STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR-0003 (REV 04/2024)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
UCPRC-TM-2020-03		

4. TITLE AND SUBTITLE	5. REPORT DATE
Early-Age and Premature Cracking in Jointed Plain Concrete Pavements: LiteratureReview	July 2021
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR A.Mateos (ORCID No. 0000-0002-3614-2858) J.Harvey (ORCID No. 0000-0002-8924-6212)	8. PERFORMING ORGANIZATION REPORT NO. UCPRC-TM-2020-03 UCD-ITS-RR-21-53
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California Pavement Research Center Department of Civil and Environmental Engineering, UC Davis 1 Shields Avenue Davis, CA 95616	10. WORK UNIT NUMBER 11. CONTRACT OR GRANT NUMBER 65A0628
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Division of Research, Innovation, and System Information P.O. Box 942873 Sacramento, CA 94273-0001	13. TYPE OF REPORT AND PERIOD COVERED Technical memorandum July 2018 to July 2020 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

doi:10.7922/G2ZC815G

16. ABSTRACT

This technical memorandum includes a literature review about the factors that may lead to early-age and premature cracking of jointedplain concrete pavements (JPCPs). The review shows that many factors are involved and that many different circumstances can resultin these types of cracking. In most of the cases reported in the literature, the early-age and premature cracking were related to poorconstruction practices. The early-age cracking of JPCP has already received considerable attention, and there is agreement regardingthe mechanisms that result in this type of cracking and about the practices recommended to reduce it. The current version of the Caltrans Standard Specifications addresses most of these practices, but Caltrans specifications for paving in adverse weather conditions are notcompletely clear. Unlike the causes of early-age cracking on JPCP, premature cracking of JPCP has not been studied extensively.Further, even though it is widely recognized that the early-age condition of concrete has an impact on mid- and long-term JPCPperformance, very few studies have focused on determining what that impact is.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
early-age cracking, premature cracking, slab replacement,jointed plain concrete pavement, plastic shrinkage cracking	No restrictions. This document is available to the public throughthe National Technical Information Service, Springfield, VA22161

19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
Unclassified	32	None

Reproduction of completed page authorized.

July 2021
Technical Memorandum: UCPRC-TM-2020-03

Early-Age and Premature Cracking in Jointed Plain Concrete Pavements: Literature Review

Authors:
Angel Mateos and John Harvey

Partnered Pavement Research Center (PPRC) Project Number 4.74 (DRISI Task 3206):
Early-Age and Premature Cracking Evaluation

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation, and System Information
Office of Materials and Infrastructure

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR-0003 (REV 04/2024)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
UCPRC-TM-2020-03		

4. TITLE AND SUBTITLE	5. REPORT DATE
Early-Age and Premature Cracking in Jointed Plain Concrete Pavements: Literature Review	July 2021
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR A.Mateos (ORCID No. 0000-0002-3614-2858) J.Harvey (ORCID No. 0000-0002-8924-6212)	8. PERFORMING ORGANIZATION REPORT NO. UCPRC-TM-2020-03 UCD-ITS-RR-21-53
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California Pavement Research Center Department of Civil and Environmental Engineering, UC Davis 1 Shields Avenue Davis, CA 95616	10. WORK UNIT NUMBER
	11. CONTRACT OR GRANT NUMBER 65A0628
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Division of Research, Innovation, and System Information P.O. Box 942873 Sacramento, CA 94273-0001	13. TYPE OF REPORT AND PERIOD COVERED Technical memorandum July 2018 to July 2020
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

doi:10.7922/G2ZC815G

16. ABSTRACT

This technical memorandum includes a literature review about the factors that may lead to early-age and premature cracking of jointedplain concrete pavements (JPCPs). The review shows that many factors are involved and that many different circumstances can resultin these types of cracking. In most of the cases reported in the literature, the early-age and premature cracking were related to poorconstruction practices. The early-age cracking of JPCP has already received considerable attention, and there is agreement regardingthe mechanisms that result in this type of cracking and about the practices recommended to reduce it. The current version of the Caltrans Standard Specifications addresses most of these practices, but Caltrans specifications for paving in adverse weather conditions are notcompletely clear. Unlike the causes of early-age cracking on JPCP, premature cracking of JPCP has not been studied extensively.Further, even though it is widely recognized that the early-age condition of concrete has an impact on mid- and long-term JPCPperformance, very few studies have focused on determining what that impact is.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
early-age cracking, premature cracking, slab replacement,jointed plain concrete pavement, plastic shrinkage cracking	No restrictions. This document is available to the public throughthe National Technical Information Service, Springfield, VA22161

19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
Unclassified	32	None

Reproduction of completed page authorized.

UCPRC ADDITIONAL INFORMATION

1. DRAFT STAGE Final	2. VERSION NUMBER 1
3. PARTNERED PAVEMENT RESEARCH CENTER STRATEGIC PLAN ELEMENT NUMBER 4.74	4. DRISI TASK NUMBER 3206
5. CALTRANS TECHNICAL LEAD AND REVIEWER(S) David Lim	6. FHWA NUMBER CA223206A
7. PROPOSALS FOR IMPLEMENTATION Not applicable	
8. RELATED DOCUMENTS None	
9. LABORATORY ACCREDITATION The UCPRC laboratory is accredited by AASHTO re:source for the tests listed in this report	AASHTO ACCREDITED

10. SIGNATURES

A. Mateos **FIRST AUTHOR**	J.T. Harvey **TECHNICAL REVIEW**	D. Spinner **EDITOR**	J.T. Harvey **PRINCIPAL INVESTIGATOR**	D. Lim **CALTRANS TECH. LEADS**	T.J. Holland **CALTRANS CONTRACT MANAGER**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

PROJECT OBJECTIVES

The primary goal of Partnered Pavement Research Center Strategic Plan Element Project 4.74 is to develop a set of recommendations for reducing the risks of early-age and premature cracking in jointed plain concrete pavement (JPCP) projects on the Caltrans road network. Project 4.74 focuses on new JPCP, lane replacement, and slab replacement projects. The first step to take to achieve that goal is to identify what factors may lead to early-age and premature cracking on California roadways. Because these cracking types are a common problem for all highway agencies, a decision was made to conduct a literature review to identify those factors in California, in other US states, and in other countries. This technical memorandum presents the results of the literature review.

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACPA	American Concrete Pavement Association
CTE	Coefficient of thermal expansion
FHWA	Federal Highway Administration
ISR	Individual slab replacement
JPCP	Jointed plain concrete pavement
LR	Lane replacements
PPRC	Partnered Pavement Research Center
RSC	Rapid-strength concrete
SCM	Supplementary cementitious materials
SRA	Shrinkage-reducing admixtures
UCPRC	University of California Pavement Research Center

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
LENGTH				
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
VOLUME				
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
MASS				
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
TEMPERATURE (exact degrees)				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
LENGTH				
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
AREA				
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
VOLUME				
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C + 32	Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised April 2021)

1 INTRODUCTION

The literature review presented in this technical memorandum is part of Partnered Pavement Research Center Strategic Plan Element (PPRC SPE) 4.74, a California Department of Transportation (Caltrans)/University of California Pavement Research Center (UCPRC) research project, whose primary goal is to develop a set of recommendations for reducing the risks of early-age and premature cracking in new jointed plain concrete pavements (JPCPs), and in lane replacement and slab replacement projects. PPRC SPE 4.74 was undertaken to investigate a specific problem: that both new and reconstructed concrete pavements and individual slab replacements sometimes reach a terminal condition before reaching 50% of their design life and, occasionally, even before they spend one year in service. This problem is not unique to Caltrans; it commonly occurs among all highway agencies that use JPCPs.

Project 4.74 can be regarded as a continuation of PPRC SPE 4.58A, “Early Age and Premature Cracking for PaveM and LCCA,” which was conducted between 2014 and 2017. In Project 4.58A, the performance of a number of California slab replacement projects was analyzed. The reported analysis indicated that “early-age and premature cracking was found to be a major issue in California such that about 17% of total individual slab replacements have cracked by the age of 5.”

Even though a number of factors were found to have affected the performance of the individual slab replacements—slab age, slab thickness, use of dowels, and traffic-loading spectrum—much about their performance still could not be explained. For example, based on the statistical model that was calibrated in PPRC SPE Project 4.58A, it is expected that in a slab replacement project with 0.7 ft. thick undoweled slabs on a heavily trafficked road, 50% of the replacement slabs will be cracked after 10 years in service. Still, the worst 20% of projects are expected to reach the same condition in less than 5 years, while the best 20% of projects would reach the same condition after 20 years. This variability, which is based on a statistical analysis of the actual performance of individual slab replacements in California, was believed to be related to factors such as slab length, base type, and cement type, which could not be included in the statistical analysis due to the lack of design data. It is also believed that construction quality and early-age conditions, including weather and curing, affect the performance of the slab replacements.

Therefore, before Project 4.74’s main goal could be met (i.e., before a set of recommendations could be made for reducing the risks of early-age and premature cracking in lane replacement and slab replacement projects), it became necessary to first identify what factors might lead to early-age and premature cracking in JPCPs in

California. The literature review that follows in Chapter 2 was undertaken to identify the factors that cause this early-age and premature cracking in California, in other US states that share this problem, and in other countries.

1.1 Objectives

The first objective of the literature review presented in this technical memorandum is to investigate the factors that lead to early-age or premature cracking in JPCPs. The review's second objective is to identify potential solutions that have already been implemented to some extent.

1.2 Scope

This literature review focuses on JPCPs, including new JPCP, lane replacement, and slab replacement projects. This pavement type presents very different cracking performance than continuously reinforced concrete pavements, which were not included in this review.

As noted, this review focused on both early-age and premature cracking. For the purposes of Project 4.74, *early-age cracking* is defined as cracking that occurs within the 12 months after construction, while *premature cracking* is defined as cracking that occurs at least 12 months after construction but before the pavement or an individual slab replacement reaches 50% of its design life. These definitions do not necessarily match the definitions found in the literature.

2 LITERATURE REVIEW

2.1 Early-Age Cracking

2.1.1 Mechanics of Early-Age Cracking

A number of definitions of early-age cracking can be found in the technical literature. The American Concrete Pavement Association (ACPA) defines early-age cracking as "any cracking that may develop within the first 7 days after concrete placement" *(1)*. Nonetheless, the ACPA also acknowledges that "60 days is generally the outer limit for cracking to be considered early age" because "some cracking may initiate at the bottom of the slab and not become visible until days or weeks pass." The National Concrete Pavement Technology Center (CP Tech Center) defines early-age cracks as "those that occur before the concrete pavement is opened to public traffic and are predominately related to the early-age properties of the concrete, restraint, and prevailing environmental conditions" *(2,3)*. Based on this definition and within the context of Caltrans *Standard Specifications* for normal-strength concrete pavements (Section 40), early-age cracking might be defined as cracking that occurs within the 10 days that follow concrete placement, because 10 days is a common time period before a concrete pavement is opened to public traffic in the Caltrans road network. *HIPERPAV*™, the software program sponsored by the Federal Highway Administration (FHWA) and widely recognized as one of the best for analyzing the early-age performance of concrete pavements, considers the "early age" of concrete pavements to be 72 hours (i.e., three days) *(4)*.

Although the existing technical references define the early-age cracking timespan differently, they all agree on the mechanics underlying this type of cracking. All use the term *early-age* to refer to an initial stage of the life of concrete, when it has developed only part of its final strength and mechanical properties. During this stage, concrete can suffer considerable damage due to its low strength and the large hygrothermal deformations that frequently follow concrete placement. The hygrothermal actions include thermal and moisture-related actions. The thermal actions result from temperature changes in the concrete caused by the ambient environment conditions and the heat released by the cement hydration process after placement. The moisture-related (hygral) actions result from the desiccation that concrete undergoes after placement due to ambient environment conditions (external drying) and the cement hydration process (internal drying).

Although these early-age cracking mechanics were first described by the ACPA as early as the year 2000 *(5,6)* and many early-age-cracking–related studies have been conducted since then, understandings about those mechanics have remained unchanged. In addition to the 2000 ACPA document *(5)*, a description of these mechanical principles is included in the *Integrated Materials and Construction Practices for Concrete Pavement* manual of the CP Tech Center's 2007 *(2)* and 2019 *(3)* editions and is condensed in its 2007 *Technical Summary* *on Early-Age Cracking (7)*. Early-age cracking mechanics are also described in the original support documentation for *HIPERPAV (8)* as well as in the updates, *HIPERPAV II (9)* and *HIPERPAV III (10)*.

As previously noted, there seems to be general agreement about the mechanics of early-age cracking. Specifically, the likelihood that early-age cracking will develop depends on the interaction of the tensile stress that develops in the concrete after placement—stress attributable to hygrothermal actions that begin to exert themselves as the concrete dries and cools—and the concrete's early-strength gain, which would impede tensile-stress-related cracking. Typically, the hygrothermal actions alone are cited as the source of early-age cracking, but the negative effects caused by traffic loading during the concrete's early age have been also highlighted *(7)*.

Hygrothermal actions are present over the entire life of a concrete pavement, but during its early life they may be critical for the following three reasons:

- First, high concrete temperatures may result when the heat released by the cement hydration process combines with a warm ambient environment; this combination can result in high tensile stresses in the concrete as it cools.
- Second, new concrete may dry considerably after placement because the lack of maturity of its cement paste leaves it highly permeable to water and water vapor. This drying can become critical under certain ambient environment conditions (high air temperature, low relative humidity of the air, and the presence of wind), especially if the curing process is inappropriate. And even if the external drying is prevented by appropriate curing, internal desiccation of the concrete can result in considerable shrinkage (autogenous shrinkage) when the water/cement ratio is low. In mixtures with a 0.30 water/cement ratio, this autogenous shrinkage can represent up to 50% of the total moisture-related shrinkage *(10)*.
- Third, concrete has low strength during its early age.

A number of factors have been traditionally considered to have an important role in early-age cracking. In practice, any factor that affects the onset of concrete tensile stress or concrete strength gain during early age will have an impact on the risk of early-age cracking. The factors included in the different reference documents *(2-10)* are briefly summarized below.

- **Concrete mixture**
  - *Cement type.* The use of rapid-setting cement (e.g., Type III portland cement or calcium sulfoaluminate cement) is typically not recommended due to its rapid release of the heat of hydration. This release may result in high concrete temperatures and tensile stresses that develop as the concrete cools. Because of this, the CP Tech Center *Technical Summary on Early-Age Cracking* recommends to "avoid using high early-strength cements unless for special conditions."

(The special conditions may include, for example, individual slab replacements with rapid-strength concrete with limited closure windows.)

  - *Cement content.* Use of high cement contents is typically not recommended because of the large amount of heat generated by hydration. A high cement content also results in a large amount of moisture-related shrinkage and a large coefficient of thermal expansion (CTE) of the concrete.
  - *Aggregate type.* Aggregate type plays a role in early-age cracking because it has a large impact on the concrete's CTE. A concrete produced with low-CTE aggregates (e.g., limestone aggregates) will have a lower CTE than a concrete produced with high-CTE aggregates (e.g., siliceous gravel).
  - *Use of supplementary cementitious materials (SCM).* Use of SCM (e.g., fly ash or ground granulated blast furnace slag) is typically recommended, particularly when paving in hot weather, since these materials reduce the heat generated by hydration during early age.
  - *Use of admixtures.* The use of water-reducing admixtures is typically recommended since they help reduce the amount of water used in the mix. A lower water/cement ratio will reduce the amount of drying shrinkage of the concrete. Use of a retarding admixture is recommended in hot weather because it helps delay cement hydration and, consequently, reduces concrete temperature after placement.

- **Weather conditions.** All the references agreed that weather is one of the most important factors in early-age cracking because the hygrothermal action—the driving force of early-age cracking—strongly depends on it. The weather conditions cited include air temperature, air relative humidity, solar radiation, and wind speed. The importance of the weather conditions is twofold since they affect both concrete temperature and moisture content (i.e., thermal and hygral actions). All the references emphasized the increased risk of early-age cracking during hot and dry weather, particularly if it is also windy. Cold weather can also increase the risk of early-age cracking since low concrete temperatures can delay the setting of the concrete. The expected weather conditions are among the inputs the *HIPERPAVE* software uses to predict the risk of early-age cracking.
- **Base conditions.** Thermal and moisture conditions of the pavement base are also important because the base can act as a thermal sink or a thermal source, depending on its temperature (compared to the temperature of the concrete). The base can also act as a moisture sink if it is not properly wet-conditioned or sealed before concrete paving.
- **Curing timing and procedure.** Concrete pavements are cured to prevent the concrete from drying. Thus, curing is critical to prevent early-age cracking since drying produces shrinkage that may result in tensile stresses and their consequent cracking in the concrete. All the references agreed on the importance of curing, particularly during hot, dry, and/or windy weather. It is commonly accepted that fog spraying or

an evaporation retarder is required when the concrete surface's water evaporation rate exceeds 0.2 lb./ft^2/hr (1.0 kg/m^2/hr). The Portland Cement Association nomogram *(11)*, based on Menzel's 1954 study, is recommended to determine the rate of evaporation as a function of concrete temperature and weather conditions.

- **Slab movement restriction.** While hygrothermal actions drive early cracking, what effect these actions have depends strongly on whether the slab's movement is restricted or not. Specifically, when the friction (bonding) between the slabs and the base is low or if the base is soft, the slabs are free to expand and contract under the hygrothermal actions. In these circumstances, the base contributes little to the tensile stresses that cause early-age cracking. But in circumstances where the base is stiff (e.g., lean concrete base) and the friction (bonding) between slabs and base is high, the interaction between the slabs and the base contributes to the tensile stresses. For this reason, all the references agreed on the need to debond the slabs and base when the latter is stiff (e.g., lean concrete base). The double application of a standard curing compound is one of the most commonly recommended means to achieve that debonding.
- **Sawcutting timing.** The goal of using joints (i.e., JPCP) is to reduce the stresses that hygrothermal actions would produce in a continuous pavement. Since a concrete pavement may experience considerable thermal contraction after setting, without jointing that contraction would result in high tensile stresses. Similarly, if the slabs were not allowed to warp/curl, the drying and cooling of the concrete surface would result in large tensile stresses. For these reasons, standard practice with JPCP is to sawcut the joints as soon as the concrete is hard enough to not ravel while being cut. All the references agreed on the importance of the timing of sawcutting, while also noting that this operation also relies heavily on the saw operator's experience.

2.1.2 Types of Early-Age Cracking

A number of early-age (uncontrolled) cracking types have been described based on their origin and morphology *(2,6,12,13,14)*. They are summarized below. The name or names assigned to each do not necessarily match those used in the literature.

- *Late-, non-existent–, or ineffective-sawing cracking.* This type of cracking is due to the tensile stresses that result when concrete hygrothermal contraction is restricted due to a lack of appropriate jointing. This lack may be due to late sawing, the absence of sawing, or to ineffective sawing, such as that due to a too-shallow sawcut or misaligned dowels. The layout of this type of early-age cracking has a clear pattern since it typically happens either longitudinally or transversally. Longitudinal early-age cracks typically extend along the center of the lane or group of tied lanes. Transverse early-age cracks extend across the full width of the slab. Pop-off and diagonal cracking, both of which intersect a transverse joint, are included in this type of cracking.

- *Sympathy cracking.* By definition, *sympathy cracking* can only occur when new concrete slabs or lanes are added to an existing concrete pavement. This type of cracking is due to the differential deformation between the new and old pavements, and specifically to their thermal and moisture-related deformations, which may differ considerably. The thermal deformation of the old concrete is mainly determined by the ambient environment conditions while the thermal deformation of the new concrete is influenced by those conditions and by the cement heat of hydration. Similarly, the moisture-related deformation of new concrete during its early age will typically be much larger than the moisture-related deformation of the old concrete over that same time. Because avoiding differential deformation between old and new concrete is not possible, disconnecting both materials is frequently the only alternative to prevent this type of cracking from happening. Further, matching the joints between old and new concrete is necessary when disconnection between both materials is not guaranteed.
- *Erratic cracking.* This type of cracking is due to the tensile stresses that result when a concrete pavement's hygrothermal contraction is restricted because of its bond to a rigid base. The thermal and moisture-related deformations of the new concrete are both expected to be considerably different than those same deformations in the underlying base. Because of that difference, considerable tensile stresses may develop if the concrete is bonded to the base and the stiffness of the base is high, as with cement-stabilized and lean concrete bases. The layout of this type of cracking is typically erratic and is determined by the differences in concrete-base bonding from one location to another. Because differential deformation between the concrete and the base is unavoidable, the only way to prevent this type of cracking from happening when the base is stiff is to disconnect both materials.
- *Subsidence cracking.* This type of cracking is due to the flow of the plastic concrete below fixed dowels or tie bars. Typically, these cracks extend along the dowels or tie bars. Using low-slump concrete, the typical type used in slip-form paving, helps to prevent this type of cracking.
- *Plastic shrinkage cracking.* This type of cracking is due to the shrinkage of fresh concrete that results when the rate of water evaporation exceeds the fresh concrete rate of bleeding. This type of cracking occurs during concrete's plastic stage, and it has been attributed to improper curing and adverse weather conditions. This type of cracking presents a clear pattern: the cracks are tight, parallel to one another (perpendicular to the wind direction), 1 to 3 ft. long, do not intersect the slab edges, and do not usually penetrate more than 2 to 4 in. into the slab. There is general agreement that proper curing, including protecting the fresh concrete from the wind, can prevent this type of cracking.

2.1.3 Prevention of Early-Age Cracking

2.1.3.1 Widely Implemented Recommended Practices

Research into the references on early-age cracking *(2–10)* yielded a set of common practices that can reduce the risk of its occurrence. These practices can be categorized in three main groups, depending on whether they are related to mixture design, pavement design, or construction process. The mixture design practices are linked to the collection of mixture design factors that were considered to have an important role in early-age cracking (see Section 2.1.1). The pavement design practices include selection of the optimal joint spacing and sawcutting depth, selection of the appropriate concrete-base bond breaker, the design of the connection between the old concrete and the new concrete in the replacement slab, lane addition, and lane replacement projects. The construction practices include the proper conditioning of the base (thermal and moisture conditioning), the proper sawcutting timing, the application of proper curing (proper in time and type), and a number of specific practices to adopt during bad weather conditions, cold or hot. All these practices are summarized in Table 2.1. This table also summarizes the way that Caltrans specifications address each practice.

Table 2.1: Recommendations to Reduce Early-Age Cracking Risk and Current Caltrans Specifications

Recommendations to Reduce Early-Age Cracking Risk	Apply to	Caltrans Specifications to Consider
CONCRETE MIXTURE DESIGN		
Cement type Avoid the use of rapid-setting cement because of its rapid release of the heat of hydration.	LR*	For regular concrete, Section 90 requires cement to be either a combination of Type II or V portland cement and SCM, or blended cements Type IL, IS, or IP. Type III portland cement may be used only if specified or authorized. For rapid-strength concrete (RSC), Section 90 allows use of Type III portland and other rapid-setting cements.
Cement content Avoid the use of a high cement content since it results in a large amount of hydration heat, high shrinkage, and increased CTE.	LR & ISR*	Section 40, which applies to new JPCP and lane replacements (LR), limits the maximum content of cementitious materials to 675 pounds per cubic yard. Section 41.9, which applies to individual slab replacements (ISR), does not limit the maximum content of cementitious materials.
Aggregate type Use coarse aggregates that have a low CTE (e.g., limestone).	LR & ISR	Section 40 requires the contractor to submit concrete CTE to Caltrans, although no prescriptive limit is specified (the submission is informational only).
Aggregate gradation Adopt aggregate gradations that minimize cement content.	LR & ISR	Section 90 includes limits to the aggregate gradation. Optimizing gradation and cement content is part of the mix design conducted by the mix producer.

Recommendations to Reduce Early-Age Cracking Risk	Apply to	Caltrans Specifications to Consider
SCM Use SCM when paving in hot weather since they help reduce concrete temperature after placement.	LR & ISR	 For regular concrete, Section 90 requires the use of SCM. This requirement is not applicable to RSC.
Admixtures Use water-reducing admixtures, which help reduce cement and water contents. In hot weather, use set-retarding admixtures since they help reduce concrete temperature after placement. Avoid calcium chloride admixtures, since they can significantly increase drying shrinkage.	LR & ISR	 Water-reducing admixtures are considered in Section 90. Retarding admixtures are considered in Section 90. Maximum chloride content of the admixtures is limited to 1%.
Shrinkage testing Test concrete mixture for shrinkage and establish appropriate specification limits.	LR & ISR	 Section 90 prescribes a 500 $\mu\varepsilon$ maximum drying shrinkage for pavement concrete after 28 days of drying, tested according to a modified version of AASHTO T 160. For RSC, the specification (non-standard special provision) is 400 $\mu\varepsilon$ maximum drying shrinkage, tested according to a modified version of AASHTO T 160.
PAVEMENT DESIGN		
Joint spacing Adopt a maximum joint spacing of 24 times the slab thickness if the base is granular and 21 times if the base is stabilized. Do not tie many lanes together.	LR & ISR	 Caltrans *Standard Plans* limit transverse joint spacing to 14 ft. in new JPCP and LR, and to 15 ft. in ISR. These joint spacing values are considerably below the maximum recommended in the left column. Caltrans *Standard Plans* limit the number of lanes that can be tied together to three (plus a concrete shoulder).
Depth of sawcutting Sawcut joints to 1/3 slab thickness unless early-entry sawing is followed.	LR & ISR	 Sawcut depth is not specified for new JPCP and LR. For ISR (Section 41.9), a minimum sawcut depth of 1/3 of the slab thickness is prescribed.
Concrete-base bond breaker Use a double application of curing compound on lean concrete and cement-stabilized bases.	LR & ISR	 Section 27 prescribes asphaltic emulsion on cement-treated bases while Section 28 prescribes a double application of curing compound on lean concrete bases.
Connection between new and old concrete Try avoiding bonding between new concrete and the edges of the old concrete; otherwise, make sure joints in the old and new concrete match. (This statement is not applicable to the bonding between new and old concrete in bonded concrete overlay on concrete.)	LR & ISR	 Section 40 prescribes the application of curing compound on hardened concrete before placing fresh concrete against it. For ISR, Section 41.9 prescribes isolation joints with a 1/4 in. thick polyethylene flexible foam to disconnect new concrete from old concrete.

Recommendations to Reduce Early-Age Cracking Risk	Apply to	Caltrans Specifications to Consider
PAVEMENT CONSTRUCTION		
Base conditions Have base surface wet-conditioned or sealed before concrete paving. Avoid paving on very cold or very hot bases.	LR & ISR	Section 40 requires the base to be uniformly moist but free of standing water before placing the concrete. Section 90 specifies that the concrete cannot be placed on a frozen or ice-coated ground or subgrade. No indication is included regarding a maximum temperature of the base.
Sawcutting timing Saw joints as soon as concrete is hard enough to resist the sawcutting without raveling.	LR & ISR	Sections 40 (LR) and 41.9 (ISR) require sawing contraction joints before cracking occurs and after the concrete is hard enough to saw without spalling, raveling, or tearing.
Concrete curing Apply curing compound as soon as possible after finishing. In hot, dry, and/or windy conditions, and at any time the rate of water evaporation from the concrete surface exceeds 0.2 lb/ft²/h (1.0 kg/m²/h), use wet initial curing such as fog spray or evaporation retarder until curing compound is applied. Do not spray water on the slab to facilitate finishing, do not finish the surface while bleed water is present, and do not over-finish. Protect the fresh concrete from significant changes in ambient temperatures.	LR & ISR	Caltrans Section 90 specifies "Apply the curing compound to the concrete after finishing the surface, immediately before the moisture sheen disappears from the concrete surface but before drying shrinkage or craze cracks start to appear." This curing application timing is different from "as soon as possible after finishing." In fact, Section 90 specifies: "Do not apply the curing compound over freestanding water." The freestanding water may be the result of fresh concrete bleeding. If the concrete surface cracks or dries, Caltrans Section 90 requires the immediate and continual application of water onto the concrete surface using an atomizing nozzle until curing compound can be applied. No indication is given regarding the rate of water evaporation. Section 40 specifies "do not apply water to the pavement surface before float finishing," while Section 41.9 specifies "after you mix and place RSC, do not add water to the surface to facilitate finishing." Section 40 requires maintaining the concrete pavement surface temperature at a minimum of 40°F for the initial 72 hours. For RSC, Section 41.9 includes a more restrictive requirement: RSC paving is only allowed if the air temperature is expected to be over 40°F for the initial 72 hours after paving. Section 90 requires protecting the fresh concrete from damage due to any cause, including rain, heat, cold, and wind.

Recommendations to Reduce Early-Age Cracking Risk	Apply to	Caltrans Specifications to Consider
Weather	LR & ISR	
Observe the weather forecast for paving day and 3 days following.		Section 40 requires a system for predicting stresses and strength during the initial 72 hours after paving, including a subscription to a weather service. Section 41.9 does not allow placing RSC whenever the ambient air temperature is expected to be less than 40°F within 72 hours of final finishing.
Adopt specific practices during adverse weather conditions either in the cold or warm side.		Recommendations for paving during adverse weather conditions are not included in the Caltrans Specifications.

[*] LR = lane replacements, ISR = individual slab replacements.

Most of the of the practices that are recommended to reduce the risk of early-age cracking included in Table 2.1 are addressed specifically in the Caltrans *Standard Specifications*. The only exception is the use of rapid-strength concrete, which is a requirement in many reconstruction and rehabilitation projects where traffic must be restored as soon as possible after paving. A collection of clear guidelines for paving in adverse weather conditions is missing.

While most of the practices included in Table 2.1 have been followed since the early 2000s, new practices have been proposed and/or implemented in recent years. Of these practices, three have been already implemented in the field: internal curing, use of shrinkage-reducing admixtures, and addition of fibers. These three practices are briefly described in the following sections.

2.1.3.2 Internal Curing

The practice of *internal curing* is defined by the American Concrete Institute as a "process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water" *(15)*. This technique is recommended particularly for mixtures with a low water/cement ratio, where significant internal drying may take place *(12)*. Internal drying occurs because the volume of the cement hydration products is smaller than the volume of the initial materials (water and cement alone) *(16);* the net volume reduction is around 10% of the volume of the initial materials *(12)*. This volume reduction is referred to as *chemical shrinkage.* Because of chemical shrinkage, additional capillary voids are created in the cement paste during the cement hydration process. These voids absorb water from the surrounding material, thus creating an internal drying. This internal drying, typically referred to as *self-desiccation,* is the reason why autogenous shrinkage exists *(17)*.

Autogenous shrinkage has been recognized for a long time, but it has become a critical problem in recent years because of the increased use of high-performance concretes, which typically have a high cement content and a low water/cement ratio. Autogenous shrinkage produces a uniform contraction of the pavement slabs, similar to a uniform temperature drop. And because a considerable part of this contraction takes place when the concrete is at an early age, the autogenous shrinkage is critical in the formation of early-age cracking.

Internal curing prevents the concrete's self-desiccation by incorporating reservoirs of water into it, typically by the addition of superabsorbent polymers, natural wood products, recycled concrete, or prewetted lightweight aggregates. As the self-desiccation is the force that drives autogenous shrinkage, internal curing is an effective means to reduce that shrinkage—even though it too has been shown to reduce the early-age strength of concrete *(18,19)*. Consequently, any evaluation of internal curing intended to reduce the risk of early-age cracking must consider balancing the reduction in concrete autogenous shrinkage against a potential reduction in concrete tensile strength. A number of studies evaluating this balance have mostly concluded that internal curing reduces the risk of early-age cracking despite negatively impacting the early-age strength of the concrete *(18,19,20)*. It should be noted, however, that none of these early-age cracking studies was focused on concrete pavements.

The use of internal curing in pavement concrete dates back to 2005, when a JPCP was built with internally cured concrete in a paving project in Hutchins, Texas *(21)*. The initial performance of this JPCP was good, as was the performance of other pavements built with internally cured concrete in Texas between 2005 and 2012 *(22)*. But other than these Texas examples, no other references reporting on the field performance of concrete pavements built with internally cured concrete were found. For example, the 2015 CP Tech Center literature review on the impacts of internal curing on concrete properties *(23)* reported on the existence of a single similar project built in Kansas in 2014 but said nothing about its field performance. Similarly, a 2016 FHWA tech brief on internal curing for concrete pavements *(24)* reported on just one new example where internal curing was applied to a concrete pavement, apart from the aforementioned Texas examples. The new example in the FHWA tech brief, a 2014 Indiana project, used internally cured concrete for full-depth repairs and individual slab replacements. Overall, although the use of internal curing has been and continues to be in common use on bridge decks, to date its use in pavements has been very limited.

A recent study at the University of California Pavement Research Center (UCPRC) used internally cured concrete to build a 4.5 in. thick concrete overlay on asphalt pavement, and the results showed that the internal curing reduced the autogenous shrinkage to almost nothing. Nonetheless, the internally cured mixture dried faster (external drying) and exhibited less flexural strength than the reference mixture (the mixture that the internally cured concrete design was based on) *(25)*. The flexural strength reduction was around 30% after 10 hours, the design opening time of the mixture *(26)*. Surface cracking (unrelated to traffic loading) was observed on the slabs with internally cured concrete one year after the construction, while no cracking was observed on the surface of the slabs the same size built with the reference mixture. The relatively poor performance of the internally cured concrete was believed to have been caused by a production issue, an excess of mixing water, and not by the internal curing.

The use of internal curing has been shown to decrease the risk of plastic shrinkage cracking in laboratory studies *(27)*. The water supplied by the curing helps to supply water to the concrete surface when the water there evaporates and the evaporation rate is greater than the bleeding of the plastic mixture. Still, field validation of this benefit is pending.

2.1.3.3 Use of Shrinkage-Reducing Admixture

Shrinkage-reducing admixtures (SRA) have been used for several decades to reduce the moisture-related shrinkage of concrete *(28)*. These admixtures reduce the surface tension of water in the pores of concrete, and thereby reduce the suction that the pore water exerts, which is the driving force behind moisture-related shrinkage. Numerous laboratory studies have shown that an SRA can reduce moisture-related shrinkage of the concrete up to 50% *(28,29,30)*.

In addition to reducing water's surface tension, the SRA changes the concrete's drying profile, as explained below. SRA use has been shown to result in a shallow drying front below which concrete saturation remains relatively high, compared to concrete without SRA *(29,31)*. This beneficial effect of SRA results in a reduction of concrete evaporative water loss during the early-age period *(29)*.

Because of the reduction in moisture-related shrinkage and the drying susceptibility of the concrete, SRA use has been recommended as a means to reduce the risk of early-age cracking *(32,33,34)*.

Some studies have raised concerns about the negative impact of SRA on concrete strength (32), but others have concluded that the impacts were either negligible (*25*) or positive *(35).* The positive impact (a strength increase attributed to the SRA) was believed to be related to a reduction in microcracking in the cement paste due to a reduction in shrinkage *(36)*.

An SRA is typically added to concrete during mixing at a rate between 0.5 and 1.5 gal./yd^3 (2.5 to 7.5 l/m^3). A number of laboratory studies have also shown that it can be sprayed onto the concrete's surface as a means of curing *(28,29,36)*. This alternative approach has been referred to as "topical use," and the goal of using this technique is to supply the SRA where it is needed most: on the surface of the concrete member where moisture is being lost through evaporation. Because SRA is expensive in standard use, it is thought that topical application will make more efficient use of the admixture.

Topical use of the SRA was evaluated in a recent UCPRC research study *(25)*. The slabs of a concrete overlay of asphalt section were treated with an SRA spray (0.03 to 0.09 gal./ft^2, 300 ml SRA/m^2) before the application of a standard curing compound. When those slabs were compared with an identical section that had only been treated with standard curing compound, it was found that the curing with SRA resulted in much less slab warping—around 50% less soon after the overlay construction and around 25% less over the first summer after construction. This UCPRC study also showed that topical application of SRA can be easily implemented in the field.

2.1.3.4 Use of Fibers

For decades, fibers have been used to improve the performance of concrete pavements *(37)*. Both macrofibers and microfibers have been used, depending on what improvement is needed. Macrofibers are usually used to bridge cracks in concrete and to improve the concrete's post-cracking performance. These fibers are typically made of steel or synthetic materials, such as polyethylene or polypropylene, and have a diameter greater than 0.012 in. (0.3 mm) and a length that ranges between 0.5 and 2.5 in. (12.5 to 65 mm). Microfibers are typically added to concrete to improve its moisture-related shrinkage performance. They are typically made of synthetic materials or natural products like cellulose, have a diameter less than 0.012 in. (0.3 mm), and are less than 0.5 in. (12.5 mm) long.

Most laboratory studies show that the addition of macrofibers does not affect the strength of the concrete considerably, including its early-age strength gain *(38,39,40)*. Nonetheless, some studies have shown a different outcome since the use of fibers either considerably decreased or considerably increased concrete strength *(41)*. However, where there was evidence of strength gain or loss, it was unlikely to be related to the fibers themselves. Instead, the strength changes were attributable to the job mix formula adjustments needed to compensate for the mixture's reduced workability after the fibers were added.

By arresting concrete cracks, the macrofibers provide the concrete with post-cracking strength that helps mitigate the consequences of cracking, including early-age cracking. Further, laboratory restrained-shrinkage testing showed that the addition of macrofibers delayed the time it took for concrete to crack. *(39,41)*. This delay was attributed to the fiber-reinforced concrete having less moisture-related (autogenous and drying) shrinkage than the plain concrete. In addition to the laboratory studies already noted *(39,41)*, others have shown that the use of both microfibers and macrofibers typically results in a reduction of moisture-related shrinkage in the short term *(38,42,43)*. The reduction in shrinkage has been attributed to the creation of water reservoirs in relatively large pores in the interfacial transition zone between the fiber and the cement paste *(39,42)*.

Because of their potential for reducing early-age shrinkage coupled with their capacity to bridge early-age cracks, the use of fibers has also been recommended for reducing the risk of plastic shrinkage cracking. While some laboratory studies have shown that the fibers increase the bleeding capacity of fresh concrete *(39),* others have shown the opposite *(42)*. But despite these contradictory results, laboratory studies systematically show that both macrofibers and microfibers reduce the risk of plastic shrinkage cracking by delaying the time of initial cracking, decreasing the cracking area, reducing cracking width, or a combination of these *(38,40,42,44,45)*.

2.2 Premature Cracking

The performance data collected as part of the Long-Term Pavement Performance Program Strategic Study of Structural Factors for Rigid Pavements (SPS-2) revealed that premature cracking is a major problem in dry states like California *(46)*. The study was based on the performance of 168 new construction JPCP sections in 14 states. The summary data from that study is replicated in Figure 2.1. In wet states, longitudinal and transverse cracking take around five years to occur, while in dry states cracking begins at the very beginning of a JPCP's service life (Figure 2.1). It is very likely that the difference in performance of JPCP in wet versus dry states is due to the drying shrinkage of the concrete. Concrete drying shrinkage results in: (1) tensile stresses at the top of the slabs, (2) upward curling of the slabs and a consequent loss of support at corners and edges, and (3) contraction of the slabs and a consequent loss of load transfer efficiency at the transverse joints.

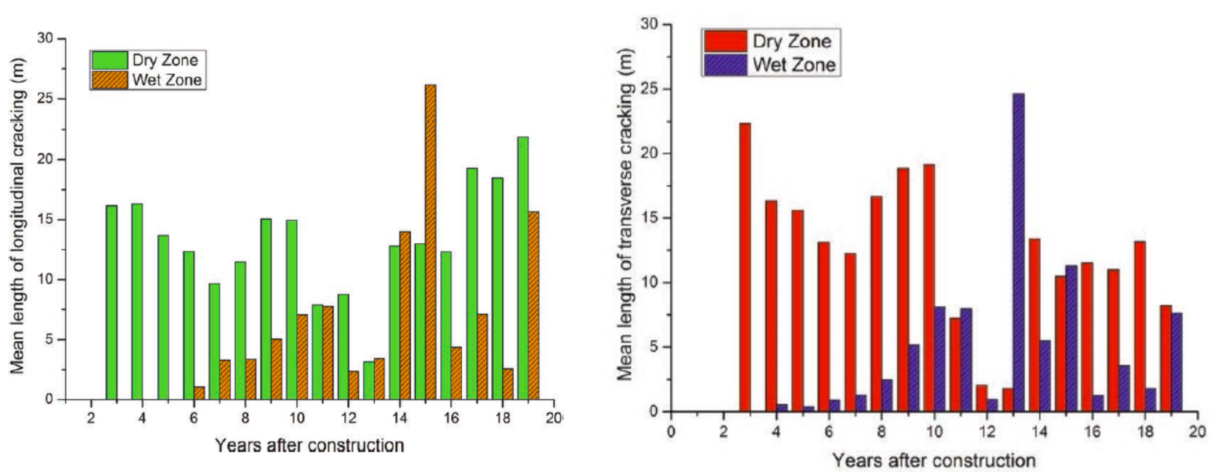

Figure 2.1: Performance of SPS-2 sections in dry and wet states *(47)*.

The relationship between design factors and cracking was explored as part of the SPS-2 study *(46)*. The most important design factors considered were slab thickness and base type. As expected, thick slabs (11 in.) exhibited considerably less cracking (longitudinal and transverse) than did thin slabs (8 in.). JPCP with asphalt-treated permeable bases presented much less cracking than JPCP with either dense-graded aggregate or lean concrete bases. Nevertheless, the study did not specify the specific causes of the premature cracking in the sections.

Since the early 2000s, finding the reasons for premature cracking of JPCP has been the goal of a number of studies, with some of them focusing specifically on longitudinal cracking *(47,48,49)*. These studies were conducted because staff at several state departments of transportation noted that the use of widened slabs might have contributed to premature longitudinal cracking, even though those slabs seemed to help reduce transverse cracking and shoulder maintenance. Results from these studies consistently showed a number of construction-related problems that could trigger the onset and development of longitudinal cracking: (1) inadequate longitudinal jointing due to late sawing, insufficient sawcut depth, or use of plastic inserts (instead of sawcutting), (2) a low-quality base and a consequent loss of support, and (3) malfunctioning of the paving machine's vibrators. Based on these observations, the Colorado Department of Transportation included the practice of measuring sawcut depth at regular intervals (every 1/10 of a mile) in the QC/QA of JPCP. Overall, however, these studies do not seem to agree on whether the use of widened slabs contributes to longitudinal cracking, as explained below.

The SPS-2 study *(46)* showed that longitudinal cracking tended to occur in JPCP with widened slabs, particularly if the slabs were thin. A recent field study in Louisiana similarly showed that longitudinal cracking increased with widened slabs and tied concrete shoulders *(49)*. But evidence to the contrary was found in a field study conducted in Colorado that concluded that premature longitudinal cracking was attributable to construction issues and not to the use of 14 ft. wide slabs *(47)*. A field study conducted in Wisconsin reached a similar conclusion *(48)*. In fact, the Colorado study concluded that the longitudinal cracking was lower in 14 ft. wide panels than in 12 ft. and 13 ft. wide panels. This outcome may be related to conditions in Wisconsin being wetter than in drier US states.

Although the studies obtained mixed results about the effects that slab width might have on longitudinal cracking—which does not seem to be fully understood—they did agree on the existence of a small number of factors or circumstances that can result in premature longitudinal cracking. However, the same cannot be said of premature transverse cracking, as explained below.

A study on premature transverse cracking was conducted in Indiana in the early 2000s *(50)*. The justification for the study was that the state's newly constructed JPCPs were experiencing premature transverse mid-panel cracking. After conducting a literature review, a survey of state departments of transportation, and a finite element analysis, the study concluded that “there is no one clear factor that can be identified as the major cause of transverse cracking of jointed plain concrete pavement.” Similarly, studies conducted in Michigan *(51)* and Pennsylvania *(52)* both identified a large number of circumstances that lead to premature JPCP cracking (longitudinal, transverse, or both). The studies found that most of these were related to poor construction practices, which included over-consolidation of the concrete, which resulted in low entrained air content and segregation; poor alignment of dowels, which resulted in the lock up of transverse joints; multi-lane paving, particularly when the two lanes were paved under very different weather conditions; paving on frozen base; non-uniform base thickness; built-in curling of the slabs due to hot weather paving; and poor concrete curing. Material-related distresses, high concrete CTE, and low load transfer efficiency were also among the circumstances cited that led to premature cracking of the slabs.

A 2018 report by the Mountain-Plains Consortium indicated that increasing the curing compound application rate improved the roughness performance of JPCP *(53)*. This result supports an idea that is part of JPCP common knowledge: the early-age condition of the concrete will impact not only the early-age performance of the JPCP but the mid- and long-term performance as well. Nevertheless, this current literature review found no studies that addressed what impact concrete’s early-age condition might have on the mid- and long-term performance of JPCP.

3 SUMMARY AND CONCLUSIONS

The literature review presented in this technical memorandum is part of PPRC Project 4.74, whose primary goal is to develop a set of recommendations for reducing the risks of early-age and premature cracking in lane replacement and slab replacement projects in the Caltrans road network. This literature review focuses on the factors that may lead to early-age and premature cracking of JPCPs.

The literature review shows that many factors are involved in the early-age and premature cracking of JPCP and that a large number of circumstances can result in these types of cracking. In most of the cases reported in the literature, the early-age and premature cracking were related to poor construction practices. This presents a challenge for Project 4.74 because this research project does not include a field investigation like the ones that constitute the basis of most of the published literature. It also presents a challenge for achieving the project's primary goal since preventing poor construction practices requires more than a set of recommendations; it also requires training and QC/QA.

Early-age cracking of JPCP has already received considerable attention, and there is agreement about the mechanisms that result in this type of cracking. The published literature generally agrees that the likelihood of early-age cracking will depend on the interaction between the tensile stresses developing in the concrete after placement and the concrete's early-strength gain. These tensile stresses are attributable to hygrothermal actions that begin to exert themselves as the concrete dries and cools.

There is also agreement regarding the practices recommended to reduce the risk of JPCP early-age cracking. These practices can be categorized in three main groups, depending on whether they are related to mixture design, pavement design, or construction process:

- The mixture design practices are linked to the collection of mixture design factors that were considered to have an important role in early-age cracking, including cement type, cement content, aggregate type, use of supplementary cementitious materials, and use of admixtures.
- The pavement design practices include selection of the optimal joint spacing and sawcutting depth, selection of the appropriate concrete-base bond breaker, and the design of the connection between the old concrete and the new concrete in the slab replacement, lane addition, and lane replacement projects.
- The construction practices include the proper conditioning of the base (thermal and moisture conditioning), the proper sawcutting timing, the application of proper curing (proper in time and type), and a number of specific practices to adopt in very hot and very cold weather conditions.

The current version of the Caltrans *Standard Specifications* addresses most of these practices, but Caltrans specifications for paving in adverse weather conditions are not completely clear. It is recommended that Caltrans develop clear guidelines for paving in very hot and very cold weather conditions. It is also recommended that future updates of Caltrans *Standard Plans* include the depth of transverse and longitudinal JPCP joint sawcutting.

Other practices that can be adopted to reduce the risk of JPCP early-age cracking, although they are not widely implemented, are the use of either internal curing, shrinkage-reducing admixtures, or fibers in the concrete.

Unlike the causes of early-age cracking on JPCP, premature cracking of JPCP has not been studied extensively. Based on the analysis of the Long-Term Pavement Performance SPS-2 JPCP sections in 14 states, premature cracking is a problem in dry states like California.

Finally, even though it is widely recognized that the early-age condition of concrete has an impact on mid- and long-term JPCP performance, very few studies have been focused on determining what that impact is.

REFERENCES

1. American Concrete Pavement Association. 2003. *R&T Update: What to Do When Faced with Early-Age Cracking*. Stokie, IL: American Concrete Pavement Association. http://overlays.acpa.org/Downloads/RT/RT4.07.pdf.
2. Taylor, P., Kosmatka, S.H., and Voigt, G.F. 2007. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual* (FHWA Publication No. HIF-07-004). Ames, IA: National Concrete Pavement Technology Center.
3. Taylor, P.C., van Dam, T.J., Sutter, L.L., and Fick, G.J. 2019. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual*, Second Edition. Ames, IA. National Concrete Pavement Technology Center. https://intrans.iastate.edu/app/uploads/2019/05/IMCP_manual.pdf.
4. Ruiz, J.M., Garber, S., and Dick, J.C. 2015. *Computer-Based Guidelines for Concrete Pavements, HIPERPAV III®, Version 3.3 User's Manual* (Publication No. FHWA-HRT-14-087). McLean, VA: Federal Highway Admnistration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/14087/14087.pdf.
5. Voigt, G.F. 2000. *Specification Synthesis and Recommendations for Repairing Uncontrolled Cracks that Occur During Concrete Pavement Construction*. Skokie, IL: American Concrete Pavement Association.
6. Voigt, G.F. 2002. *Early Cracking of Concrete Pavement-Causes and Repairs*. Skokie, Il: American Concrete Pavement Association.
7. Taylor, P., Kosmatka, S.H., and Voigt, G.F. 2007. *Technical Summary on Early-Age Cracking*. Ames, IA: National Concrete Pavement Technology Center.
8. Mccullough, B.F., and Rasmussen, R.O. 1999. *Fast Track Paving: Concrete Temperature Control and Traffic Opening Criteria for Bonded Concrete Overlays, Volume 1: Final Report* (Publication No. FHWA-RD-98-167). McLean, VA: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/98167/98167.pdf.
9. Ruiz, J.M., Rasmussen, R.O., Chang, G.K., Dick, J.C., Nelson, P.K., and Ferragut, T.R. 2005. *Computer-Based Guidelines for Concrete Pavements, Volume I: Project Summary*. Publication No. FHWA-HRT-04-121. McLean, VA: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/04121/04121.pdf.
10. Ruiz, J.M., Rasmussen, R.O., Chang, G.K., Dick, J.C., Nelson, P.K., Schindler, A.K., and Wilde, W.J. 2006. *Computer-Based Guidelines for Concrete Pavements, Volume III: Technical Appendices* (Publication No. FHWA-HRT-04-127). McLean,VA: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/04127/04127.pdf.
11. Kosmatka, S.H., Kerkhoff, B., and Panarese, W.C. 2011. *Design and Control of Concrete Mixtures*. Skokie, IL: Portland Cement Association.

12. Bentz, D.P. 2008. “A Review of Early-Age Properties of Cement-Based Materials.” *Cement and Concrete Research* 38, no. 2: 196–204. https://doi.org/10.1016/j.cemconres.2007.09.005.
13. Maggenti, R., Knapp, C., and Fereira, S. 2013. “Controlling Shrinkage Cracking.” *Concrete International* 35, no. 7: 36–41.
14. National Ready Mix Concrete Association. 2014. *CIP 5 – Plastic Shrinkage Cracking*. Concrete in Practice. Silver Springs, MD: National Ready Mix Concrete Association.
15. American Concrete Institute. 2013. *ACI Concrete Terminology* (ACI CT-13). Farmington Hills, MI: American Concrete Institute.
16. Bentz, D.P., and Weiss, W.J. 2011. *Internal Curing: A 2010 State-of-the-Art Review*. Gaithersburg, MD: National Institute of Standards and Technology. https://doi.org/10.6028/NIST.IR.7765.
17. Bentz, D.P., and Peltz, M.A. 2008. “Reducing Thermal and Autogenous Shrinkage Contributions to Early-Age Concrete.” *American Concrete Institute (ACI) Materials Journal* 105, no. 4: 414–420. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=923433.
18. Craeye, B., Geirnaert, M., and De Schutter, G. 2011. “Super Absorbing Polymers as an Internal Curing Agent for Mitigation of Early-Age Cracking of High-Performance Concrete Bridge Decks.” *Construction and Building Materials* 25, no. 1: 1–13. https://doi.org/10.1016/j.conbuildmat.2010.06.063.
19. Shen, D., Jiang, J., Jiao, Y., Shen, J., and Jiang, G. 2017. “Early-Age Tensile Creep and Cracking Potential of Concrete Internally Cured with Pre-Wetted Lightweight Aggregate.” *Construction and Building Materials* 135 (March 15): 420–429). https://doi.org/10.1016/j.conbuildmat.2016.12.187.
20. Shen, D., Wang, X., Cheng, D., Zhang, J., and Jiang, G. 2016. “Effect of Internal Curing with Super Absorbent Polymers on Autogenous Shrinkage of Concrete at Early Age.” *Construction and Building Materials* 106 (March 1): 512–522. https://doi.org/10.1016/j.conbuildmat.2015.12.115.
21. Villareal, V., and D. Crocker, D. 2007. “Better Pavements through Internal Hydration.” *Concrete International* 29, no. 2: 32–36.
22. Rao, C., and Darter, M. 2013. *Evaluation of Internally Cured Concrete for Paving Applications*. Champaign, IL: Applied Research Associates.
23. Babcock, A.E., and Taylor, P. 2015. *Impacts of Internal Curing on Concrete Properties*. Ames, IA: National Concrete Pavement Technology Center.
24. Weiss, J. 2016. *Internal Curing for Concrete Pavements*. (Tech Brief: FHWA-HIF-16-006). Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/pavement/concrete/pubs/hif16006.pdf.
25. Mateos, A., Harvey, J.T., Wu, R., Paniagua, F., and Paniagua, J. 2018. *Development of Improved Guidelines and Designs for Thin Whitetopping: Environmental Response of Full-Scale BCOA Sections* (UCPRC-RR-2017-03). Davis and Berkeley, CA: University of California Pavement Research Center. https://escholarship.org/uc/item/5hx556j4.

26. Mateos, A., Harvey, J.T., Paniagua, F., Paniagua, J., and Wu, R. 2018. *Development of Improved Guidelines and Designs for Thin Whitetopping: Construction and Initial Environmental Response of Full-Scale BCOA Sections* (UCPRC-RR-2017-02). Davis and Berkeley, CA: University of California Pavement Research Center. https://escholarship.org/uc/item/14t4f662.
27. Henkensiefken, R., Briatka, P., Bentz, D., Nantung, T., and Weiss, J. 2010. "Plastic Shrinkage Cracking in Internally Cured Mixtures Made with Pre-Wetted Lightweight Aggregate." *Concrete International* 32, no. 2.: 49–54. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=901532.
28. Nmai, C., Tomita, R., Hondo, F., and Buffenbarger, J. 1998. "Shrinkage-Reducing Admixtures." *Concrete International* 20, no. 4: 31 –37.
29. Bentz, D.P. 2005. "Curing with Shrinkage-Reducing Admixtures." *Concrete International* 27, no. 10: 55–60.
30. Rodden, R., and Lange, D. 2004. *Feasibility of Shrinkage Reducing Admixtures for Concrete Runway Pavements*. Urbana, IL: Center of Excellence for Airport Technology.
31. Weiss, W.J. 2015. "Thoughts on Curling in Plain and SRA Concrete Slabs: Moisture Gradients, Surface Tension, and Viscosity". In *CONCREEP 10: Mechanics and Physics of Creep, Shrinkage, and Durability of Concrete and Concrete Structures*. Vienna, Austria, September 21–23, 2015. https://ascelibrary.org/doi/10.1061/9780784479346.038.
32. Villani, C., Lucero, C., Bentz, D., Hussey, D., Jacobson, D.L., and Weiss, W.J. 2014. "Neutron Radiography Evaluation of Drying in Mortars With and Without Shrinkage Reducing Admixtures." In *Novel Characterization Techniques and Advanced Cementitious Materials: Tribute to James J. Beaudoin*. Washington, DC, October 25-29, 2014.
33. Yoo, D.Y., Min, K.H., Lee, J.H., and Yoon, Y.S. 2014. "Shrinkage and Cracking of Restrained Ultra-High-Performance Fiber-Reinforced Concrete Slabs at Early Age." *Construction and Building Materials* 73: 357–365. https://doi.org/10.1016/j.conbuildmat.2014.09.097.
34. Ghourchian, S., Wyrzykowski, M., Baquerizo, L., and Lura, P. 2018. "Performance of Passive Methods in Plastic Shrinkage Cracking Mitigation." *Cement and Concrete Composites* 91: 148–155. https://doi.org/10.1016/j.cemconcomp.2018.05.008.
35. Weiss, W.J., Yang W., and Shah, S.P. 1998. "Shrinkage Cracking of Restrained Concrete Slabs." *Journal of Engineering Mechanics* 124, no. 7: 765–774.
36. Dang, Y., Qian, J., Qu, Y., Zhang, L., Wang, Z., Qiao, D., and Jia, X. 2013. "Curing Cement Concrete by Using Shrinkage Reducing Admixture and Curing Compound." *Construction and Building Materials* 48 (November): 992–997. https://doi.org/10.1016/j.conbuildmat.2013.07.092.
37. Roesler, J., Bordelon, A., Brand, A.S. and Amirkhanian, A. 2019. *Fiber Reinforced Concrete for Pavement Overlays: Technical Overview*. Ames, IA: National Concrete Pavement Technology Center, https://intrans.iastate.edu/app/uploads/2019/04/FRC_overlays_tech_ovw_w_cvr.pdf.

38. Myers, D., Kang, T.H., and Ramseyer, C. 2008. "Early-Age Properties of Polymer Fiber-Reinforced Concrete." *International Journal of Concrete Structures and Materials* 2, no. 1: 9–14.
39. Aly, T., and Sanjayan, J.G. 2010. "Shrinkage-Cracking Behavior of OPC-Fiber Concrete at Early-Age." *Materials and Structures* 43, no. 6: 755–764.
40. Mazzoli, A., Monosi, S., and Plescia, E.S. 2015. "Evaluation of the Early-Age-Shrinkage of Fiber Reinforced Concrete (FRC) Using Image Analysis Methods." *Construction and Building Materials* 101 (December): 596-601. https://doi.org/10.1016/j.conbuildmat.2015.10.090.
41. Shen, D., Wang, W., Liu, J., Zhao, X., and Jiang, G. 2018. "Influence of Barchip Fiber on Early-Age Cracking Potential of High Performance Concrete Under Restrained Condition." *Construction and Building Materials* 187 (October 30): 118–130. https://doi.org/10.1016/j.conbuildmat.2018.07.121.
42. Wang, K., Shah, S.P., and Phuaksuk, P. 2001. "Plastic Shrinkage Cracking in Concrete Materials-Influence of Fly Ash and Fibers." *American Concrete Institute (ACI) Materials Journal* 98, no. 6: 458-464.
43. Saje, D., Bandelj, B., Sustersic, J., Lopatic, J., and Saje, F. 2010. "Shrinkage of Polypropylene Fiber-Reinforced High-Performance Concrete." *Journal of Materials in Civil Engineering* 23, no. 7: 941–952.
44. Banthia, N., and Gupta, R. 2006. "Influence of Polypropylene Fiber Geometry on Plastic Shrinkage Cracking in Concrete." *Cement and Concrete Research* 36, no. 7: 1263–1267. https://doi.org/10.1016/j.cemconres.2006.01.010.
45. Rahmani, T., Kiani, B., Bakhshi, M., and Shekarchizadeh, M. 2012. "Application of Different Fibers to Reduce Plastic Shrinkage Cracking of Concrete." In *7th RILEM International Conference on Cracking in Pavements*, edited by Scarpas A., Kringos N., and Al-Qadi I., A. L, 362–369. Dordrecht, Germany: Springer. https://doi.org/10.1007/978-94-007-4566-7_62.
46. Xu, C., and Cebon, D. 2017. *Analysis of Cracking in Jointed Plain Concrete Pavements*. (FHWA-HRT-16-073). McLean, VA: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/16073/16073.pdf.
47. Ardani, A., Hussain, S., and LaForce, R. 2000. *Evaluation of Premature PCCP Longitudinal Cracking in Colorado* (Report No. CDOT-DTD-R-2003-1). Denver, CO: Colorado Department of Transportation. https://expresslanes.codot.gov/programs/research/pdfs/2003/prematurepccpcracking.pdf.
48. Owusu-Ababio, S., and Schmitt, R. 2013. *Longitudinal Cracking in Widened Portland Cement Concrete Pavement* (WisDOT ID no. 0092-12-05). Madison, WI: Wisconsin Department of Transportation. https://wisconsindot.gov/documents2/research/WisDOT-WHRP-project-0092-12-05-final-report.pdf.
49. Xiao, D.X., and Wu, Z. 2018. "Longitudinal Cracking of Jointed Plain Concrete Pavements in Louisiana: Field Investigation and Numerical Simulation." *International Journal of Pavement Research and Technology* 11, no. 5: 417-426. https://doi.org/10.1016/j.ijprt.2018.07.004.

50. Chen, H., Dere, Y., Sotelino, E., and Archer, G. 2002. *Mid-Panel Cracking of Portland Cement Concrete Pavements in Indiana* (FHWA/IN/JTRP-2001/14). West Lafayette, IN: Joint Transportation Research Program, Purdue University. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1617&context=jtrp.
51. Smiley, D., and Hansen, W. 2007. *Investigation of Early Cracking on Selected JPCP Projects*. (No. RC-1501). Lansing, MI: Michigan Department of Transportation. https://www.michigan.gov/documents/mdot/MDOT_Research_Report_RC1501_221899_7.pdf.
52. Ramirez, L., Geary, M., Vandenbossche, J.M., Gatti, K., and Mu, F. 2011. *Premature Deterioration of Jointed Plain Concrete Pavements*. Harrisburg, PA: Pennsylvania Department of Transportation. https://gis.penndot.gov/BPR_PDF_FILES/Documents/Research/Complete%20Projects/Construction/Premature%20Deterioration%20of%20Jointed%20Plain%20Concrete%20Pavement.pdf.
53. Wehbe, N., Reid, R., Stripling, J., Edgar, B., Mahgoub, H., and Underberg, M. 2018. *Jointed Plain Concrete Pavement Design and Construction Review* (MPC 18-364). Fargo, ND: Mountain-Plains Consortium. https://www.ugpti.org/resources/reports/downloads/mpc18-364.pdf.