Concrete Pavement in Desert Environments: An Investigation of Design and Construction Issues

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Abstract

The extreme conditions of desert environments present special challenges for the design and construction of concrete pavement. These conditions include very low humidity, high winds, high temperatures, and high diurnal temperature changes that increase the risk of cracking, both soon after construction under loads caused solely by environmental conditions and the curing of the concrete, and in the long term under the combined effects of the environment and traffic. This paper summarizes the results of several projects that developed recommendations for concrete pavements in the desert of Southern California. These investigations included a sensitivity analysis based on tens of thousands of runs of the HIPERPAV software for various climate regions in the state and long-term monitoring of four pavement sections from construction through the first several years of heavy traffic for comparison with HIPERPAV predictions. They also included the evaluation of design strategies for tying new truck lanes to existing passenger car lanes, and evaluation of pavement design and mix options using the NCHRP 1-37A software. The results have been used to make recommendations for best practice for these conditions to maximize the life of the pavements.

Practical Significance of Research

This research presents recommendations for design of jointed plain concrete pavements in desert environments based on field results and analyses of use for concrete pavement designers.

Introduction

The successful design and construction of concrete pavements on every project requires careful consideration of materials and structural design and their interaction with the environment and traffic. Concrete pavements in the desert of Southern California present unique challenges because of the hot, dry environment and heavy truck traffic.

The California Department of Transportation (Caltrans) is currently rehabilitating and reconstructing much of its highway network, which was mostly built between 1955 and 1975 with 20-year design lives. Hundreds of miles of interstate highway cross the Mojave and Sonoran Deserts, including I-8, I-10, I-15

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and I-40. I-10, I-15, and I-40 are truck corridors of major economic importance, connecting the manufacturing centers in the Los Angeles Basin and the ports of Long Beach and Los Angeles with the Middle West, East Coast, and southern states, as well as several state routes that serve as important connectors between the interstates. These routes currently have rigid, flexible, and semi-rigid structures of various designs.

Many of these routes will be reconstructed or rehabilitated as rigid pavements. These rigid pavements will include new concrete pavements, white-topping of flexible and semi-rigid pavements, the addition of new lanes to existing rigid pavements, and the reconstruction of deteriorated truck lanes while rehabilitating adjoining passenger car lanes that are in better condition.

Traffic and Environment. Design and construction must account for the heavy truck traffic and the very hot, dry conditions in the desert. Typical traffic information on the interstate routes is shown in Table 1. It can be seen that nearer to the urban areas, average annual daily traffic (AADT) is high and there are more single unit trucks (Type 5). Trucks in those areas tend to have shorter hauls for distribution and thus lower average axle loads. In the essentially uninhabited areas, the percentage of trucks is much higher, and they are mostly semi-tractor trailers (Type 9) carrying long-haul loads, resulting in heavier average axle loads (Lu et al. 2002).

Table 1. Weigh-In-Motion (WIM) Data on Major Interstate Routes in the Desert.

WIM Location	1997 AADT	1997 percent trucks	1997-2001 AADTT	Truck Growth Rate (linear)	30 Year ESALS	Ratio of Type 5/Type 9 Trucks
El Centro (I-8)	22,700	10%	2,830	6.9%	8,566,819	0.36
Indio (I-10)	15,200	40%	7,075	6.5%	29,261,114	0.10
Calico (I-15)	29,500	20%	6,168	1.6%	10,341,296	0.27
Newberry Springs (I-40)	11,000	42%	5,181	2.8%	13,419,632	0.08
Fontana (I-15)	88,000	12%	11,686	5.2%	30,303,129	0.30

*1997 AADT and percent trucks from PMS database, from locations near WIM station.

**ESALs in this paper calculated using Caltrans assumption of 4.2 exponent, divide tandem and tridem axles into multiple singles.

Figure 1 shows monthly average minimum and maximum temperatures for Daggett (junction of I-15 and I-40), El Centro (I-8), and Riverside (junction of I-15 and I-10). Also shown is the average daily change in the surface temperature of the concrete at Daggett, calculated using the Enhanced Integrated Climate Model (Larson and Dempsey 2003). Figure 2 shows average monthly rainfall for Daggett, El Centro and Riverside, and Oklahoma City. Average annual rainfall is 103 mm for Daggett, 74 mm for El Centro, 275 mm for Riverside, and 848 mm for Oklahoma City (Mohseni 2004, Ongel 2004).

The climate data show the high daytime temperatures, high day-to-night temperature changes which cause thermal gradients in the concrete, and low rainfall (as an indicator of humidity) which causes drying shrinkage gradients. The Oklahoma

City data shows that even the hotter regions of the mid-western states experience much of their rainfall and high humidity during the hot months, which minimizes drying shrinkage gradients, whereas the hot months are the driest months in the desert.

Current and Previous Practice. Current practice in California calls for the use of plain jointed concrete pavement with dowels and lean concrete or asphalt bases with granular subbases. Base types in the past have typically been asphalt or cement treated permeable base, lean concrete, or cement treated base, sometimes with a thin asphalt concrete layer between the base and slabs. Concrete pavement built prior to 2000 did not have dowels. Typical thicknesses in the past were 200 or 225 mm; current designs are 200 to 305 mm thick. Joint spacing in the past has included straight joints with 4.5-m slabs or alternating skewed joints of 3.6, 3.9, 5.5, and 5.8 m. Since the 1990s, straight or alternating skewed joints of 3.6, 3.9, 4.5, and 4.2 m have been used. Concrete strength is usually specified in terms of modulus of rupture from third-point beams, with a typical minimum strength of 3.8 MPa at 10 days. Shrinkage has usually been specified in terms of free mortar bar shrinkage. Coefficient of thermal expansion is not measured or specified.

Many projects in the intermediate climate area around Riverside/San Bernardino are in urban areas that use high early strength mixes in order to speed construction and minimize traffic delay (Lee et al. 2002, Lee et al. 2004). These mixes must achieve a modulus of rupture of at least 2.8 MPa at 4 to 12 hours.

Few concrete pavements have been built in the extreme desert environment until recently, although many were built in intermediate areas between the mild coast climate and the desert in the 1960s and 1970s with slab thicknesses of 200 or 225 mm. A 1998 survey of those pavements showed that most had noticeable faulting—nearly all of the 5.5- and 5.8-m slabs had transverse cracks, and many slabs had longitudinal cracks. Corner cracks were not as prevalent (Harvey et al. 2000a).

When truck lanes are to be reconstructed while passenger car lanes remain intact, a decision must be made to either tie the new slabs into the existing slabs and match joint spacings, or install a longitudinal isolation joint. This was a major concern when existing lanes have 5.5- and 5.8-m long slabs.

The hot, dry environment causes rapid curing of the concrete and differential shrinkage between the top and bottom of the slabs, which raises questions regarding materials, structural design, and construction practice to minimize early-age cracking. Some projects have had problems with early cracking.

Long-term differential shrinkage causes a "warped up at the corners and edges" shape which causes tension at the top of the slabs. The high day-to-night temperature changes cause temperature gradients and therefore curling in the slabs,

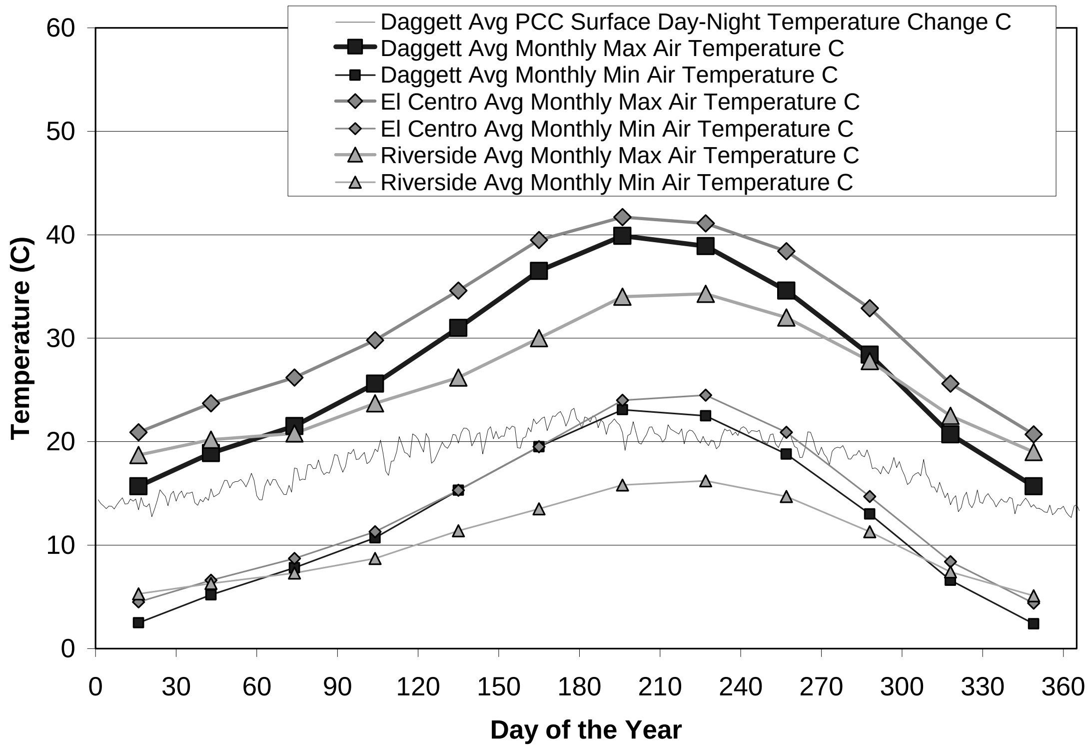

Figure 1. Average monthly minimum and maximum air temperatures for Daggett (I-40), El Centro (I-8), and Riverside (I-15), and calculated average daily pavement surface temperature change for Daggett.

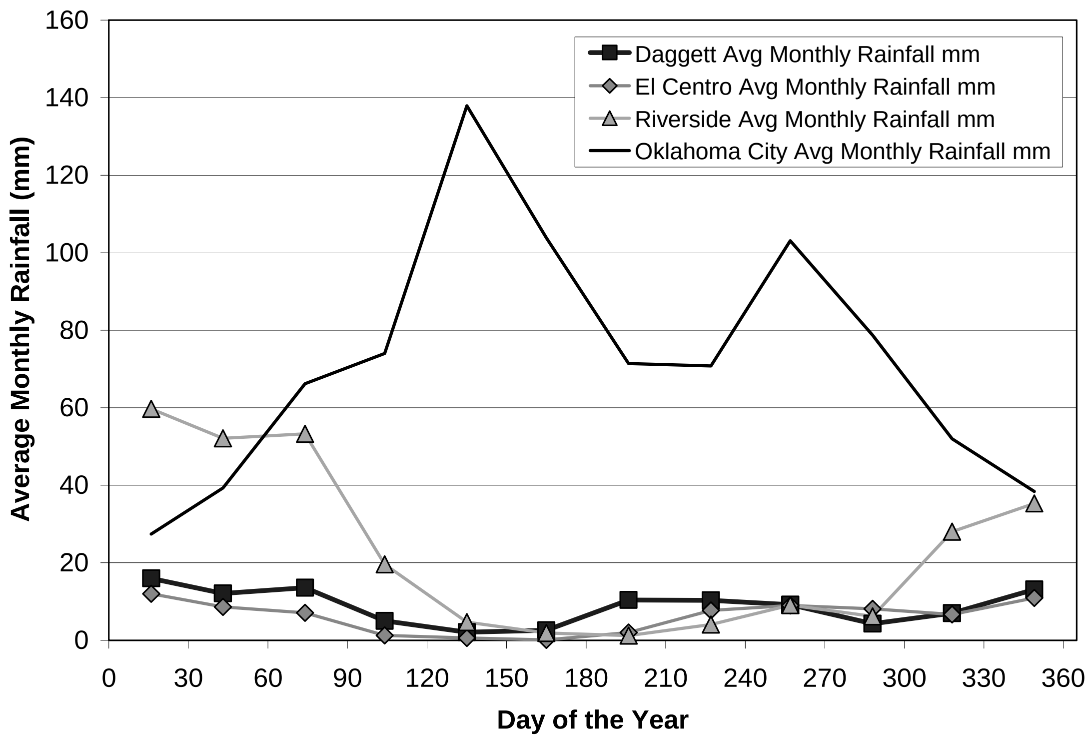

Figure 2. Average monthly rainfall for Daggett (I-40), El Centro (I-8), Riverside (I-15), and Oklahoma City.

which increases tensile stresses at the top during the night and the bottom during the day. The warping caused by differential shrinkage and curling caused by temperature gradients combined with heavy truck traffic raise questions regarding materials, design, and construction to provide adequate resistance to faulting and transverse and longitudinal cracking. With 5- to 20-kilometer projects costing tens of millions of dollars, it is extremely important that the best engineering possible is included in these pavements, and that a “trial and error” learning process be avoided as much as possible.

Approach. HIPERPAV software was developed under a Federal Highway Administration (FHWA) research contract to predict early-age behavior of jointed concrete pavements. The software is a design and construction analysis tool for the first 72 hours following the placement of new concrete (FHWA 2003). HIPERPAV was used to perform a sensitivity study to evaluate the variables affecting early-age cracking and to perform sensitivity studies considering typical California desert practice. HIPERPAV was also run for several projects built in the last several years to help determine its usefulness as a prediction tool for individual projects in addition to providing general guidance.

The finite element program EverFE (Davids 2001) was used to evaluate tensile stresses under extreme conditions in the desert, which were compared to typical flexural strengths to make a recommendation regarding whether to tie new slabs into existing slabs and match joint spacings with 5.5- and 5.8-m slabs, or install a longitudinal isolation joint and use shorter joint spacings.

The NCHRP Project 1-37A software (ERES Consultants 2004) was used to perform a sensitivity study to evaluate the effects of several design variables on transverse cracking and faulting.

Conclusions drawn from these analyses were used to make recommendations for concrete pavements in the desert.

Results from HIPERPAV Software

Early-age cracking is a complex phenomenon that includes many variables, and many interactions between those variables. The individual effects of each of these variables are generally understood. However, on a project it is usually not cost-effective or logistically possible to “do the right thing” with regard to every variable, and it is impossible for an engineer to understand the combined effects of all of these variables at one time through the use of engineering judgment. The HIPERPAV sensitivity analysis had the intention of determining which variables had the greatest effect on reducing the risk of early-age cracking, especially in the desert, so that particular attention could be paid to them in practice.

Use of HIPERPAV Software. HIPERPAV contains algorithms to model the parameters that influence the behavior of the concrete pavement. These are grouped into the following four categories (Rasmussen et al. 2002):

- Mix Design Parameters
- Pavement Design
- Construction Parameters
- Environmental Parameters

The program prompts the user with screens to provide input data for each of the four categories, and provides default values for many variables if the user does not have data. HIPERPAV analyzes the input values using a series of prediction equations and presents a graph comparing the tensile stresses caused by temperature and drying shrinkage changes with strength development over the initial 72-hour period after placement to provide the engineer with information necessary to determine whether there is potential problem with early-age cracking.

The FHWA has reported extensive validation of HIPERPAV for several sites in the United States, and that the validation results demonstrated an excellent predictive capability for HIPEPRAV for the overall early-age behavior. On some of the projects included in the validation study, HIPERPAV did not predict cracking because the predicted tensile stress was not greater than the predicted tensile strength. On those projects, the researchers assumed that cracking was predicted by HIPERPAV at the time in the 72-hour prediction period when the maximum ratio of stress over strength occurred. (Rasmussen et al. 2002)

The minimum ratio of stress over strength occurring in the initial 72 hours from HIPERPAV predictions, referred to in this study as "Ratio Mode," was used for the results presented in this paper, as opposed to yes/no predictions for cracking, referred to as "Failure Mode" (Lee et al. 2003). HIPERPAV currently provides results only in the Failure mode, although the user can perform the calculation to obtain a Ratio mode result.

In Ratio Mode analysis, the dependent variable from HIPERPAV is the ratio of the predicted strength divided by the predicted stress, referred to as the strength-to-stress ratio in this report. This variable provides an indication of the risk of cracking, with increasing values indicating reduced risk of cracking. The average risk of cracking for a given factor level in the experiment can be evaluated from the average of the strength-to-stress ratios for that factor level. Rules were developed to select the strength-to-stress ratio for statistical analysis from the cycles of stress and strength estimated by HIPERPAV in the first 72 hours after placement of the concrete:

If at any time in the 72-hour period HIPERPAV predicted a strength-to-stress ratio of 1.0 or less, indicating failure, the strength-to-stress ratio at the peak of the cycle in which failure occurred was used. If the ratio was less than 1.0 more than one time, the ratio at the first failure was used.

If the strength-to-stress ratio was never less than 1.0, then the smallest strength-to-stress ratio (highest risk of cracking) predicted by HIPERPAV in the 72-hour period was used.

The experiment design factorial for this study results in 93,312 cases (the product of 18 design variables, 16 mixes, 9 environmental conditions, and 36 construction variables), for which the case-by-case operating mode of HIPERPAV is extremely inefficient. An arrangement was made with the developers of HIPERPAV to create a customized batch mode version of the program, which is a Microsoft

Excel based program, modified to give flexibility in the input system (TransTec 2002). All possible combinations of input variables can be input at once in this version, and it produces the output on one sheet.

The results were exported to the software SPLUS for sensitivity analysis plots. The sensitivity analysis plots included in this report show the mean stress/strength ratio for all cases as a solid horizontal line. It shows each variable as a vertical line, cross-hatched with a short horizontal line at the mean stress/strength ratio for each factor level of that variable.

Summary of Input Parameters. Variables for the HIPERPAV sensitivity analysis were selected for typical California concrete pavement scenarios. Table 2 summarizes all of the variables included in this study. The HIPERPAV option of a design reliability of 50 percent was used, which means that the mean value of both the stress and strength curves was used to determine evaluate the ratio of strength to stress. (Lee et al. 2003)

Only two PCC slab thicknesses were included in the experiment design, 229 mm (9 in.) and 305 mm (12 in.) because preliminary analysis showed the slab thickness had little effect on the results compared with other factors. Default values were used for slab/base restraint stress versus displacement.

Most of the properties of concrete depend on the interaction of many parameters—including water/cement ratio, cement content, and admixtures—that are usually correlated to each other and other properties. Rather than design a factorial for mix design variables that would result in many mixes that could never be produced in the field, two realistic mixes were designed for each cement type to meet typical project specifications. The four variables included in the mix design calculations were: cement type, aggregate type, target strength, and Type F fly ash content.

Water content was not selected as a variable for the analysis because HIPERPAV does not directly take into account the drying shrinkage caused by the diffusion of water through the concrete. Instead, the drying shrinkage is directly correlated to the type and content of cementitious materials. A preliminary analysis confirmed this statement.

The key features considered in the mix designs are summarized in Table 3, and the design considerations were based on Caltrans practice and UC research (Roesler et al. 1998, Heath et al. 1999, Harvey et al. 2000a). The final experiment design includes 16 concrete mixes. The mix designs without fly ash were developed following the ACI 211.1-91 procedure for "Normal, Heavy Weight, and Mass Concrete," while the concretes with fly ash were designed by using the ACI 211.4R93 procedure for "High Strength Concrete with Ordinary Portland Cement and Fly Ash." The resulting mix designs were in some cases adapted to meet Caltrans specifications for minimum cementitious material, water content, and fly ash content. Type F fly ash with low reactivity was chosen for the purpose of alkali-silica reaction mitigation. Water reducer and superplasticizer agents have been added for low water-to-cement ratio high strength concretes.

Table 2. Summary of Variables and Factor Levels Included in Sensitivity Study.

Category	Variable	Factor Levels	Total Cells
Design	Subbase Type (3)	HMAC-smooth; HMAC-rough; CSB	18
	Joint Spacing (3)	2.7 m (9 ft.) 4.2 m (14 ft.) 5.7 m (19 ft.)	
	PCC Slab Thickness (2)	229 mm (9 in.) 305 mm (12 in.)	
Mix Design	Cement Type (2)	Portland cement Type II Portland cement Type III	16
	Aggregate Type (2)	Gravel Granite	
	Target Flexural Strength for Mix Design (2 for each cement type)	For Type II mixes, at 10 days: 3.8 MPa (550 psi); 4.5 MPa (650 psi) For Type III mixes, at 12 hours: 2.8 MPa (400 psi); 3.1 MPa (450 psi)	
	Fly Ash Content (2 for each cement type)	Type II mix, 15 %; Type II mix, 25 % Type III mix, 0 %; Type III mix, 25 %	
Environmental Conditions	Climate Region (3, one representative weather station for each region)	South Coast (Los Angeles); Desert (Daggett); Bay Area (San Francisco)	9
	Construction Month (3)	February; May; September	
Construction	Curing Method (3)	None; Double Coat of Curing Compound Liquid; Burlap	36
	Starting Time (3)	6 A.M.; 2 P.M.; 10 P.M.	
	Cure/Saw Cut Start Time (4 combinations of time to curing seal application, delay in saw cut time)	(0 hours, 0 hours); (0 hours,24 hours); (6 hours, 0 hours); (6 hours, 24 hours)	
Total number of tests (1 Reliability case: 50 percent)			93,312

Notes on HIPERPAV acronyms: HMAC = Hot Mix Asphalt Concrete; CSB = cement stabilized base

Table 3. Combinations of Properties of Concrete.

Key feature	Set 1	Set 2
Kinetics of hydration	Type III cement (rapid)	Type II cement (slow)
Thermo-elastic properties	Gravel coarse aggregate (soft)	Granite coarse aggregate (stiff)
Total heat of hydration	Less fly ash (0%)	More fly ash (15% for Type III or 25% for Type II)
Ultimate strength (Center point beam strength)	Lower strength (3.8 MPa/550 psi at 10 days for Type II concrete, 2.8 MPa/400 psi at 12 hours for Type III concrete)	Higher strength (4.5 MPa/650 psi at 10 days for Type II concrete, 3.1 MPa/450 psi at 12 hours for Type III concrete)

The center point beam strength and the elastic modulus of concrete E were estimated using the following relationships in units of megapascals (MPa):

$$f_t \text{ centerpoint} = \frac{f_t \text{ thirdpoint}}{0.85} \quad \textbf{(1)}$$

$$f_t \text{thirdpoint} = 0.3 f'c^{2/3} \quad \textbf{(2)}$$

$$E = 4.73 f'c^{0.5} \quad \textbf{(3)}$$

HIPERPAV does not permit input of beam strengths, which is the test Caltrans uses to test and specify pavement mixes.

The environmental variables were contained in two factors: region and season. Three climate regions, Desert, South Coast and Bay Area, and representative weather stations for each region were included in the experiment as shown in Table 4.

Construction variables are divided into four factors:

- curing method,
- construction start time,
- time to application of curing method
- time to saw cutting of joints

Three types were chosen from the seven in HIPERPAV: none, double coat liquid curing compound, and cotton mats or burlap. Construction starting times of 6 A.M., 2 P.M., and 10 P.M. were selected. In the results, zeros for curing application and saw cutting time mean that a curing method was applied and joints saw cut at the correct times with no delay. The other values for these variables indicated that curing method and saw cutting were delayed or never performed.

Results for All Climate Regions Combined. Construction parameters have the greatest effect on the strength-to-stress ratio while the environment parameters have

Table 4. Combinations of Environmental Parameters.

Code*	Region	Season	Max. Temp. (°C)	Min. Temp. (°C)	Max. Humidity (%)	Min. Humidity (%)	Cloud Cover	Avg. Wind Speed (km/h)
E1	South Coast (Los Angeles)	February	18.7 (65.6°F)	10.5 (50.9°F)	89.7	53.2	Partly cloudy	14.4 (8.9 MPH)
E2	South Coast (Los Angeles)	May	20.9 (69.7°F)	14.2 (57.5°F)	90.4	61.0	Partly cloudy	13.3 (8.2 MPH)
E3	South Coast (Los Angeles)	September	24.7 (76.5°F)	17.6 (63.6°F)	90.7	59.3	Sunny	12.2 (7.6 MPH)
E1	Desert (Daggett)	February	19.1 (66.3°F)	5.3 (41.5°F)	72.9	28.8	Sunny	15.1 (9.4 MPH)
E2	Desert (Daggett)	May	31.6 (88.8°F)	15.1 (59.2°F)	54.3	15.6	Sunny	22.9 (14.2 MPH)
E3	Desert (Daggett)	September	35.8 (96.4°F)	18.7 (65.7°F)	46.8	14.9	Sunny	15.8 (9.8 MPH)
E1	Bay Area (San Francisco)	February	15.3 (59.6°F)	8.3 (47.0°F)	94.7	63.0	Cloudy	13.9 (8.6 MPH)
E2	Bay Area (San Francisco)	May	19.6 (67.3°F)	11.1 (51.9°F)	89.7	54.3	Partly cloudy	21.9 (13.6 MPH)
E3	Bay Area (San Francisco)	September	22.9 (73.2°F)	13.1 (55.6°F)	92.6	54.2	Sunny	17.6 (11.0 MPH)

*Note: For the California case overview analyses, the environmental parameters had to be summarized because of the limits of the customized (spreadsheet-based) HIPERPAV software. The environmental parameters were averaged into three seasonal groups (E1, E2, and E3), representing February, May, and September for the entire state, respectively. That is, E1 is the average of February for all three climate regions (South Coast, Desert, and Bay Area). This decision was made based on the preliminary sensitivity analysis for the input categories, which showed that the environmental parameters have the least effect on the HIPERPAV results compared to the other categories (i.e., design, mix design, and construction).

the least. Among the construction parameters, the curing method and the time to saw cutting of joints are especially critical for minimizing early-age cracking, as shown in Figure 3. The high variability between burlap curing and no curing is mainly due to the insulating effect of the burlap. The burlap reduces the solar radiation (lower absorption coefficient) and the temperature difference between the top and the bottom of the pavement by thermal insulation.

As expected, HIPERPAV does not predict any improvement due to a double coat of liquid curing compound because the program does not model the diffusion process of water. The double coat of liquid curing compound will not change the solar radiation absorption properties of the concrete surface, but it will greatly reduce the drying rate at the concrete surface. Therefore, it would be expected that a double coat of liquid curing compound would significantly reduce early-age cracking even though HIPERPAV does not indicate that result. The high sensitivity to the time to saw cutting of joints is expected because early cracking usually occurs during the first 24 hours of hydration if sawing is not performed.

The construction start time, which because of the temperature at a given time of the day will affect the initial time of hydration, shows a small effect on the cracking phenomena. The 6 A.M. (0600 hours) and 2 P.M. (1400 hours) start times have a greater risk of early-age cracking than 10 P.M.

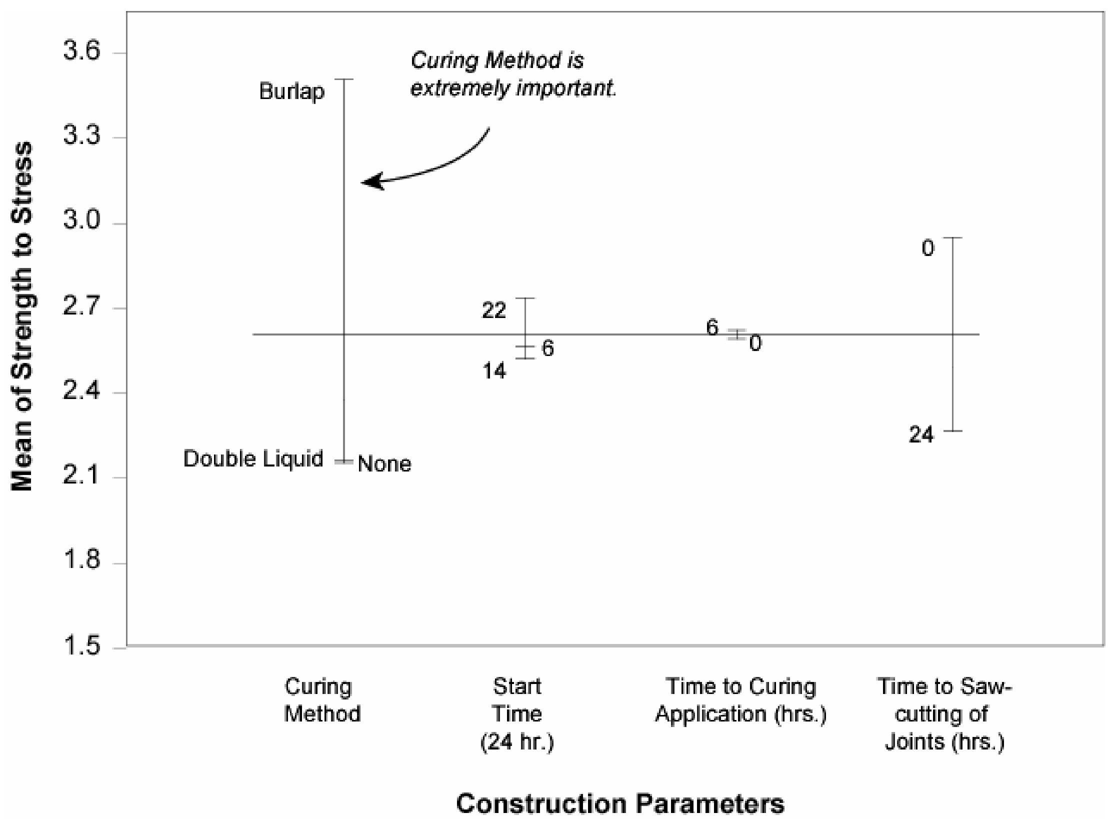

Figure 3. Effects of construction parameters on strength-to-stiffness ratio (Ratio mode analysis).

A 10 P.M. start time results in a low initial temperature of the concrete and a low temperature during the rapid hardening process (usually occurring between 4 and 8 hours after initial hydration). A 6 A.M. start time will cause a low initial temperature of the concrete, but a high temperature during the rapid hardening process, which will exacerbate the temperature increase due to hydration heat. A 2 P.M. start time will cause a high initial temperature of the fresh concrete, but a low temperature during the rapid hardening process, which will increase the stresses in the cooling process.

HIPERPAV indicates that the timing of the placement of a curing treatment has a minor influence on early-age cracking, regardless of whether the treatment is placed immediately after placing the concrete or 6 hours after placing the concrete because the insulation effect is not affected by the time at which burlap is applied.

However, it is likely that HIPERPAV would predict a larger effect of the time to placement of a curing treatment if the diffusion of water were taken into account in the model. A water diffusion model would affect HIPERPAV prediction because most bleeding occurs within the first hours of hydration, and it is critical to apply the curing compound early enough to mitigate bleeding water on the surface of the concrete.

Cement type, aggregate type, fly ash content, and strength gain are all determined in the mix design. According to HIPERPAV, among cement type and aggregate type, the effect of aggregate type has the greatest impact on the risk of early-age cracking. This effect can be explained by the difference in the coefficient of thermal expansion (COTE) and in the stiffness of the two aggregate types.

The effect of angularity is not taken into account in HIPERPAV. Gravel aggregates are softer but have a higher COTE compared to granite aggregates. On average across the three climate regions, HIPERPAV predicts that gravel aggregates significantly reduce the risk of early-age cracking compared to granite coarse aggregates, which shows that the elastic properties are more important than the thermal properties. In other words, the effect of stress generation from the strain is more important than the strain generation itself.

The strength and the amount of fly ash both affect early-age cracking. The replacement of cement by fly ash reduces the heat generation during hydration, thereby reducing the risk of early-age cracking. If the two types of cement are considered separately, then the addition of fly ash will always decrease the risk of cracking. It is important to note that the effect of fly ash is probably greater than that predicted by HIPERPAV because the software does not account for the diffusion of water through the concrete (lower permeability and bleeding rate for fly ash concretes).

Considering all three climate regions together, Type II cement mixes generally had lower risk than Type III mixes because of their lower heat generation and lower elastic modulus. Higher strength Type II mixes did better than lower strength Type II mixes because the greater strength had a greater effect than the slightly greater heat generation. In the case of Type III concretes (2.8 MPa/400 psi and 3.1 MPa/450 psi tensile strength in 12 hours), higher strength increases the risk of cracking as heat generation and development of elastic properties become the key factors.

However, it will be seen that in the desert the Type III mixes had a lower risk than the Type II mixes—the opposite of the mild South Coast and Bay Area climates.

The risk of cracking as predicted by HIPERPAV is particularly sensitive to subbase type and joint spacing, as shown in Figure 4. A cement stabilized base creates a condition of higher friction at the subbase/concrete pavement interface and higher risk of cracking compared to a smooth hot mix asphalt (HMA) concrete base. Similarly, a 5.7-m (19-ft.) joint spacing will create more stresses than a 2.7-m (9-ft.) joint spacing because the accumulated drying strains and the curling stresses are higher. Thickness does not significantly affect the strength-to-stress ratio computed by HIPERPAV, primarily due to offsetting of the positive effect of the thickness on the structural behavior of the slab (lower stress) and the negative effect of higher temperature gradients and greater self-weight.

On average, for the three California climates analyzed, HIPERPAV indicates that the season in which concrete is placed has a weak effect on early-age cracking. The month of February poses less risk of early-age cracking than May, which is in turn safer than September. This difference can be explained by the harsher average conditions (greater solar radiation, more wind, higher temperature, and lower humidity) of September compared to May and February for the three regions.

Parametric Sensitivity Analysis by Climate Region. The results of the sensitivity analysis performed by climate region are similar to the overall sensitivity analysis results except for of the mix design parameters.

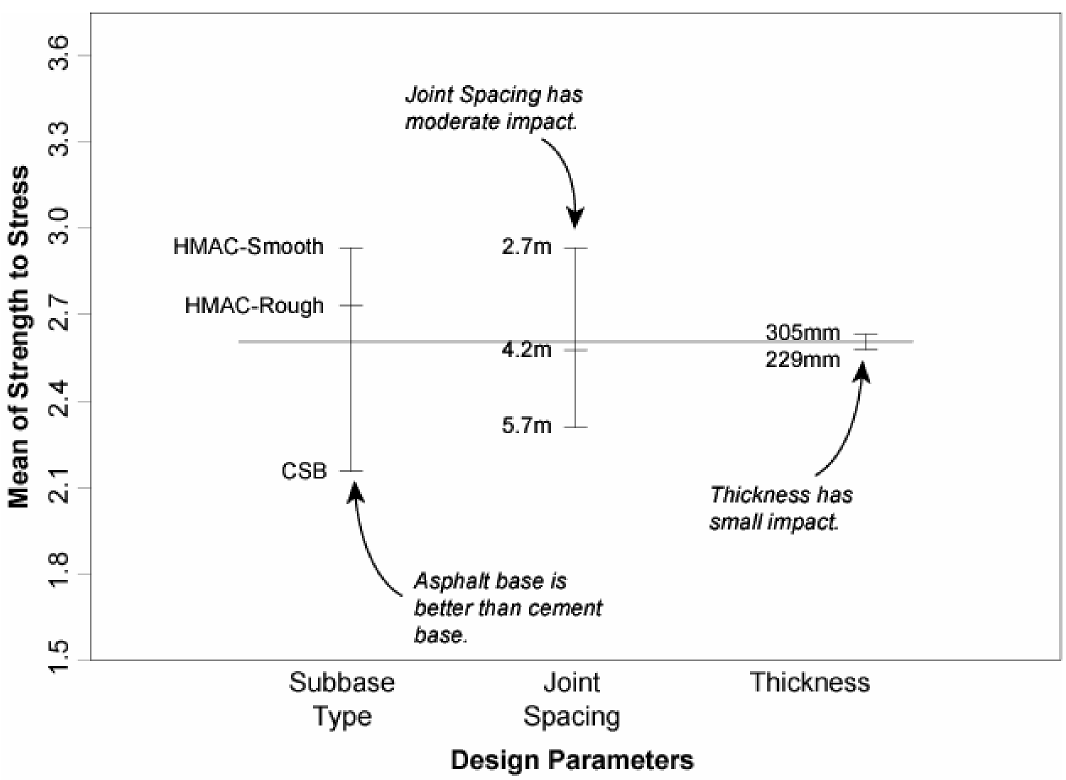

Figure 4. Effect of pavement design parameters on strength-to-stiffness ratio (Ratio mode analysis) for overall California case.

Table 5 summarizes the effect of each group of parameters for Daggett. The results are most sensitive to construction parameters. The second most influential group of parameters is mix design, followed by the design and environment parameters.

In the Desert region (Daggett) the effect of external temperature rise from the hot environment surpasses the differences in heat of hydration for the different cements and mixes.

For this reason, the risk of early-age cracking due to mix design parameters such as cement type and fly ash quantity is generally more sensitive in the South Coast (Los Angeles) and Bay Area (San Francisco) climate regions. However, the effect of aggregate type, especially the coefficient of thermal expansion of the aggregate, is greater for the Desert region because of its interaction with the external conditions (solar radiation, temperature) in the desert area. Figure 5 shows the sensitivity to aggregate type and mix type for Daggett.

For the Desert region (Daggett), Type III cement is shown to be less risky for early-age cracking than Type II cement. This seemingly contradictory result can be explained by the fact that the ultimate strength is the key factor in this case. Type III cements have much higher 28-day strengths than Type II cements. The heat of hydration is less of a key factor for Type III cements than the external environment on slab temperatures in hot regions, therefore, for Type III cements, the kinetics of hydration do not increase the risk of early-age cracking as much as the higher early strength reduces this risk, compared to Type II cements. This is also shown by the

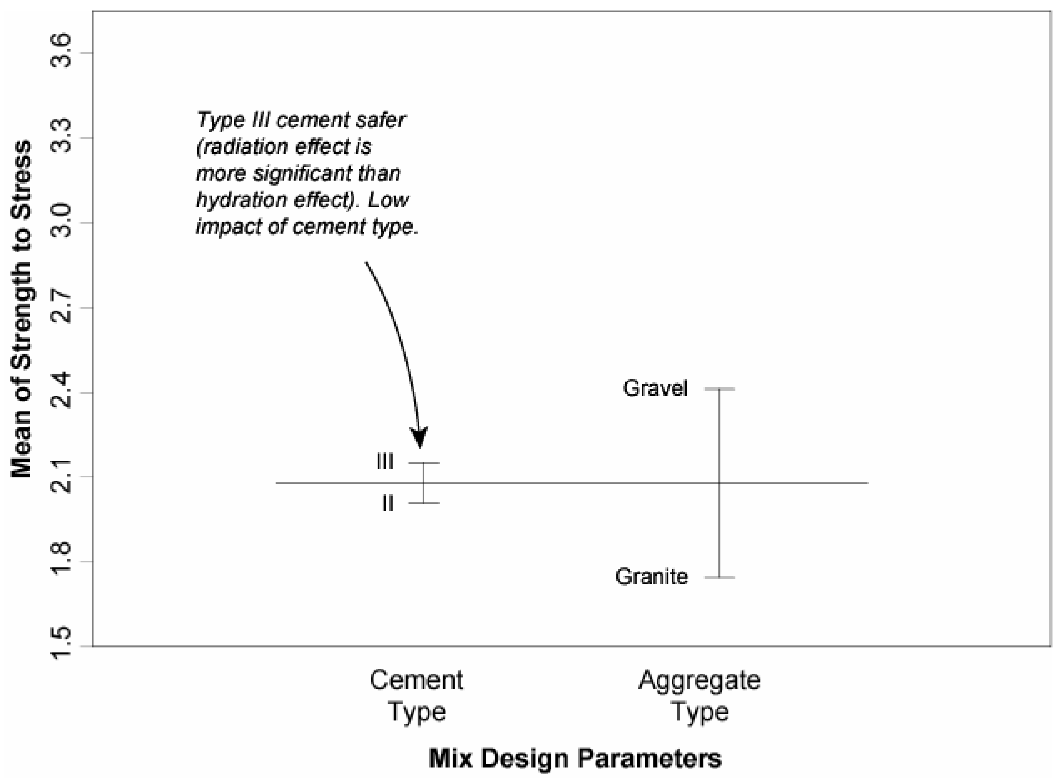

Figure 5. Effect of mix design parameters on strength-to-stiffness ratio (Ratio mode analysis) for Desert region (Daggett).

Table 5. Relative Sensitivity to Parameter Types for Desert Region.

Climate Region	Mean Strength-To-Stress Ratio Across All Parameters	Parameter	Maximum Strength-To-Stress Ratio	Minimum Strength-To-Stress Ratio	Range	Relative Sensitivity (%)*
Desert (Daggett)	2.4	Mix Design	2.6	1.6	1	21.1
		Design	2.5	1.55	0.95	20.0
		Environment	2.2	2	0.2	4.2
		Construction	3.8	1.2	2.6	54.7
South Coast (Los Angeles)	2.6	Mix Design	3.9	1.9	2	30.3
		Design	3.5	2	1.5	22.7
		Environment	3.1	2.7	0.4	6.1
		Construction	4.5	1.8	2.7	40.9
Bay Area (San Francisco)	2.8	Mix Design	4	1.9	2.1	23.9
		Design	3.8	1.9	1.9	21.6
		Environment	3.7	1.3	2.4	14.8
		Construction	5	1.5	2.0	39.8

*Relative sensitivity is calculated as the range of a given parameter divided by the sum of the ranges for the climate region. For example, the relative sensitivity of mix design in Daggett is 0.211 = 1/ (1+0.95+.2+2.6).

effect of strength on the strength-to-stress ratio—higher strength will uniformly reduce the risk of early-age cracking.

Predicted and Actual Performance of Field Projects. Two field projects in the Desert region were instrumented for deflections, strains and temperatures in the slab and with weather stations (no space for results in this paper). The two projects were:

- Type II mix in Ludlow on I-40
- Type II mix in Victorville on I-15

HIPERPAV was run for those projects using actual mix and pavement designs and construction practice used, and maturity and environmental data collected during the first 72 hours after placement, and optimal construction variables. On both projects HIPERPAV predicted early-age cracking at the 50 percent reliability level. Inspection of the project showed that no early-age cracking had occurred in the of both projects. Long-term monitoring is continuing. These results strongly indicate that HIPERPAV should be used as an indicator of which variables are important, rather than an actual predictor of whether a given project will fail or not. They also indicate that HIPERPAV currently should not be used as a mix design acceptance tool.

Analysis of Joint Spacing versus Longitudinal Edge Support

Calculations were performed to evaluate matching of long joint lengths (5.9 m and 5.5m for 1970s Caltrans specifications) in truck lanes being reconstructed adjacent to relatively undamaged passenger car lanes, and the impact of tying or isolating the longitudinal joint (Bian et al., unpublished technical memorandum for Caltrans 2003). These calculations were performed using EverFE 2.21 (Davids 2001), a three-dimensional FE analysis tool for rigid pavement. The analysis looked at whether the calculated tensile stress is greater than the concrete strength, which would be expected to cause cracking after several repetitions, and not a full fatigue analysis, although the results are expected to provide an indication of fatigue life.

Two axle configurations were used: a dual-single axle for the mid-slab edge load position, and a dual-tandem axle for the corner loading position. Two loads were used for each configuration: the legal load limit; and the 99th percentile for that axle type from a state-wide average of Weigh-In-Motion data (Lu 2002). These were 89 and 100 kN for the dual-single and 150 and 100 kN for the dual-tandem, respectively. Annual maximum and minimum temperature gradients for nighttime and daytime, averaged over 30 years, were taken from calculations for different slab thicknesses made using the Enhanced Integrated Climate Model and climate data for the desert and central valley regions (Harvey et al. 2000b). The mid-slab edge loading was combined with daytime gradients and the corner loading with the nighttime gradients.

The stress-to-strength ratio was evaluated for typical early and long-term concrete stiffnesses and strengths for Caltrans mixes. Typical stiffness values for lean concrete and asphalt concrete base were used. Various longitudinal joint conditions evaluated and the calculated stresses are shown in Table 6 for the mid-slab edge/daytime temperature gradient and dual-single overload case, which was generally found to be critical.

It can be seen that the maximum tensile stresses in concrete slabs depend significantly on slab length. Comparing the maximum tensile stresses in the 5.9-m slabs with tied joints and the stresses in the 4.6-m slabs with isolated joints, it can be seen that the tensile stresses in these two cases are generally close. However, the stresses depend on slab thickness. For thicker slabs, the stresses are higher in 5.9-m long slabs with tied joints; while for thinner slabs, the stresses in 4.6-m long isolated slabs are greater.

Since Caltrans is generally using 260- to 290-mm thick slabs for these pavements, the isolated longitudinal joint with 4.6-m slab lengths was recommended. Cutting of the 5.9-m passenger car lane slabs in two and then tying them to 2.95-m slabs in the new truck lanes was analyzed, and produced low stresses, but is likely not feasible from a construction and maintenance cost viewpoint.

Table 6. Maximum Tensile Stresses (MPa) in Slabs for Overloaded (100 kN) Conditions with ACB Base, and Desert/Valley Annual Maximum Daytime Temperature Gradient.

Condition			Maximum tensile stress (MPa) for condition	
			Slab length = 5.9m, tied joint*	Slab length = 4.6m, isolated joint*
Early Age	SG k = 0.03 MPa/mm	t = 200mm	3.972	4.094
		t = 230mm	3.507	3.449
		t = 260mm	2.998	2.872
		t = 290mm	2.619	2.394
	SG k = 0.08 MPa/mm	t = 200mm	3.871	4.007
		t = 230mm	3.560	3.516
		t = 260mm	3.121	3.045
		t = 290mm	2.790	2.619
Late Age	SG k = 0.03 MPa/mm	t = 200mm	4.944	4.825
		t = 230mm	4.278	3.977
		t = 260mm	3.677	3.266
		t = 290mm	3.130	2.668
	SG k = 0.08 MPa/mm	t = 200mm	4.980	4.953
		t = 230mm	4.461	4.248
		t = 260mm	3.964	3.616
		t = 290mm	3.476	3.040

*Note: Bold tensile stress value indicates stresses greater than strength.

Preliminary Analysis Using 1-37A Software

The version of the design software produced by NCHRP Project 1-37A (ERES 2004) delivered to Caltrans for review was used in a two-part sensitivity study to evaluate design variables affecting faulting, transverse cracking and IRI.

First, Caltrans designs typical of 1955 to 1980 were run with four climate regions. The variables considered in this part were:

- Climate region: Desert (Daggett), South Coast (Los Angeles), Valley (Sacramento), Mountain (Reno)
- Slab lengths: 19, 15 ft.
-

The results in Table 7 show that the coastal climate has the lowest risk of transverse cracking. It also shows that transverse cracking in the other regions is significantly mitigated by the shorter slabs currently used. The cracking and faulting results generally correspond to the 1998 survey of Coastal and Desert region pavements (Harvey et al. 2000a).

Table 7. Comparison of Predicted Faulting, Transverse Cracking and IRI for Typical Caltrans Designs 1955-1980.

Climate Region	Slab Length (ft.)	Faulting (inches)	Transverse Cracks (% slabs)	IRI (inches/mile)
Desert	15	0.07	19	117
	19	0.09	94	177
South Coast	15	0.05	0	87
	19	0.06	2	87
Valley	15	0.10	24	130
	19	0.12	96	187
Mountain	15	0.10	17	126
	19	0.12	92	184

Constants: Long-haul axle load spectrum from I-5, truck repetitions to produce 11.2 million ESALs over 30 years, 200-mm (8-in.) thick PCC slabs, asphalt shoulder, no dowels, cement treated base, sandy subgrade, 50 percent reliability, modulus of rupture of 626 psi at 28 days, surface short-wave radiation absorptivity of 0.65, granite aggregate, Type II cement, all other variables used default values.

Second, a larger factorial (576 cases) was run mostly using current design options for the Desert region (Daggett) to evaluate the sensitivity to important variables calculated by the 1-37A software. The following variables were analyzed:

- Slab thickness: 8, 10, 12 in.
- Slab lengths: 19, 15 ft.
- Base type: asphalt concrete, cement stabilized base
- Shoulder type: asphalt, widened lane, tied concrete
- Dowels: 1.5-in. dowels, no dowels
- Axle load Spectra: Redlands (SR30, typical short-haul), Daggett (I-40, typical long-haul)
- Design ESALs (truck count adjusted to achieve these values): 11.2 and 41.0 million
- Surface absorptivity: 0.65, 0.85

The results in Table 8 present evidence for preliminary general design recommendations in the Desert region.

The joint spacing conclusion of the first study is further emphasized, here with doweled pavements. Thicker slabs and dowels used today by Caltrans are warranted, based on traffic level. Wide truck lanes appear to provide better performance than tied concrete shoulders, although longitudinal cracking risk is not considered (cannot be evaluated in software).

Variables that the software indicated did not, on average, make much difference were base type and axle load spectrum (for a fixed number of ESALs). It was assumed that the base and slab were unbonded. Default values for stress-displacement between base and slab were assumed.

The software indicates that the range of surface radiation absorptivity in the study is as significant for transverse cracking as increasing ESALs from 11.2 million to 40 million. The software was calibrated assuming a coefficient of 0.85.

Table 8. Comparison of Predicted Faulting, Transverse Cracking, and IRI for Design Options in the Desert Region, Average Values Across All Cases for Each Factor Level.

Factor	Factor Levels	Average Faulting (inches)	Average Transverse Cracks (% slabs)	Average IRI (inches/mile)
Dowels	No	0.07	55	165
	Yes	0.00	55	130
Slab Thickness (in.)	8	0.06	77	153
	10	0.04	54	123
	12	0.02	35	100
Shoulder Type	Asphalt	0.05	67	140
	Tied	0.04	55	127
	Wide Lane	0.02	44	110
Surface Absorptivity	0.65	0.03	46	117
	0.85	0.04	65	135
Design ESALs	11.2 million	0.02	46	112
	41.0 million	0.05	64	140
Base Type	Asphalt	0.04	58	129
	Cement Stabilized	0.04	52	123
Joint Spacing (ft.)	15	0.03	26	100
	19	0.05	85	151
Axle Load Spectra	Long-haul	0.04	57	126
	Short-haul	0.04	53	125

Measurements in California have shown a range of 0.65 to 0.85 (more reflective) with absorptivity decreasing with concrete age (Pomerantz et al. 2000).

Coefficient of thermal expansion (COTE) is not currently a specified property in California. A quick comparison was made using typical values for the aggregate available in the desert (Table 9). The results indicate a strong effect on transverse cracking above a "critical" COTE, because of the effect of curling from large temperature gradients in the concrete. It would be expected that there would be a similar, or greater effect of COTE on longitudinal cracking. A recommendation regarding specification of COTE or its explicit consideration in design (difficult in a design-bid-build system) may be possible after verification and calibration of the software.

The results, as presented in Tables 7–9, do not show the interactions of the variables that would occur on a specific site. The Caltrans/UC team is currently evaluating a much larger sensitivity factorial and will be using accelerated pavement testing and PMS data to validate and calibrate the software, after which a design catalog will be prepared. These calculations also do not consider longitudinal cracking, a major distress in the region. Longitudinal cracking risk is being evaluated using another software package (Hiller et al. 2005).

Table 9. Comparison of Predicted Faulting, Transverse Cracking, and IRI for Typical Coefficients of Thermal Expansion in the Desert Region.

Coefficient of Thermal Expansion ($10^{-6}/^{o}F$)	Slab Length (ft.)	Faulting (in.)	Transverse Cracks (% slabs)	IRI (in./mi.)
4.5	15	0.00	0	64
	19	0.00	0	65
5.5	15	0.00	1	65
	19	0.00	4	68
7.0	15	0.00	28	87
	19	0.00	50	106

Constants: Daggett (Desert) climate, long-haul axle load spectrum from I-40 (Newberry Springs), truck repetitions to produce 40.0 million ESALs over 30 years, 255 mm (10 inch) thick PCC slabs, wide truck lane, 1.5 inch dowels, cement treated base, sandy subgrade, 50 percent reliability, modulus of rupture of 626 psi at 28 days, surface short-wave radiation absorptivity of 0.85, Type II cement, all other variables used default values.

Conclusions and Recommendations

The following conclusions and recommendations are drawn from the results presented in this paper:

1. The phenomena involved in early-age cracking in concrete are very complex, and the exact prediction of cracking in jointed plain concrete (JPC) is still an open subject for academic research. However, simplified methods based on reasonable assumptions, such as those provided by HIPERPAV, can help the designer to identify critical factors and the best solutions to reduce the risk of failure due to early-age cracking in JPC.

2. The software should be used to consider the risk of cracking (Ratio mode), not whether it will occur or not (Failure mode). The Ratio mode was not explicitly provided in the version of HIPERPAV used for this study.
3. The HIPERPAV sensitivity study leads to the following conclusions:
    a. Improvement of construction practice has the most significant impact in reducing the risk of early-age cracking. Greater attention should be particularly paid to proper joint sawing and curing times.
    b. Asphalt subbases have much lower risk than cement treated bases, using default models. These results should be evaluated in the field, to see if current methods of reducing cemented base/slab friction used by Caltrans are effectively captured by the software. Thickness has little effect.
    c. Overall, the Desert climate region is much more critical than the two Coastal regions. Mix design factors are not so important for the Desert region (Daggett) because the heating caused by the climate has a much stronger effect than does heating caused by the mix design, including the use of Type III instead of Type II cement.
    d. In the Desert climate region, the type of aggregate is the primary mix design factor affecting cracking in the pavement. In this case, using gravel (softer but greater COTE) is much safer than using granite (harder but smaller COTE).
4. The results of the analysis of tied 5.9-m slabs versus use of an isolation joint and 4.5-m slabs indicated that the tensile stresses from the critical daytime mid-slab edge loading case are generally similar, but tend to be lower for the isolated short slabs as slab thickness increases. The use of isolated short slabs was recommended for this reason, and to minimize reflection cracking from eventual transverse cracks in the adjacent long passenger car slabs.
5. The following conclusions are based on the 1-37A sensitivity analysis:
    a. Preliminary comparison of predicted performance from the 1-37A software and observed performance for historical Caltrans designs.
    b. Some results from the 1-37A sensitivity analysis were expected: shorter joint spacings, thicker slabs, and use of dowels.
    c. Unexpected results were the sensitivity to surface radiation absorptivity coefficient and the insensitivity to axle load spectra for a given design ESALs.
    d. Gravel in the PCC (high COTE, lower stiffness) resulted in worse transverse cracking performance than granite (low COTE, high stiffness). HIPERPAV predicts that gravel has best early-age cracking risk compared to granite. These contradictory results need to be calibrated against overall field performance before a general recommendation can be made, and their interactions and mitigation by other variables needs to be further explored.

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