steel restrains the vertical movement of CRCP, thus reducing stresses. Cyclic loadings commonly cause crushing of the concrete particles at the dowel

interface due to the high compressive stresses that develop at those locations. Eventually the dowel becomes loose, because voids are created around the dowel as the crushed concrete particles are removed.

5.1.7.3   Load Transfer through Aggregate Interlock

In the absence of dowels, aggregate interlock can provide load transfer at the joints and cracks. Aggregate interlock is primarily a function of the characteristics of the aggregate, including aggregate size, angularity, and abrasion. In a controlled laboratory study, Nowlen investigated the effect of aggregate characteristics on load transfer.[13] Major findings from that study included:

- Larger maximum aggregate size and aggregate angularity improved load transfer efficiency, especially for wider joint openings.

- Load transfer efficiency decreases with cumulative load repetitions; however, aggregates with increased hardness maintained a higher load transfer efficiency.

The loss in load transfer efficiency with application of loads has been corroborated by McCullough et al. in a load transfer study on CRCP.[2]

5.1.7.4   Effect of Joint/Crack Width on Load Transfer

The width of the contraction joint or crack plays an important role in the load transfer efficiency provided by aggregate interlock. Nowlen developed a looseness factor, which is a function of aggregate size and joint opening.[13] In his study, he showed that wider joints correspond to less effective load transfers provided by the aggregate interlock. In the study performed by McCullough et al., a reduction in load transfer efficiency in CRCP was also found with larger crack widths.[2]

5.1.8   Reinforcement

Primary steel properties known to influence CRCP transverse cracking include the percent of longitudinal steel, bar size, and vertical location of longitudinal steel with respect to slab thickness.

5.1.8.1   Percent of Longitudinal Steel

An increase in percent of longitudinal reinforcement will increase restraint. As the level of restraint increases, so does the number of cracks that develop, resulting in shorter crack spacings. In addition, the spacing of the transverse steel is commonly a function of the amount of steel used. It is believed that as the amount of steel increases, the average steel stresses are reduced, producing less elongation of the steel, which, in turn, leads to a decrease in crack width.[16] Previous investigations have shown that this effect is significant for steel percentages of 1 percent or less.

5.1.8.2   Steel Surface Area (Bar Size)

For a given amount of steel, larger bar sizes result in less steel surface area. The average crack spacing decreases with an increase in ratio of steel surface area to concrete volume. A possible explanation to this effect is that the high tensile stresses in the steel at crack locations are transferred to the concrete as a function of the steel surface area and deformation characteristics of the longitudinal steel.[46] On the other hand, the greater the bond area, the more the steel imposes restraint to movement of the concrete, and therefore, tighter cracks are expected to result. However, some studies have found that

although this theory holds for limestone aggregates, the opposite trend is observed for the case of siliceous aggregates.[19]

5.1.8.3   *Vertical Location of Steel and Number of Steel Layers*

During the early age, the concrete is subjected to differential thermal and moisture gradients through the depth of the slab, primarily as a function of climatic conditions and curing methods. The location of the steel with respect to pavement depth will affect the crack widths. For example, since drying shrinkage is more pronounced at the surface of the slab, placing the steel close to the surface maintains crack widths tight more effectively. However, adequate concrete cover also should be maintained around the steel. Two-mat placement has been implemented in the Texas DOT specifications for pavements thicker than 330 mm. This helps in maintaining optimum steel bond area to concrete volume ratio and also allows for steel closer to the CRCP surface, where shrinkage strains tend to produce larger crack widths. In HIPERPAV II, the number of steel mats is used to determine the change in percent steel only. As new models are available that consider the effects on shrinkage and other behaviors as a function of the steel depth and number of bar mats, they maybe included in HIPERPAV II.

5.2   MATERIALS AND MIX DESIGN INPUTS

PCC consists of three basic constituents: aggregate, cement, and water. To modify a particular property of the PCC, SCM and chemical admixtures can also be used. SCM include, but are not limited to, pozzolans, fly ash, and ground granulated blast furnace slag (GGBFS). Chemical admixtures that can be used include superplasticizers, water reducers, and retarders. Fiber reinforcement, synthetic or steel, is another additive. SCM and admixtures can often affect the early-age behavior of the PCC during the hydration period, especially in fast-track mixes. However, modifications of the three basic PCC components, both in type and content, can also affect the overall concrete performance.

The following sections will highlight the influence of material parameters on the behavior of PCC, with emphasis on the fast-track mixes.

5.2.1   Aggregates

Aggregates are, both by volume and by mass, the largest component of a PCC mix. By volume, they account for 60 to 80 percent of normal weight concrete. Because of this, aggregate properties can significantly affect the early-age and long-term performance of the concrete. The characteristics of the bond between the concrete paste and the aggregate is also a significant factor on concrete performance. At very early ages, the bond between the aggregate and the cement mortar is not yet at its maximum. Failure will most likely occur in this weak zone. At this very early age, aggregate strength does not strongly influence concrete behavior. However, once this bond has formed, then aggregate strength has a greater influence on concrete strength. PCC properties typically are modeled as a weighted combination of the individual component's properties.

Chemically, aggregates are composed of one or more minerals. Aggregates typically are formed naturally, but they can be manmade (such as steel slags). Many aggregates can be divided into two general categories of calcareous or siliceous. Calcareous aggregates include limestones and dolomites. Siliceous aggregates include granites and quartzes. Some aggregates, particularly sands and gravels, can be a blend of these two types.

All other factors being equal, concrete pavements constructed with aggregates that have a low CTE (e.g., many calcareous aggregates) perform better than those built with aggregates with a high CTE (e.g., many siliceous aggregates). Higher stresses can form in the pavement because the high coefficient aggregates experience greater expansion and contraction from temperature changes. These higher stresses may produce cracks that reduce long-term performance. If an aggregate with low CTE is used, there is less thermal shrinkage. In the final selection of aggregate type, factors other than CTE, such as availability and cost, should be included in the decisionmaking process. If siliceous aggregate with a high CTE is the only locally available material, precautions should be taken to minimize early-age damage. These precautions, such as cooling the coarse aggregate before use, will be discussed in more detail in the following sections.

The aggregate proportion of the mix design can also influence early-age behavior, although it is considered to be relatively insensitive when compared to others. However, by increasing the relative proportion of aggregate in the mix design as compared to the other constituents, the stiffness of the mix will be higher for both the plastic and solid states. Therefore, the stresses will be greater, and the potential for early-age damage will be greater.

Other aggregate properties, including shape and gradation, influence the behavior of the pavement in the long term, as well as at early ages. In JPCP, it may be only aggregate interlock that transfers the load across the joints. Aggregates with an angular shape provide better load transfer across the joint than do round aggregates. Likewise, large aggregates are better able to bridge a joint opening, and hard aggregates are able to resist the joint shear stresses. The bond between the angular aggregate and the cement matrix is generally higher as well, often resulting in a higher flexural strength. However, angular aggregate can reduce workability of the fresh mix, increasing the air content during placement.

Durability of aggregate also affects the long-term performance of pavements. Aggregate should resist deterioration caused by weathering, such as freezing-thawing and wetting-drying. Clay balls and shales should be avoided because of their susceptibility to moisture swelling. If freeze-thaw susceptible aggregates are near the surface of the pavement, they can expand and break out of the surface of the pavement. Low durability aggregates typically have a higher porosity, and are easily saturated. In pavements with poor drainage, saturated aggregates at the bottom of the slab can cause D-cracks to form, which can progress upward.

The absorptivity of aggregate directly correlates to concrete shrinkage. Granites and quartz have low absorption and low shrinkage, while sandstone and slate have higher absorption and therefore have higher shrinkage.

The type of coarse aggregate also has a marked effect on spalling and cracking distresses. In CRCP, it was found that pavement constructed with crushed limestone had less damage that those constructed with siliceous river gravel. Reasons for this may include the lower stiffness and better bond to the cement matrix in the limestone concrete.

Primary aggregate factors known to influence the cracking characteristics of CRCP include its angularity, bond strength properties, the CTE, and the drying shrinkage properties. Previous investigations have shown how the angularity and bond strength properties of the aggregate play an important role in the development of tensile strength in the concrete. As cracking in CRCP form whenever the tensile stresses exceed the tensile strength of the concrete, the characteristics of the coarse aggregate type used will have an effect on crack spacing. Particularly, aggregates with increased angularity provide higher tensile strengths than rounded aggregates.[46] Because the coarse aggregate type is one of the major components in the mix, the drying shrinkage and CTE of the aggregate commonly will govern the contraction/expansion of the concrete. As previously mentioned, differences in the CTE of the

steel and concrete induce an internal restraint to volume changes that generates stresses in the concrete and therefore influences cracking. In general, coarse aggregates with a high CTE result in shorter crack spacings than aggregates with low CTE.[19] Some studies have also found that aggregates with low CTE result in smaller crack widths.[19] Drying shrinkage in the concrete is a result of several factors, including the w/c ratio, relative humidity, curing method, and coarse aggregate type. The resulting drying shrinkage will affect crack spacing, as drying shrinkage contributes to the volume changes in the concrete and therefore to stress development. Aggregates with higher drying shrinkage characteristics usually result in wider cracks and closer crack spacings.

5.2.2   Cement

Properties of concrete change as a function of time, primarily due to changes in the cement paste. This is particularly true at early ages. Because the hydration process is complex and mix specific, these general guidelines should be used with caution. Improper selection of the cement type can lead to a poor performing pavement. The four basic types of cement commonly used in paving concrete are:

- Type I: Normal cement.

- Type II: Moderate sulfate resistance.

- Type III: High early strength.

- Type V: High sulfate resistance.

Of these, Types I, II, and III are most commonly used for fast-track mixes. Type V is only occasionally used for PCCP construction, in areas of high sulfate contents in the soil due to deicing salts or in saline environments near the sea.

These four types of cement are all hydraulic cements that react chemically with water. This reaction generates heat, and for each cement type, heat is released in different quantities at different rates. The strength of PCC is directly related to the amount of heat generated by this chemical reaction. In general, Type III cement releases its heat earlier than do the other types of cement. It is a high early strength cement. Type V is at the other extreme. It releases heat slowly and gains strength slowly as a result.

Type III cement often is specified in fast-track mixes. It allows pavements to open only a short time after construction. However, detrimental side effects can result. Because of the high heat generated, the early-age pavement stresses can be quite significant. Cracks may be noticeable as the concrete cools down from the maximum heat of hydration. The use of Type III cement for fast-track paving should be monitored carefully. In addition to Type III cements, Type I and even Type II cements have been used in fast-track mixes. These applications can be successful if measures are taken to maximize the concrete's strength gain during pavement construction for all but the shortest opening criteria.

In general, Type I cement is recommended in fast-track mixes, unless a very short opening criterion is demanded, or if Type I cement can not generate the required strength gain. When a Type III cement is needed, it is recommended that the time of the maximum heat of hydration be set to a different time as the maximum air temperature. This may require that construction takes place in the late afternoon or evening. Night paving is recommended in the southwest United States during the summer months, for example.

The amount of cement in a concrete mix influences its early-age behavior. Large cement contents usually cause shrinkage problems and also produce significant levels of heat in the slab. However, higher

cement contents can improve workability and strength. However, the same two benefits can be achieved by adjusting the w/cm ratio, or by using admixtures. The later is recommended to improve concrete's workability and strength. The w/cm ratio is defined as the mass of mix water (including free moisture on the aggregates) divided by the combined mass of the cement and any additional cementitious materials, including fly ashes, silica fume, and GGBFS. This ratio is important, as it determines the overall strength of the mix as well as other mechanical properties, such as creep and shrinkage. Because increasing the w/cm ratio generally will decrease strength, it should be kept as low as possible while still maintaining a workable mix. Additional information on mix design proportioning can be found in the literature.

The different types of cement also have different long-term performance. Generally, the finer the cement is ground (as for Type III), the higher the strength gain at early ages, but the lower the strength gain at later ages. Concrete constructed using Type I cement continues to gain strength as it matures in the field. The finely ground cements (Type III) are less durable in the long term than are the coarser ground cements (Type I).[5] Likewise, higher strength concretes often have numerous cracks.

5.2.3 Chemical Admixtures

Several types of chemical admixtures can be added to concrete for pavement construction. Admixtures can be used to allow concreting in hot and cold weather conditions. The following is a list of the various types of chemical admixtures and how their use affects PCC mixes.

5.2.3.1 Accelerators

Accelerator admixtures increase concrete's strength gain at early ages. Calcium chloride commonly is used in accelerator admixtures. Accelerators can be used in place of Type III cement if the cement is not available or is too expensive. The same cautions for using Type III cements are given for using accelerators. Their use can also lead to long-term durability problems associated with early-age high heat generation, increased drying shrinkage, reduced creep capacity, potential reinforcement corrosion, and scaling.

5.2.3.2 Air Entrainers

Air entrainers are the most commonly used PCC admixture. They entrain microscopic air bubbles in the concrete. A minimum level of air entrainment commonly is mandated in construction specifications, since it has been shown to increase concrete's long-term durability as well as its workability. However, air-entrainment does reduce concrete strength, so care should be taken when using it, especially in hot-weather conditions.

5.2.3.3 Retarders

Retarders extend the concrete's set time, reduce the rate of strength gain, and commonly act as water reducers. They can be useful with long haul times from the batch plant to the pour site. However, they can be detrimental to the concrete's structure. Retarders can offset the increased strength gain when constructing in hot weather, but they are rarely used in fast-track pavements.

5.2.3.4 Superplasticizers

Superplasticizers can reduce the amount of water required to achieve a workable concrete mix, if used properly. They are high range water reducers that can reduce water demand by 12 to 30 percent. They can be used to reduce the w/cm ratio, increase concrete strength, and expedite strength development. Superplasticizers are often used in fast-track mixes because of these beneficial effects under hot weather conditions. Typically, they are added at the construction site because the increase in workability is short-lived, from 30 to 60 minutes.

5.2.3.5 Water Reducers

Water reducers act in a similar manner to superplasticizers, but to a lesser extent. They reduce water demand at least 5 percent and can produce the desired slump. They can extend the working time of concrete by a couple of hours and also accelerate the concrete's strength gain. However, they may significantly increase drying shrinkage, so caution must be exercised when using them. Water-reducing admixtures improve workability by changing the electric charge of the cement particles, which improves dispersion of the cement particles and makes more water available for hydration. Therefore, the hydration of the cement is improved, with a consequent slight increase in strength development.

Of these chemical admixtures, air entrainers are considered to be an essential element in PCC (where applicable). In general, many mix designs can be developed using an air entrainer, superplasticizer, and possibly accelerators. These materials should be used based on past experience, availability, and economics.

5.2.4 Supplementary Cementitious Materials

Fly ash, silica fume, and GGBFS have all been shown to increase later age compressive and tensile strengths and/or durability of concrete (reduced permeability) when used properly. It is difficult to generalize the effect of SCMs on concrete properties. Each one can influence the behavior of the concrete differently.

5.2.4.1 Fly Ash

Pozzolans such as fly ash are the most common type of SCM. These minerals partially replace the cement, and some (particularly Class F fly ash) improve workability, reduce the heat of hydration of the concrete, and retard concrete's setting time. Benefits of replacing cement with fly ash include improved workability and lower cement demand.[48] The strength of concrete at early ages is usually reduced by incorporating fly ash.[49] However, satisfactory long-term strength gains are obtained. Common ranges of cement replacement with fly ash are between 10 and 50 percent. In general, fly ash retards cement hydration, consequently retarding the strength gain. This retarding effect is more considerable at low temperatures. Class C fly ash possesses more cementitious properties than Class F fly ash due to its higher free lime content.

5.2.4.2 Ground Granulated Blast Furnace Slag

GGBFS is used commonly in concrete operations for economy reasons at proportions of 25 to 50 percent by weight replacement of cement. Higher slag contents are used for durability or sulfate resistance. Incorporating GGBFS in the mix tends to prolong the hydration, but in the long term, strength increases to a satisfactory level depending on the percentage of cement replacement. The setting time of

concrete increases with the use of GGBFS.[49] Final setting of PCC can be delayed as much as several hours, depending on the ambient temperature and mixture proportions.[49] Significant retardation in setting time of the PCC has been observed for curing temperatures lower than 23 ºC.[49] At temperatures lower than 10 ºC, the strength development of GGBFS is poor, and using it is not desirable.

5.2.4.3 Silica Fume

Silica fume reduces the permeability of the mix and significantly increases its compressive strength. The use of silica fume, despite its benefits, is often limited due to reduction in workability, placeability, flowability, and finishability. Replacing cement with silica fume has been limited in some standards to 10 percent.[48] However, up to 15 percent of silica fume has been incorporated successfully in concrete.[49] Incorporating silica fume improves cement hydration. The development of heat of hydration in ordinary PCC with silica fume has been observed to be as high as that of rapid hardening cement alone for certain mix proportions.[9]

5.2.5 Mix Design

Concrete mix designs should be optimized for workability, strength, economy, and other concrete properties before using these guidelines. Several mix designs are appropriate for concrete pavements. The selected design should be tailored to the specific environment the pavement will be subjected to during its lifetime. For concrete pavements, high early strength, high ultimate strength, and low permeability are all desired criteria for high-performance pavements. A number of other factors should be considered in mix design.

One of the most important factors affecting the properties of hardened concrete is the w/cm ratio. This ratio controls the quality of the paste and therefore impacts the durability and strength of the concrete. The concrete is a mixture of the paste and the aggregate, so the aggregate properties and characteristics are very important to the concrete's quality. Aggregate gradation and particle size, shape, and surface texture are all important.

Another key factor is the concrete's 28-day strength. The 28-day strength should be selected to satisfy the long-term design criteria. Proper selection can delay, or even prevent, fatigue and traffic-induced cracking. It is recommended that the highest possible strength be selected in design, balancing the adverse effects of high shrinkage and rapid heat generation that can result.

Other factors, such as shrinkage, should also be accounted for during the mix design process. If the concrete's paste content is too high, shrinkage cracks can form. To achieve a lower paste content, the gradation of the aggregate can be optimized and, in some cases, also will result in an increase in the strength of the mix.

Because many of the PCC constituents can exert both positive and negative influences on the properties of the concrete, the engineered mix should first be verified against the numerical guidelines. If the mix fails this test, modifications can be made to the mix based on engineering judgment and the criteria outlined here.

5.2.6 Strength and Maturity

The strength development in concrete begins after the concrete sets. Strength develops primarily as a function of the w/cm ratio; cement, admixtures, and aggregate characteristics and content; the curing

temperature; and moisture state. The strength of the concrete depends on the strength of the cement paste, the strength of the aggregates, and the bond strength of the cement/aggregate interface.

The rate of strength development is a function of the cement properties such as the cement fineness and cement compounds, along with SCM and admixtures used. In general, cements with a higher fineness will tend to hydrate faster and develop a high early strength, although the strength development at later ages may be lower when compared to coarser cements. Furthermore, it has been observed that fine ground cements are associated with durability problems.[5] A similar effect on the strength development occurs when the concrete is cured at high temperatures. A rapid strength increase is observed at early ages, and a less steeper strength increase is noted on the long-term strength.

It is also important to mention the effect of moisture on concrete strength. For concrete pavements, pronounced moisture profiles may occur as a consequence of climatic conditions. Whenever the internal relative humidity in the concrete drops below 80 percent, the strength development is affected significantly.[6]

The primary mode of failure during early-age behavior is tensile stress; therefore, the tensile strength of the concrete is commonly the primary concern when evaluating the behavior of concrete pavements.

Maturity information can be obtained from laboratory tests as outlined in American Society for Testing and Materials (ASTM) C 1074.[50] With this approach, concrete strength is predicted by relating the strength obtained in the laboratory to a particular maturity of the concrete in the field according to its temperature history.

5.2.7   PCC Modulus of Elasticity

As with strength, the hardening process of concrete contributes to its stiffness or modulus of elasticity. The concrete modulus of elasticity is directly related to the concrete strength, and it also depends on the type of aggregates and its volume in the concrete mix. In general, a higher stiffness of the concrete leads to higher stresses induced to the pavement.

5.3   CLIMATIC INPUTS

Climatic parameters typically have the greatest variability of all the HIPERPAV II inputs. Actual weather conditions are unpredictable, so caution should be used when selecting these inputs. "Average" values of the climatic input may be satisfactory for most simulations, but the user should also test the effect of extreme conditions. The necessary climatic data for HIPERPAV II is available from the National Weather Service, from the meteorological department of the local media, or from a weather almanac. HIPERPAV II has the added advantage of storing this information in an internal database.

5.3.1   Early-Age Climatic Inputs

No one has direct control over the environmental conditions at the time of construction, but indirect control is available by selecting the time of day and the season. Five key climatic parameters directly influence the early-age performance of concrete pavements:

- Ambient air temperatures.
- Solar radiation (dependent on cloud cover).

- Windspeed.
- Average relative humidity.
- Relative humidity.

The first three parameters affect pavement temperature, and subsequently the stresses that form due to thermal expansion and contraction. The last two parameters (as well as the first three to a lesser degree) primarily influence the pavement's drying shrinkage, and must be considered.

Cloud cover is a necessary input to the guidelines. The cloud cover corresponds to the solar radiation and heat that the pavement is subjected to at the time of construction. The cloud cover can be estimated based on the knowledge of regional weather patterns for the specific construction season. For hot weather, sunny is the critical condition, compared to partly cloudy and overcast. On the other hand, overcast conditions may be more critical during cold weather concreting, as this condition may affect the strength gain. Again, these inputs can be pulled from the electronic database in the HIPERPAV II software.

Windspeed also influences early-age pavement behavior. Wind can cause convective cooling of an unprotected or minimally protected pavement. This can contribute to undesirable behavior, such as thermal shock. In addition, high windspeeds remove moisture from the surface of the pavement, increasing the potential for excessive shrinkage. Measures can be taken to reduce the effect of wind by various curing methods, such as blankets or polyethylene sheeting.

5.3.2   Long-Term Climatic Inputs

In the long term, influential climatic conditions are primarily:

- Air temperatures.
- Precipitation.
- Freeze-thaw cycles.

5.3.2.1   Air Temperatures

Similar to pavement behavior at early ages, air temperatures will affect the thermal gradient in the slab in the long term, influencing the curling and warping stresses. Expansion and contraction of the concrete is also affected by changes in temperature in the long term. Slab contraction will increase the crack or joint width and will affect the load transfer capacity at those locations. In addition, infiltration of water and incompressibles are more likely to occur at wider cracks or joints.

5.3.2.2   Precipitation

The effect of precipitation on pavement performance will depend, in large part, on the efficiency of the pavement drainage. Water from rainfall usually infiltrates through cracks or joints, shoulders, and pavement edges. The presence of water in the pavement, combined with the repetition of heavy loads, commonly results in the pumping of fines, degradation of subbase material, and loss of support, thus affecting pavement performance. Prolonged periods of rainfall, even of low intensity, may be more damaging to the pavement than short periods of rainfall with high intensity. Moisture absorption by the soil will be more pronounced under the former condition.

5.3.2.3   Freeze-Thaw Cycles

Frost heave in a pavement structure is a result of freezing temperatures combined with presence of water in the pavement, either from precipitation or other sources such as groundwater and movement of water table in liquid or vapor form. Frost heave is the raising of the pavement due to formation of ice crystals in a frost-susceptible subgrade or subbase.[51] Unlike HMA pavements, where damage occurs due to loss of subgrade support during frost melting, for concrete pavements, the capacity to distribute loads over larger areas make this type of pavement less susceptible during the thawing period.[52] However, the differential heave under the pavement slabs during freezing temperatures and presence of moisture at the subgrade increases stresses when combined with the action of traffic loads.

The freeze-thaw action also affects the durability of concrete. During freezing temperatures, water in the cement paste pores tends to expand, generating cumulative damage in the concrete with time. Lower w/cm ratios and air entrainment admixtures generally are used in freezing areas to reduce concrete damage. Low w/cm ratios usually result in fewer pores in the cement paste. Air entrainment in the concrete provides room for the water that is freely available in the cement paste to expand during freezing temperatures.

5.4   CONSTRUCTION INPUTS

Factors affecting the moisture or temperature state of the concrete pavement during construction will also affect its early-age behavior. Construction methods for JPCP and CRCP provide some of the most critical parameters that influence the pavement's early-age behavior and long-term performance. They are also the most flexible parameters, because these factors often can be modified onsite. This can, in most cases, prevent early-age damage and ensure a long-lasting pavement. In this section, five construction issues are discussed: curing, time of day of construction, initial PCC mix temperature, sawcutting methods and timing, and initial subbase temperature.

5.4.1   Curing

Curing methods and timing usually affect the development of concrete stresses and strength. Curing procedures control the moisture loss in the pavement, affecting drying shrinkage stresses. In addition, moisture loss due to poor curing conditions can decrease concrete strength. Several curing methods are readily available for PCCP construction. Selecting the proper curing method is key to constructing a high-performance concrete pavement. Because of the complexity of the pavement construction process, sound judgment should be used in addition to the general recommendations made here.

The most common curing method is the application of a liquid membrane, which is commonly white. The purpose of this type of curing compound is to minimize shrinkage cracking by minimizing excess moisture loss through evaporation. One of the two common methods of applying this type of compound is using a sprayer bar, which traverses the width of the pour and applies the membrane by sprayer jets evenly spaced across the pavement width. The second method is using a wand or other hand-held device, which is directed by human control. Neither of these application methods is fail-safe. The application rate is usually uneven, subjecting some areas of the pavement to greater moisture loss than others. A liquid membrane is beneficial in minimizing moisture loss, when used correctly. A double or triple application of liquid membrane can lead to an even lower potential for moisture loss-related distresses (e.g., plastic shrinkage cracking).

A second type of curing method is polyethylene sheeting. If used properly, this method is very beneficial in retaining moisture. By applying the sheeting, the moisture is trapped beneath the nearly impervious layer. This minimizes evaporation, thus drying shrinkage. However, if the sheeting is not securely fastened to the surface by edge weighting, wind can enter through the openings and increase the potential for early-age damage. In addition, because the sheeting cannot be placed until the PCC has hardened enough to sustain the disturbance from the sheeting application, a liquid membrane is usually applied first, with the sheeting placed later. Polyethylene sheeting also acts as a thermal insulator. This property can be beneficial if the construction site is subjected to rapid cooling following construction. However, it can be detrimental if used improperly. The insulation, in concert with the excess heat produced by fast-track PCC mixes, can result in too great a curing temperature, causing damage after placement.

Cotton mats or burlap are the third most common curing method used on PCC pavements. The benefits of this method are similar to that of polyethylene sheeting. However, in addition to blocking moisture loss, the cotton mats or burlap are usually wetted, providing free moisture that may counter the negative effects of drying on the surface of the slab. The cotton mats or burlap also serve as thermal insulators, so they are subject to the same benefits and drawbacks described for polyethylene sheeting.

The thinner the pavement, the more critical is the curing of the pavement, such as for overlays or whitetopping. The effects of drying shrinkage are limited to the surface; therefore, the large surface area of bonded concrete overlay (compared to the volume of concrete) subjects it to a greater sensitivity towards moisture loss than full depth paving. This, coupled with the greater heat loss, increases the probability of delamination or other types of early-age distress. Using an insulating curing method such as polyethylene sheeting, cotton mats, or burlap can minimize these distresses in many instances.

5.4.2   Time of Day of Construction

Unpredictable climate conditions at the time of construction can create a high level of uncertainty in the pavement's early-age behavior. However, the time of construction can be controlled, which can help offset some climatic uncertainty. By adjusting the time of day of construction, the pavement's temperature buildup due to hydration can be controlled. The concrete's strength gain can be maximized, and the pavement's early-age damage can be minimized. This control is especially critical for fast-track mixes. However, other factors, such as traffic, will often dictate construction schedules. Adjusting the time of construction should still be considered as a relatively inexpensive way to minimize early-age pavement damage. The optimal time of construction for hot and cold weather concreting is discussed below.

For hot weather concreting (ambient temperature greater than 32 °C), paving in the early evening and into the night generally is recommended. Delaying the time of paving to evening takes advantage of nighttime cooling. This offsets the concrete's heat gain during hydration. The subsequent warmup the following day also counters the effects of thermal shock, caused by the loss of hydration heat. This strategy minimizes early-age damage and also means that construction will take place during off-peak traffic periods. The user costs associated with construction will be minimized.

For cold weather concreting (mean daily temperatures less than 4 °C for 3 successive days), early morning paving is recommended. Construction in the early morning takes advantage of daytime solar radiation and heat generation to promote increased concrete strength. Cold weather retards the rate of hydration as well as the concrete's strength gain. For this method of construction, insulating curing methods such as cotton mats and/or polyethylene sheeting should be used in the evening for heat retention. This will minimize early-age damage.

5.4.3 Initial PCC Mix Temperature

The temperature of the air during construction, the hydration characteristics of the cement, and the subsequent increase or decrease of the air temperature after placement all govern the concrete set. The development of stresses in the concrete is a function of the temperature at set and the subsequent temperature changes. As a general rule, the most critical placement time is that which results in a peak temperature due to hydration of the cement coinciding with the maximum air temperature during the day. When the pavement is placed at higher temperatures, larger temperature drops are expected. Therefore, higher stresses in the concrete develop.

Because concrete temperature control is critical in constructing high performance pavements, the initial mix temperature is important. Several methods have been developed in the past to reduce its temperature by cooling one or more of the mix ingredients. Five of them are discussed below. The influence of cooling each ingredient on the mix temperature is related to the temperature, specific heat and quantity of each material. These techniques can be used during hot weather concreting.

1. **Cooling Concrete with Chilled Mixing Water**—Chilling the mix water effectively reduces the temperature of the concrete mixture. It is also one of the concrete materials that is the easiest to cool. Because the amount of chilled water cannot exceed the amount of mix water, this method can reduce the concrete's temperature a maximum of 5 °C. Chilling the mix water requires a sizable initial investment in mechanical refrigeration equipment and insulated water storage tanks, unless other chilled water sources are available, such as groundwater sources.

2. **Using Liquid Nitrogen to Cool Mix Water**—Another method used to cool mix water is to inject the water storage tank or feed line with liquid nitrogen. This method can reduce the concrete's temperature by as much as 10 °C. The cost of installing and supplying a liquid nitrogen supply vessel must be considered.

3. **Cooling Mixed Concrete with Liquid Nitrogen**—A cooling technique related to the one described above is to directly inject liquid nitrogen into the concrete mixture. This method provides one of the most effective means to utilize the cooling capacity of liquid nitrogen. It can reduce the mix temperature by 10 °C. It requires installing a liquid nitrogen supply vessel and an injection nozzle at the central mixers. Because this method is relatively expensive, its benefits must be carefully weighed against cost in fast-track concrete pavement projects.

4. **Cooling Concrete with Ice**—Adding ice to concrete's mix water can reduce the concrete's temperature by 10 °C, and it is more effective than chilled water in reducing this temperature. However, the actual temperature reduction is limited to the amount of cooled mixing water the concrete batch can accommodate. At the time of mixing, the ice must be weighed separately, because it has a different specific gravity from water. Block ice is a suitable alternative, but it must be crushed before addition. The heat of fusion of the ice also must be considered when calculating the final temperature of the mix. Using ice to cool concrete requires a large capital investment and may only be applicable when mixing occurs during transit.

5. **Cooling of Coarse Aggregate**—Another method commonly used to cool concrete is to cool the coarse aggregate. This can be done by spraying cool or chilled water onto the aggregate as it passes by on a conveyor belt. The water is then chilled to meet the concrete production requirements. To lower the temperature of the concrete mix 6 °C, the aggregate temperature

must be reduced 8 °C. The coarse aggregate should be saturated uniformly to avoid large variations in slump from batch to batch. Some other methods to cool the aggregate are to protect the stockpiles from direct sunlight, refrigerate them, or sprinkle them with water; these techniques can reduce the temperature of aggregate significantly.

Reducing the temperature of the cement portion of the concrete mix is not commonly done, because a temperature change of 6 °C generally will change the temperature of the concrete mix by only 0.6 °C.

For cold weather paving, it may be necessary to heat the mix. This also can be an issue for thin pavements or overlays, because heat is dissipated faster from them than from newly constructed pavements. Some of the techniques currently used are:

- **Heating Mixing Water**—Heating the mix water is one of the simplest and most cost-effective ways to increase concrete temperature. Because the specific heat of water is four to five times greater than that of most aggregate, its ability to retain heat is much greater. The mix water temperature can be increased by simply mixing the hot and cold feed water lines. When paving at temperatures below 10 °C, it may be more appropriate to heat the mixing water than to use an admixture designed to accelerate the set of the paving mixture.

- **Heating Aggregate**—To increase the temperature of the concrete mix, the aggregate also can be heated. Although this technique is less efficient than preheating the mix water, it may be required in extreme cold weather cases where increased strength gain is necessary. The recommended method for heating aggregate is to circulate steam through pipes over which the aggregate are stockpiled. Because of the large aggregate content in the mix, increasing their temperature can significantly affect the mix temperature. Steam heating the aggregate also is appropriate for cold weather concreting operations.

When using HIPERPAV II, the initial concrete temperature first should be estimated based on past experience. If a heating or cooling method is used, the initial mix temperature should be adjusted accordingly.

5.4.4   Sawcutting Methods and Timing

Joints in concrete pavements create vertical weakening planes in the concrete pavement to induce the cracks along their controlled axis, thus facilitating pavement maintenance and crack sealing. To minimize the potential for uncontrolled cracking in a PCCP, proper joint sawing procedures should be established. In general, the time of joint sawing should consider the following limiting criteria:

- The joint sawing should be performed before stresses develop in the pavement that are large enough to cause cracking. These stresses are the result of restrained volumetric changes from both temperature and moisture changes in the young pavement.

- The joints must not be sawed until the pavement is strong enough to support the weight of the sawing equipment and operator, and also strong enough to avoid excessive raveling due to the forces introduced by the cutting blade.

The results of various research efforts may provide the user with additional guidance in regard to this particular aspect of PCC construction. FHWA conducted one such research effort in 1994 that

produced guidelines for timing contraction joint sawing and the earliest loading for concrete pavements.[53]

5.4.5   Initial Subbase Temperature

Ideally, the temperature of the subbase should be as close as possible to the temperature of the concrete when placing the concrete during cold weather concreting. The ground should not be frozen, but could be thawed by steaming, coving with insulation, or spreading a layer of hot sand, gravel, or another material.

5.5   TRAFFIC LOADING INPUTS

Traffic is one of the most important factors influencing pavement performance. In fact, pavements are designed to resist traffic and climatic loads under specified levels of safety and comfort. Primary traffic characteristics include load configuration, traffic volume, traffic classification, traffic distribution, growth rate, and traffic wandering.

5.5.1   Load Configuration

Vehicular loads for highway pavements are conformed with varied axle configurations, including single, dual, tandem, and tridem axles. The type of axle typically will depend on the type of vehicle and the load that vehicle is intended to carry. In addition, vehicle axles are designed to resist specific loads according to the pressure at the tires. The stress imparted on the pavement at the surface will depend on the magnitude of the load and wheel contact area. The pressure imparted by the wheel on the pavement is practically equal to the tire pressure. The damage to which a pavement is subjected by a traffic load will depend on the axle configuration and tire pressure. In addition, because the elastic modulus is influenced by the loading rate at which a given material is subjected, the vehicle speed is also a significant factor in determining damage to the pavement.

5.5.2   Classification

Because traffic typically consists of varied wheel configurations and loading magnitudes, it is common to group traffic in these terms. In particular, for mechanistic methods of design or analysis, different groups of axle configuration and distribution of magnitude of load per axle configuration (vehicle load spectra) are used more commonly to characterize traffic. Other methods of traffic characterization include fixed traffic or fixed vehicle methods. For fixed traffic methods, the most damaging load anticipated is considered for design. This method typically is used for airport pavement design. On the other hand, the fixed vehicle method involves considering a standard vehicle or axle load (typically 80-kilonewton (kN) equivalent single axle load (ESAL) for highway pavements). For this case, the number of repetitions of that load is considered, and traffic factors are used to convert axles with other configurations and load magnitudes. In more practical terms, traffic commonly is classified according to the type of vehicle such as automobiles, recreational vehicles, buses, trucks, and trailer trucks. This simple classification may provide an estimate of the axle configuration and magnitude of load per vehicle category.

5.5.3   Traffic Volume, Growth Rate, and Distribution

Knowing the amount of traffic loads expected during the design period is fundamental for long-term pavement analysis. The volume of traffic expected is usually provided in terms of annual average daily traffic and in terms of percentage per each vehicle category.

In addition, to predict the traffic expected for a given facility accurately, it is important to accurately estimate the rate of growth of traffic. For a given region, the traffic growth rate typically is affected by land development, construction of new facilities, economic growth, and other factors. A common practice of estimating traffic growth is by using methods similar to estimating the worth of money in the future with simple, exponential, or logistical growth functions.

Highway pavements typically are designed according to the traffic directional distribution (direction with greater percentage of traffic) and lane distribution (lane with greater percentage of traffic) for the case of facilities with more than one lane per direction. In addition, because pavement conditions are different depending on the time of the day (curling and warping) and season (soil support), the distribution of traffic through the day and throughout the year significantly affects pavement performance. Traffic distribution usually depends on the type of facility in question. For example, the traffic through the day for a city street typically concentrates early in the morning and in the afternoon (rush hours), while traffic for rural roads is typically less concentrated, and rather, spread throughout the day.

CHAPTER 6.   CASE STUDIES

This section illustrates the application of the HIPERPAV II guidelines to solve realistic case studies. The first two case studies demonstrate the application of the HIPERPAV II guidelines in identifying early-age factors that affect long-term pavement performance. The last two case studies demonstrate the use of the HIPERPAV II guidelines in identifying early-age factors that influence the cracking characteristics of CRCP.   Two scenarios are illustrated for each of the JPCP and CRCP case studies: a proactive scenario and a post-mortem scenario.

The proactive scenario may occur during the planning, design, or construction stage of a project. Under this scenario, the user of the guidelines may refer to chapter 5—HIPERPAV II Input Parameters— for the proper selection of HIPERPAV II inputs under the five categories of pavement design, materials and mix design, environment, construction, and traffic. Because these guidelines provide only general guidance with the selection of the input parameters in these categories, the user should employ engineering judgment in the final selection of the inputs.

For the post-mortem scenario, the user of the guidelines may be experiencing a particular problem, either occurring in the early age or during the long term. For this particular case, the user may refer to chapter 3, Early-Age Pavement Distresses, or chapter 4, Impact of Early-Age Behavior on Long-Term Performance, according to the nature and timeframe of the specific problem.

Under both scenarios, the user may refer to chapter 2, Early-Age Pavement Behavior, for a detailed understanding of the mechanisms occurring during the early age that influence the performance of the pavement in the long term.

6.1   PROACTIVE JPCP CASE STUDY: TIME OF PLACEMENT

During high temperature conditions, at what time of day should concrete be placed to minimize the probability of cracking?

6.1.1   Background

Under hot weather conditions, when air temperatures exceed 32 °C, concrete temperatures often increase rapidly after placement. This causes the concrete to set at a high temperature, and any significant cooling soon after set will produce high thermal stresses in the pavement. Cracks likely will develop and adversely affect pavement performance. This premature random cracking is commonly called thermal shock (see section 3.2).

The contractor, Jane Q. Buildalot, is scheduled to construct a 305-mm JPCP in Austin, TX, on July 18, one of the hottest days of the year. Knowing that high temperatures can cause unwanted cracking, she reviews the HIPERPAV II guidelines to help determine the optimal time to begin construction and still produce a pavement with good early-age and long-term performance. The time of day recommended in the guidelines for construction is early evening and into the night (see section 5.4.2). Delaying the time of construction to evening takes advantage of nighttime cooling, thereby offsetting the concrete's heat of hydration. Jane can use HIPERPAV II to solve for the exact window of time when paving will produce a high quality pavement at early age and also in the long term.

6.1.2   HIPERPAV II Analysis Strategy

HIPERPAV II can be used to assess how changing the time of placement impacts concrete stresses. For this case study, the HIPERPAV II temperature database will be used to estimate the climatic conditions on July 18. It is anticipated that the maximum temperature will be approximately 40 ºC and the minimum temperature 18 ºC. Jane is planning to use a concrete mix specified to reach a laboratory 28-day tensile strength of 3.2 MPa, with siliceous river gravel as the coarse aggregate. Sawcutting will occur at the optimal time.

Jane has several options besides changing the time of placement to avoid excessive concrete temperatures. She could use Type II cements or cool the concrete mix components. For this case study, however, she will determine the optimal time of placement for this specific concrete mixture (Type I + fly ash) to minimize the probability of cracking.

Twelve HIPERPAV II runs will be performed to determine how the time of placement affects the pavement stresses and the concrete strengths. The maximum stress-to-strength ratio will be determined for each scenario. A stress-to-strength ratio greater than 1 indicates the pavement will likely crack. A window of caution will be noted when the stress-to-strength ratio is greater than 1. Not willing to risk problems, she decides that no paving should be performed during this timeframe.

As illustrated in figures 66 and 67, changing the time of construction shifts the concrete's peak heat of hydration, allowing it to be offset from the maximum daily temperature.   Figure 66 illustrates how the concrete temperature rises sharply when its heat of hydration coincides with the peak daily temperature.
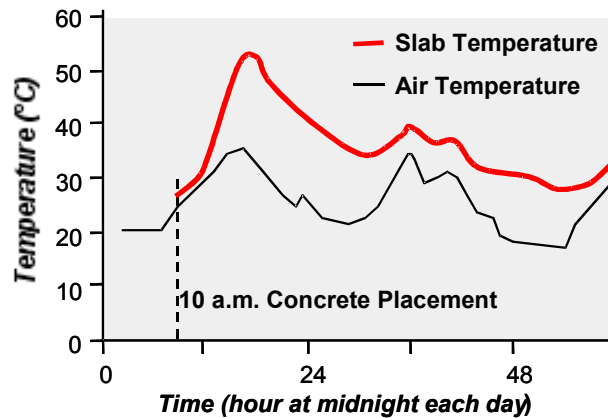
Figure 66. Typical temperature development in the slab for concrete placement at 10 a.m.

Intuitively, it is expected that concrete placed after the maximum air temperature (6 p.m.) and before sunrise (5 a.m.) will offset the concrete's heat of hydration and the maximum daily air temperature. This will produce the most desirable placing conditions, because it forces the peak heat of hydration to coincide with the minimum air temperature. The resulting temperature in the concrete will be low. The effect of early evening placement on concrete temperature is shown in figure 67.
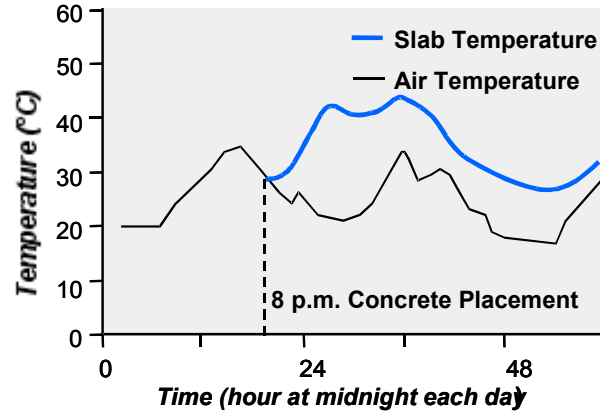
Figure 67. Typical temperature development in the slab for concrete placement at 8 p.m.

6.1.3   Solution

Jane performs multiple HIPERPAV II analyses at 2-hour intervals using a design reliability of 90 percent. The impact of changing the time of placement during hot weather conditions on the stress-to-strength ratio can be seen clearly in figure 68. For the conditions analyzed, the window of caution is from 7 a.m. to 5 p.m. These results clearly demonstrate how HIPERPAV II can be used to determine the best time of day for placing concrete to minimize the probability of cracking in JPCP.

Under these assumed conditions, the peak heat of hydration occurs about 6 to 8 hours after placement. Placement at 9 a.m. should produce the worst conditions, since 8 hours later, the peak air temperature is reached, thereby matching and amplifying the peak heat of hydration temperature.

After the window of caution is determined, Jane can use HIPERPAV II in an iterative manner to further investigate the effects of other proactive changes on minimizing the potential for cracking during the high-risk period of 7 a.m. to 5 p.m. The measures Jane can examine include different cement types, different aggregate types, cooled batching water, and base whitewashing.
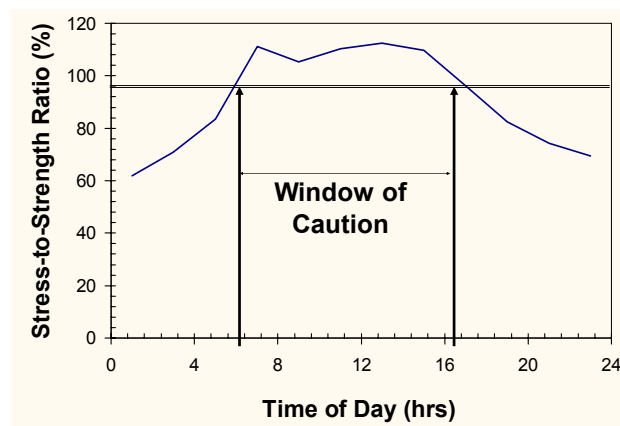
Figure 68. Early-age stress-to-strength ratio as a function of time of placement.

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6.1.4   Long-Term Performance

Now that Jane has determined the most favorable time to construct the pavement to prevent early-age failures, she wants to see how the time of placement influences the pavement's long-term performance. Reviewing the HIPERPAV II guidelines, she sees that joint opening, delamination, and built-in curling are some of the primary early-age indicators of long-term performance.

Jane suspects that built-in curling will definitely play a significant role in the long-term performance analysis, since the concrete is being placed during one of the hottest summer months, and the pavement likely will set with a positive thermal gradient. According to the guidelines, this will affect pavement smoothness, faulting, and cracking.

Entering the specific load transfer, construction, and traffic inputs for this project, she assesses long-term performance as a function of placement time at 90 percent reliability. For all of the runs, joint faulting is a constant 0.25 mm, and it is not affected by placement time. However, transverse cracking and smoothness of the pavement change as a function of the time of placement.

Figure 69 shows that pavements placed during the window of caution have the highest percentage of transverse cracking in the long term at 30 years, the expected design life. The pavements placed early in the morning and during the night have the lowest amount of long-term damage. Similarly, she finds that the serviceability and ride of the pavement will be the best if she places the JPCP outside of the window of caution (see figure 70).
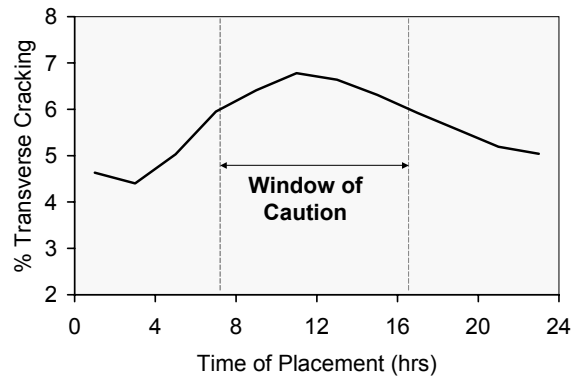
Figure 69. Transverse cracking as a function of time of placement.
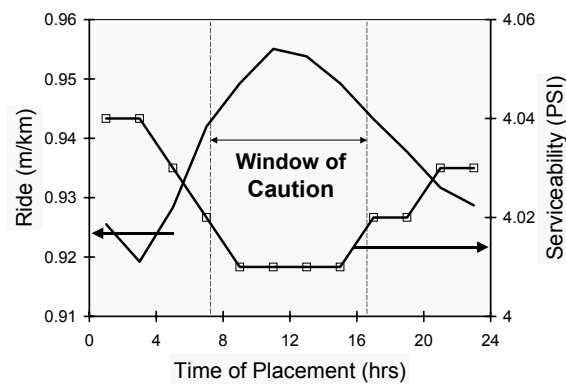
Figure 70. International Roughness Index (IRI) and serviceability as a function of time of placement.

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Based on this HIPERPAV II analysis, Jane is confident that placing the pavement at night and during the early morning hours will result in a pavement with few early-age distresses, and that the pavement will perform well in the long term.

6.2   POST-MORTEM JPCP CASE STUDY: FAULTING

After 10 years of use, a concrete pavement is faulting. Is it possible that this behavior was caused by early-age factors?

6.2.1   Background

The faulting of a nondoweled JCP in Austin, TX is increasing, and the engineer, Joe Q. Thinksalot, is determined to find out why. More specifically, he wants to see if early-age conditions may be a contributing factor. With the HIPERPAV II guidelines in hand, he turns to section 4.1: Faulting of JPCP without Dowels. He wants to connect the early-age behavior of this pavement to its long-term performance. The early-age joint design is cited as being one of the most influential factors. The joint opening of a nondoweled pavement is a function of the temperature change, joint spacing, slab-subbase restraint, and the load transfer efficiency.

Joe decides to use HIPERPAV II to help him understand how these four influential parameters affect JPCP performance. He will perform a post-mortem analysis on this 250-mm thick JPCP. Looking at the construction records, Joe finds that the slab length varied between 4.5 and 7.6 m, and that the pavement was constructed on a smooth asphalt concrete subbase. Additional information and measurements collected during a field inspection visit are presented below:

- 28-day lab indirect tensile strength: 3.6 MPa.

- The mix design specified a Type I cement mix with 18 percent Class F fly ash replacement. The aggregate used in this project is of siliceous origin.

- The air temperature at the time of placement ranged from a high of 32 ºC to a low of 16 ºC.

- The placement time was around noon on September 1, 1995. Skies were sunny and the windspeed averaged 10 kilometers per hour (kph).

- The slab was covered soon after placement with a single coat of the white curing compound. The initial PCC mix temperature recorded at placement was 24 ºC.

- Sawing operations occurred at the optimum time.

6.2.2   Analysis Strategy

Faulting occurs in JPCP as a result of several factors. Water enters the joint in the JPCP, and the subbase under the pavement becomes saturated. As the truck loads pass over the joint, the loose subbase material pumps. It comes out of the joint and causes the difference in elevation, as illustrated in sections 4.1 and 4.2 of this guide.

6.2.3   Solution

Joe uses HIPERPAV II to examine the effect of slab length, from 4.5 to 7.6 m, and dowels on JPCP early-age and long-term performance. The early-age critical stresses for the 4.5- and 7.6-m slab lengths are shown in figures 71 and 72. As expected, the stresses in the 7.6-m slabs are higher. The longer slabs experience more contraction and expansion around their centerline.
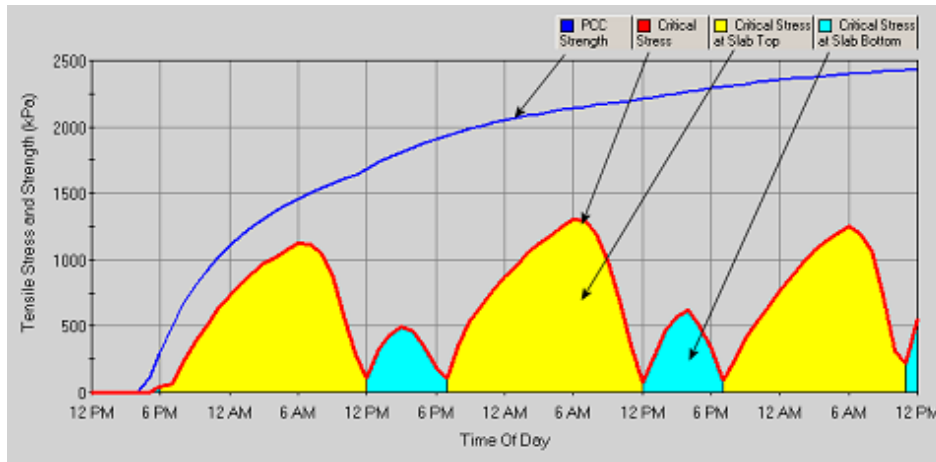
Figure 71. Early-age analysis results for 4.5-m joint spacing.
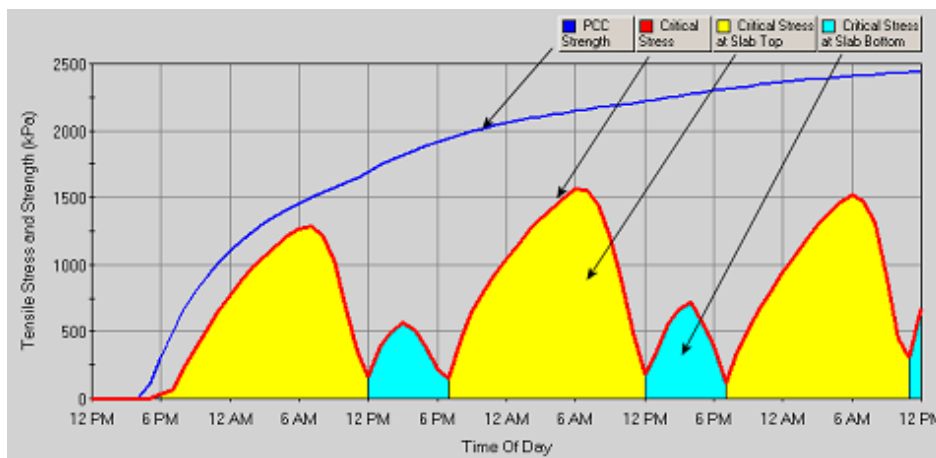
Figure 72. Early-age analysis results for 7.6-m joint spacing.

A long-term HIPERPAV II analysis yields the faulting results for the 4.5- and 7.6-m nondoweled jointed pavements shown in figure 73. The faulting of the 7.6-m slabs is approaching an objectionable level at 30 years. Comparatively, the faulting of the 4.5-m slabs is about 25 percent less.
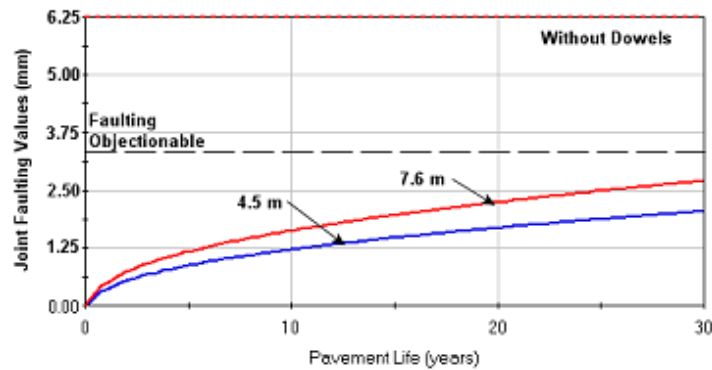
Figure 73. Predicted faulting for 4.5-m and 7.6-m joint spacing alternatives with no dowels.

Several design changes can be made to the JPCP to reduce its faulting. One possible alternative is to use dowels at the joints. Dowels are one of the most effective means to reduce faulting. The HIPERPAV II results demonstrate this, as illustrated in figure 74. Faulting of the pavements with dowels is 36 to 50 percent less than it was when the pavement was nondoweled.
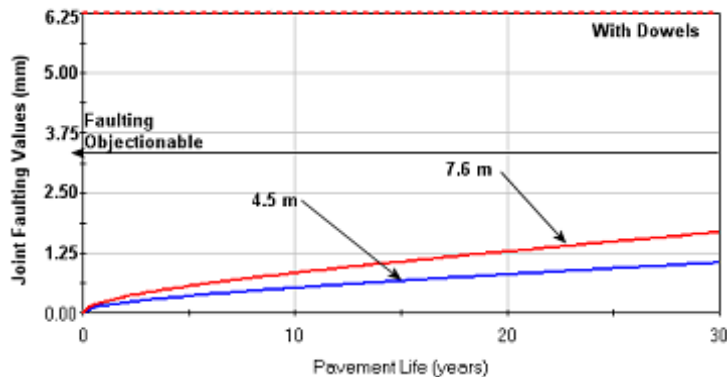
Figure 74. Predicted faulting for 4.5-m and 7.6-m joint spacing alternatives with dowels.

6.3   PROACTIVE CRCP STUDY: SEASONAL TEMPERATURE DROP

How does hot versus cold weather placement of CRCP influence its behavior?

6.3.1   Background

Cracks develop in CRCP a few hours to a few days after construction due to thermal stresses. In some cases, the cracks may not be apparent for 5 or 10 years, but after they do appear, they can rapidly progress into distresses that significantly affect the long-term performance of the pavement. Excessive thermal cracking often is due to high temperature differentials, excessive subbase friction, aggregates with high CTE/contraction, or a combination of the above.

6.3.2 Analysis Strategy

In this case study, a proactive seasonal analysis is performed on a 280-mm CRCP. The engineer, Mary T. Rifick, wants to see the influence of summer and winter placements on CRCP performance for a given steel design. She knows that thermal stresses play a significant role in CRCP crack development, and subsequently their long-term performance.

For guidance, Mary refers to the HIPERPAV II guidelines. In section 5.3, Climatic Inputs, there is a discussion on the effect of early-age and long-term climatic inputs on CRCP performance. She decides to perform two series of HIPERPAV II runs, one for summer placement (July 25) and another for winter placement (January 2) using the weather estimates contained in HIPERPAV II. Because of the unpredictability of actual weather conditions, she decides to adjust the posted 72-hour temperatures. She lowers the minimum air temperature after the critical analysis to 1 ºC.

When evaluating the HIPERPAV II analyses, Mary will examine the early-age indicators of long-term CRCP performance: crack spacing, crack width, and steel stress (described in section 2.3). She knows that if the average crack spacing is less than 1.1 m, it is likely that punchouts will form in the CRCP, decreasing its long-term performance (described in section 4.7).

6.3.3 Solution

To perform her analysis, Mary modifies the post-72 hour climatic data, but keeps all other inputs at their default values. Over time, the crack spacing decreases, as shown in figure 75. She finds that a winter placement yields a CRCP with a larger average crack spacing at 1 year (2.1 m) than does a summer one (1.7 m). This means that punchouts are not as likely to form when a CRCP is constructed in winter.
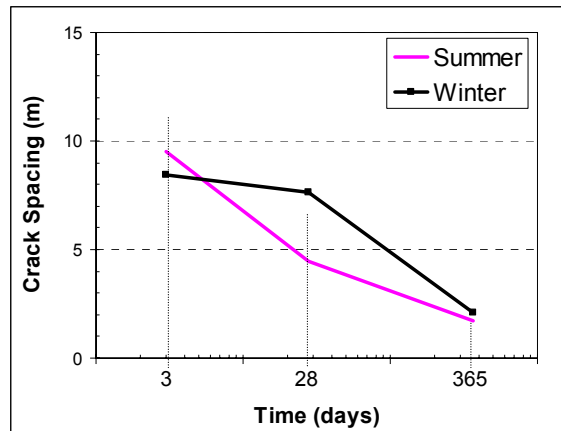
Figure 75. Change in crack spacing with time for summer and winter placements.

For both the summer and winter placements, increasing the temperature differential in the pavement (increasing ΔT) causes the crack spacing to decrease. As ΔT increases, the slab is subjected to a larger temperature change, as shown in figure 76. This means that more cracks are likely to form, because cracking in concrete pavements is highly influenced by temperature variations.
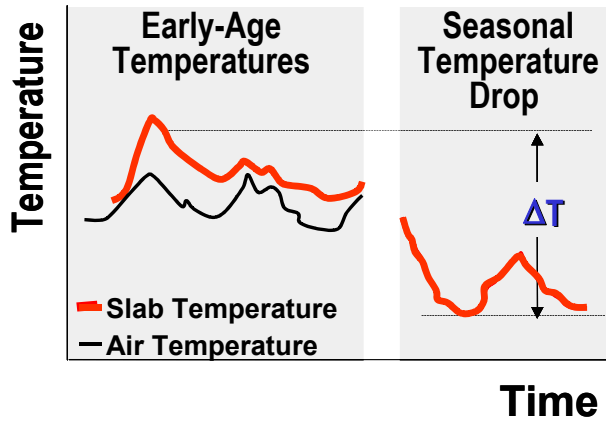
Figure 76. Representation of PCCP temperatures in the early age and at the lowest seasonal air temperature.

HIPERPAV II takes into account the thermal processes due to the concrete's heat of hydration, the curing temperature, the daily minimum temperatures, and the annual minimum temperature when predicting crack formation. A cumulative frequency plot of crack spacing at 1 year for the summer and winter placements (with $\Delta T = 33$ ºC and 12 ºC, respectively) is shown in figure 77. The trend at 1 year is consistent: the CRCP placed in the summer has more closely spaced cracks.
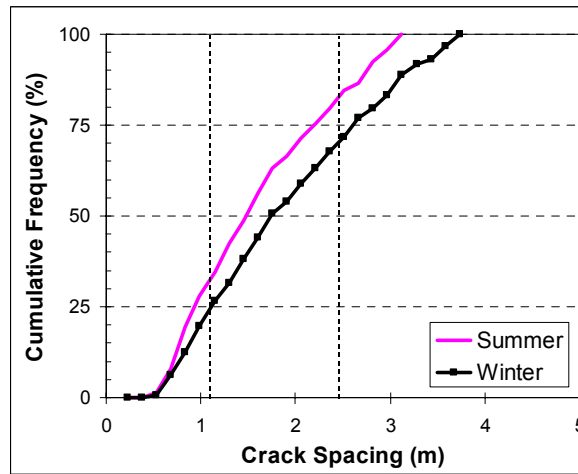
Figure 77. Crack spacing distribution for pavements constructed during summer and winter.

Using this HIPERPAV II analysis, Mary realizes that with proper analysis, she will be able to construct a CRCP with good long-term performance during the winter. If a CRCP can only be placed in the summer, she can modify the construction process to improve its performance. She has other options to control the concrete temperature, such as improving the curing method. They can be investigated with HIPERPAV II, as well. HIPERPAV II allows her to take the guesswork out of CRCP performance and helps her construct CRCP with consistently good long-term performance.

6.4   POST-MORTEM CRCP CASE STUDY: AGGREGATE SELECTION

How does coarse aggregate type affect the performance of CRCP for a set of climatic conditions?

6.4.1   Background

Two CRCP sections, pavement A and pavement B, were placed at the same time on the same day, December 12, 1997. However, pavement A has been performing significantly better with fewer punchouts and lower maintenance costs than pavement B for the past 5 years. To determine what is causing this difference in performance, the engineer, Sam K. Pable, picks up the HIPERPAV II guidelines and looks at chapter 2, Early-Age Pavement Behavior; chapter 3, Early-Age Pavement Distresses; and chapter 4, Impact of Early-Age Behavior on Long-Term Performance. The early-age indicators of long-term CRCP performance are crack spacing, crack width, and steel stresses. Walking down the CRCP, Sam notices that the cracks are spaced closer in pavement B than in pavement A, as shown in figure 78. On pavement A, crack spacings are distributed between 1.1 and 2.4 m, while on pavement B, the spacing is less than 1.1 m in some instances.
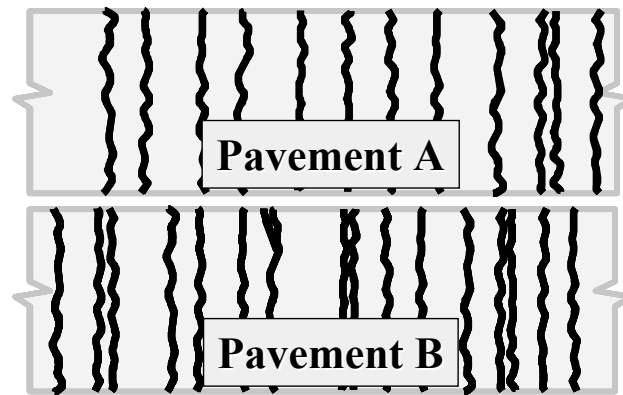
Figure 78. Illustration of differences in cracking patterns for pavements A and B.

Further investigating the reasons behind this performance difference, Sam studies the construction documents to see if there is a difference in materials used or construction procedures followed when building pavements A and B. After studying the mix designs, the only significant difference he can find is that limestone aggregate was used in pavement A and that siliceous river gravel was used in pavement B.

Sam decides to use HIPERPAV II to assess the behavior of a 280-mm CRCP constructed with concrete containing different aggregate types, namely siliceous river gravel, basalt, granite/gneiss, sandstone, and limestone. The climatic database in HIPERPAV II is used to estimate the temperatures at noon on December 12.

6.4.2   Analysis Strategy

HIPERPAV II can be used to understand how aggregate type affects the early-age performance of CRCP. The expansion and contraction of the concrete greatly depends on the coarse aggregate CTE, since coarse aggregate comprises about half of the concrete volume. Because temperature changes are the greatest in the pavement immediately after construction, its volume changes are significant at early ages.

Figure 79 shows how the concrete volume changes based on its CTE when it is subjected to a temperature drop.

	Temperature = 40°C	Temperature = 15°C
Low thermal coefficient		
High thermal coefficient		
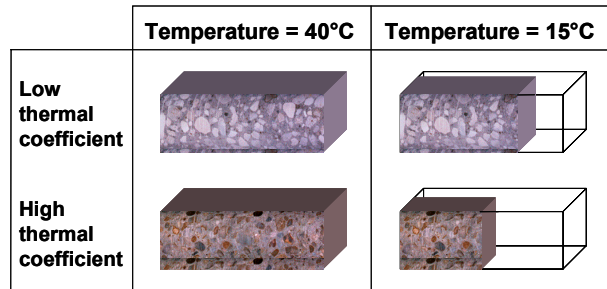
Figure 79. Illustration of difference in volumetric changes with temperature for concretes with different CTE.

The CTE is especially important for pavements placed in the summer season when temperature extremes are high, as in Sam's analysis. During hot weather placement, the peak ambient temperature may coincide with the peak heat of hydration (as in morning placements). Under such conditions, concrete pavements having a high concrete CTE tend to have an increased probability for early-age cracking, when compared to pavements constructed with coarse aggregate having a lower thermal coefficient. The following are the HIPERPAV II default CTE values for the selected aggregates:

- Siliceous river gravel: 11.7 m/m/°C.

- Sandstone: 11.2 m/m/°C.

- Granite/gneiss: 7.6 m/m/°C.

- Basalt: 6.7 m/m/°C.

- Limestone: 4.7 m/m/°C.

For each of these aggregate types, HIPERPAV II analyses are performed to determine how aggregate CTE impacts CRCP crack spacing, crack width, and steel stresses. It is expected that the aggregate with the lower CTE will yield a pavement with longer crack spacings and fewer long-term failures (punchouts) (see section 4.7).

6.4.3   Solution

Sam performed HIPERPAV II runs to assess how the aggregate types listed above influence CRCP performance. PCC CTE is assumed to be 20 percent higher than aggregate CTE. The impact of changing the aggregate CTE on crack spacing can clearly be seen in figure 80.
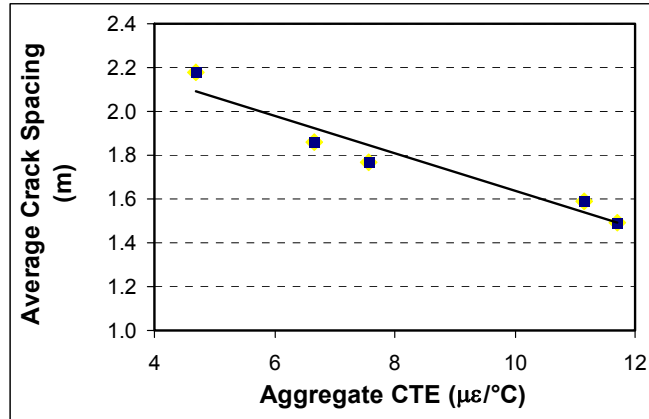
Figure 80. Average crack spacing after 1 year for aggregates with different CTE.

For aggregate with a low CTE, the crack spacing is high (2.1 m), which translates to a reduced number of punchouts in the long term.

Figure 81 shows the cumulative crack spacing for the pavements containing siliceous river gravel and limestone at 1 year. It is apparent that the average crack spacing is smaller for the pavement with the siliceous river gravel.
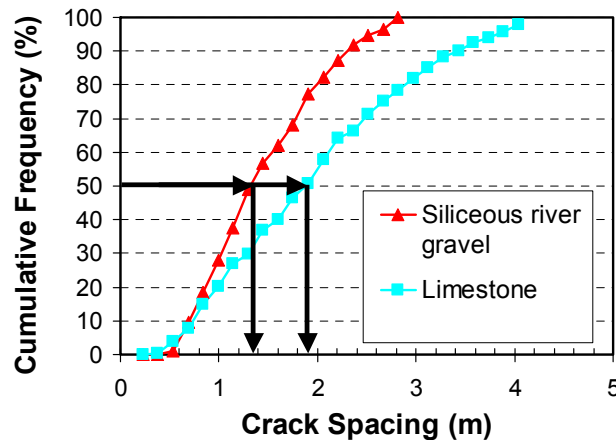
Figure 81. Crack spacing distribution after 1 year for the siliceous river gravel and limestone strategies.

From these results, Sam concluded that CRCP will have better long-term performance if the concrete used in its construction has a low CTE. In this case study, changing the aggregate in the concrete from one with a high CTE to one with a low CTE resulted in a larger average crack spacing. This translates to less distress in the long term.

Sam discovered that the pavement constructed with the low CTE aggregate provides better performance because the thermal stresses are reduced. If low CTE aggregates are not available (as is often the case) and a high CTE aggregate must be used, he knows that HIPERPAV II can optimize the time of day and the season of placement to ensure the best CRCP performance possible.

CHAPTER 7.   HIPERPAV II USER'S MANUAL

In HIPERPAV II (software version 3.0), several changes were made to the software from the previous release of HIPERPAV I (software version 2.X). This user's manual outlines those changes and discusses the new input needed. For information on the theory behind HIPERPAV II, refer to the guidelines (chapters 2 through 5).

In HIPERPAV II, the user can now perform early-age behavior analyses for jointed concrete pavement, evaluate the impacts of early-age factors on JPCP long-term performance, and perform analysis for CRCP (see figure 82).
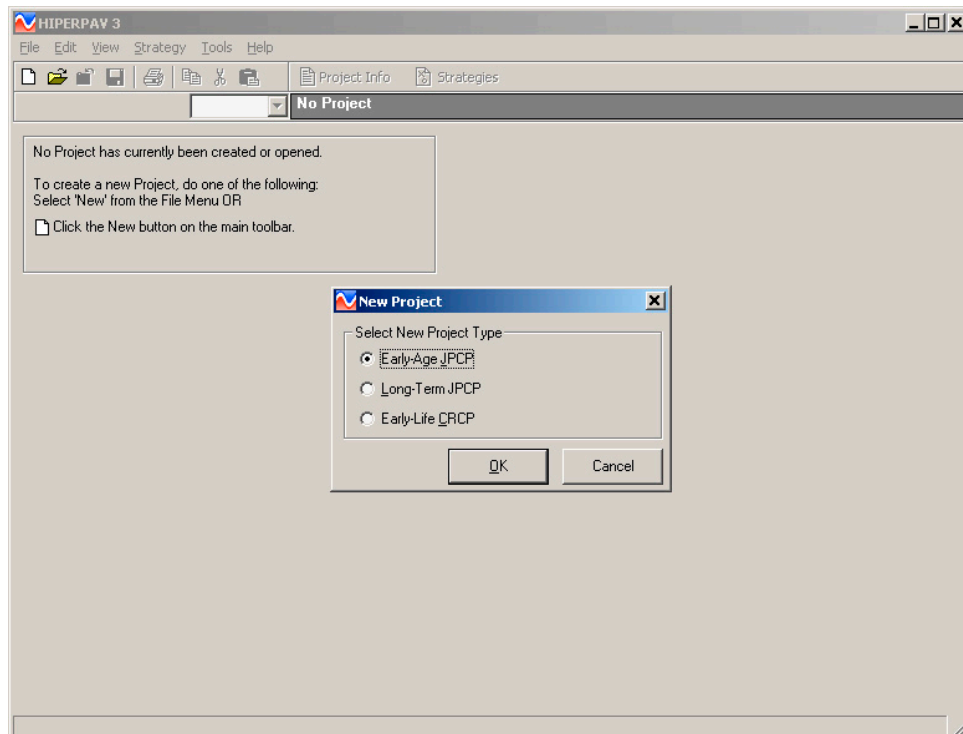
Figure 82. Project type selection screen for HIPERPAV II analysis.

The input screens for these three project types are described below.

7.1   PROJECT INFORMATION

After the user selects a project type in the new project window (figure 82), the software creates a strategy with default inputs that the user can modify with the inputs for a specific situation.

There are two primary sections in HIPERPAV II: the project information section discussed below, and strategies section discussed later.

Regardless of the project type, project information is needed for all of the HIPERPAV II analyses. Under the project information screen (figure 83), the user can enter general project information,

including the project name, project ID, section name, and beginning and ending stations. A comment box is also provided for any additional information.
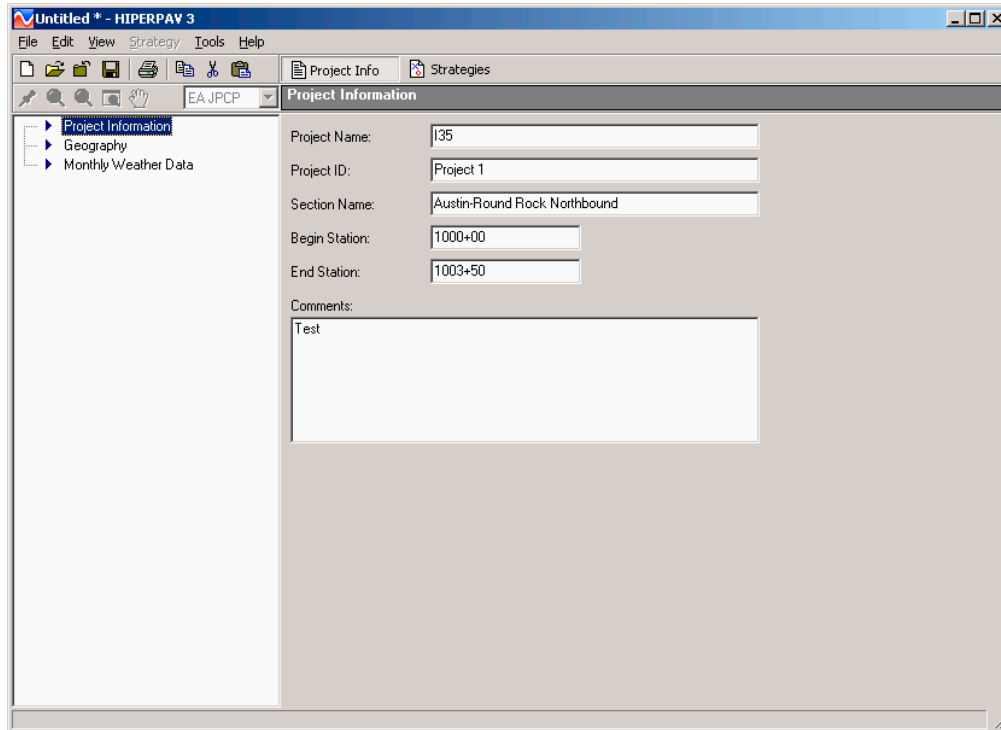
Figure 83. Project information screen for HIPERPAV II analysis.

7.1.1 Geography Screen

In the geography screen, the user can select the position within the 50 U.S. States where the project is located (figure 84). Historical weather data from nearby weather stations to the site can be used during the analysis if desired. Climatic information including air temperatures, windspeed, relative humidity, cloudiness, and annual rainfall conditions will be estimated based on this location from the nearest weather stations. Section 7.3.7 provides additional information on selecting the project location.

To navigate the geography screen, five icons are available for use. The user can:

  Magnify the map.

  Decrease magnification of the map.

  Select the location of the project.

  Drag the map.

  Zoom to show the entire map.
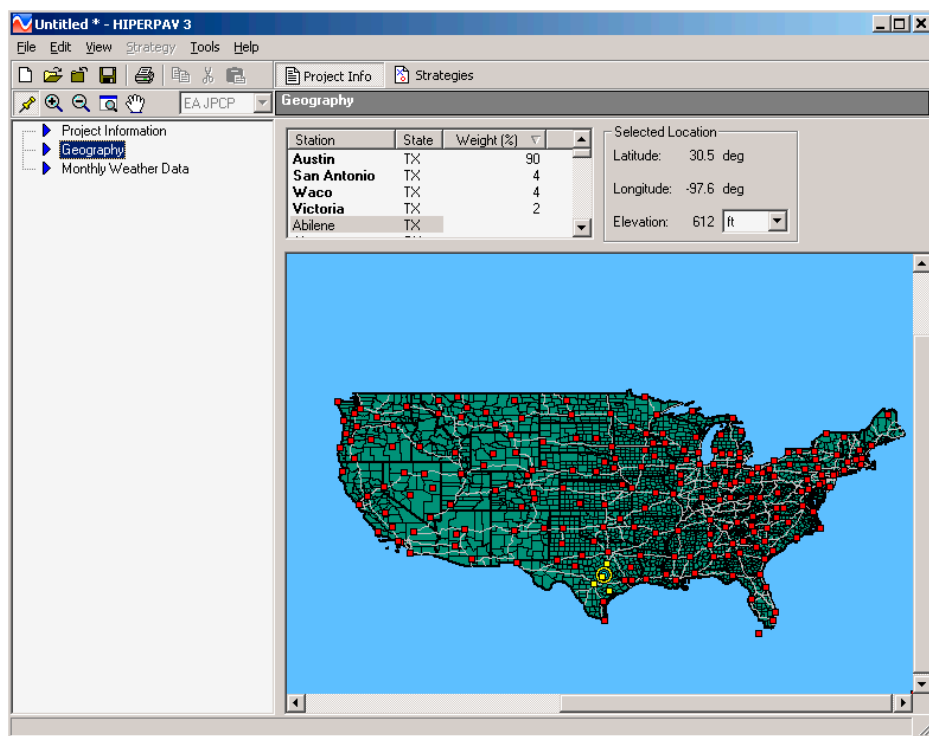
Figure 84. Geography screen for HIPERPAV II analysis.

7.1.2   Monthly Weather Data Screen

Monthly rainfall data is used for the long-term analysis only. If the user has more accurate rainfall data, it can be entered in the monthly weather data screen (figure 85).
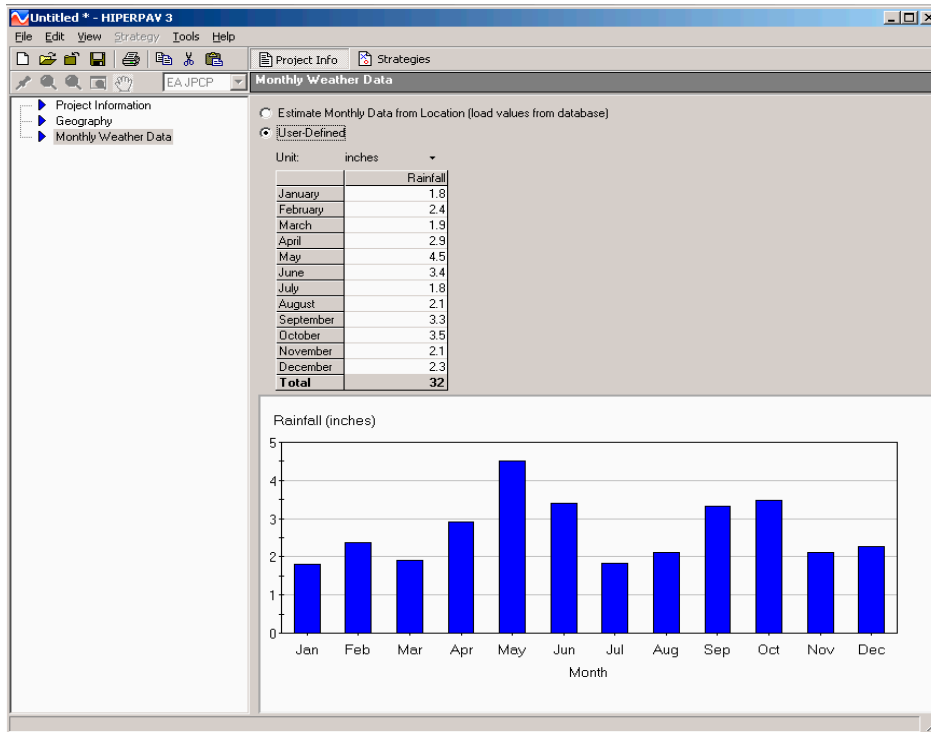
Figure 85. Monthly weather data screen for HIPERPAV II analysis.

7.2   EARLY-AGE JPCP ANALYSIS

After the user selects option 1 in the project type selection screen (figure 82), and the general project information is entered, one or more strategies for that specific location can be created for analysis under the strategies section (figure 86).

7.2.1   Strategies

The strategies section contains, in tree view, the specific input data required to perform an early-age JPCP analysis under the categories of:

- Design.

- Materials and mix design.

- Construction.

- Environment.

7.2.1.1   Strategy Toolbar

It is possible to have multiple strategies in one project. Each of the strategies can have different design, materials and mix design, construction, and environment inputs.

The strategy toolbar is provided to manipulate strategies. The strategy toolbar includes the following commands:

📄 Add a strategy

📄 Copy the currently selected strategy.

📄 Delete a strategy.

📄 Validate a strategy to verify that inputs are within allowable ranges.

📈 Run an analysis for the currently selected strategy.

All the above functions can also be performed by right clicking on the strategy name.

7.2.1.2 JPCP Early-Age Strategy Information

To perform an early-age JPCP analysis, a new strategy must be added. With the strategy created, the strategy information including design, materials and mix design, construction, and environment information can be entered. The screens where this information is entered are listed in a menu format on the left side of the HIPERPAV II screen. As shown on the strategy information screen (figure 86), the user can enter his or her name and chosen reliability level. After the strategy is run, the date of analysis also will appear on this screen. A comment box is available for each strategy.
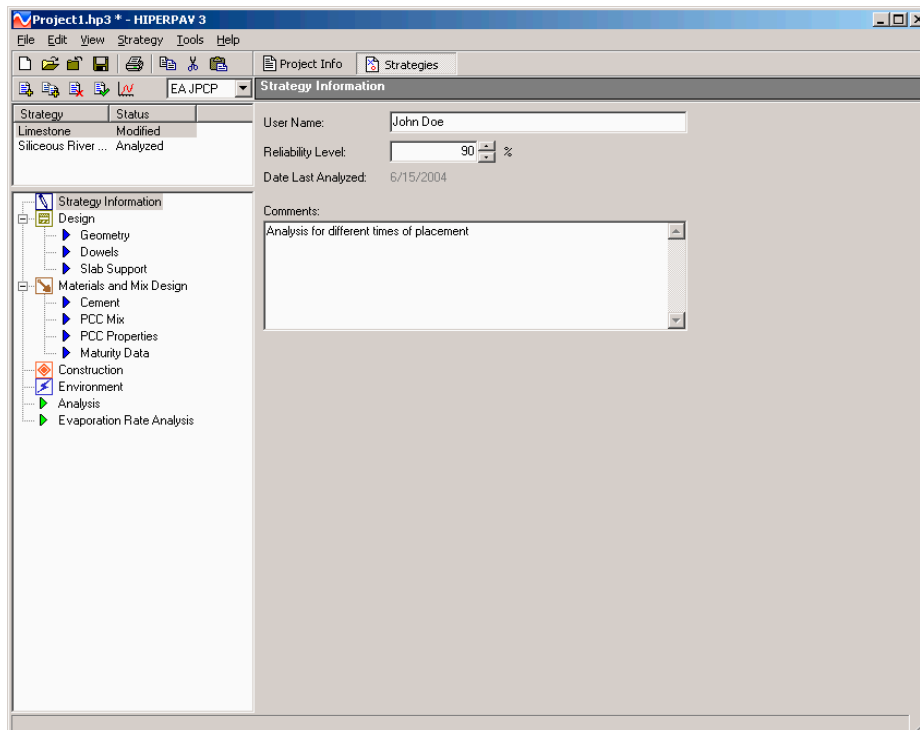
Figure 86. Strategy information screen for HIPERPAV II analysis.

7.2.2   Design Inputs

Under the design inputs, the user can enter the pavement design information, including pavement geometry, dowel design, and slab support information.

7.2.2.1   Geometry Screen

Under geometry (figure 87), fields to enter the slab thickness, slab width, and transverse joint spacing are provided. For any input in HIPERPAV II, the user can select from several either metric or English units and can convert between unit systems. To convert value, check the convert value box and click on the desired unit.
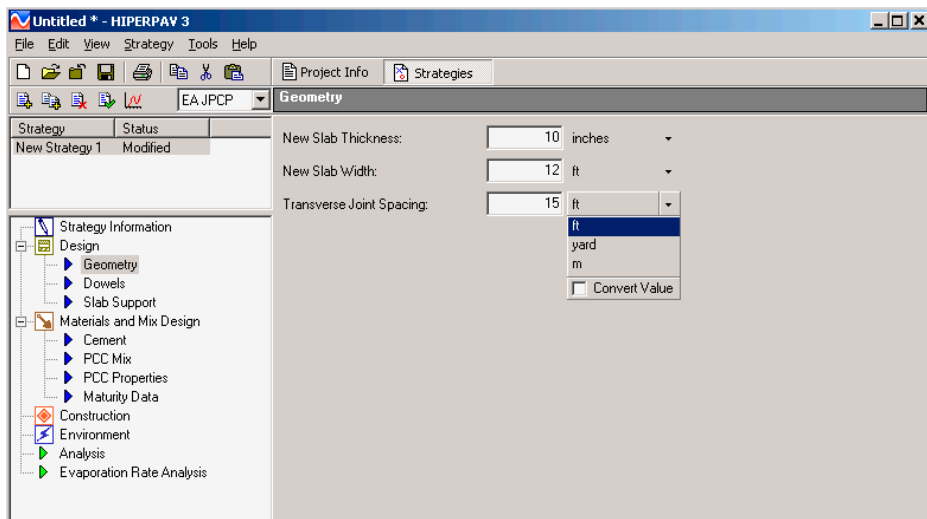
Figure 87. Geometry screen.

A schematic of the geometry input entered in HIPERPAV II is shown in figure 88.   The slab width that should be input in HIPERPAV II is the widest spacing between adjacent longitudinal joints. Similarly, the transverse joint spacing in the case of random joint spacings should be the largest spacing between transverse joints (although the user can run each joint spacing as a separate strategy to compare the results).
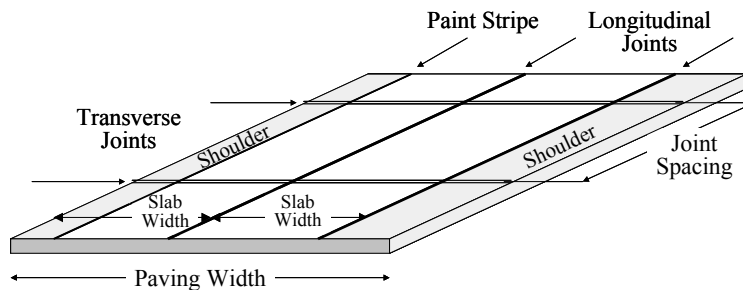
Figure 88. Schematic of the geometry input in HIPERPAV II.

7.2.2.2 Dowels Screen

The dowels design information is entered only if the user wants to evaluate the bearing stresses at the dowels during the early age. The dowel analysis module can assess how dowel bars affect the early-age performance of the joint in jointed concrete pavements (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, particularly during the early age, 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 load transfer efficiency.

If this module is enabled, then the dowel size, Poisson's ratio, and modulus must be input (figure 89). In addition, the 28-day effective modulus of dowel support is required. The modulus of dowel support is defined as "the bearing stress in the concrete mass developing under unit deflection of the bar."[54] Additional information is required on concrete compressive strength under the PCC properties screen if a dowel analysis is to be performed.
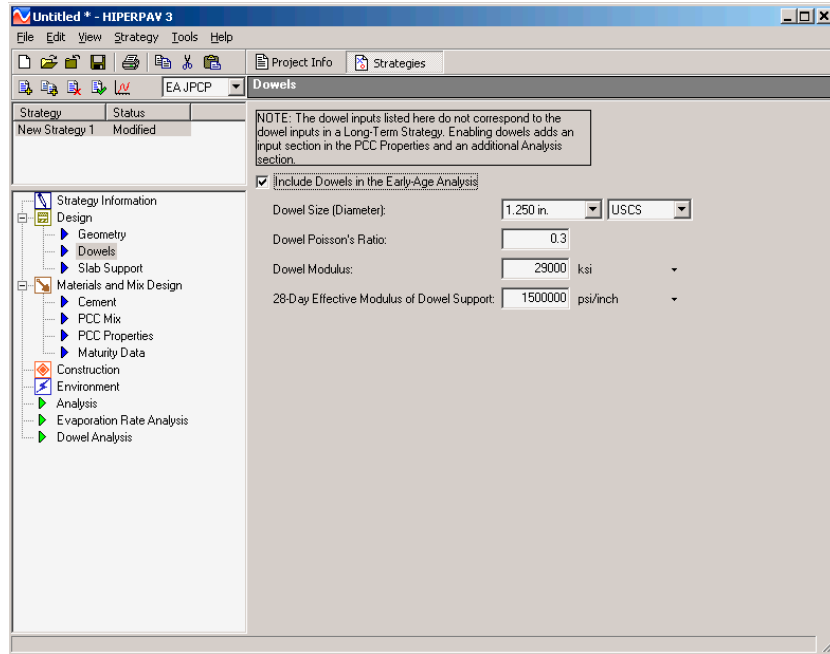
Figure 89. Dowel input screen.

7.2.2.3 Slab Support Screen

The slab support screen requires information on the material type directly underneath the slab (see figure 90). Options are provided for different subbase types or subgrade conditions (see pulldown menu in figure 91). Additionally, information on the subgrade stiffness in terms of modulus of subgrade reaction (*k*-value) or subgrade resilient modulus, and subbase thickness and subbase elastic modulus are required.

The *k*-value may be obtained by: 1) correlations with soil types and other subgrade support tests (i.e., CBR, *R*-value, etc.); 2) determination of elastic modulus of individual layers (e.g., with the use of deflection testing) and backcalculation methods; or 3) plate load testing methods.

AASHTO T 274 may be used to characterize relatively low stiffness materials such as natural soils, unbound granular materials, stabilized materials, and asphalt concrete. Alternatively, the repeated-load indirect tensile test method ASTM D 4123 may be used to test bound or higher stiffness materials such as stabilized bases and asphalt concrete. The elastic modulus of base materials with a high cement content may be obtained with the ASTM C 469 test method.
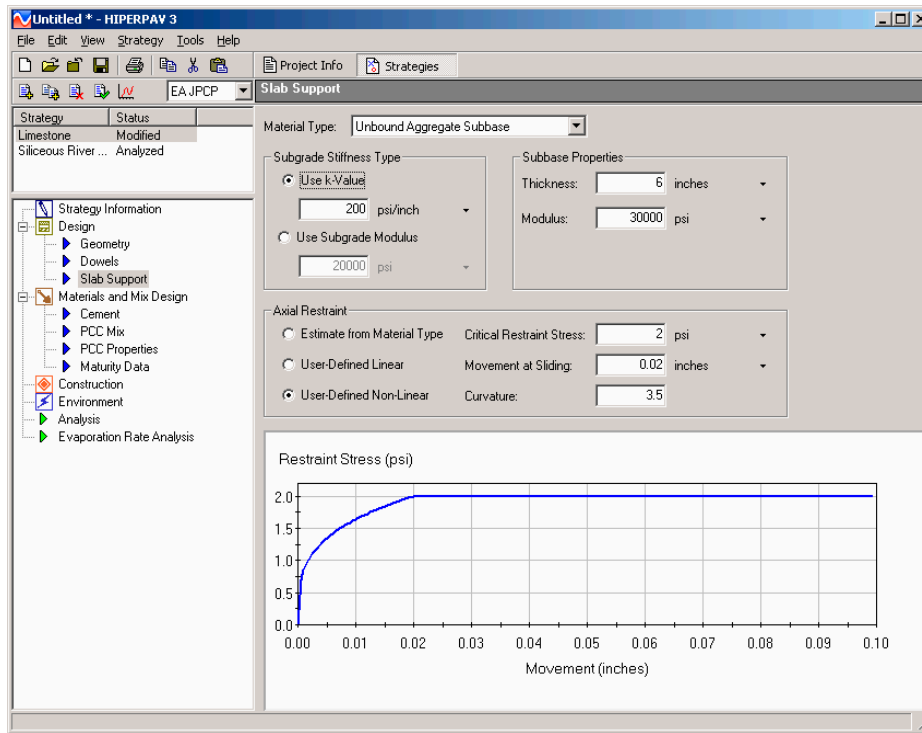
Figure 90. Slab support input screen.
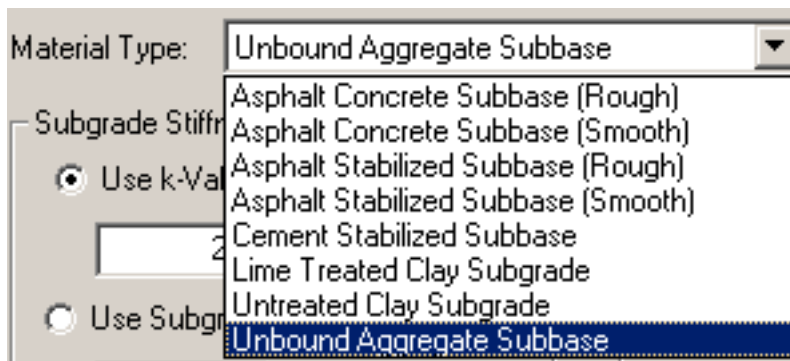
Figure 91. Available subbase types or subgrade conditions.

The axial restraint conditions can be estimated based on the layer directly underneath the slab, or can be user-defined with linear or nonlinear functions that best match the restraint stress-movement curve from field restraint tests. A restraint or pushoff test consists of casting a small slab with an approximate thickness of the projected pavement on top of the same subbase type. A horizontal force is applied on one side of the slab with a hydraulic jack and a load cell is used to measure the applied load. Dial gages are installed at the opposite side to measure the slab movement. The restraint stress is determined from the applied force divided by the area of the test slab. The testing history of restraint stress and slab movement during the pushoff procedure is recorded, and the restraint stress at free sliding is evaluated.[55]

7.2.3   Materials and Mix Design Inputs

The second input category is materials and mix design. This input category includes the cement, PCC mix, PCC properties, and maturity data inputs.

7.2.3.1   Cement Screen

Under the cement input screen shown in figure 92, the user selects the type of cement either by ASTM cement type classification (pulldown in figure 93), user-defined oxides, or user-defined Bogue compounds. If selected, the user-defined oxides or user-defined Bogue compounds are entered in tabular form.

Blaine fineness can be estimated from the cement type or user-defined if this information is available.
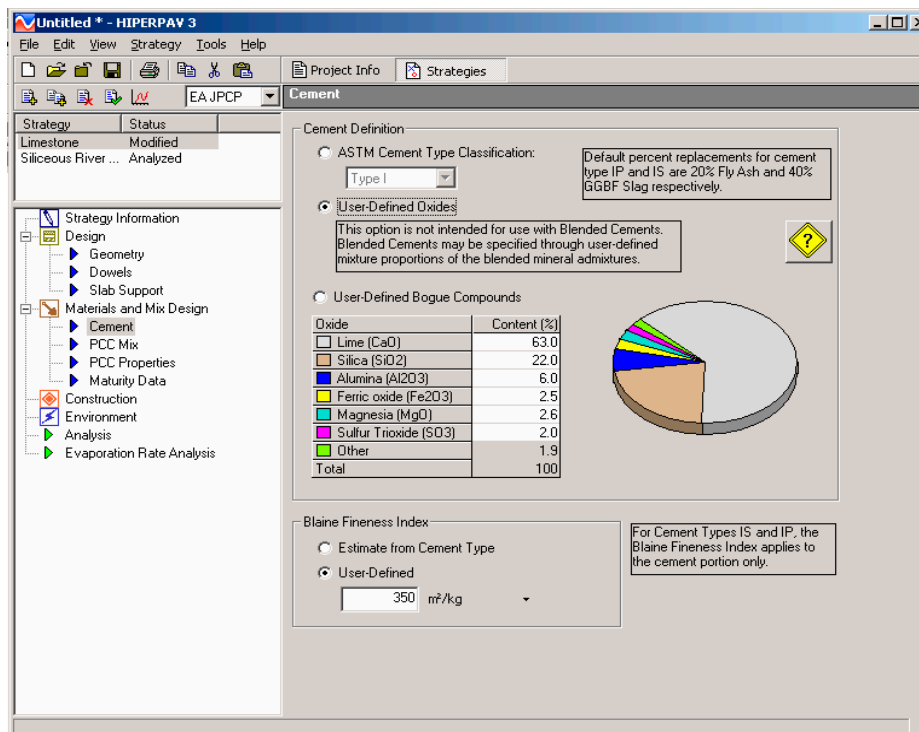
Figure 92. Cement input screen.
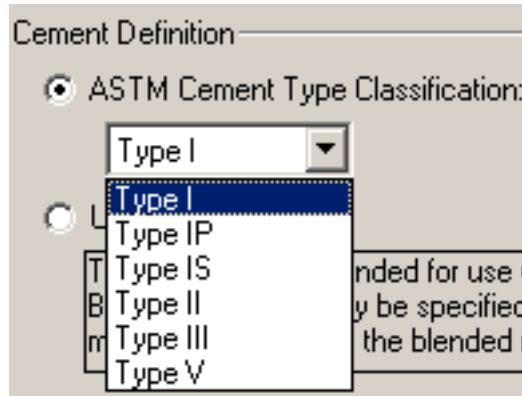
Figure 93. Available cement types in HIPERPAV II.

A help screen that explains the heat of hydration effects of different cementitious materials in HIPERPAV II is available in this screen (see figure 94).
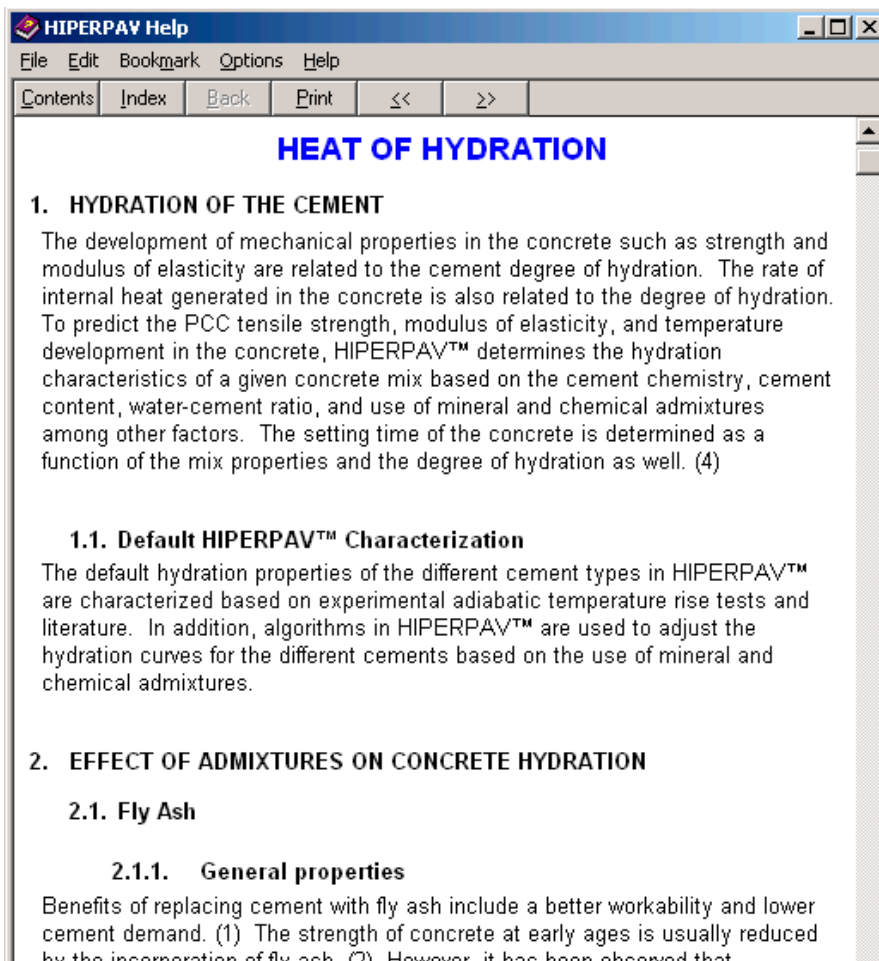
Figure 94. Heat of hydration help screen in HIPERPAV II.

7.2.3.2   PCC Mix Screen

The PCC mix screen is used to enter the mix design related information (figure 95). Under the PCC mix screen, the user selects the type of coarse aggregate used in the mix (see pulldown menu in figure 96), the user can also enter the type of chemical admixtures according to ASTM C 494 (see pulldown in figure 97). Note that Type A and F are not included, because they would not affect the analysis (hover over to see tool tip). If fly ash is used, it is necessary to specify the fly ash class and approximate calcium oxide (lime) content for Class F (see pulldown menu in figure 98). Batch proportions by mass are also entered in this screen.

Help icons are provided in several software screens to provide additional guidance on the proper selection of inputs.
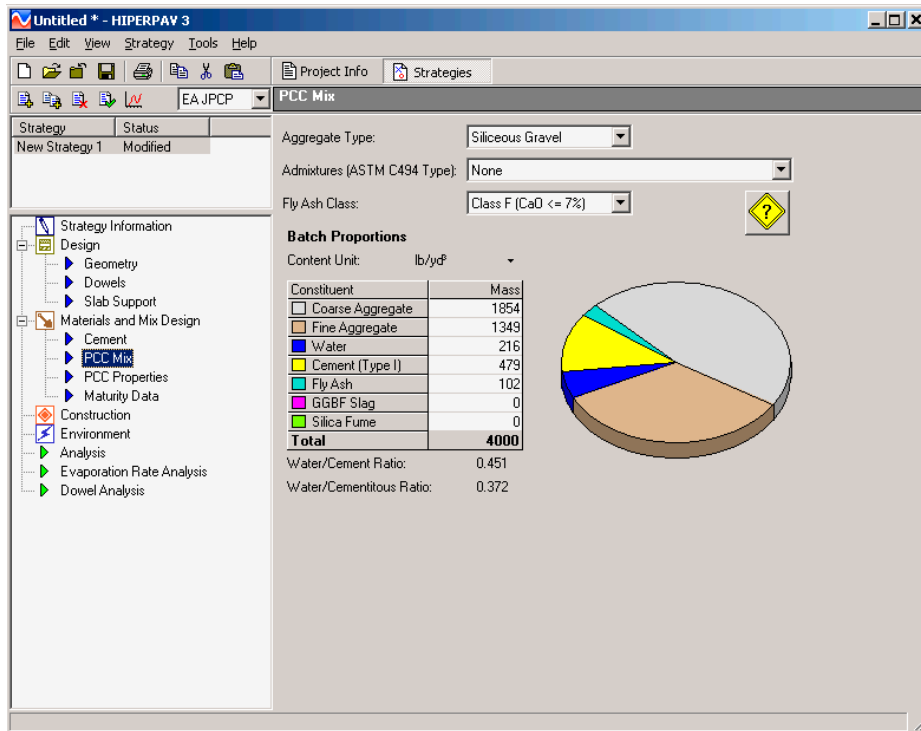
Figure 95. PCC mix input screen.
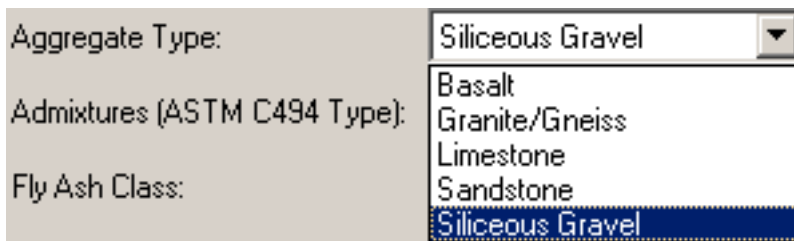
Figure 96. Available coarse aggregate types in HIPERPAV II.

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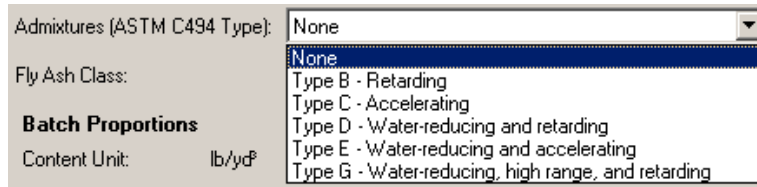
Figure 97. Available admixture types in HIPERPAV II.
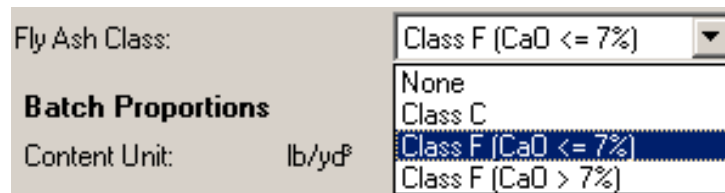
Figure 98. Fly ash class drop-down menu.

7.2.3.3   PCC Properties screen

The PCC properties screen includes inputs for the 28-day strength, concrete CTE, 28-day modulus, and ultimate drying shrinkage (figure 99).

The 28-day tensile strength is determined through the ASTM C 496 or AASHTO T 198 splitting tensile test. Alternatively, the user can estimate the splitting tensile strength based on relationships with other strength types (see pulldown menu in figure 100). In the equations shown on the screen, "STR" is the PCC 28-day strength type. The splitting tensile strength (STS) is used to predict the formation of cracks in the early-age JPCP. The compressive strength (CS) is used to assess dowel-bearing stresses at early ages with the dowel analysis module. Default conversion values are provided in HIPERPAV II, however, the user is cautioned to develop project specific coefficients based on laboratory testing for the mix in study (see figure 101).

The PCC modulus of elasticity may be determined with ASTM C 469. AASHTO T 160 test procedure at 40 percent relative humidity may be used to determine PCC ultimate drying shrinkage. This test is equivalent to ASTM C 157. The PCC CTE can be entered or estimated by HIPERPAV II based on the coarse aggregate CTE. The latter can be user-defined or estimated based on default values. AASHTO has recently developed a provisional standard that can be used for testing the concrete CTE: TP–60–00, "Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete."

110
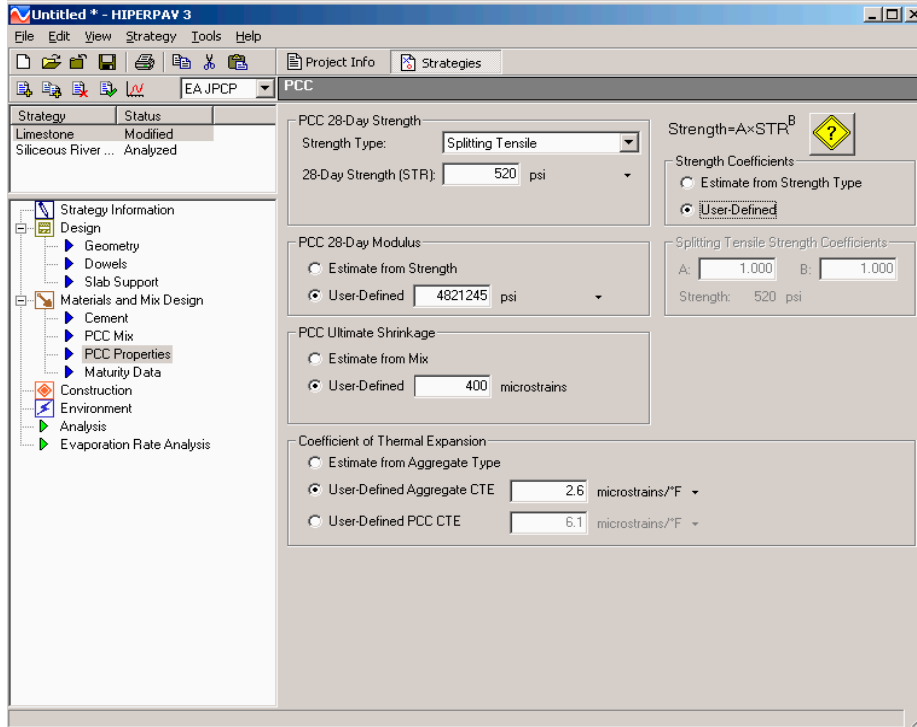
Figure 99. PCC properties screen for early-age JPCP analysis.
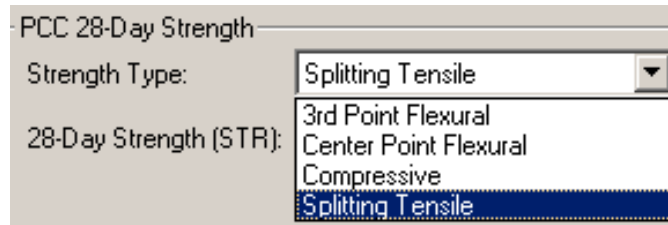
Figure 100. Strength type drop-down menu.
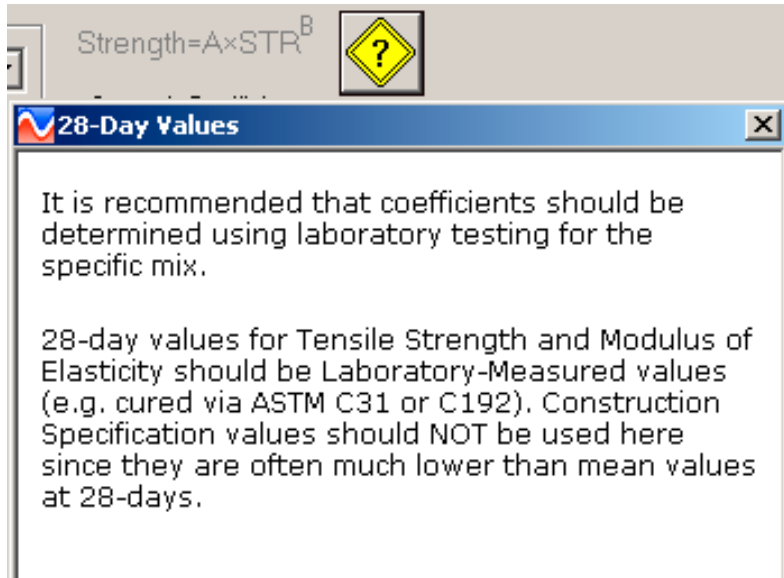
Figure 101. Help icon under PCC properties screen.

7.2.3.4   Maturity Data Screen

The last input under the materials and mix design category is used to enter maturity data, if available. Two methods of maturity are provided: the temperature-time factor with the use of the Nurse-Saul maturity relationships according to ASTM 1074; or the equivalent age method with the use of the Arrhenius relationships. For either method, maturity and strength information are entered in a gridline and automatically plotted on the screen, as shown in figure 102.
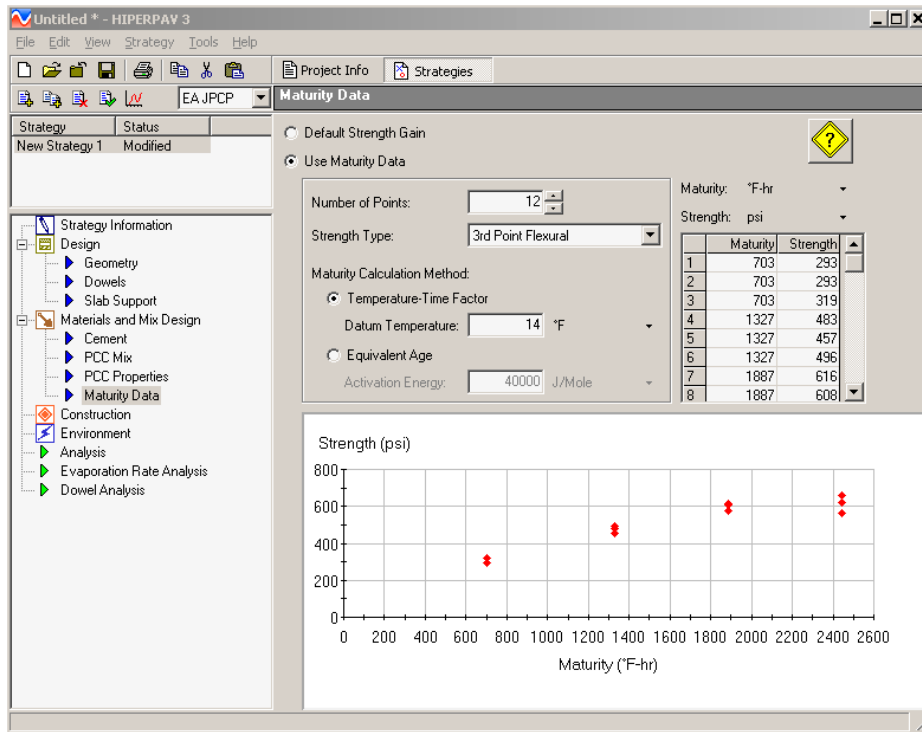
Figure 102. Maturity data input screen.

7.2.4 Construction Inputs

The third input category corresponds to construction information (figure 103). In this screen, the initial temperatures of the concrete mix and support layer are entered. Information on the curing method used is required, as is the age at which curing is applied. The age when curing is applied is defined as the time elapsed from construction to the time when the slab is covered with membrane curing compounds or polyethylene sheeting. If removable curing methods such as polyethylene sheeting are selected, the age when curing is removed is required. Available curing methods are presented in the drop-down menu for curing method shown in figure 104. A help icon is also available in the curing method inputs, which includes information on the effects of curing type selection.

Information on when joints are cut is also entered in this screen. Three sawcut options are available to the user:

- Saw at optimum time: HIPERPAV assumes that as soon as the concrete is strong enough to sawcut, the joints are formed, and HIPERPAV performs the analysis based on the transverse joint spacing entered.

- User-defined sawing age: HIPERPAV simulates the stress development for a semi-infinite slab until the specified sawing age. After that time, the stress development is simulated based on the transverse joint spacing entered.

- No sawing: HIPERPAV simulates the stress development for a semi-infinite slab for the 72-hour analysis. This option is useful to estimate the latest sawcutting time. The time when the stress exceeds the strength for this scenario would correspond to the latest sawcutting time. However, this option must be used with caution, since a great liability is involved.

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Although not a recommended practice, the user may also estimate the effect of skip sawcutting for the first two options. Options for skip sawcutting, varying from every other joint to every fifth joint, may be specified in the drop-down following the "skip sawcutting every" checkbox. If this option is selected, the user also needs to enter the time when the skipped joints are cut.

In addition, if a given strength for opening to traffic is required, this information can be entered in the construction inputs screen. Figure 104 shows the strength types that can be entered. Also, as shown in figure 104, a help icon for strength for opening to traffic input is provided. After the analysis is run, the strength for opening to traffic is indicated in the analysis screen (later shown in figure 110) if this strength is achieved within the 72-hour analysis period.
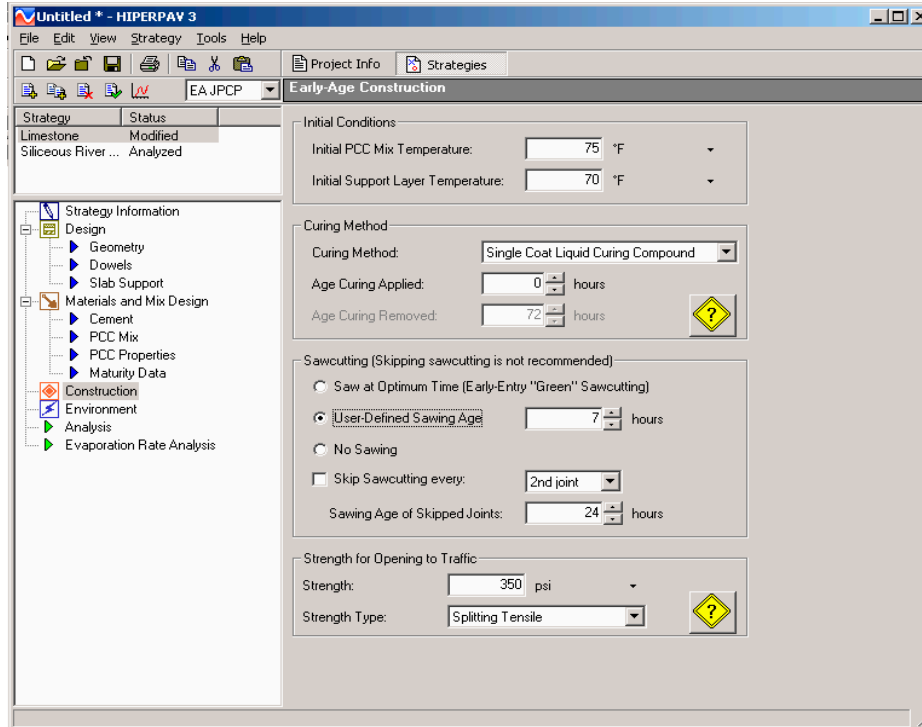
Figure 103. Construction screen.
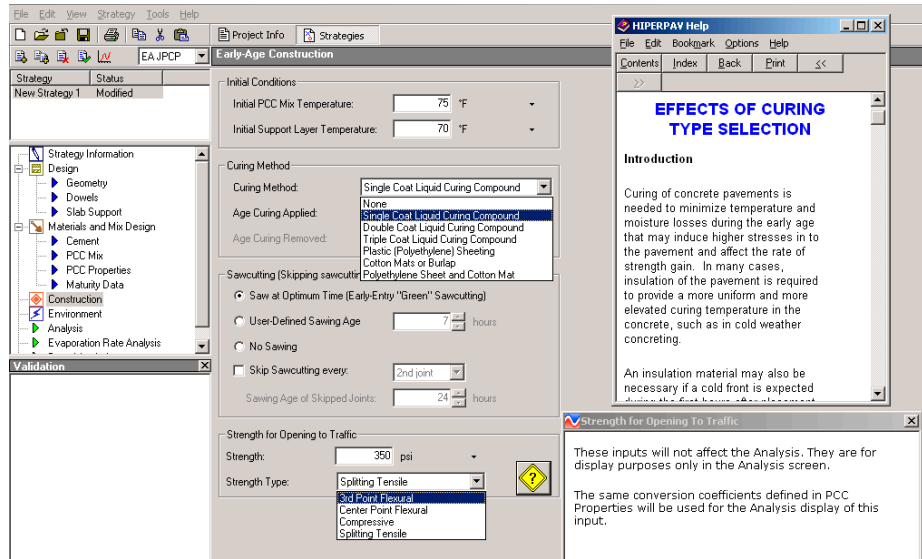
Figure 104. Drop-down menus and help screens under construction inputs.

7.2.5   Environment

The last input category corresponds to environment. Under this input category, the user can enter climatic conditions for the 72 hours following construction, as shown in figure 105.

Using the HIPERPAV II environmental database, it is possible to estimate temperature, windspeed, humidity, and cloud cover for any location selected in the geography screen (figure 84). Or, if the user wishes, specific hourly weather data can be entered in the gridlines provided. The information displayed in this screen corresponds to the climatic input selected in the data to display drop-down menu shown in figure 106.
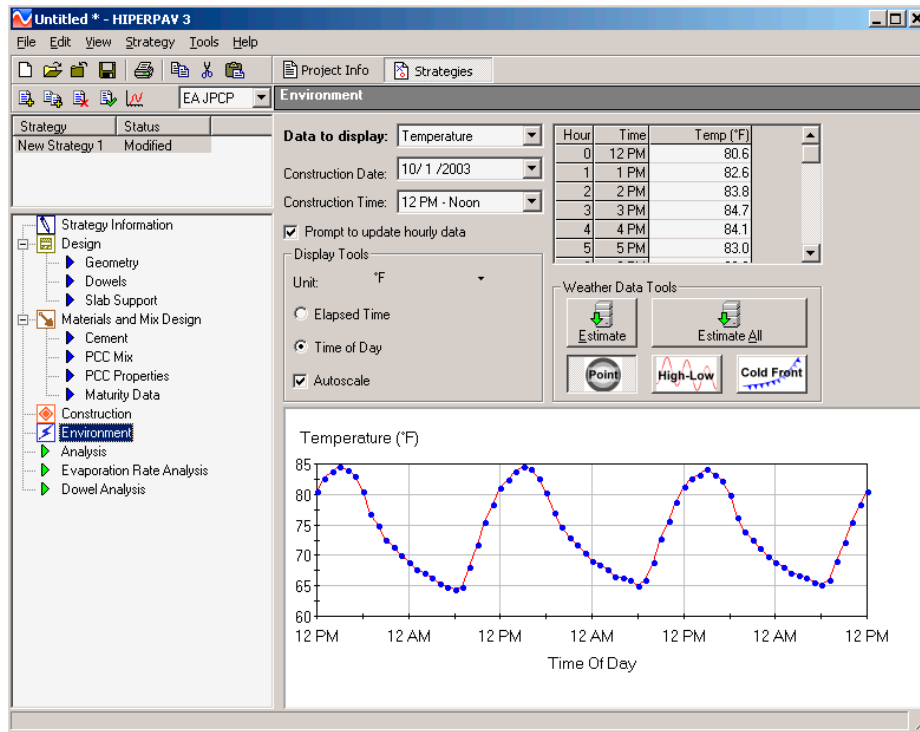
Figure 105. Environment screen.
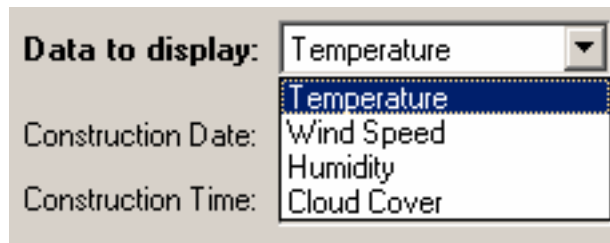
Figure 106. Drop-down menu for selection of climatic input screen to display.

If the construction date or time are changed, it is important that all of the temperature, windspeed, humidity, and cloud cover inputs be estimated again using the "estimate" or "estimate all" icons to match the selected point in time based on the geographic location selected. "Estimate" updates only the data displayed on the current screen. "Estimate all" updates all the weather data under temperature, windspeed, humidity, and cloud cover. The "prompt to update hourly data" checkbox can be unchecked to automatically update weather data as a function of changes in construction time or construction date. Otherwise, a prompt asking to update weather data will appear whenever a change in construction time or date is made.

The user also has the options to:

- Drag individual points on the plot with the point feature (see figure 107).

- Specify high and low values for each day by selecting the high-low feature and dragging the red points (see figure 108).

- Simulate a cold front condition by selecting the "Cold Front" icon and dragging down the desired point (see figure 109).

Options for plotting weather data in terms of elapsed time from construction or for time of day are provided. In addition, an autoscale feature can be selected to cover a wider or narrower weather data range.
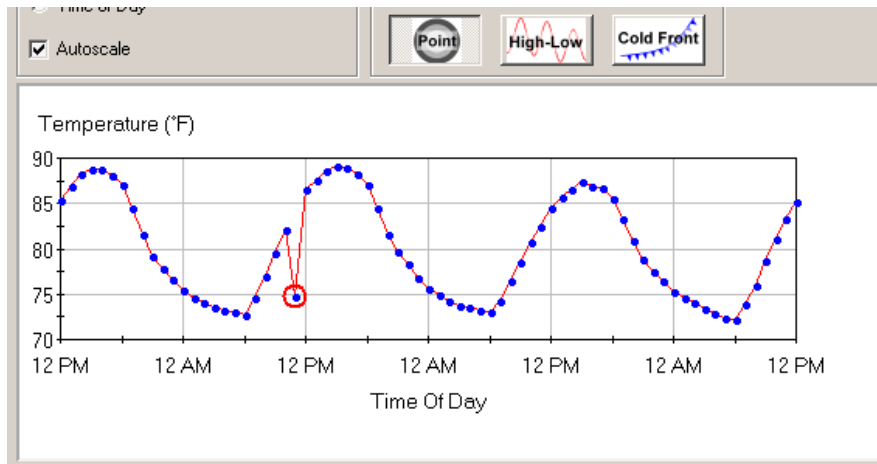
Figure 107. Time-temperature distribution modified with the point feature.
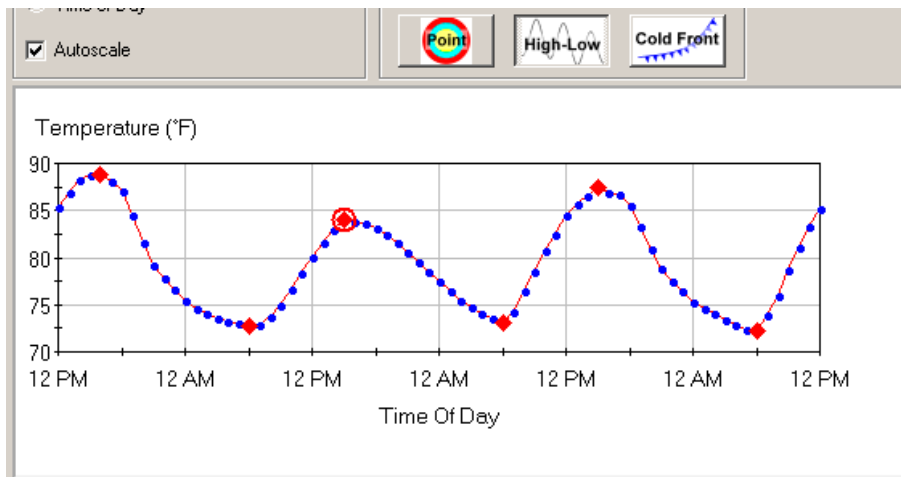
Figure 108. Time-temperature distribution modified with the high-low feature.

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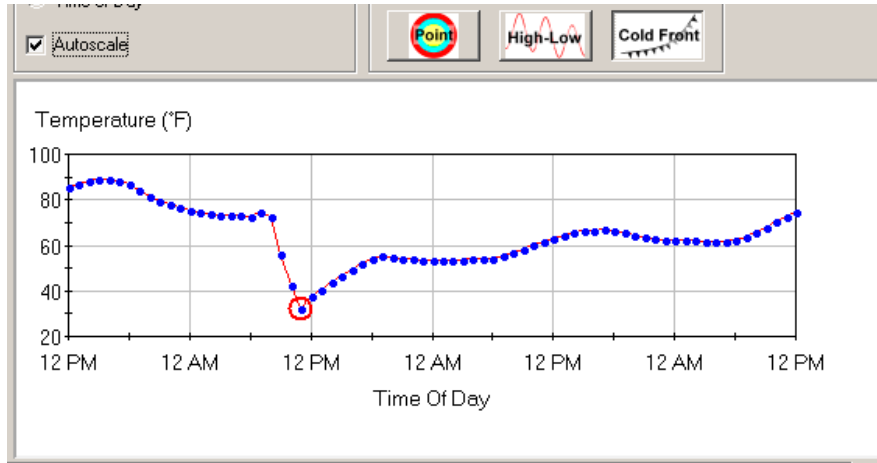
Figure 109. Time-temperature distribution modified subjected to a cold front.

7.2.6   Early-Age JPCP Analysis

With the input assigned, the user should save the inputs before performing an early-age JPCP analysis.

After the analysis is run, a window appears showing the analysis status, and the stresses at the top and at the bottom of the slab are plotted along with the development of the tensile strength in the concrete, as shown in figure 110.
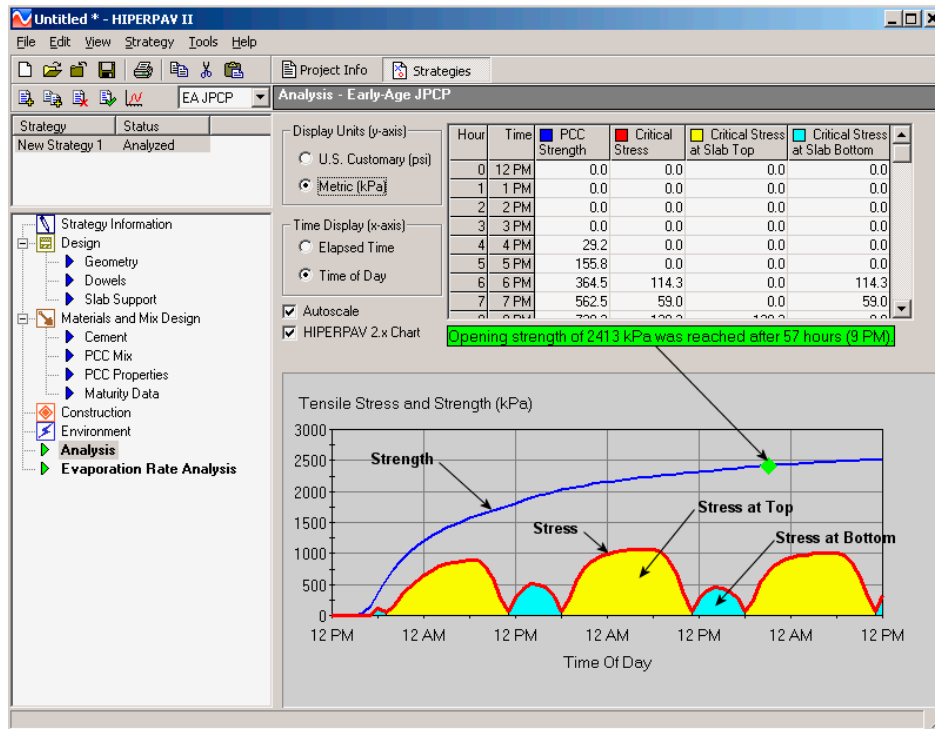
Figure 110. Analysis screen for early-age JPCP.

The numerical stress and strength values also are presented. The critical stress is the largest tensile stress, whether it is at the top or at the bottom of the slab. The numerical value of tensile stress and strength can also be obtained by hovering the mouse over the point of interest. The point in time when the strength for opening to traffic is reached is indicated here in green (highlighted with an arrow and circle for clarity).

Also, because more than one strategy can be analyzed with HIPERPAV II, comparisons can be made between the analysis results more easily. It is possible to toggle between the analysis screens by selecting one strategy and then the other one (for this, the user must have at least two strategies previously analyzed for comparison and toggle between them).

7.2.6.1   Interpretation of Analysis Results

HIPERPAV executes a series of powerful algorithms that calculate the PCC pavement stress and strength development continuously for the first 72 hours following placement. The user is presented with a graphical screen, which plots the results of the analysis as they are computed in real time. The user can observe the trend of the strength and stress development and assess the behavior of the pavement based on the specific user inputs. Following processing, HIPERPAV will then identify possible problem areas and inform the user that the potential for early-age damage is present with the given set of inputs.

Figure 110 shows an output screen from a typical run that demonstrates mix design, pavement design, and construction during PCC pavement placement that lead to a high probability of good performance. The strength curve is the top curve, which remains above the stress curve at all times during the first 72 hours. Note the cyclical manner in which the critical stress occurs. Peaks in the stress curve occur at critical periods when either the axial stresses are dominant or when curling stresses are dominant; the former is in the early morning hours, and the latter is just after midday. In this scenario, the probability for PCC pavement distress (random transverse cracking) is low, because the stress does not exceed the strength during the first 72 hours after placement.

Figure 111 shows an output screen from a typical run where the combination of mix design, pavement design, construction, and the conditions during placement are such that the probability of a poorly performing PCCP is significant. The inputs for this particular run differ from that in figure 110 only by the minimum ambient temperature. A lower value of minimum ambient temperature was used for the scenario presented in figure 111, thus resulting in a thermal shock, which can lead to premature cracking.

The objective of the HIPERPAV guidelines and the accompanying computer software module is to minimize damage to the PCCP during early ages (first 72 hours after placement). By following the general recommendations made in previous chapters of this document in conjunction with the software described in this manual, the chances for achieving this objective are increased substantially.
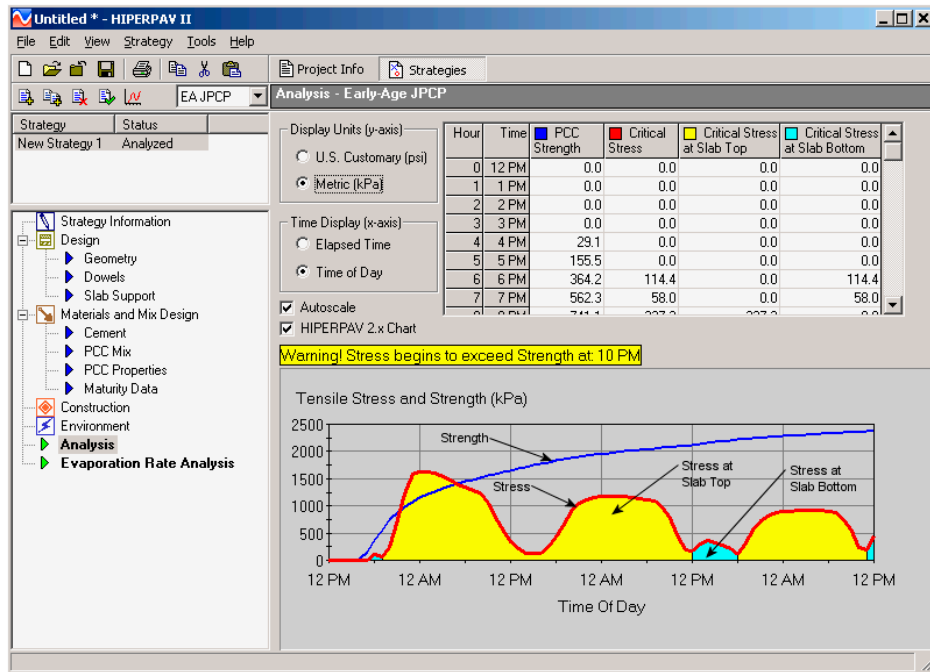
Figure 111. HIPERPAV II early-age analysis showing poor performance.

7.2.6.2 *Evaporation Rate Analysis*

An analysis screen also is provided for evaporation rate (figure 112). The effect of curing methods is not considered on the evaporation rate analysis. The evaporation rate analysis is a function of the windspeed, relative humidity, air temperature, and HIPERPAV II predicted concrete temperatures. The predicted evaporation rate is presented in both graphic and tabular form in this screen.
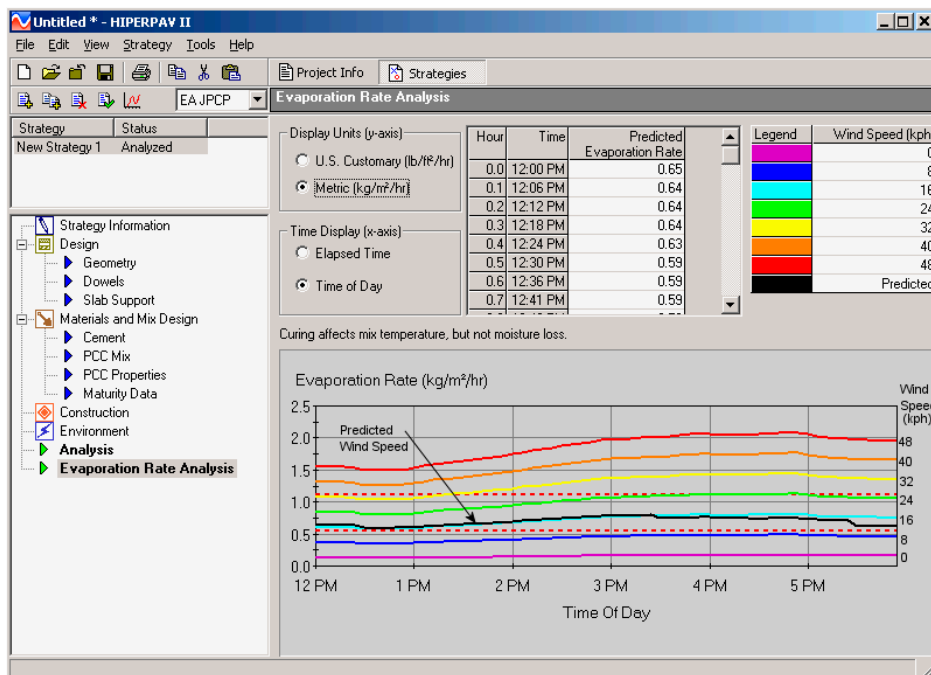
Figure 112. Evaporation rate analysis for early-age JPCP analysis.

7.2.6.3   Dowel Analysis

The dowel analysis screen compares the concrete bearing strength to the bearing stress generated in proximity to the dowels due to slab curling as shown in figure 113. Because slabs in the field may show different curling conditions from one slab to the other, two scenarios are considered: 1) two slabs with similar curling conditions (curl-curl stress); and 2) one slab flat and the adjacent slab in a curled shape (flat-curl stress). It is believed that the actual stress to which a concrete/dowel may be subjected would be intermediate between these two conditions. Like the analysis screen, the analysis results are presented in both a graphical and a tabular form.
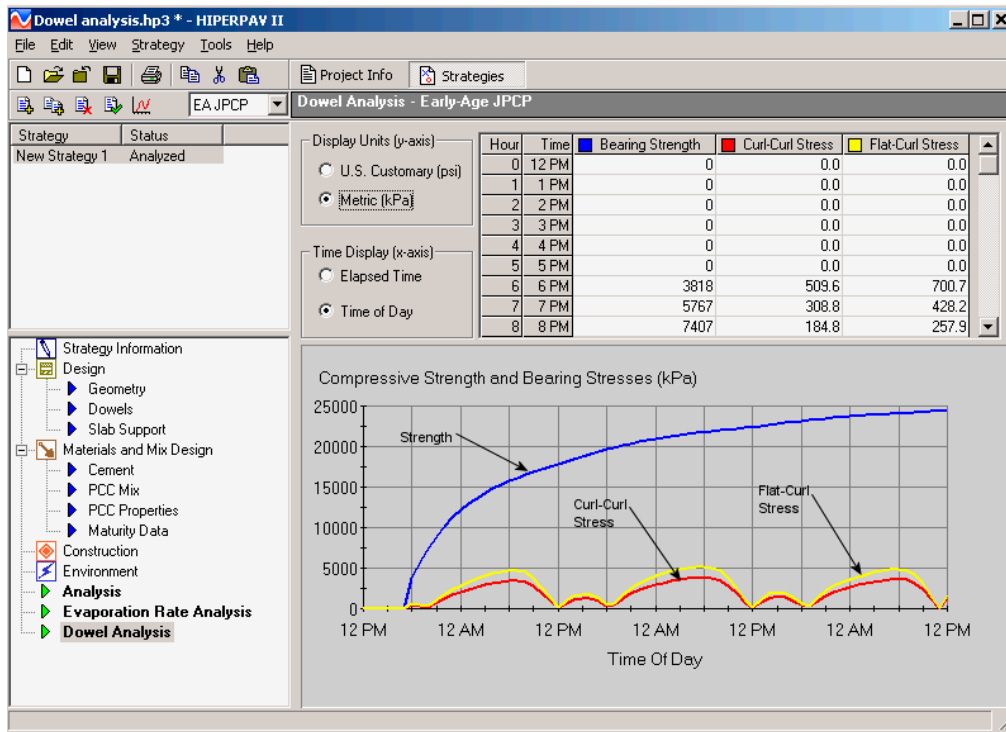
Figure 113. Dowel analysis screen for early-age JPCP.

7.3   JPCP LONG-TERM COMPARATIVE ANALYSIS

The main focus of the software is in the early-age behavior of JPCP. The long-term performance module should be used to further optimize early-age pavement design, materials selection, and construction procedures. The long-term performance modeling should examine relative (strategy comparison) rather than absolute performance, based on early-age factors. In this way, the long-term module can reinforce good paving practices. It must not be used for pavement (structural) design purposes.

In this section, the long-term comparative analysis of early-age strategies is demonstrated. The user should be familiar with the early-age JPCP analysis screens before proceeding with this section.

After the user selects option 2 in the project type selection screen (figure 82), the software creates two early-age JPCP strategies with default inputs that the user can modify with the inputs for his or her specific situation.

In the example in figure 114, a limestone coarse aggregate is selected for the second strategy to observe the impact of this change in the long term as compared to the siliceous coarse aggregate used in the first strategy. The strategies are automatically sorted alphabetically. After both strategies have been analyzed, the user can switch to the long-term analysis module by selecting "LT JPCP" under the strategy type pulldown menu.

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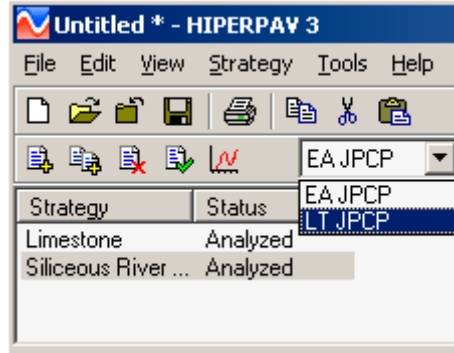
Figure 114. Strategy type pulldown menu.

After generating at least two early-age JPCP strategies and performing analyses on them, it is possible to run a long-term JPCP analysis.

This long-term analysis is designed to be comparative, so an early-age base strategy is selected and compared to the early-age comparison strategy. This allows the user to see how early-age factors affect long-term pavement performance. In this way, long-term performance effects can be reduced with the optimum selection of early-age factors.

7.3.1   Long-Term Strategy Information

Under strategy information, the user selects the base strategy and the comparison strategy (figure 115). Fields for user name and comments also are provided. After the strategy is run, the date of analysis will appear on this screen.
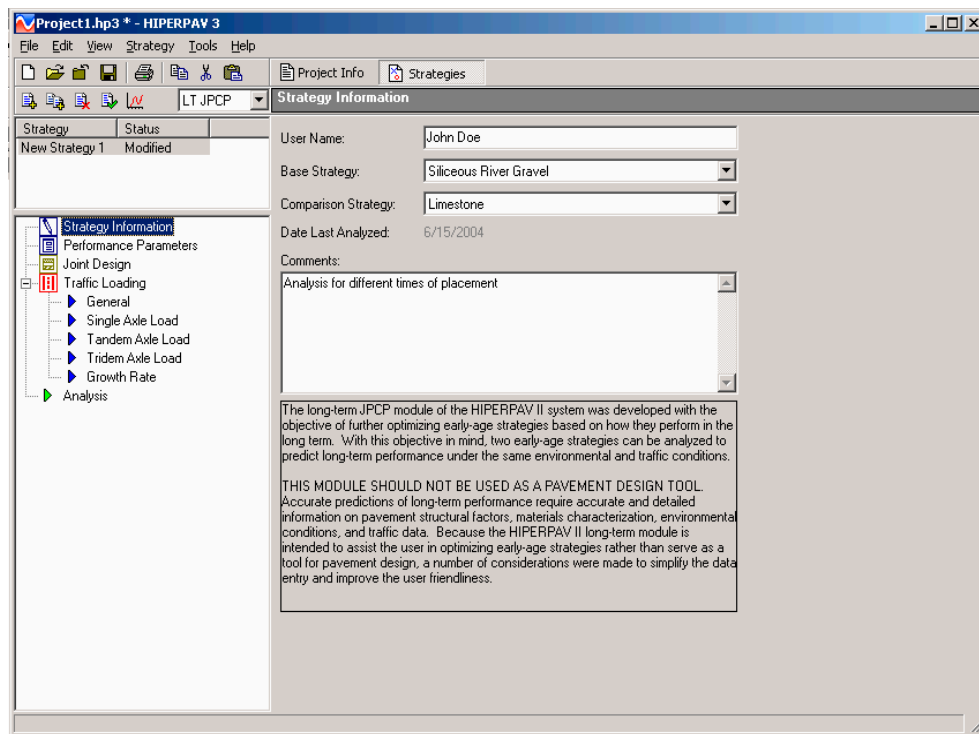
Figure 115. Strategy information for long-term JPCP analysis.

7.3.2 Performance Parameters

In the performance parameters screen, the user is able to enter the long-term analysis period, the reliability level, and the initial roughness index (figure 116). An option is also provided to assess the effect of built-in curling. 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 (see section 2.4.2.2). HIPERPAV II considers two slab curling conditions:

- Consider built-in curling effect checkbox—unchecked: Curling stresses are computed for thermal gradient at time of loading only (assumes flat slab when thermal gradient is zero).

- Consider built-in curling effect checkbox—checked: Curling stresses are computed for thermal gradient at time of loading plus built-in curling present at PCC set time.

Because built-in curling relaxes with time, none of the above conditions is actually correct, but it is believed that the actual condition will lie between these two. During the model validation, it was observed that, depending on the thermal gradient built-in at set (positive or negative), considering built-in curling would show greater potential of cracking in some instances, and for others, not considering built-in curling would be more critical. Therefore, this option was left in the user's control. The most critical case can be identified by running long-term strategies for both built-in curling and no built-in curling conditions at different times of placement. Long-term relaxation effects are difficult to assess at present, due to limitations of available models. In the future, these limitations may be overcome with the development of more sophisticated built-in curling models.

In addition to the above inputs, the user can set the maximum allowable joint faulting, transverse cracking, longitudinal cracking, IRI, and serviceability in this input screen. These set limits are compared to the analysis results in the long-term analysis screen. If the analysis has predicted a level of distress that the user denotes as "terminating" (beyond the predefined distress threshold), HIPERPAV II reports it as the end of the service life for that analysis. However, the analysis continues until the analysis period is reached.
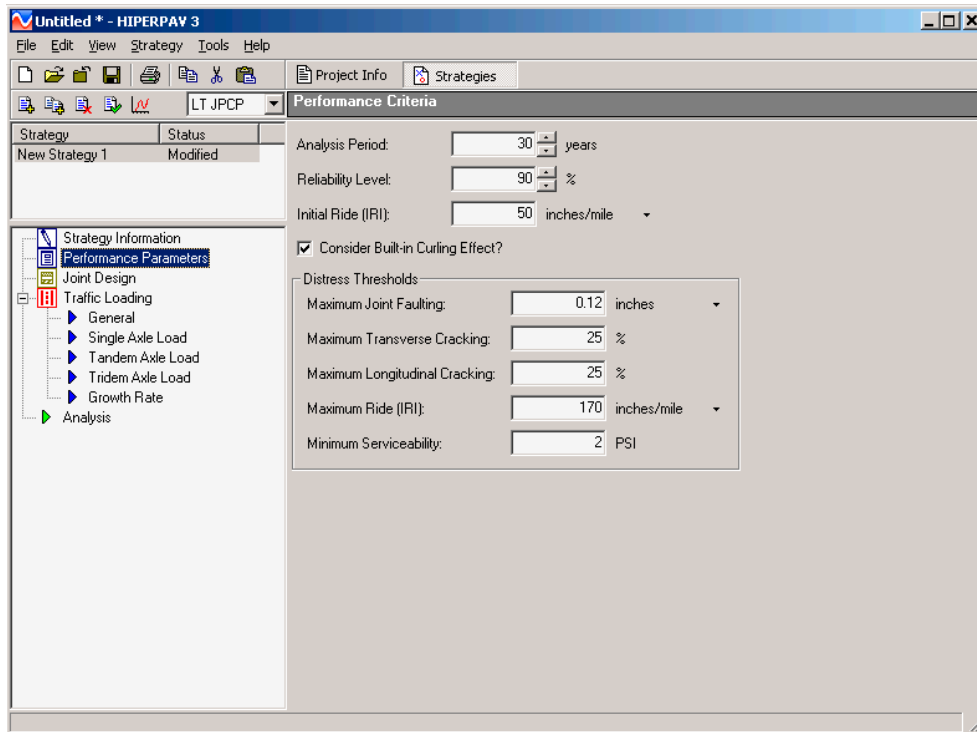
Figure 116. Performance criteria screen for long-term JPCP analysis.

7.3.3   Joint Design

Under the joint design the user selects weather dowels and tie bars are provided. Dowels reinforce the transverse joint while tie bars reinforce the longitudinal joint (figure 117).

Note: The inputs in the early-age dowel analysis module do not apply to the long-term analysis. If dowels are selected as the load-transfer device in the long-term analysis, then for every strategy, dowels are used in the analysis, regardless if they were used or not used in the early-age analysis.

The user can select from no transfer devices, only dowels, only tie-bars, or both dowels and tie bars. If dowels are selected, dowel spacing and length are required in addition to dowel size and modulus. If tie bars are selected, their size and spacing must be input. The transverse sawcut depth is also entered as part of the joint design inputs.
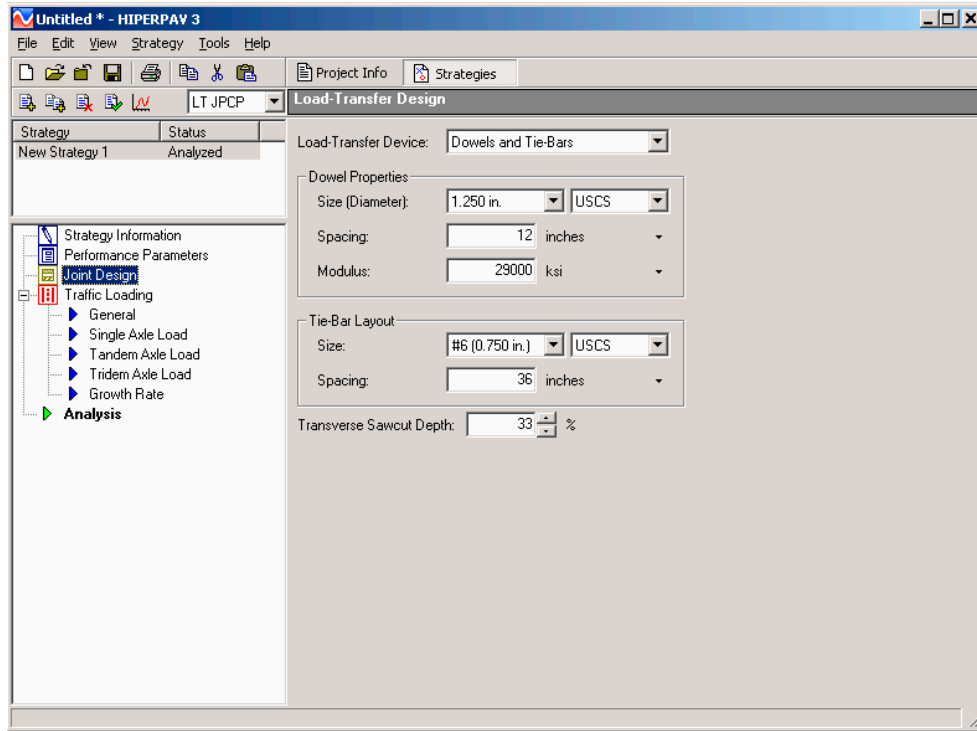
Figure 117. Load-transfer design for long-term JPCP analysis.

7.3.4 Traffic Inputs

Traffic loading also must be input to the long-term analysis, in addition to the strategy information, distress thresholds, and load-transfer design input. Five input screens are provided for this category: one for general traffic information, three for traffic load spectra, and one for traffic growth rate.

7.3.4.1 *General Traffic Input Screen*

In the general traffic input screen (figure 118), the mean truck tire pressure is required. The user can enter a user-defined traffic load spectra or have HIPERPAV II estimate the load spectra based on the input annual ESALs for the design lane. The default traffic load spectra generated by HIPERPAV II is based on typical averages of rural and urban highway traffic (see section B.2.5.4 in appendix B, volume III of this report series). If the user-defined option is selected, the user can enter specific single axle, tandem axle, or tridem axle load values in the gridlines for traffic loading.
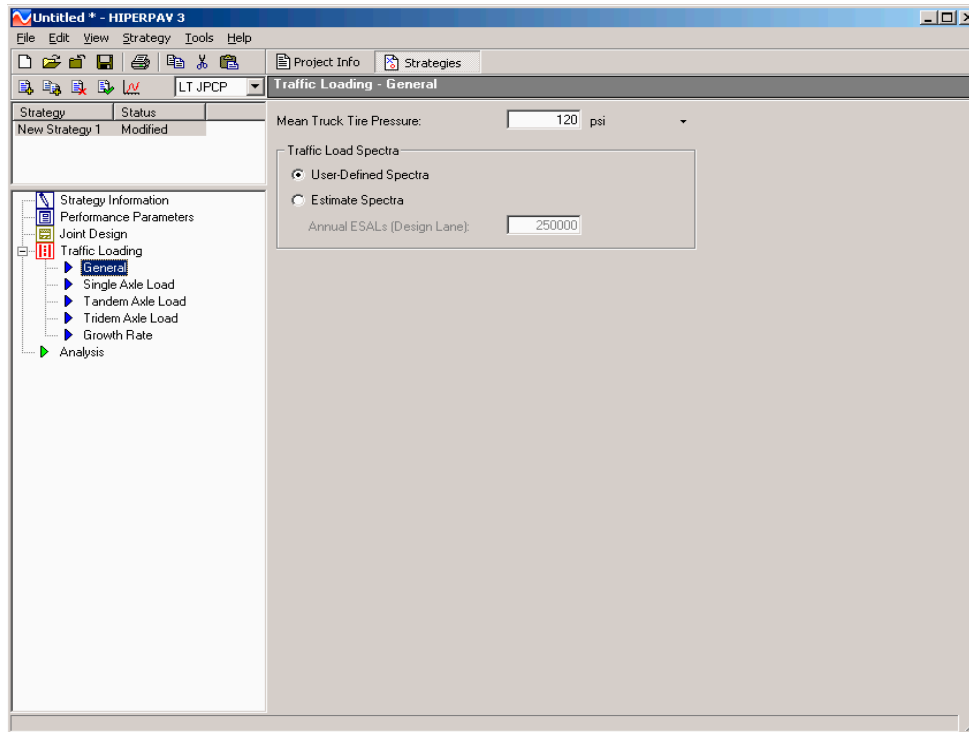
Figure 118. General traffic loading screen for long-term JPCP analysis.

7.3.4.2   Axle Load Spectra Input Screens

If the user enters the load spectra information, this information is entered in the single axle load, the tandem axle load, and the tridem axle load screens (figure 119).

For each traffic load spectra category, the number of single tire and dual tire axle loads per year are entered against the axle load group. The single tire, dual tire, or total load spectra per axle type is shown on the plot, depending on the column selected. The total number of axles per axle load group is the sum of the respective single tire and dual tire values.
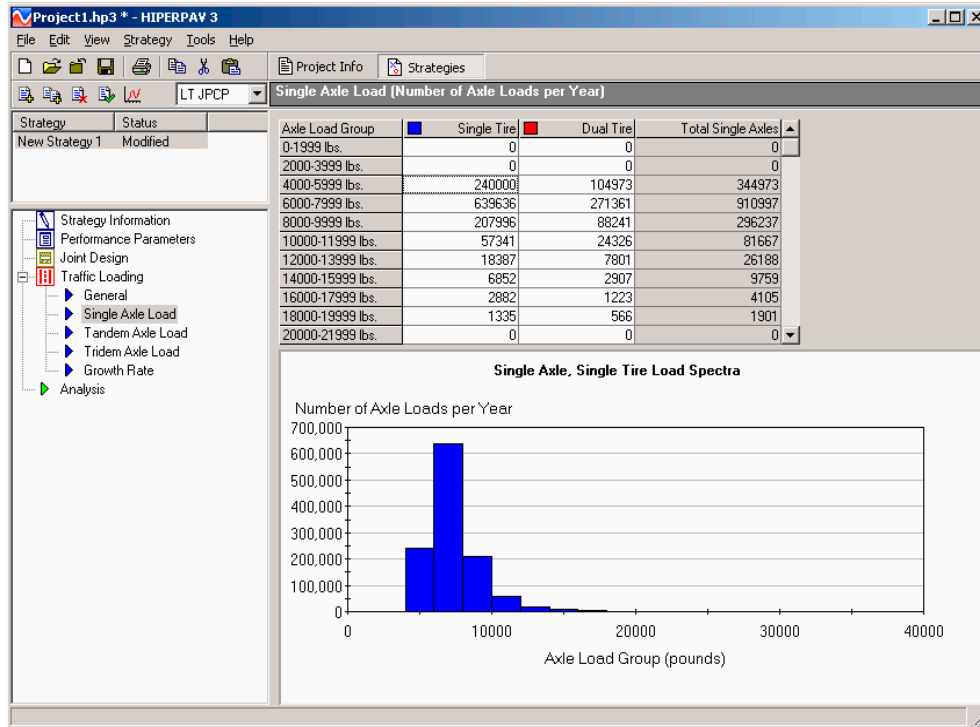
Figure 119. Single axle load screen for long-term JPCP analysis.

7.3.4.3   Traffic Growth Rate Input Screen

Finally, the traffic growth rate information is entered in the growth rate screen (figure 120).
Three different growth functions can be specified: linear, exponential, or logistic. Depending on the
function selected, the input required varies. For any function shown, the traffic loading is divided by the
base-year traffic loading and plotted against time. Two plot methods may be selected: annual or
cumulative.
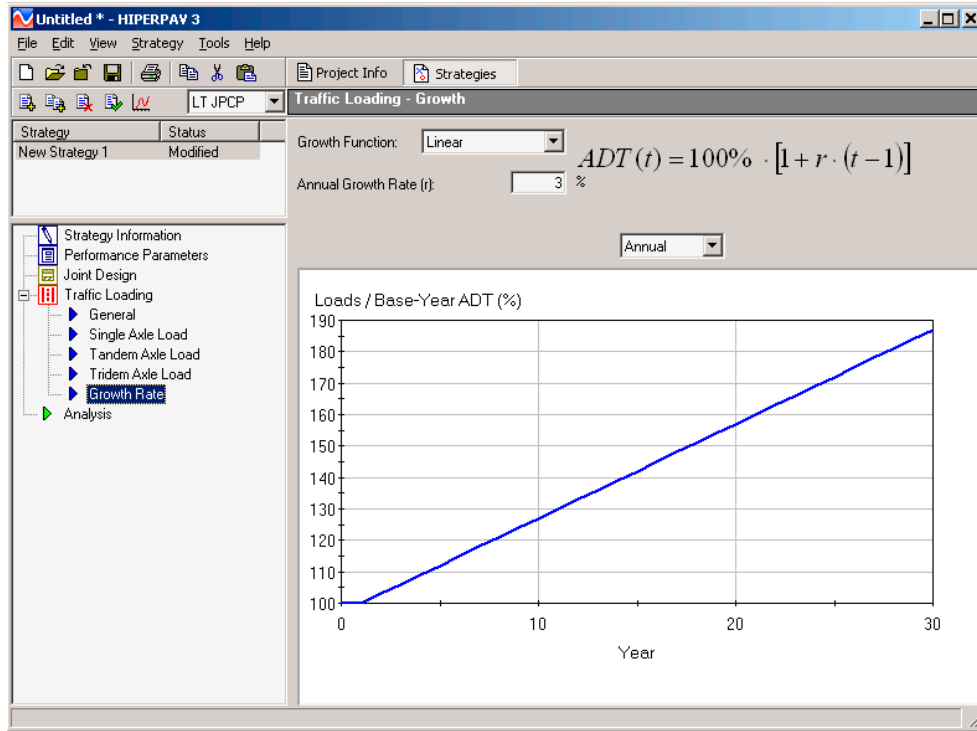
Figure 120. Traffic loading growth rate screen for long-term JPCP analysis.

7.3.5   Long-Term Analysis

With the input assigned, the user should save the project file before performing a long-term JPCP analysis. Icons to manipulate strategies similar to those available for early-age strategies can be used for long-term analyses (see section 7.2.1.1).

After the analysis is run, a window appears showing the analysis status. The base strategy first is analyzed followed by the comparison strategy (figure 121). For each strategy, several structural and functional distresses are predicted, including:

- Joint faulting.

- Transverse cracking.

- Longitudinal cracking.

- IRI.

- Serviceability.

After the analysis is complete, users can now select the type of distress to plot by selecting the distress drop-down window (figure 122).

Each distress type is plotted as a function of time. The distress magnitudes are presented in tabular format at the end of the prediction lifetime or at the time the threshold value is reached, whichever occurs first.

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Using the data values plot method, absolute values of the distress are provided (see plot method drop-down in figure 123. If the change plot method is chosen, the change in predicted distresses between the base strategy and the comparison strategy is plotted.
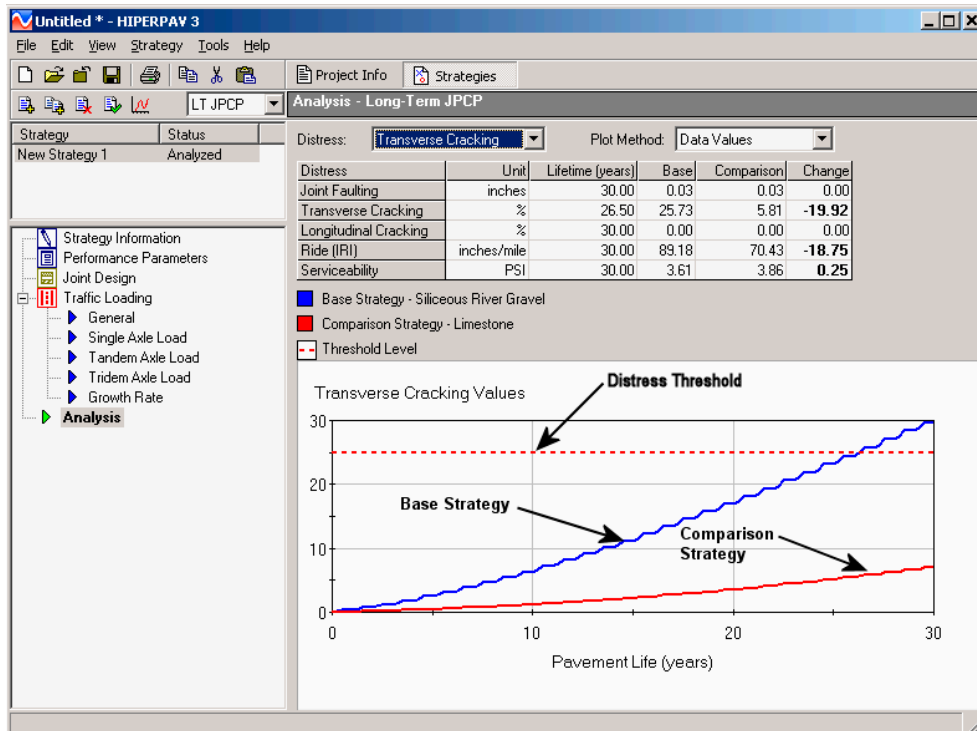
Figure 121. Analysis screen for long-term JPCP.
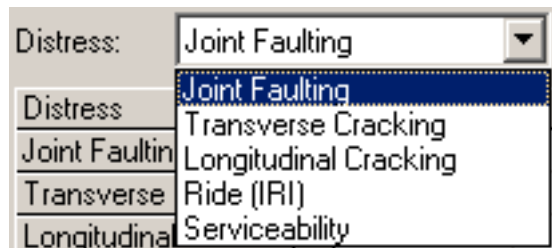
Figure 122. Drop-down menu for distress to plot.
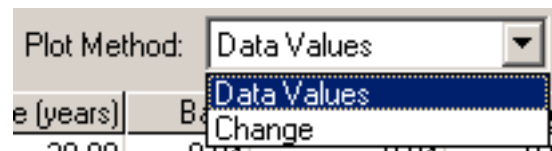
Figure 123. Plot method drop-down menu.

7.3.6 Multiple Long-Term Comparative Strategies

In the long-term module, if more than two early-age strategies are to be compared, this can be done by creating additional strategies with the strategy toolbar. Once the strategy is created, the additional strategies to compare are selected in the strategy information window, as previously described.

7.3.7 Early-Age and Long-Term JPCP Analysis—Sample Scenario

In this section, step-by-step instructions are provided to show the effect of aggregate selection on early-age thermal cracking potential and on long-term transverse cracking. The early-age inputs used for this exercise are presented in table 1. Input values in bold represent the inputs that are different for these two early-age strategies.

Table 1. Inputs for 11 a.m. and 7 p.m. times of placement strategies.

Input Category	Input Screen	Input Value
Project Information	Geography	Austin, TX
	Monthly Weather Data	Estimate Monthly Data from Location
Strategy Information	Reliability Level	90%
Design	Geometry	New Slab Thickness = 250 mm New Slab Width = 3.65 m Transverse Joint Spacing = 4.5 m
	Dowels Analysis	Disabled
	Slab Support	Material Type = HMA (rough) k-value = 55 MPa/m Subbase Thickness = 15 mm Subbase Modulus = 3500 MPa Axial Restraint = Estimate from Material Type
Materials and Mix Design	Cement	ASTM Cement Type Classification = Cement Type I Blaine Fineness Index = Estimate from Cement Type
	PCC Mix	Aggregate Type = Siliceous River Gravel (Baseline Strategy) Limestone (Comparison Strategy) Admixtures = None Fly Ash Class = Class F (CaO <= 7.0% Coarse Aggregate = 1100 kg/m^3 Fine Aggregate = 800 kg/m^3 Water = 128 kg/m^3 Cement = 284 kg/m^3 Fly Ash = 60 kg/m^3 GGBFS = 0 kg/m^3 Silica Fume = 0 kg/m^3
	PCC Properties	28-Day Splitting Tensile Strength = 3.2 MPa PCC 28-Day Modulus = 35,000 MPa PCC Ultimate Drying Shrinkage = Estimate from Mix PCC CTE = Estimate from Aggregate Type
	Maturity Data	Default Strength Gain
Construction	Construction	Initial PCC Mix Temperature = 32.2 ºC Initial Support Layer Temperature = 31.7 ºC Curing Method = Single Coat Curing Liquid Compound Age Curing Applied = 0 Hours Sawcutting: Saw at Optimum Time Skip Sawcutting: Not Used Strength for Opening to Traffic = Not Relevant for This Analysis
Environment	Environment	Construction Date: July 18, 2002 (year irrelevant for analysis since temperatures are historical averages) Construction Time: 11:00 a.m. Temperature, Windspeed, Relative Humidity, and Cloud Cover = Estimate from Location

To perform this analysis, a new long-term JPCP analysis is selected in the project type selection screen (see figure 82). The first step is to select the project location under the geography screen of the project information tab (see section 7.1). If not yet chosen, use the following icons in the geography toolbar to select Austin, TX, in the U.S. map (see figure 84):

 pin

 zoom

 drag

Next, select "Estimate monthly data from location" under the monthly weather data screen (see figure 85).

To enter the early-age inputs for the siliceous river gravel strategy, select the strategies tab (see figure 86). To rename this strategy "Siliceous River Gravel," right click on it and select "Rename," or select "Rename" from the strategy option on the HIPERPAV II top menu. Under "Strategy Information," the reliability level is set to 90 percent. In the same way, all other inputs shown in table 1 are entered under the design, materials and mix design, construction, and environment input screens. For this exercise, data for temperature, windspeed, relative humidity, and cloud cover are set to the default values estimated for that location.

After all the above inputs are entered, the user may perform the analysis by clicking on the analysis icon of the strategy toolbar (see section 7.2.1.1) or by selecting "Run Analysis" from the strategy option on the HIPERPAV II top menu. The results from this analysis are presented in figure 124. The results show a high risk of thermal cracking for the siliceous river gravel strategy.
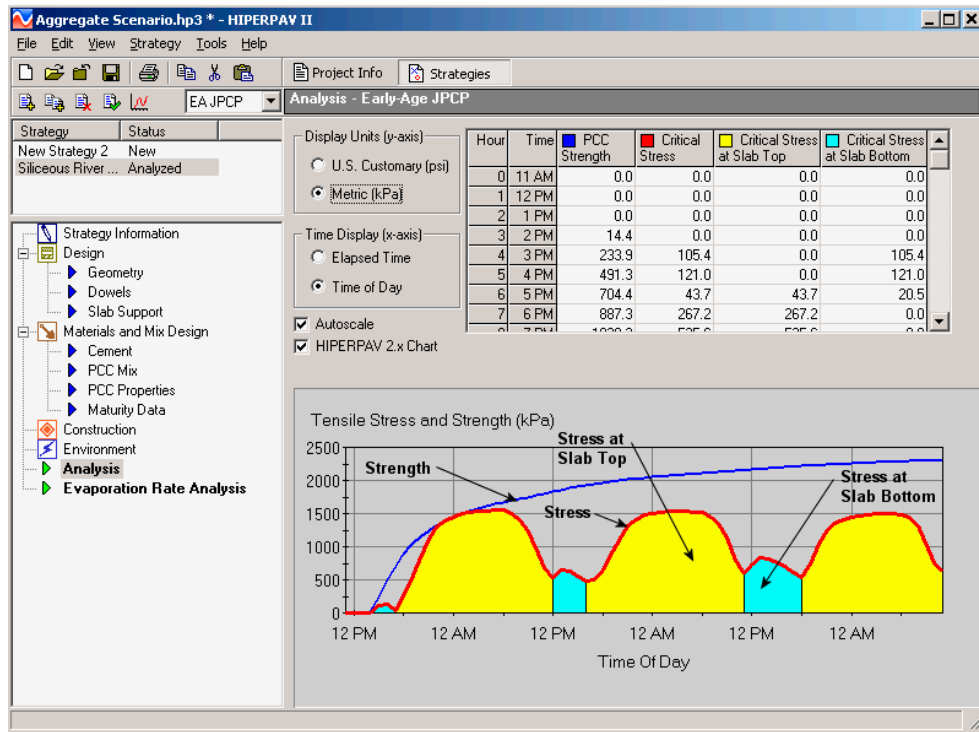
Figure 124.   Analysis results for the siliceous river gravel strategy.

To proceed with the second strategy (using limestone coarse aggregate), the user may either enter the information on a new strategy or create a copy of the siliceous river gravel strategy. The later is recommended, since all previously entered data that is identical for the second strategy will be automatically copied to the second strategy. To do this, select the siliceous river gravel strategy and click

on the ⬛ copy strategy icon. "Copy of Siliceous River Gravel Strategy" appears under the strategy list. To rename this strategy "Limestone," right click on it and select "Rename," or select "Rename" from the strategy option on the HIPERPAV II top menu.

For the limestone strategy, change the aggregate type to limestone in the aggregate type drop-down menu under the PCC mix input screen (see figure 96).

After completing the inputs for the limestone strategy, perform the analysis by clicking on the analysis icon of the strategy toolbar. The result from this analysis is presented in figure 125. Less potential for thermal cracking is observed from the results of the limestone strategy as compared to the siliceous river gravel strategy.

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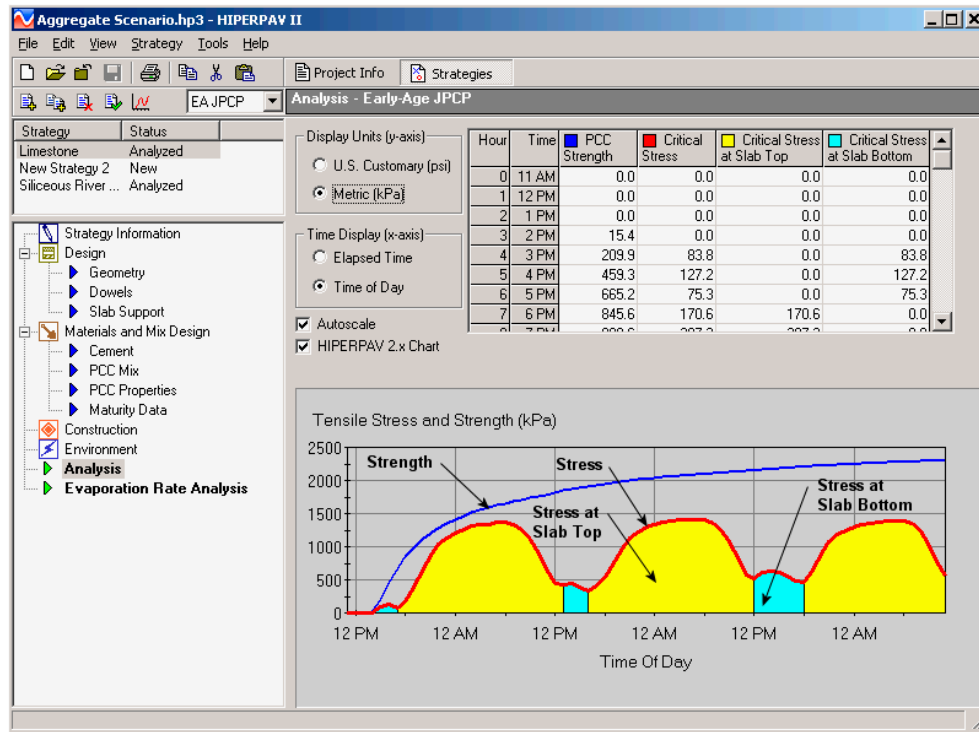
Figure 125. Analysis screen for limestone strategy.

After the two early-age strategies have been analyzed, the long-term analysis is performed using the inputs shown in table 2.

To begin the long-term analysis, select "LT JPCP" under the analysis type drop-down (see figure 114). Then, under "Strategy Information," select the siliceous river gravel early-age strategy as the base strategy and the limestone early-age strategy as the comparison strategy (see figure 126). Complete the rest of the input screens with the information provided in table 2.

Table 2. Long-term inputs for aggregate selection sample scenario.

Input Category	Input Screen	Input Value
Strategy Information	Strategy Information	Base Strategy: Siliceous River Gravel Comparison Strategy: Limestone

Performance Parameters	Performance Parameters	Analysis Period: 30 Years
		Reliability Level: 90%
		Initial Ride: 0.8 m/km
		Consider Built-in Curling Effect: Yes
		Distress Thresholds:
		    Maximum Joint Faulting: 3 mm
		    Maximum Transverse Cracking: 25%
		    Maximum Longitudinal Cracking: 25%
		    Maximum Ride (IRI): 2.7 m/km
		    Minimum Serviceability: 2.0

Joint Design	Joint Design	Load Transfer Devices: Dowels and Tie-bars
		Dowel Properties:
		    Size (Diameter): 32 mm
		    Spacing: 300 mm
		    Modulus: 200,000 MPa
		Tiebar Layout:
		    Size: 19.1 mm
		    Spacing: 0.9 m
		Transverse Sawcut Depth: 33% of Thickness

Traffic Loading	General	Mean Truck Tire Pressure: 0.84 MPa Traffic Load Spectra: Estimate Spectra from ESAL Annual ESAL (Design Lane): 250,000
	Single Axle Load	Estimate from ESAL
	Tandem Axle Load	Estimate from ESAL
	Tridem Axle Load	Estimate from ESAL
	Growth Rate	Growth Function: Linear Annual Growth Rate: 3% Plot Method: Annual

After all the inputs have been entered, the user may perform the analysis by clicking on the analysis icon of the strategy toolbar (see section 7.2.1.1) or by selecting "Run Analysis" from the strategy option on the HIPERPAV II top menu. The joint faulting analysis is presented after the analysis is run. Transverse cracking may be selected from the distress to plot drop-down menu (see figure 122). The transverse cracking results for the siliceous river gravel and limestone early-age strategies are shown in figure 127. The strategy with siliceous river gravel coarse aggregate shows a greater development of transverse cracking compared to the strategy with limestone coarse aggregate. From this analysis, selecting the limestone coarse aggregate source with a lower CTE appears to result in better performance, both in the early age and in the long term.
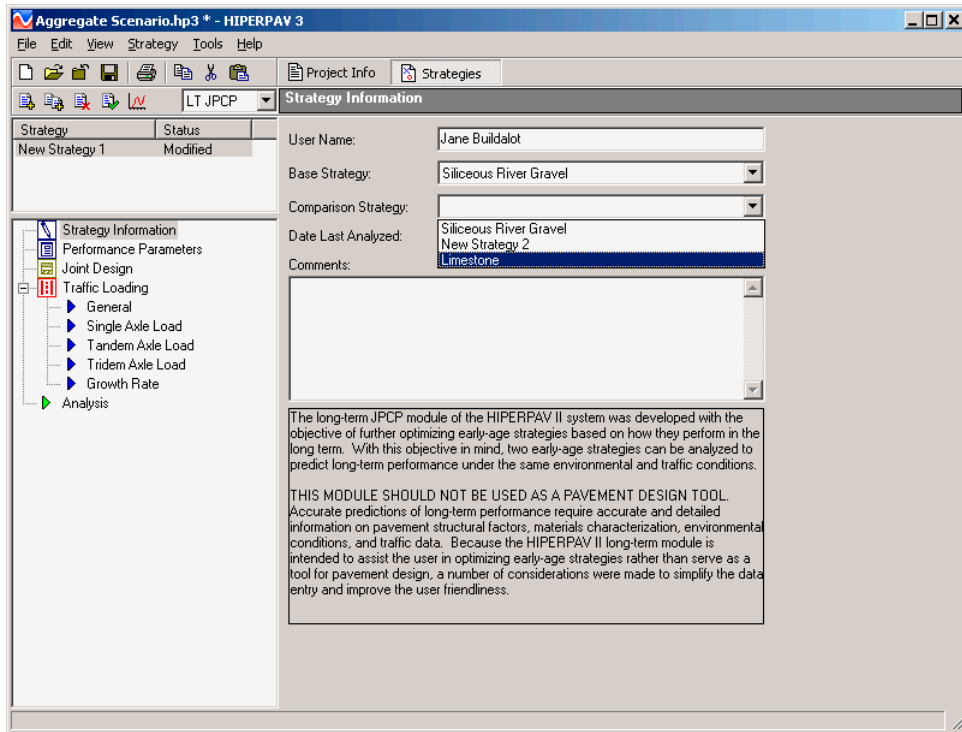
Figure 126. Selection of early-age strategies to compare.
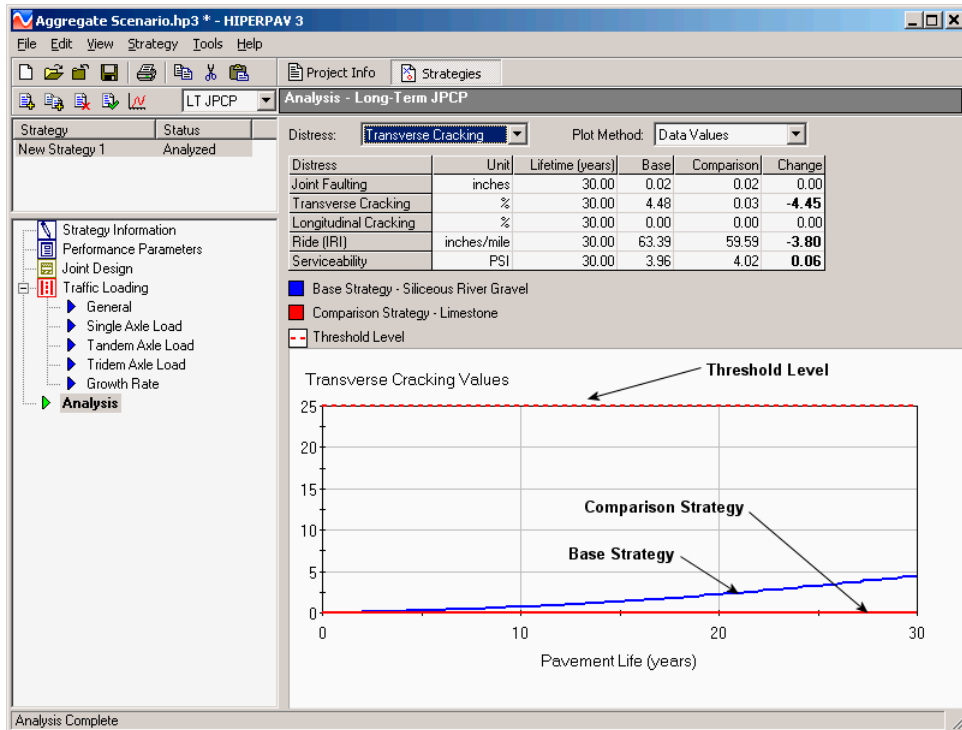
Figure 127. Long-term strategy transverse cracking results.

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7.4   EARLY-AGE CRCP ANALYSIS

In this section, the analysis for an early-age CRCP project is demonstrated.

After the user selects option 3 in the project type selection screen (figure 82), the software creates an early-age CRCP strategy with default inputs that the user can modify with the inputs for the specific situation. The input screens are similar to those required for the early-age JPCP analysis, with some differences.

After the general project information is entered, as shown in section 7.1, one or more strategies for that specific location can be created for analysis under the strategies section.

7.4.1   Early-Age CRCP Strategies Section

The strategies section contains, in tree view, the specific input data required to perform an early-age CRCP analysis under the categories of:

- Design.

- Materials and mix design.

- Construction.

- Environment.

7.4.1.1   Strategy Toolbar

For information on the strategy toolbar, see section 7.2.1.1.

7.4.1.2   CRCP Strategy Information

Under the strategy information screen, the user can enter his or her name. After the strategy is run, the date of analysis also will appear on this screen. A comment box is available for each strategy. This screen is similar to the strategy information screen for early-age JPCP analyses, although no reliability information is required (see figure 86).

7.4.2   CRCP Design Inputs

Under the design inputs, the user can enter the pavement design information, including pavement geometry, steel design, and slab support information.

7.4.2.1   CRCP Geometry

The geometry screen (figure 128) provides fields to enter the slab thickness and slab width. The slab width that should be input in HIPERPAV II is the widest spacing between adjacent longitudinal joints.
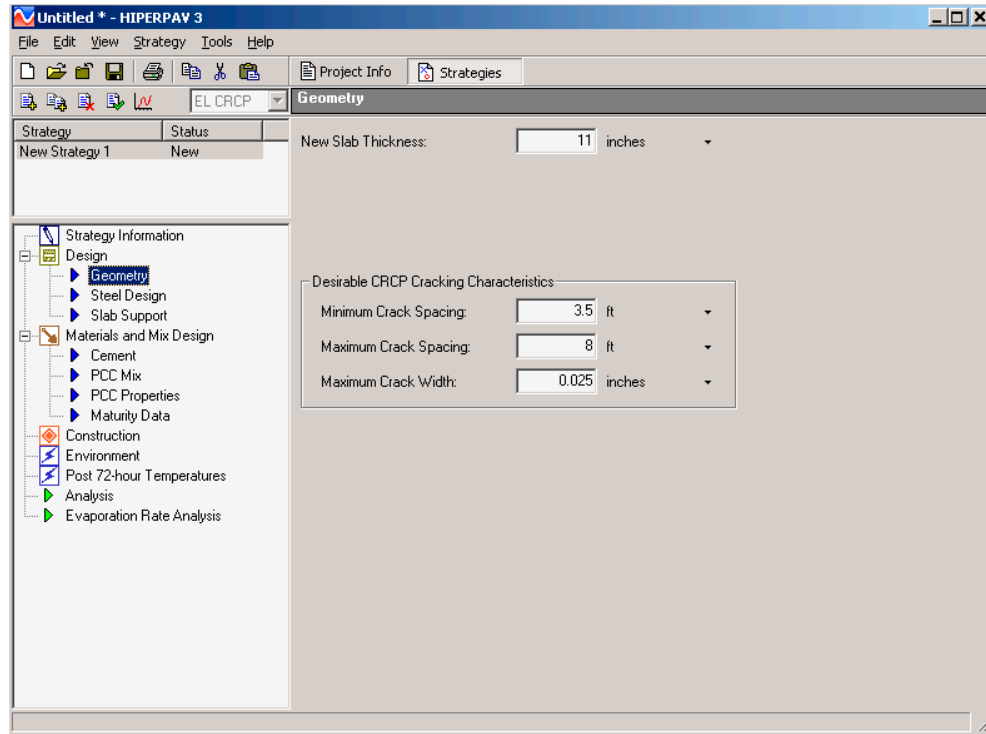
Figure 128. Geometry screen for early-age CRCP analysis.

In addition, long-term desirable CRCP cracking characteristics (after 1 year), including minimum and maximum crack spacing and average crack width, can be entered; these later will be shown by the dashed lines in the early-age CRCP analysis plot.

7.4.2.2   *CRCP Steel Design*

The longitudinal steel information can be input to the program in the steel design screen (figure 129). Information about the longitudinal steel layout and steel properties is required. For the steel layout, the bar spacing and size are needed, as well as the number of steel mats. The steel properties needed are the steel yield strength, steel modulus, and CTE. HIPERPAV II then calculates, based on the input, the percent steel for the current slab thickness.
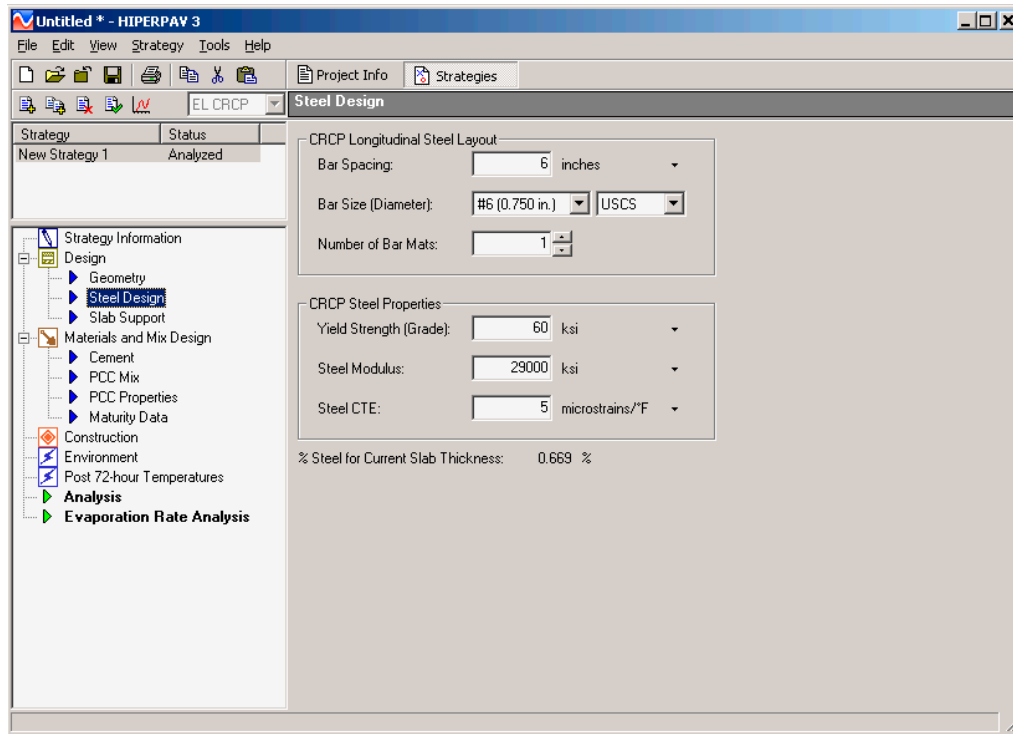
Figure 129. Steel design screen for early-age CRCP analysis.

7.4.2.3   *Slab Support*

For information about this screen, see section 7.2.2.3.

7.4.3   Materials and Mix Design Inputs

The second input category is materials and mix design (see section 7.2.3).

7.4.4   Construction

The third input category corresponds to construction information. The construction screen for the early-age CRCP analysis is shown in figure 130. In this screen, the initial temperatures of the concrete mix and support layer are entered. Information on the curing method used (pulldown) is required along with the time of application, and if removable curing methods are selected, the age when curing is removed also is required.

In addition, if the effect of construction traffic is enabled, loading conditions are required. The user can assess the influence of construction traffic on the performance of the CRCP by inputting the days before the wheel load is applied, the wheel load, and the radius of the circular loaded area.
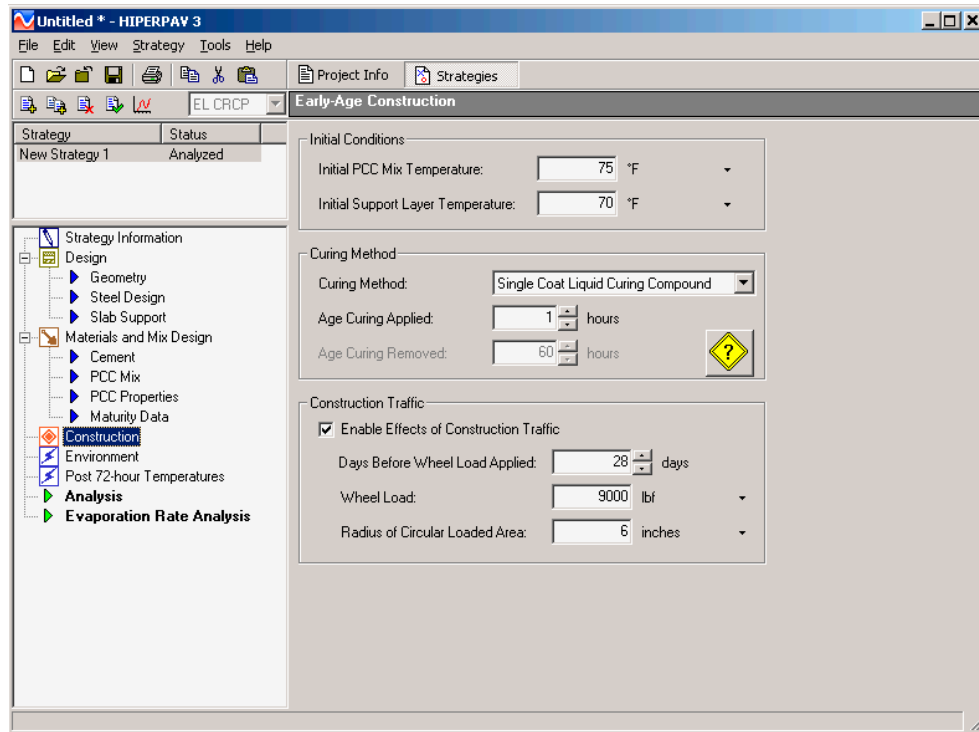
Figure 130. Early-age construction screen for early-age CRCP analysis.

7.4.5 Environment

The environment screen is the same as the early-age JPCP screen seen in section 7.2.5.

7.4.6 Post 72-Hour Temperatures

For the early-age CRCP analysis, the post 72-hour temperatures are required (figure 131). The user may estimate these inputs using the HIPERPAV II environmental database, or the user can define them. The critical analysis period corresponds to the time when construction traffic is applied. For this period, the minimum and maximum air temperatures are also required. In addition, after the critical analysis period, the date of the minimum temperature for the year is needed to estimate the pavement age for the largest temperature drop to which the pavement will be subjected. This date can be estimated by HIPERPAV II, or it can be defined by the user. Similarly, HIPERPAV II can either estimate the minimum and maximum temperatures, or these can be input.

Early age in HIPERPAV II includes the first 72 hours after construction for both JPCP and CRCP. Cracking in CRCP typically progresses until approximately 1 year after construction. After 1 year, cracking typically remains constant. The HIPERPAV II analysis extends beyond early age up to 1 year (early life) to realistically assess the behavior of CRC pavements inservice.
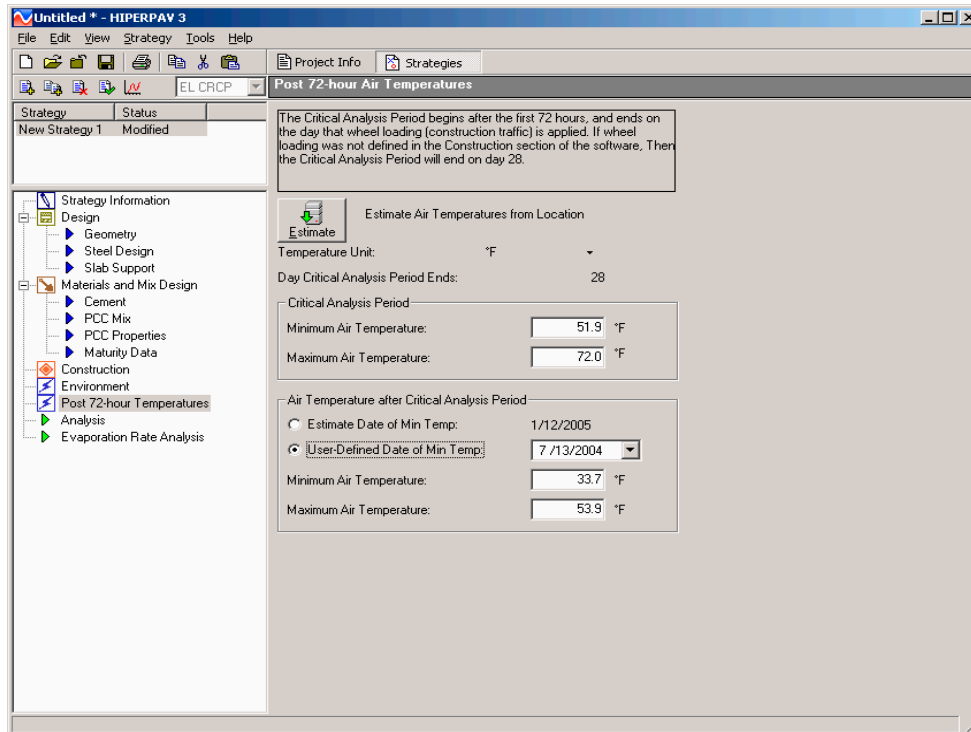
Figure 131. Post 72-hour air temperatures screen for early-age CRCP analysis.

7.4.7   CRCP Analysis

With the input assigned, the user should save the file before performing an early-age CRCP analysis. The analysis screen for an early-age CRCP strategy is shown in figure 132. After the analysis is run, a window appears showing the analysis status. The analysis output, in tabular format, includes the average crack spacing and its standard deviation, the average crack width, the maximum steel stress, and the bond development length. Interpretation of the analysis is performed by comparing the cracking results with the thresholds previously set in "Desirable CRCP Cracking Characteristics" in the geometry input screen. These thresholds are also presented in the analysis screen for comparison.

The plot can either show the incremental or cumulative frequency versus crack spacing. Plots for three different points in time are provided: 1) at 3 days after construction; 2) for the critical analysis period when construction traffic is applied; and 3) at 1 year of age ("Time Period to Plot" pulldown in figure 133). The crack spacing frequency also is presented in tabular format. The numerical value of crack spacing frequency can also be obtained by hovering the mouse over the point of interest in the plot. As shown in figure 134, a help window is provided to caution the user on the validation of the crack width model incorporated in HIPERPAV II. This window also defines the analysis period used for CRCP behavior analyses.

Also, because more than one strategy can be analyzed with HIPERPAV II, comparisons can be made between the analysis results more easily. It is possible to toggle between the analysis screens by selecting one strategy and then the other one (for this, the user must have analyzed at least two strategies previously for comparison and toggled between them).

An analysis screen also is provided for evaporation rate. The evaporation rate analysis is the same as for the early-age JPCP (see section 7.2.6.2).

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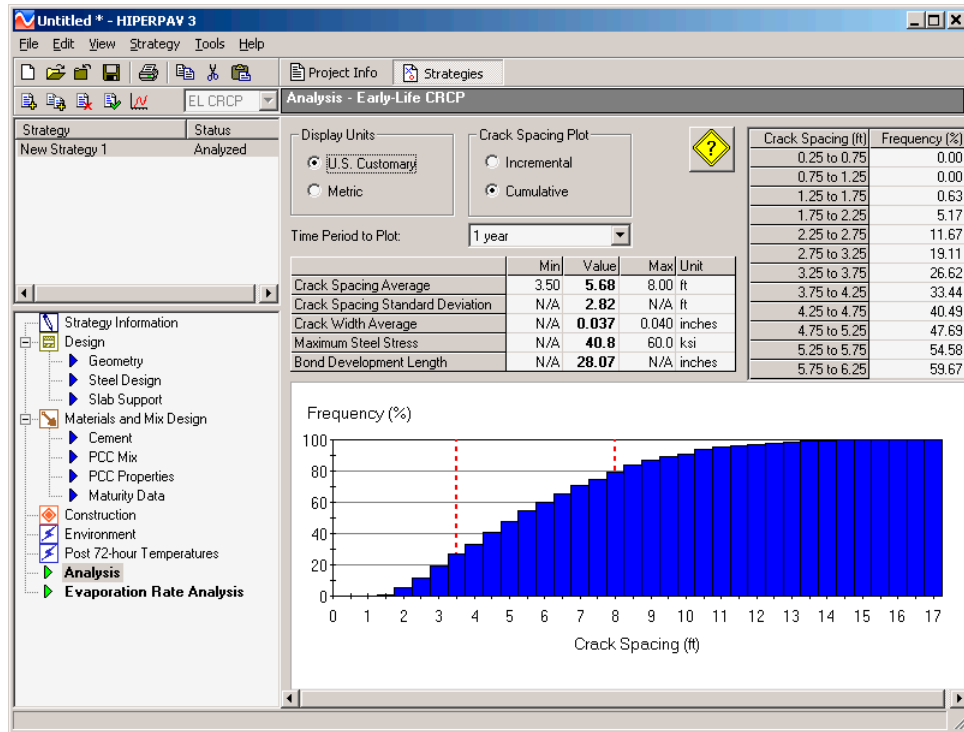
Figure 132. Analysis screen for early-age CRCP.
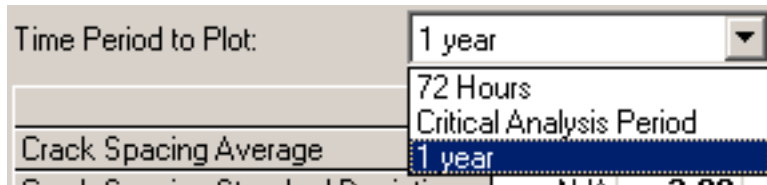
Figure 133. Drop-down menu for time period to plot.
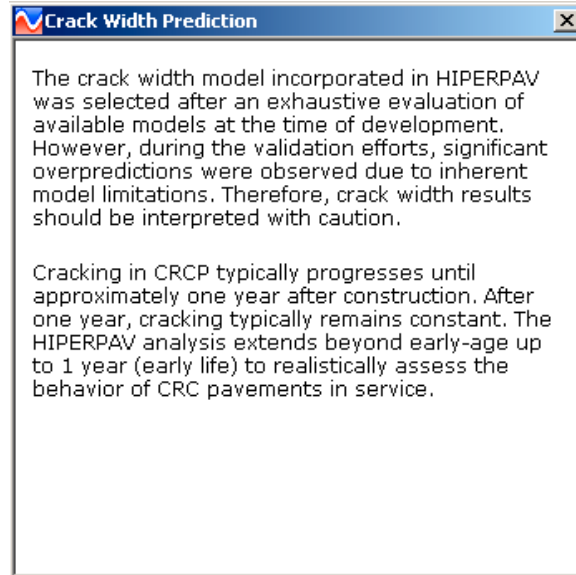
Figure 134. Help icon under CRCP analysis screen.

7.4.8   Interpretation of CRCP Analysis

One of the objectives of the CRCP analysis is to achieve a crack spacing distribution that falls within the predefined thresholds, with only a small percentage of cracks falling above and/or below the maximum and minimum crack spacing limits, respectively, as shown in figure 132. In this analysis, both crack width and crack spacing are within acceptable limits. An example of a CRCP analysis with poor cracking characteristics is shown in figure 135. In this second analysis, neither crack spacing nor crack width fall within acceptable limits. In addition, a large percentage of crack spacings fall below the predefined minimum crack spacing threshold.
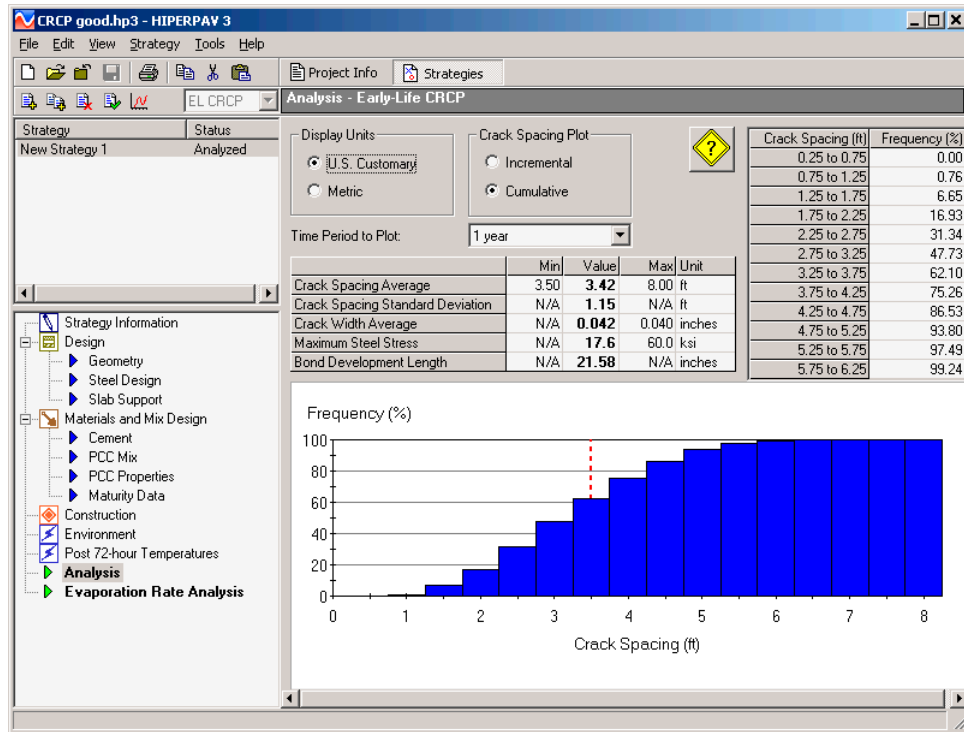
Figure 135. CRCP analysis with poor cracking characteristics.

It is also recommended to compare the maximum steel stress predicted with the steel yield strength to evaluate the potential of wide cracks or steel rupture. The bond development length is predicted to compare with the predicted crack spacing. The user should achieve a minimum average crack spacing of twice the bond development length to ensure good CRCP behavior. For additional information on CRCP behavior, refer to section 2.3.

7.5   HIPERPAV II Reports

For any HIPERPAV II analysis, reports can be generated by clicking on the print icon on the upper icon toolbar or by selecting "Print" from the file menu. After selecting "Print," a HIPERPAV II report screen is displayed as shown in figure 136. In this screen, options are available to select printing options under the setup icon, send the report to the printer as-is under the print icon, preview the report under the preview icon, and export the results to a Microsoft Excel spreadsheet under the export icon.
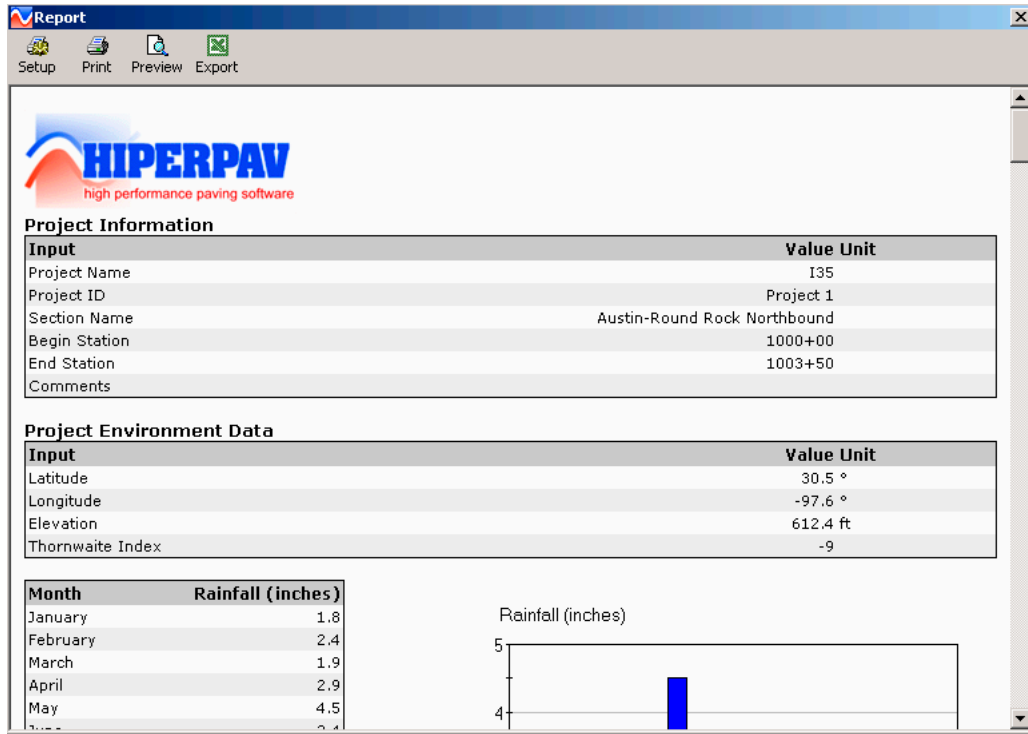
Figure 136. HIPERPAV II report screen.

7.6   COMET Module

The Concrete Optimization, Management, Engineering, and Testing (COMET) module is a simplified derivation of the Concrete Optimization Software Tool (COST) that was developed by FHWA and the National Institute of Standards and Technology (NIST) for optimizing concrete mixes. COMET can be accessed within HIPERPAV II by selecting "COMET" in the tools top menu bar shown in figure 137. COMET optimizes concrete mixes based on early-age strength, 28-day strength, and cost.
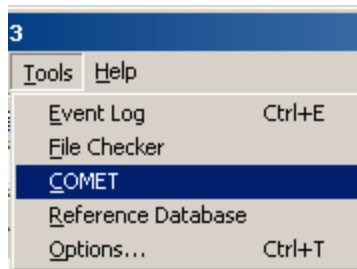
Figure 137. Tools drop-down menu in HIPERPAV II.

Once selected, the COMET initial window appears as shown in figure 138. Inputs and outputs can be selected on the tree view on the left side of the screen. The inputs for the screen selected are displayed on the right. The first item on the tree view, "Event Log," reports potential problems that may arise while running the software. Also, the tree view shows two levels of inputs and outputs. Level 1 inputs generate the experiment design of trial batches required for optimization. Level 2 inputs produce a set of optimum mixes based on the trial batch test results, and desirability functions defined for each response (early-age strength, 28-day strength, and cost).

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As shown in figure 138, mix constituents are limited to cement, pozzolan, water, coarse aggregate, and fine aggregate. For each constituent, the specific gravity and cost is required.
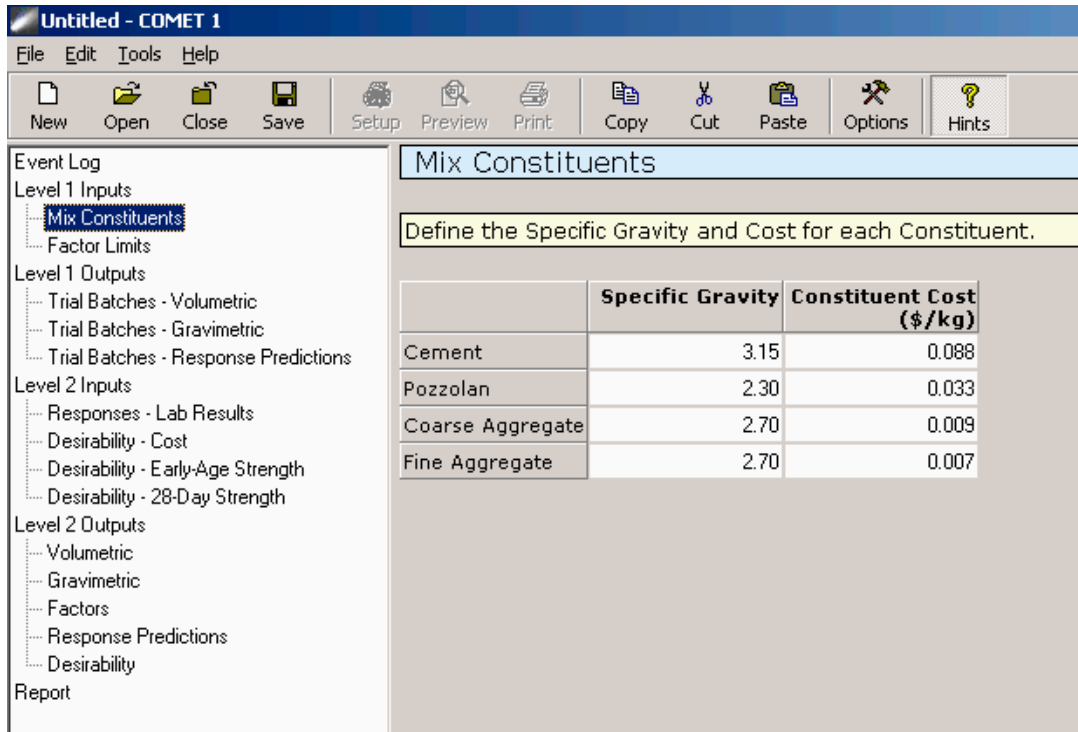
Figure 138. Mix constituents input screen in COMET.

The user provides optimization ranges for coarse aggregate fraction, cementitious content, pozzolan substitution, and w/cm ratio (see figure 139).
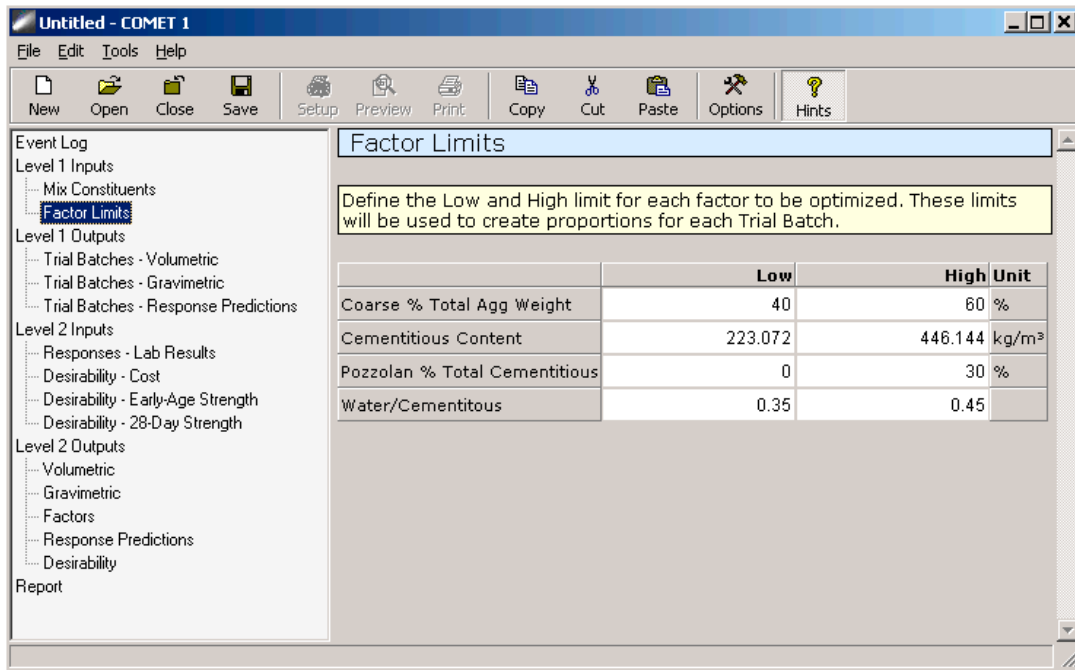
Figure 139. Factor limits input screen in COMET.

With the inputs in level 1, trial batches are developed for the experimental program by running the "Create Trial Batches" command button in the level 1 outputs screen, as shown in figure 140. As a result, 29 trial batches are generated, which can be displayed in volumetric (percent of total volume) and gravimetric (weight per unit of volume) form. The gravimetric form is presented in figure 141.
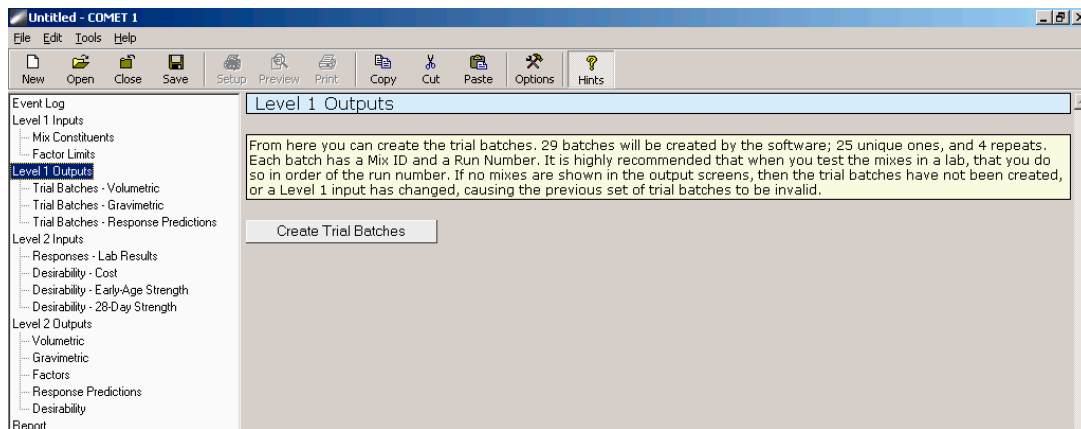
Figure 140. Create trial batches command button in level 1 outputs.

Figure 141. Trial batches in kg/m^3, gravimetric form.

In addition, as shown in figure 142, the cost for every trial batch is computed and default models in COMET are used to predict early-age strength and 28-day strength as a function of mix constituents. Predicted responses are only approximate and may be used in a planning stage in which the mix constituents may not be known or are not available for testing.

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Figure 142. Predicted responses for each trial batch.

After the level 1 inputs and outputs are complete, the user can proceed with level 2 analysis. To continue with this analysis, the user must enter the laboratory testing results for each response for the trial batches generated in level 1 (see figure 143). Alternatively, the user may fill in these values using default models by clicking on the "Reset to Predicted Values" command button, if a preliminary analysis is desirable.
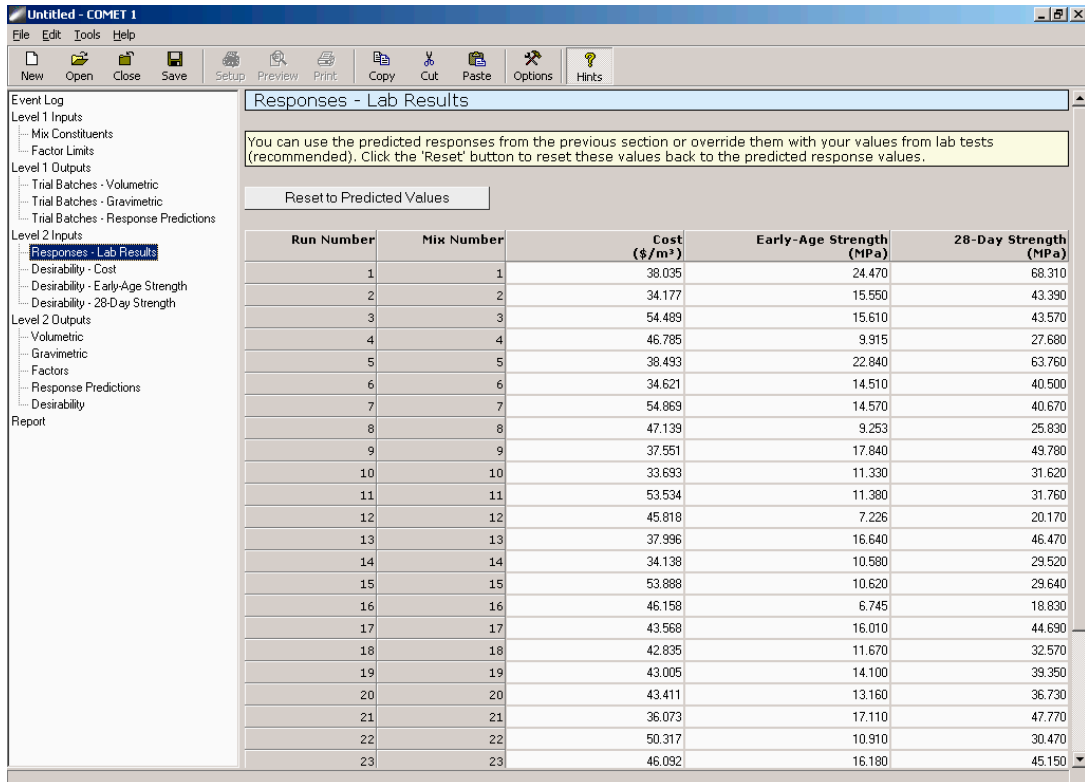
Figure 143. Lab results screen.

The user can assign desirability functions for each of the optimization responses under the cost, early-age strength, and 28-day strength desirability screens (a sample desirability function is shown in figure 144 for 28-day strength).
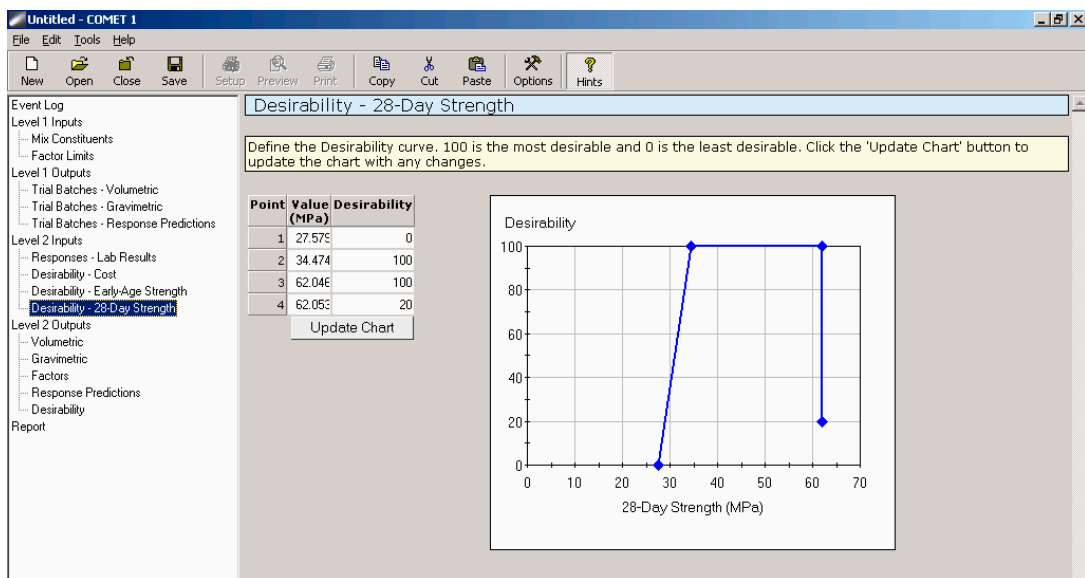

Figure 144. Desirability function for 28-day strength.

After the level 2 inputs are entered, optimization of mixes is performed by clicking the "Optimize Mixes" command button in the level 2 outputs screen (see figure 145). With this command, regression models based on the results from the experimental program or from the predicted responses are developed as a function of the mix proportions.
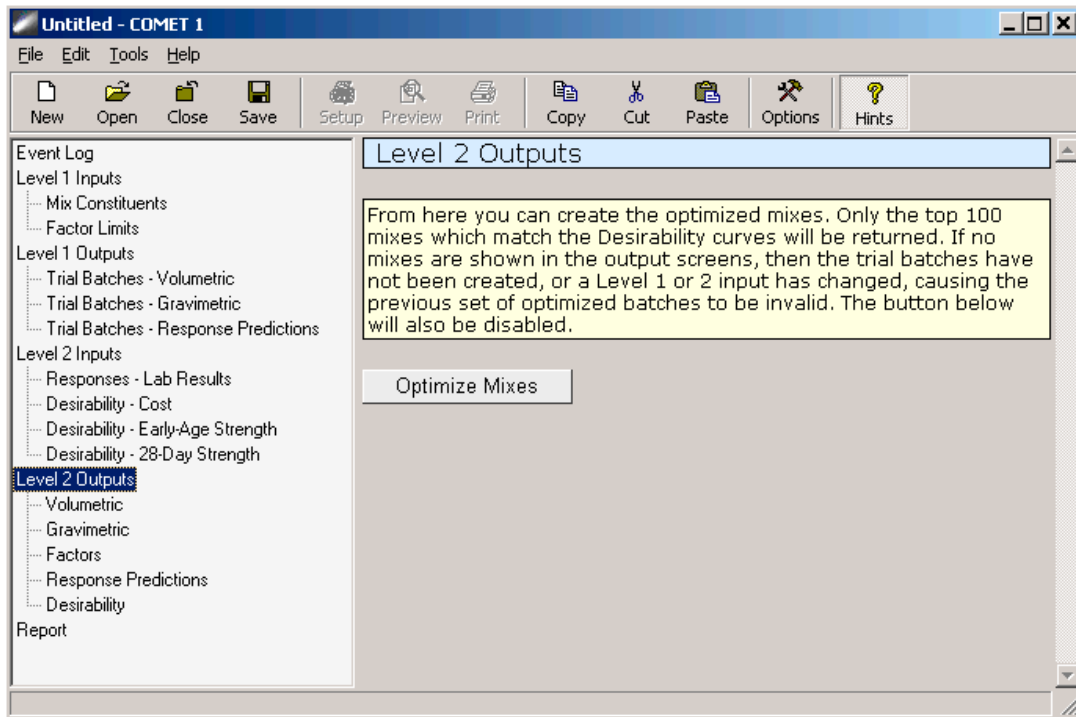

Figure 145. Level 2 outputs—command to optimize mixes.

These models predict responses for a comprehensive set of mixtures within the factor limits specified in the factor limits screen. Finally, optimum mixes are identified in terms of the individual desirability for every response and the maximum overall desirability for all responses, and are presented in volumetric and gravimetric form. Optimum mixes are shown in volumetric form in figure 146.

Figure 146. Optimum mixes sorted by desirability in volumetric form.

In addition, the optimum mixes are also displayed in terms of the optimization factors, predicted responses, and individual response desirabilities as shown in figures 147, 148, and 149, respectively.

Figure 147. Optimum mixtures in terms of optimization factors.
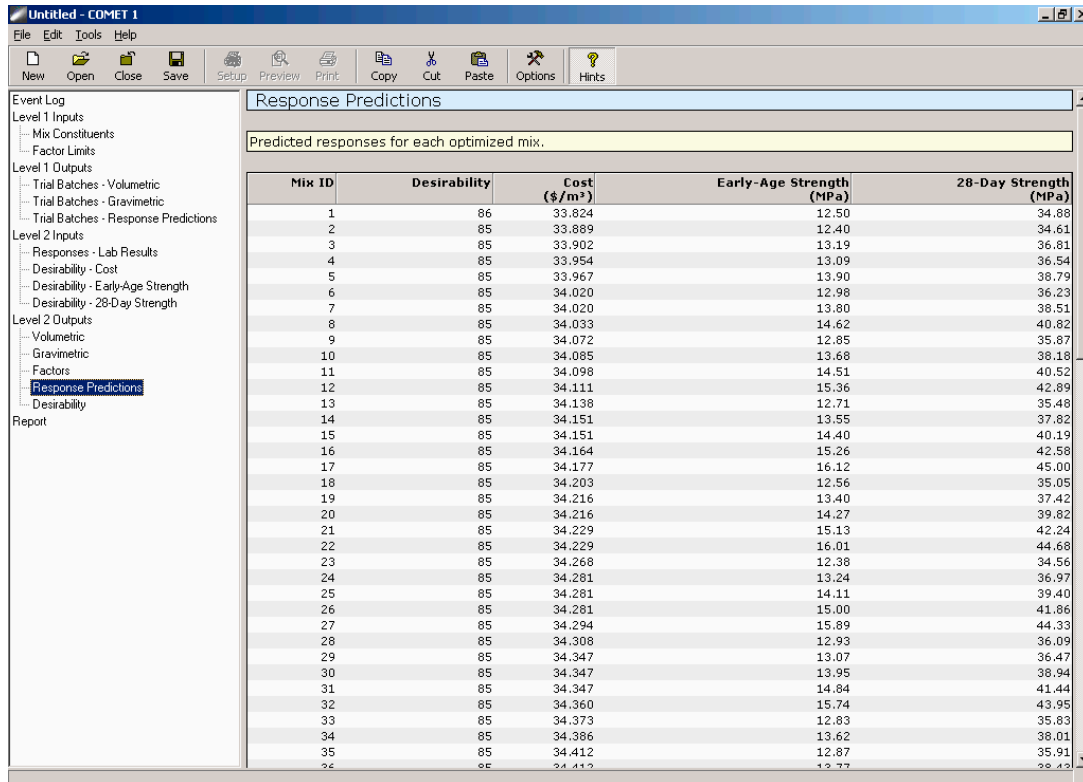
Figure 148. Response predictions for optimum mixtures.

Response Predictions

Predicted responses for each optimized mix.

Mix ID	Desirability	Cost ($/m³)	Early-Age Strength (MPa)	28-Day Strength (MPa)
1	86	33.824	12.50	34.88
2	85	33.889	12.40	34.61
3	85	33.902	13.19	36.81
4	85	33.954	13.09	36.54
5	85	33.967	13.90	38.79
6	85	34.020	12.98	36.23
7	85	34.020	13.80	38.51
8	85	34.033	14.62	40.82
9	85	34.072	12.85	35.87
10	85	34.085	13.68	38.18
11	85	34.098	14.51	40.52
12	85	34.111	15.36	42.89
13	85	34.138	12.71	35.48
14	85	34.151	13.55	37.82
15	85	34.151	14.40	40.19
16	85	34.164	15.26	42.58
17	85	34.177	16.12	45.00
18	85	34.203	12.56	35.05
19	85	34.216	13.40	37.42
20	85	34.216	14.27	39.82
21	85	34.229	15.13	42.24
22	85	34.229	16.01	44.68
23	85	34.268	12.38	34.56
24	85	34.281	13.24	36.97
25	85	34.281	14.11	39.40
26	85	34.281	15.00	41.86
27	85	34.294	15.89	44.33
28	85	34.308	12.93	36.09
29	85	34.347	13.07	36.47
30	85	34.347	13.95	38.94
31	85	34.347	14.84	41.44
32	85	34.360	15.74	43.95
33	85	34.373	12.83	35.83
34	85	34.386	13.62	38.01
35	85	34.412	12.87	35.91
36	85	34.412	13.77	38.43

Figure 149. Individual response desirabilities for optimum mixtures.

Desirability

Predicted response desirability values for each optimized mix.

Mix ID	Desirability	Cost	Early-Age Strength	28-Day Strength
1	86	57	100	100
2	85	56	100	100
3	85	56	100	100
4	85	56	100	100
5	85	56	100	100
6	85	56	100	100
7	85	56	100	100
8	85	56	100	100
9	85	56	100	100
10	85	56	100	100
11	85	56	100	100
12	85	56	100	100
13	85	56	100	100
14	85	56	100	100
15	85	56	100	100
16	85	56	100	100
17	85	55	100	100
18	85	55	100	100
19	85	55	100	100
20	85	55	100	100
21	85	55	100	100
22	85	55	100	100
23	85	55	100	100
24	85	55	100	100
25	85	55	100	100
26	85	55	100	100
27	85	55	100	100
28	85	55	100	100
29	85	55	100	100
30	85	55	100	100
31	85	55	100	100
32	85	55	100	100
33	85	55	100	100
34	85	55	100	100
35	85	55	100	100
36	85	55	100	100

A report that can be used for printing the inputs and outputs for the entire analysis is generated, as shown in figure 150. To print, click on the print icon on the upper icon toolbar.

Figure 150. Report view for printing purposes.

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