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The following changes were made to the document after publication on the Federal Highway Administration website:

Location	Incorrect Values	Corrected Values
Page 1, top of page	Additional text	*Researchers: Changwei Xu and David Cebon, Department of Engineering, University of Cambridge
Page 24, “Researchers” section	Correction to text	*“Changewei Xu” has been changed to “Changwei Xu.”

SUMMARY **REPORT**

Analysis of Cracking in Jointed Plain Concrete Pavements

FHWA Publication No.: FHWA-HRT-16-073
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Abstract

This paper investigates the trends of longitudinal and transverse cracking in jointed concrete pavements based on Long-Term Pavement Performance (LTPP) Program Strategic Study of Structural Factors for Rigid Pavements (SPS-2) data. The impacts of slab properties, base type, traffic volume, and environmental factors on the occurrence and extent of longitudinal and transverse cracking were identified from a simple analysis of the raw cracking data. SPS-2 sites in Arizona and Arkansas were chosen to investigate cracking mechanisms in detail. A new hypothesis for the prevalence of premature cracking on these sites was proposed and tested by numerical simulations.

The analysis showed that longitudinal and transverse cracking were more sensitive to slab thickness and base type than other construction variables. Surface cracking was worse in dry climatic zones than wet zones. Most transverse cracks initiated from the slab edge close to the shoulder, and two forms of longitudinal cracks can initiate from transverse edges of slabs: a single long crack or multiple short cracks along the whole section. In addition to inadequate compaction of the base layers during construction and rehabilitation, the major contribution to premature longitudinal cracking appeared to be voiding beneath the outer edge of the pavement. This is caused by localized plastic deformation of "depressurized" soil, which occurs principally due to slab curl.

Introduction

Premature cracking can severely degrade concrete pavement structures. Many studies have suggested that premature longitudinal cracking is primarily caused by improper construction or rehabilitation practices combined with heavy load repetitions.[1–3] In this report, an alternative mechanism is hypothesized for premature cracking in jointed concrete pavements.

The LTPP SPS-2 project was designed to investigate the effects of design features and site conditions and their interactions on the long-term performance of jointed concrete pavements.[4] All SPS-2 sections were built between 1992 and 1999. The availability and completeness of data for the SPS-2 experiments were studied in 2005.[5] Early trends of some distresses, such as transverse cracking and roughness, were analyzed statistically in several studies.[6–9] However, because the majority of the test sections were quite new at that time, the extent and occurrence of many distresses were low and even reached zero. By 2014, most SPS-2 sections had more than 20 years of service life, and significant cracking was apparent. Many of the sites had extensive environmental and traffic data available. These data were an outstanding source for an investigation of cracking mechanisms in jointed plain concrete pavements.

The aims of the study reported here were to understand the key factors affecting cracking of the SPS-2 sections (including the effects of foundation and

*Revised September 1, 2017

slab design over-layers) and investigate the causes of premature cracking in these sections. The general statistics of cracking in all SPS-2 sections were investigated, and then a detailed case study was conducted on sites in Arkansas and Arizona covering wet and dry zones. The initiation, growth, and patterns of cracking were investigated. A new hypothesis for the mechanism of premature longitudinal cracking was proposed, and a finite element model was presented.

Analysis of LTPP SPS-2 Performance Data

Analysis of Raw Crack Data

The length of longitudinal and transverse cracking is recorded in the LTPP database, and each crack is assigned one of three severity levels.[10] In this study, the sum of crack lengths at all three severity levels (the total length of cracking) was used to assess performance. The mean length of cracking per pavement section (denoted as "mean length of cracking") was also introduced as a performance metric (i.e., the total length of cracking divided by the number of pavement sections involved).

Figure 1 and figure 2 show the mean length of longitudinal and transverse cracking in all SPS-2 sections as a function of the year post construction for two climatic zones, respectively. Sections in the dry zone cracked sooner and more extensively than those in the wet zone for both longitudinal and transverse cracks. Significant cracks appeared in the dry zones in year 3. Pavements in the wet zones cracked more gradually, with minor transverse cracking from year 4. However, major longitudinal and transverse cracks were only present from about year 8 onward. Maintenance work was performed at various times but particularly in years 10 and 12, when a significant reduction in crack lengths was apparent.

Figure 1. Mean crack length of longitudinal cracking per section for two climatic zones.

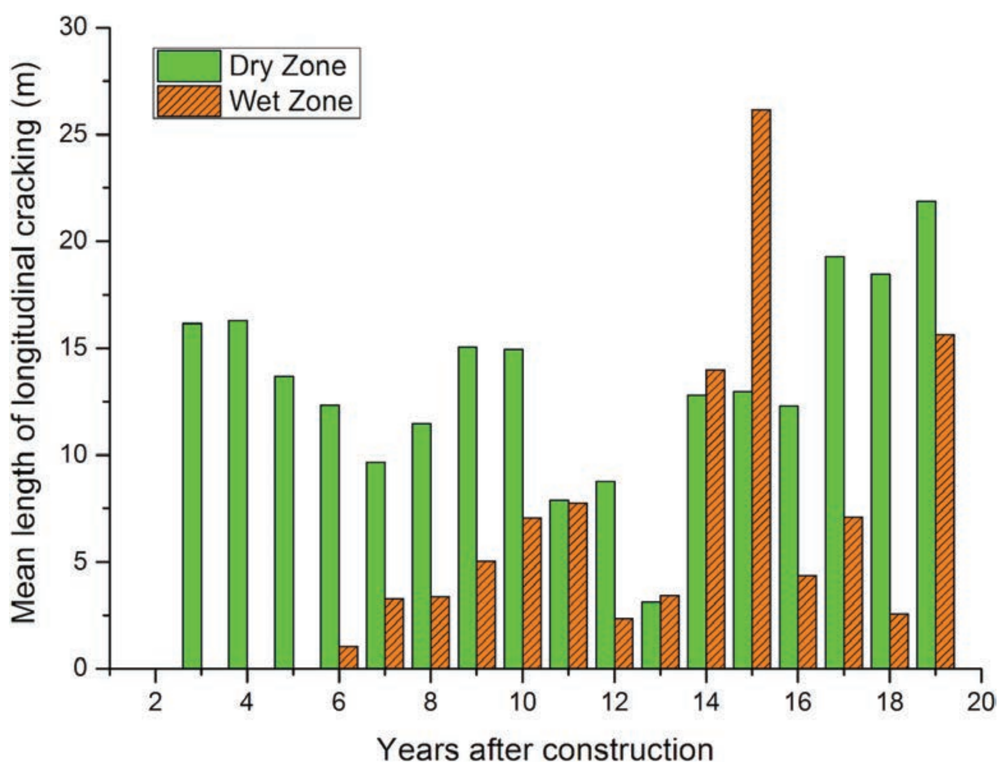


Figure 3 and figure 4 show the effects of pavement base type on longitudinal and transverse cracking performance throughout the life of the SPS-2 sections. The SPS-2 sections were constructed with three types of base: dense-graded aggregate base (DGAB), lean concrete base (LCB), and permeable asphalt-treated base (PATB).[4,5] As shown in figure 3 and figure 4, the PATB bases provided pavements with the best cracking resistance. DGAB provides pavements with moderate cracking resistance, while LCB provided pavements with the worst cracking resistance. This conclusion concerning the influence of base type for transverse cracking was also drawn in some earlier studies.[6,5]

Figure 2. Mean crack length of transverse cracking per section for two climatic zones.

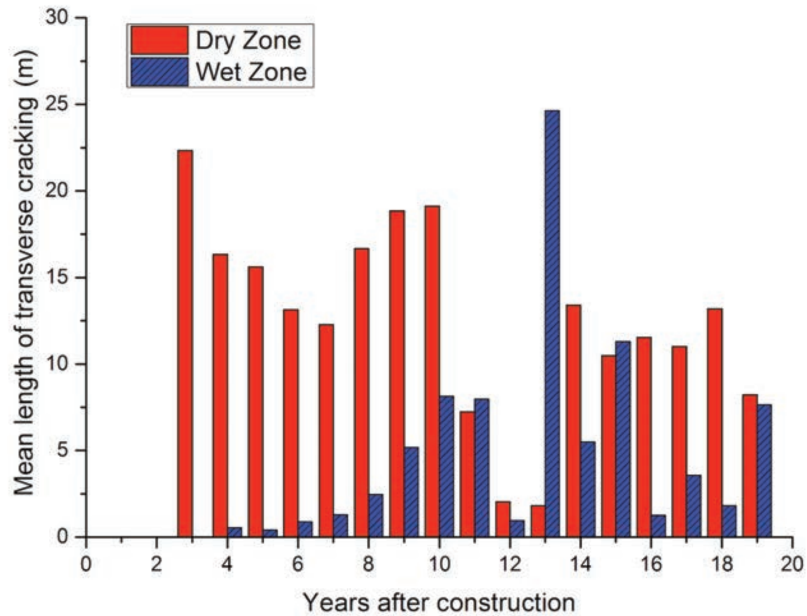
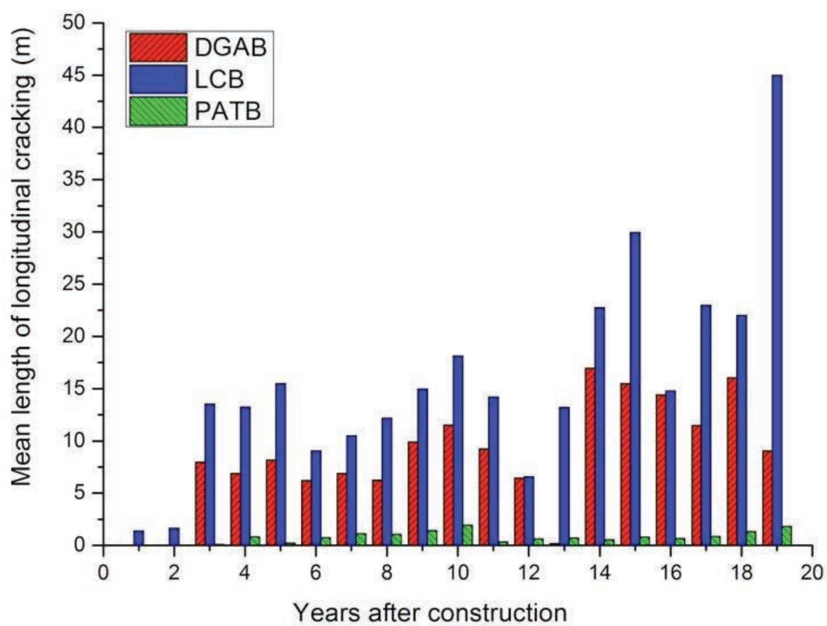


Figure 3. Mean longitudinal crack length per section over time for three different pavement base types.



In the SPS-2 experiment, two thicknesses of portland cement concrete (PCC) slabs were used: 203-mm ("thin") slabs and 279-mm ("thick") slabs.[5] In some sections, large differences may exist between the design and construction values.[5] Figure 5 and figure 6 demonstrate that thicker PCC slabs have better cracking resistance—they develop fewer cracks later in life than the thinner ones.

Figure 4. Mean transverse crack length per section over time for three different pavement base types.

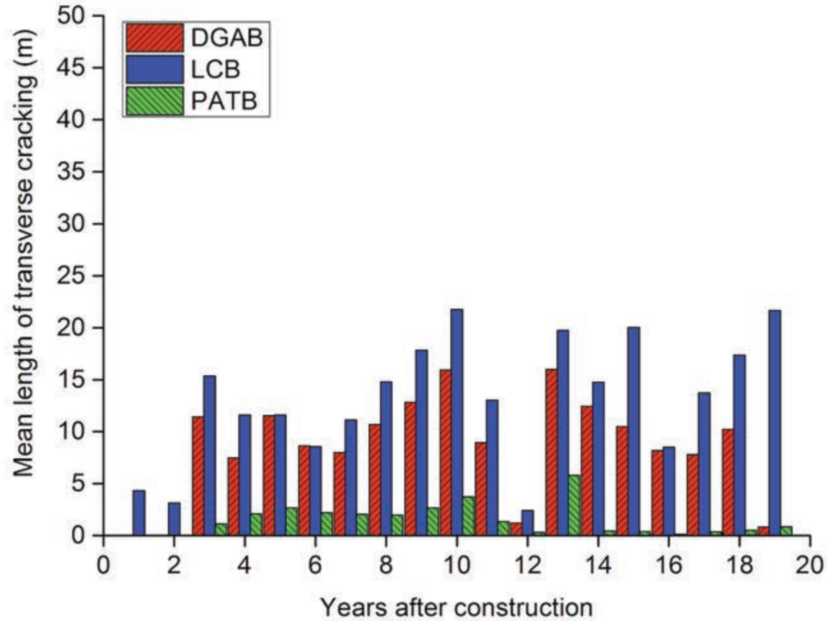
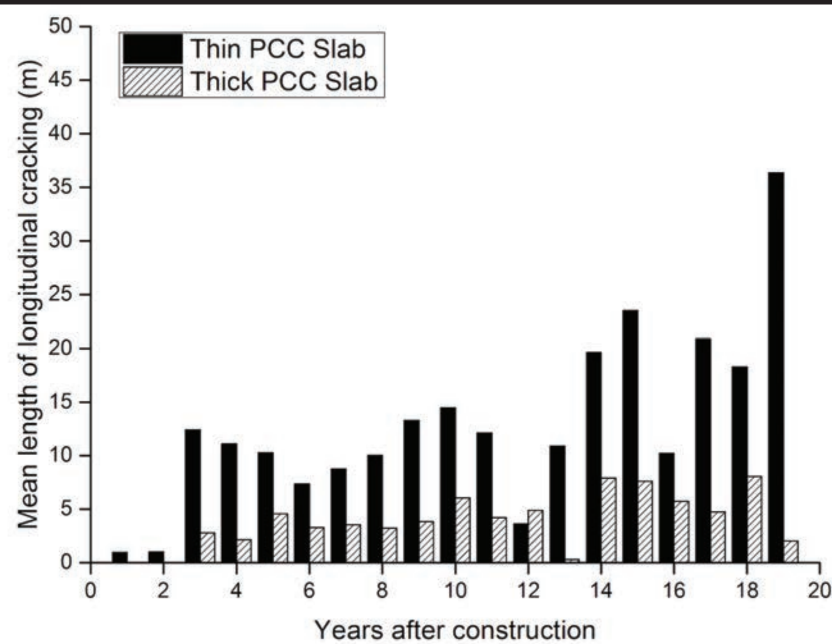


Figure 5. Mean longitudinal crack length per section over time for thin PCC slabs and thick PCC slabs.



The SPS-2 pavement sections were constructed with two different slab widths: "standard" slabs of 3.66 m and "wide" slabs of 4.27 m.[5] Figure 7 and figure 8 show that, on average, the sections with widened PCC slabs developed more extensive longitudinal cracking. Conversely, standard slabs appeared to start cracking transversely earlier in life. Overall, the long-term levels of transverse cracking were approximately the same for both slab widths.

Figure 6. Mean transverse crack length per section over time for thin PCC slabs and thick PCC slabs.

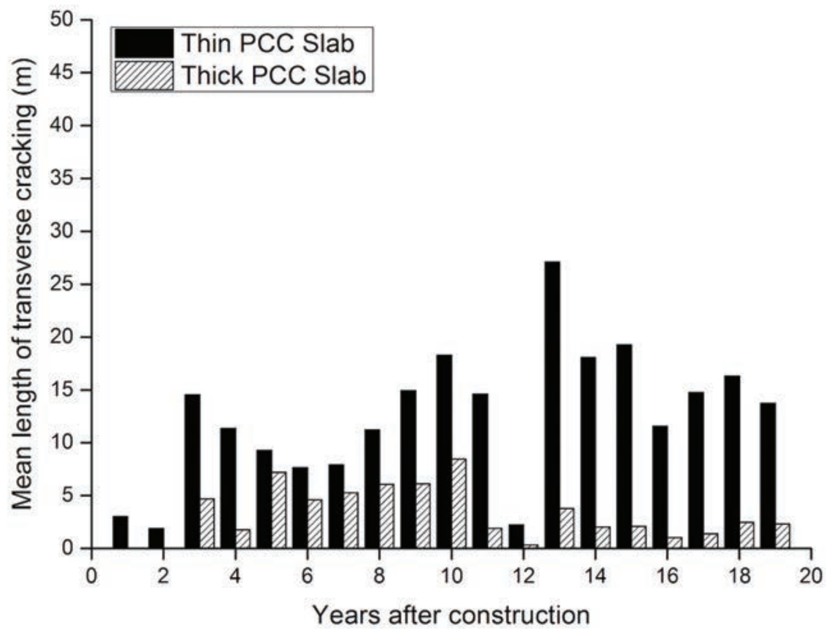
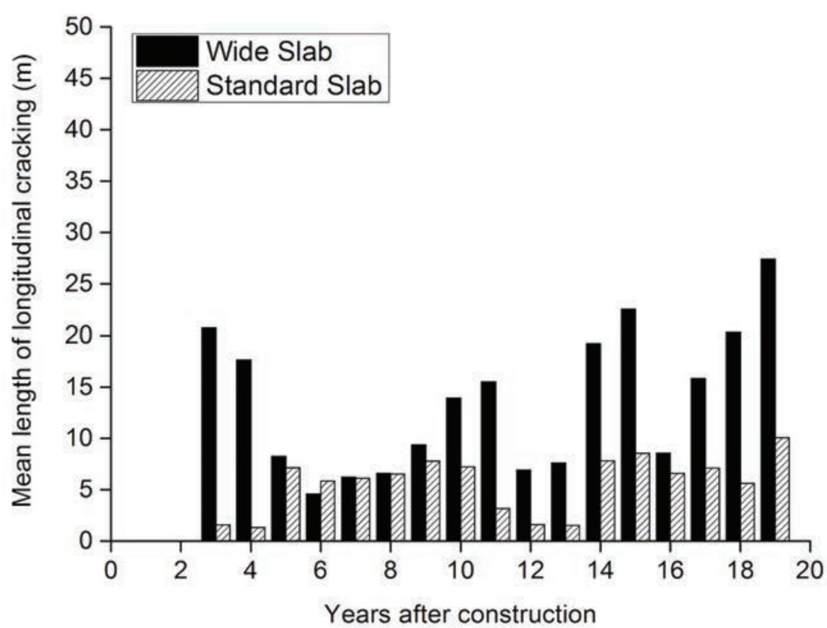


Figure 7. Mean longitudinal crack length per section over time for wide PCC slabs and standard PCC slabs.



The SPS-2 experiment specification included two levels of concrete strength (at 14 d): 3.8 and 6.2 MPa. Figure 9 and figure 10 show that some sections with high slab strength display earlier longitudinal and transverse cracking. Between 6 and 12 years after construction, the weaker concrete showed more cracking, but, in the long term, there was little to distinguish between them.

Figure 8. Mean transverse crack length per section over time for wide PCC slabs and standard PCC slabs.

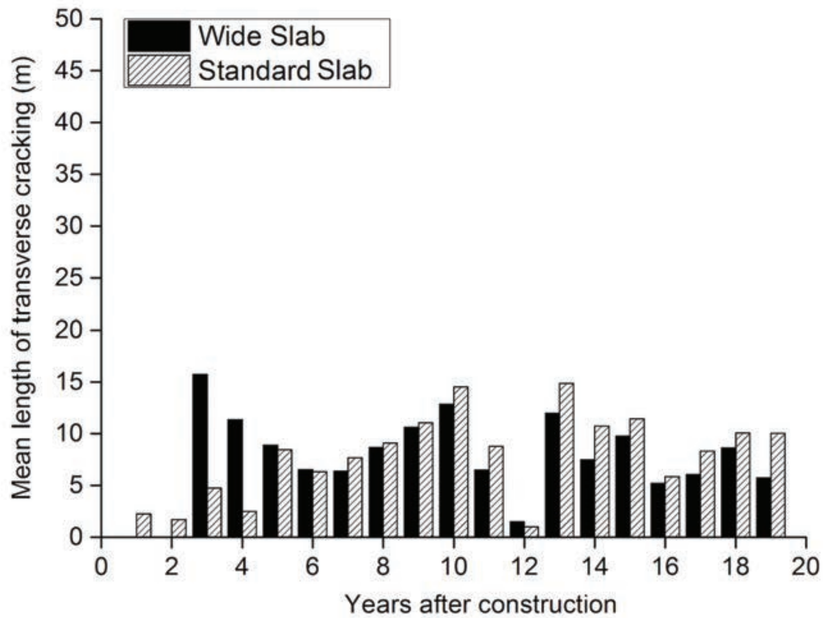


Figure 9. Mean longitudinal crack length per section over time for low-strength slabs and high-strength slabs.

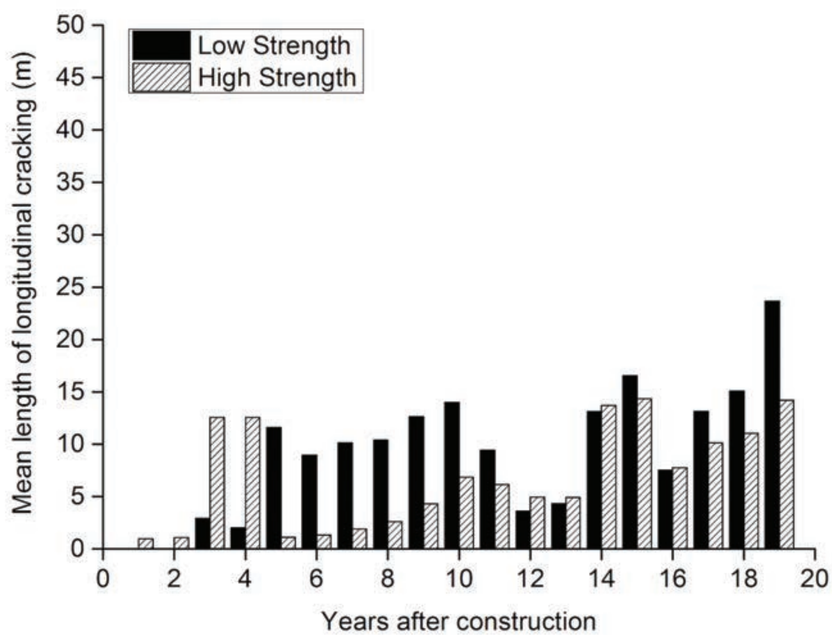
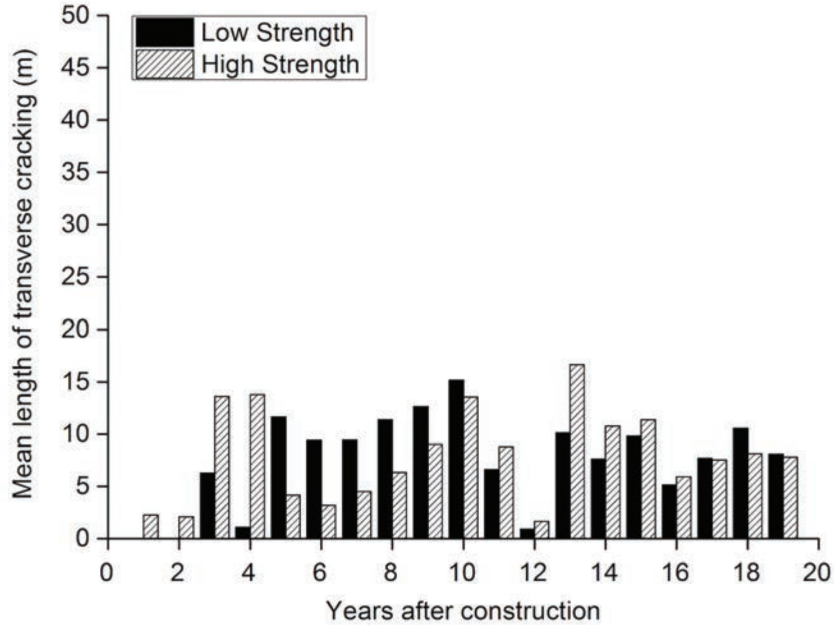


Figure 10. Mean transverse crack length per section over time for low-strength slabs and high-strength slabs.



Case Study: Arizona and Arkansas Sites

The SPS-2 experiment consisted of 168 core sections in 14 States. Although the data in the database for each section were generally of very high quality, there was considerable variation in the levels of completeness. An extensive review of the availability of data in the database was conducted to choose sites and sections with data suitable for detailed simulation.

The usefulness of the information about a particular test site for validating the vehicle-pavement interaction model depends on the following five main factors:

- **Survey period:** The survey period should be long enough to show useful trends in long-term damage evolution.
- **Distress types:** Not all distress types are recorded for all sites. To be chosen for this study, the sites had to have information about longitudinal, transverse, and "map" cracking; pumping; and faulting.
- **Traffic data:** High-quality traffic data is essential for simulation of pavement performance. Fortunately, the traffic data on many of the SPS sites were collected in the traffic data pooled fund study, for which both the quality and quantity of the traffic data were excellent.[11] SPS-2 sites with at least 5 years of research-quality traffic data collected by the pooled fund study were considered to be suitable.[11]
- **Maintenance work:** The LTPP Navigator Table lists 57 types of maintenance work.[12] The database contains the date on which each item of maintenance was performed for each section, but the details of the work done are not listed. Consequently, when examining the trends in performance variables such as surface roughness, it is difficult to account for the specific repairs in analysis of damage evolution. To account for this, sites were chosen for which maintenance work was distinct, with fewer than three maintenance interventions during the survey period.
- **Other data:** The sites chosen had to have a complete set of structural, material, and environmental data available.

Table 1 shows a summary of the availability of data in the database for 2 of the 14 SPS-2 sites: Arkansas (wet zone) and Arizona (dry zone). These sites were used for the case studies in this report. The structural and material factors for each of the 12 core sections in each site are listed in table 2. Equivalent data were collected for all of the SPS-2 sites.[13] Note that the section numbers, (e.g., 0213) in table 1 and table 2 indicate the nominal design. Pavement section 0213 in Arkansas has the same nominal design (i.e., slab width, thickness, concrete strength, base type, etc.) as the section numbered 0213 in other States (e.g., Arizona).

Table 1. Summary of information available in the LTPP database for the SPS-2 sites in Arizona and Arkansas.

State	Section	Distress Type												Date Assigned to LTPP	Survey Period		Maintenance			Traffic Data
		Transverse Cracks	Longitudinal Cracks	Map Cracking	D Cracking	Corner Breaks	Longitudinal Spalling	Transverse Spalling	Pumping	Blow-ups	Polished Aggregate	Faulting	Scaling		Date	Survey Number	Number	Reason ID	Date (Year)	
Arizona (04)			P	Y			T	SF	LB		S	D	G	01/01/1993	02/28/95–02/23/12	12	1	6, 54	2009	84.6 percent (2012-07)
	0214	R		Y			T	SF				D	G		02/27/95–02/23/12		0	—	—	
	0215		P	Y			T	SF			S	D			02/27/95–02/22/12	26	0	—	—	
	0216			Y			T					D			02/27/95–02/22/12	12	0	—	—	
	0217	R	P	Y			T	SF			S	D	G		02/28/95–02/22/12		1	6, 54	2009	
	0218	R	P	Y		B	T	SF				D			02/27/95–02/23/12		1	54	2007	
	0219	R	P	Y			T	SF			S	D			02/28/95–02/22/12		0	—	—	
	0220	R	P	Y			T					D			02/27/95–02/23/12		0	—	—	
	0221		P	Y			T	SF			S	D	G		02/28/95–02/23/12		2	6, 54; 54	2007 and 2009	
	0222	R	P	Y			T	SF				D			02/27/95–02/23/12		0	—	—	
	0223			Y			T	SF			S	D			02/28/95–02/23/12		0	—	—	
	0224		P	Y			T	SF				D			02/27/95–02/2412		0	—	—	
	0262		P	Y			T	SF			S	D			03/01/95–02/28/12	10	1	6	2009	
	0263	R	P	Y			T	SF			S	D	G		02/03/95–02/28/12		0	—	—	
	0264			Y			T	SF			S	D	G		03/01/95–02/28/12		0	—	—	
	0265			Y			T	SF			S	D	G		03/01/95–02/29/12		0	—	—	
	0266		P	Y			T	SF			S	D			03/01/95–02/29/12		0	—	—	
	0267			Y			T	SF			S	D	G		03/01/95–02/29/12	9	1	12	2008	
	0268		P	Y			T	SF				D	G		03/01/95–03/01/12		0			

Table 1. Summary of information available in the LTPP database for the SPS-2 sites in Arizona and Arkansas. (Continued)

State	Section	Distress Type: Transverse Cracks	Longitudinal Cracks	Map Cracking	D Cracking	Corner Breaks	Longitudinal Spalling	Transverse Spalling	Pumping	Blow-ups	Polished Aggregate	Faulting	Scaling	Date Assigned to LTPP	Survey Period: Date	Survey Number	Maintenance: Number	Reason ID	Date (Year)	Traffic Data
Arkansas (05)	0213	R	P			B	T	SF	LB		S	D		01/01/1993	11/19/96–05/24/07	7	4	3; 1; 6; 6	1997, 2002, 2003, and 2006	96.9 percent (2012-07)
	0214	R					T	SF	LB		S	D			11/08/96–04/18/12	10	1	3	1997	
	0215						T	SF	LB		S	D			11/06/96–04/18/12		1	3	1997	
	0216						T	SF	LB		S	D					2	3; 2, 3	1997 and 02	
	0217	R	P			B	T	SF	LB		S	D	G		11/14/96–04/19/12		3	3; 1, 54; 54	1997, 2002, and 2006	
	0218	R	P			B	T	SF	LB			D			11/14/96–04/19/12		3	3; 1, 2; 54	1997, 2002, and 2006	
	0219		P			B	T	SF	LB		S	D			11/12/96–04/18/12		1	3	1997	
	0220					B	T	SF	LB			D			11/15/96–04/19/12		2	3; 2	1997 and 2002	
	0221	R				B	T	SF	LB		S	D			11/20/96–04/19/12		2	3; 2, 3	1997 and 2002	
	0222						T	SF	LB		S	D			11/08/96–04/18/12		1	3	1997	
	0223						T	SF			S	D			11/06/96–04/18/12		1	3	1997	
	0224					B	T	SF			S	D			11/18/96–04/19/12		4	3; 54; 3; 2	1996, 1997, 2001, and 2002	

Note: Commas separate different maintenance activities on the same date, and semicolons separate different maintenance activities on different dates.
R = Transverse cracks occurred.
P = Longitudinal cracks occurred.
Y = Map cracking occurred.
B = Corner breaks occurred.
T = Longitudinal spalling occurred.
SF = Transverse spalling occurred.
LB = Pumping occurred.
S = Polished aggregate occurred.
D = Faulting occurred.
G = Scaling occurred.
Blank cell = No distress.
— = No maintenance.

Table 2. The constructed layer information for Arkansas (05) and Arizona (04).

State	Section	Design Type[1]	PCC Slab Thickness (mm) Measure	PCC Slab Thickness (mm) Design	Base Layer Type	Base Layer Thickness (mm) Measure		Base Layer Thickness (mm) Design		Dowels (mm)	Subgrade	Climatic Condition
Arkansas (05)	0213	PCC3	188	203	DGAB	152		152		32	Fine-grained	Wet, no-freeze
	2014	PCC2	211			254						
	0215	PCC1	284	279		152				38		
	0216	PCC4	277			152						
	0217	PCC3	191	203	LCB + DGAB	160	102	152	102	32		
	0218	PCC2	188			163	102					
	0219	PCC1	282	279		160	102			38		
	0220	PCC4	272			178	152					
	0221	PCC3	208	203	PATB + DGAB	84	104	102	102	32		
	0222	PCC2	213			59	279					
	0223	PCC1	277	279		99	203			38		
	0224	PCC4	277			64	221					
Arizona (04)	0213	PCC3	201	203	DGAB	147		152		32	Coarse-grained	Dry, no-freeze
	2014	PCC2	211			155						
	0215	PCC1	287	279		160				38		
	0216	PCC4	284			160						
	0217	PCC3	206	203	LCB	155		152		32		
	0218	PCC2	211			155						
	0219	PCC1	274	279		158				38		
	0220	PCC4	287			158						
	0221	PCC3	208	203	PATB + DGAB	107	107	102	102	32		
	0222	PCC2	218			99	109					
	0223	PCC1	282	279		104	89			38		
	0224	PCC4	272			112	97					

[1]Slab widths and concrete strengths: PCC1: 3.66 m and 3.8 MPa, PCC2: 3.66 m and 6.2 MPa, PCC3: 4.27 m and 3.8 MPa, and PCC4: 4.27 m and 6.2 MPa.

Figure 11 shows the annual average daily truck traffic over time for the two test sites. The dashed lines are periods when data were not available. The two sites had similar levels of truck traffic, although Arkansas had a slightly higher volume than Arizona.

Figure 12 shows the annual average precipitation in the two sites. According to the average precipitation level, Arkansas is defined as a wet site, and Arizona is defined as a dry site. The rainfall level was implicated in some failures of concrete pavements such as pumping.

Figure 11. Annual average daily truck traffic at the SPS sites in Arizona and Arkansas.

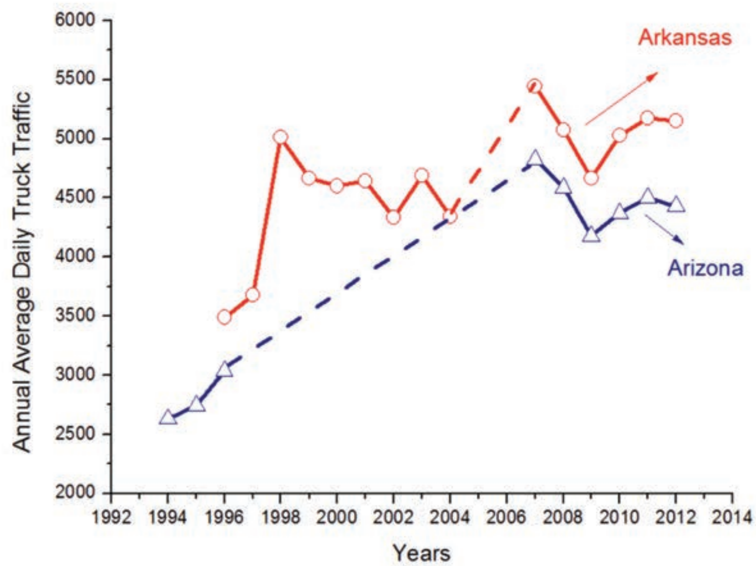


Figure 12. Annual average precipitation at the SPS sites in Arizona and Arkansas.

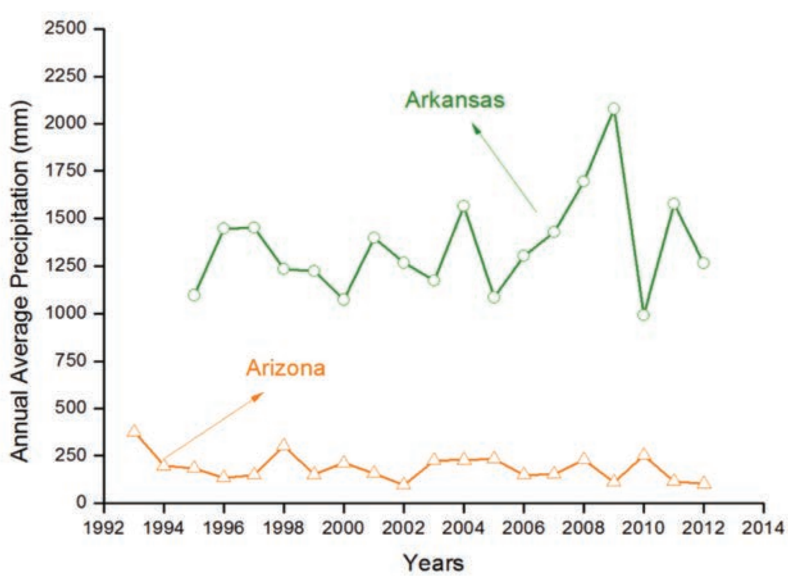


Figure 13 shows the total length of longitudinal cracking and transverse cracking over time on the Arkansas SPS-2 site. The following can be seen:

- Sections 0213, 0217, and 0218 had both longitudinal and transverse cracks.
- Sections 0214 and 0221 had only transverse cracks with low severities.
- Sections 0215, 0216, 0219, 0220, 0222, 0223, and 0224 had no cracks.

Figure 13. The total length of cracking over time in the Arkansas SPS-2 sites. (Transverse cracking is plotted below the axis for convenience.)

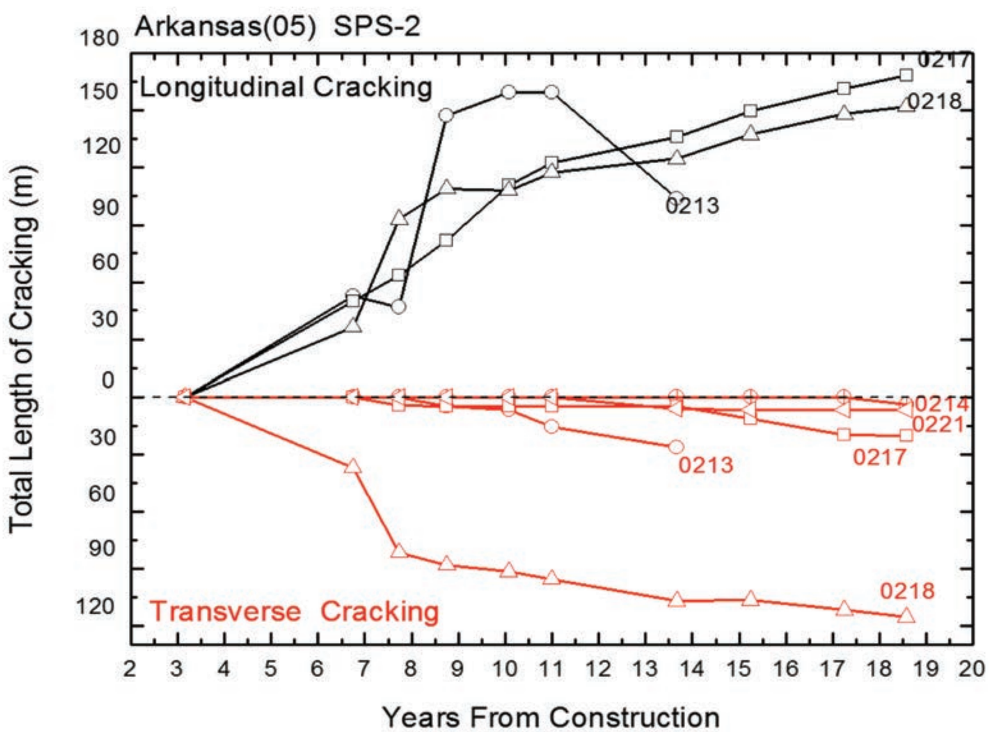


Figure 14 shows the total length of longitudinal cracking and transverse cracking over time in Arizona. The following can be seen:

- Sections 0217 and 0218 had longitudinal and transverse cracks.
- Sections 0213 and 0221 had only longitudinal cracks.
- Sections 0214, 0215, 0219, 0220, and 0222 had very small magnitude of cracking.
- Sections 0216 and 0223 had no cracks.

Figure 15 through figure 20 display details of the cracking process in three sections (0213, 0217, and 0218) for Arizona and Arkansas, respectively. Each figure shows the percentage cracking along with recorded snapshots of the patterns of longitudinal and transverse cracks.

The percentage of longitudinal cracks is defined as the total length of longitudinal cracks in a section normalized by the length of the section; 100 percent corresponds to a single crack along the entire length of the section. *The percentage of transverse cracks* is defined as the total length of transverse cracks normalized by the sum of the widths of all slabs in the section; 100 percent corresponds to a single transverse crack across every slab in the section. Both of these metrics can exceed 100 percent.

The crack patterns revealed that most longitudinal cracks initiated at slab transverse edges, and the rest initiated from transverse cracks. Most transverse cracks initiated at the concrete slab edge close to the shoulder, and the rest initiated either at the slab edge in the middle of the lane (i.e., with the longitudinal joints) or from longitudinal cracks.

The following two patterns of longitudinal cracks were apparent at 20 years of service:

- Almost continuous single crack relatively near the shoulder (as seen for sections 04-0213, 05-0213, and 05-0217).
- A set of discrete cracks closer to the longitudinal centerline of slabs (as seen for sections 04-0217, 04-0218, and 05-0218).

Analysis of the pumping data for these sites showed that Arizona sections did not display significant edge pumping, whereas edge pumping occurred in the Arkansas sections a year and a half later than the appearance of cracking. It appears that pumping failure occurred because of cracking in these sections rather than cracking occurring due to water ingress.

Figure 14. The total length of cracking over time in the Arizona SPS-2 sites. (Transverse cracking is plotted below the axis for convenience.)

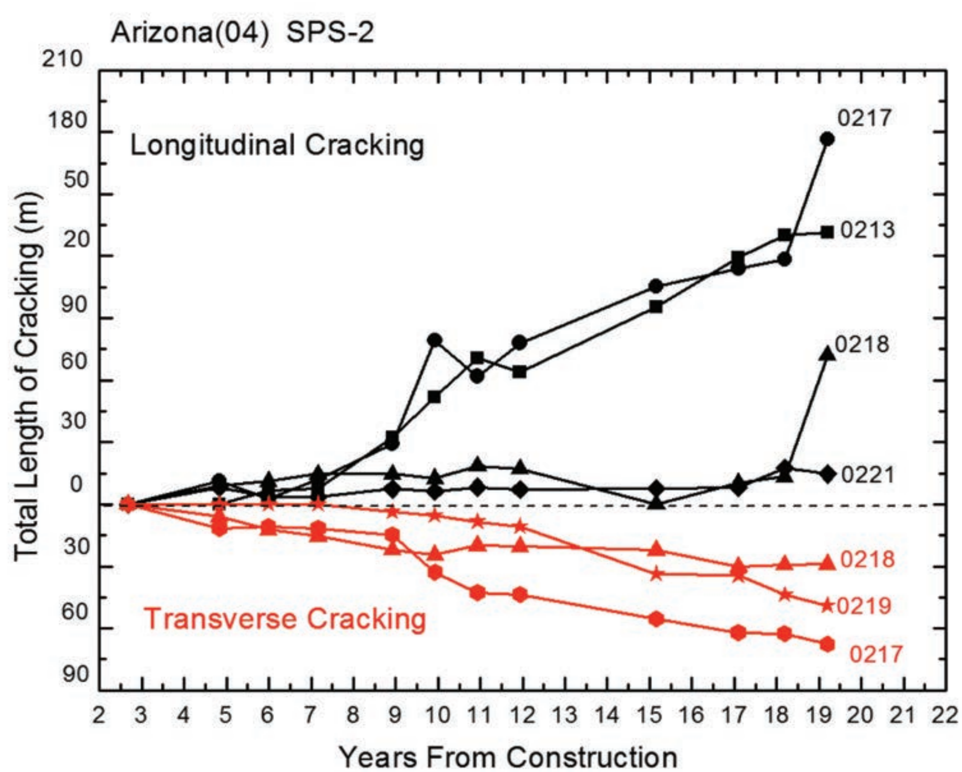


Figure 15. The development of cracking in Arizona-0213 section.

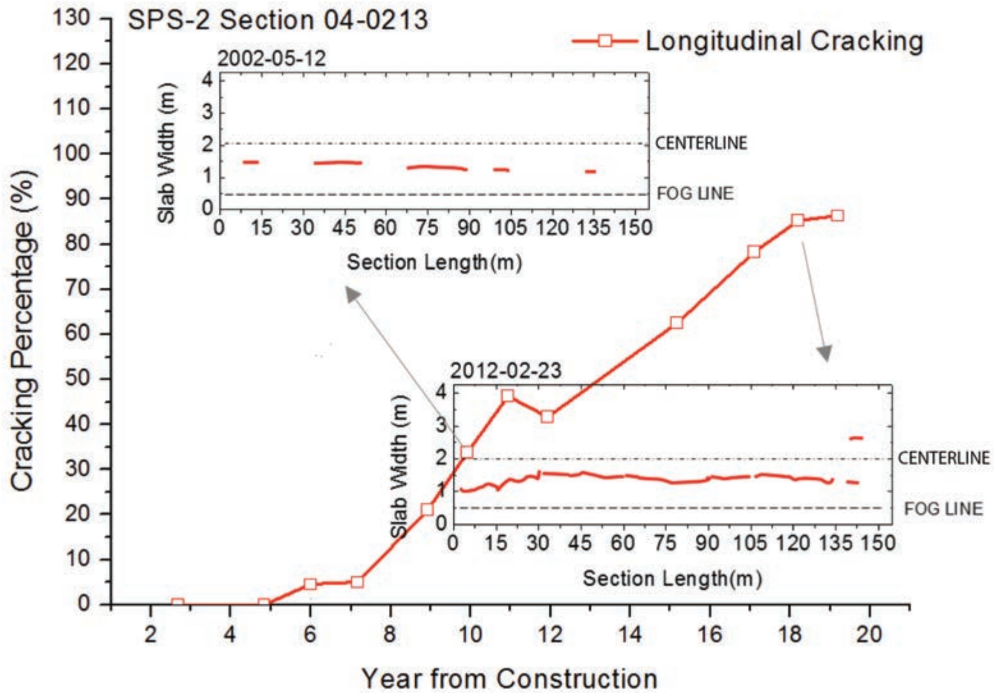


Figure 16. The development of cracking in Arizona-0217 section.

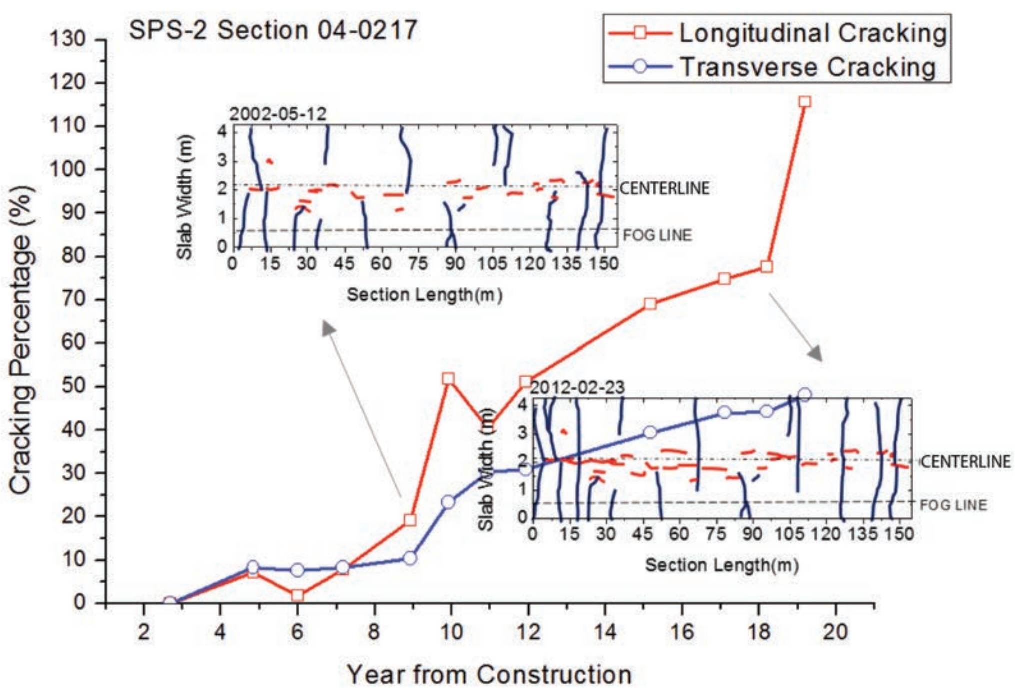


Figure 17. The development of cracking in Arizona-0218 section.

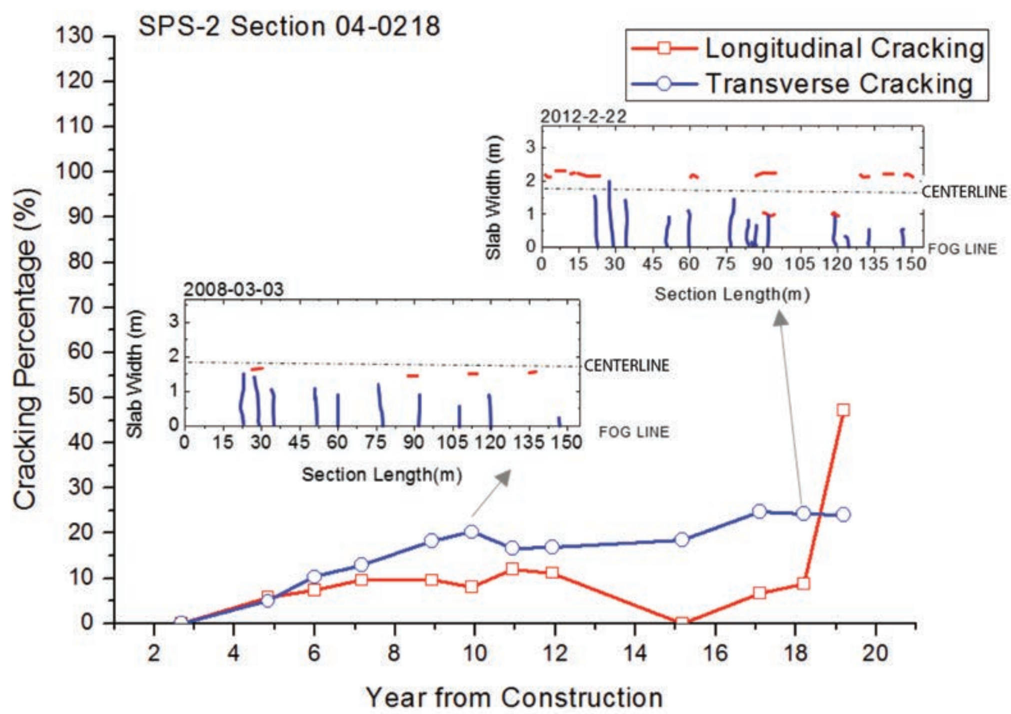


Figure 18. The development of cracking in Arkansas-0213 section.

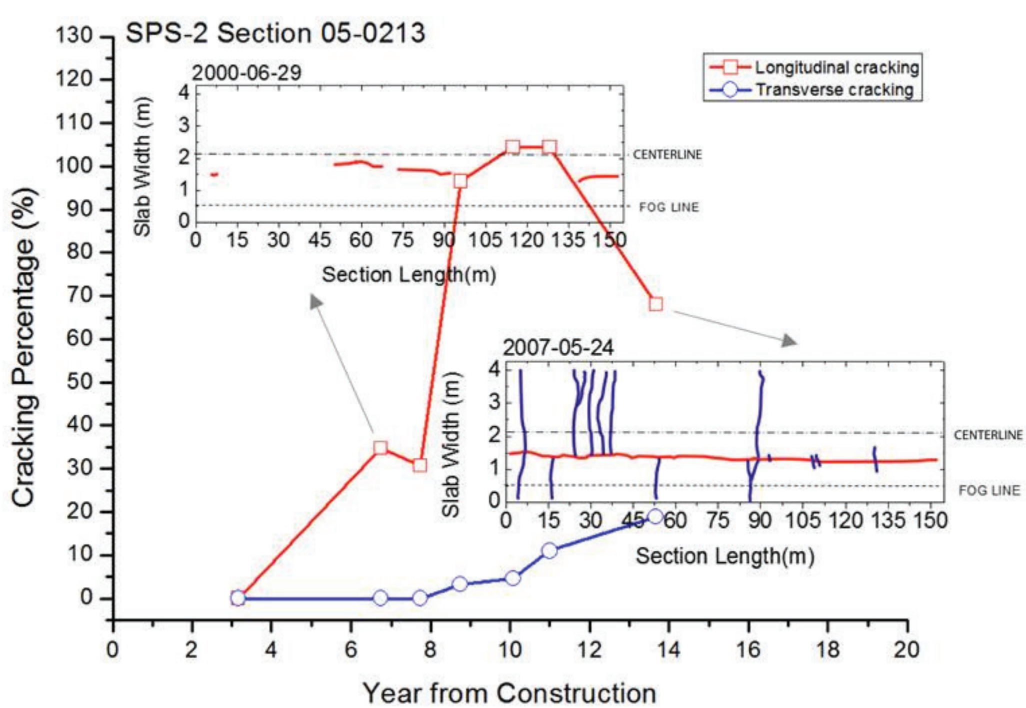


Figure 19. The development of cracking in Arkansas-0217 section.

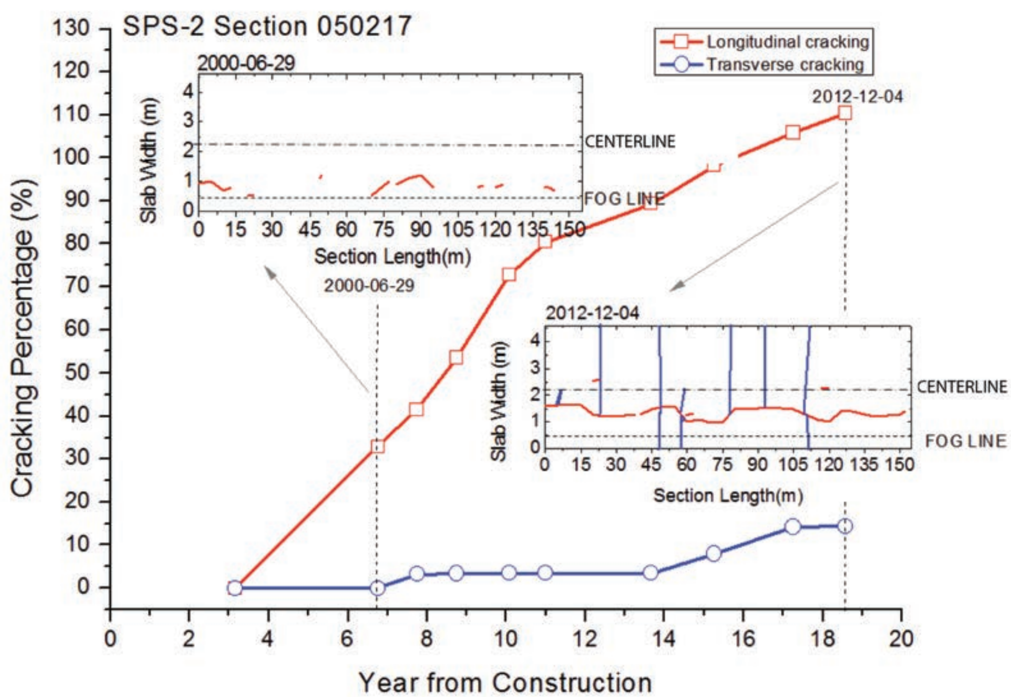
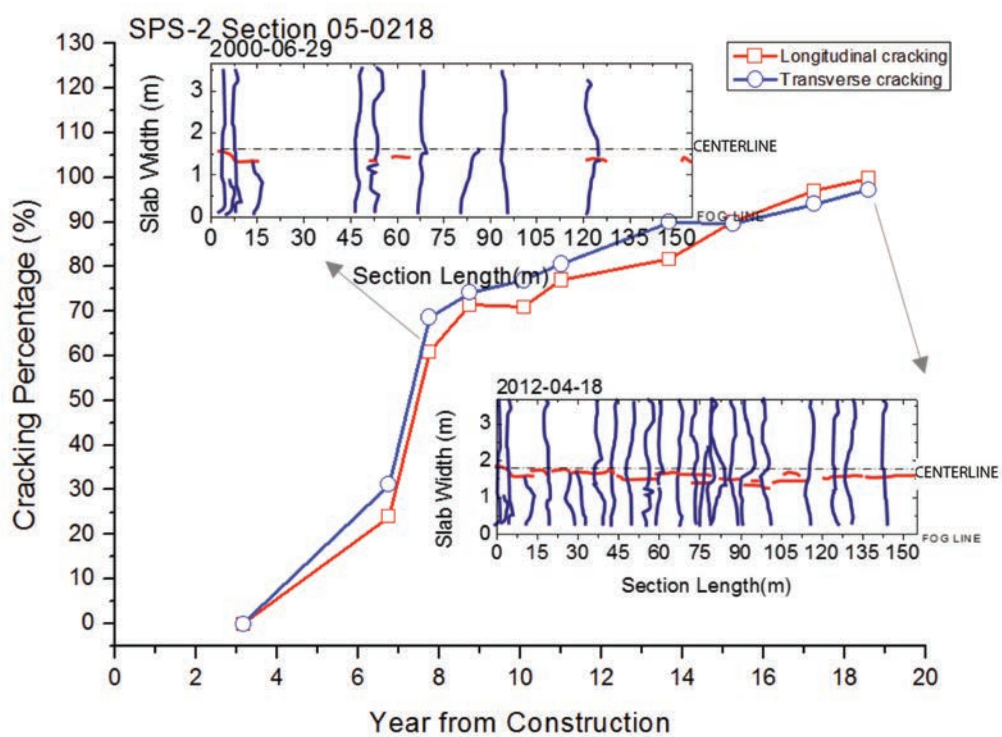


Figure 20. The development of cracking in Arkansas-0218 section.



The snapshots featured in figure 21 through figure 30 were selected from 10 different sections in 7 sites (States). They share almost continuous single cracks relatively near the shoulder. These cracks occured only in the sections with DGAB (section 0213) and LCB (sections 0217, 0218, and 0206). This pattern of cracking was only found in the 10 sections in LTPP SPS-2 (according to monitoring results updated in 2013).

Figure 21. Longitudinal cracking near the shoulder in Arizona-0213 section (February 16, 2011).

Figure 22. Longitudinal cracking near the shoulder in Arizona-0262 section (February 16, 2011).

Figure 23. Longitudinal cracking near the shoulder in Arkansas-0213 section (May 24, 2007).

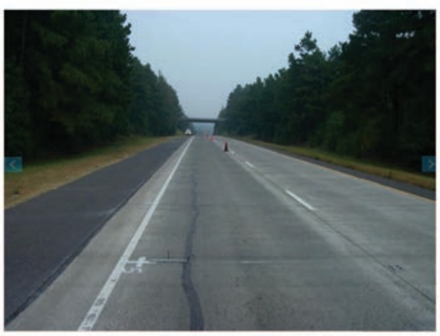


Figure 24. Longitudinal cracking near the shoulder in Arkansas-0217 section (December 4, 2012).

Figure 25. Longitudinal cracking near the shoulder in Colorado-0217 section (September 20, 2011).

Figure 26. Longitudinal cracking near the shoulder in Colorado-0218 section (September 20, 2011).

Figure 27. Longitudinal cracking near the shoulder in North Dakota-0217 section (August 21, 2012).

Figure 28. Longitudinal cracking near the shoulder in Iowa-0217 section (March 30, 2011).

Figure 29. Longitudinal cracking near the shoulder in Ohio-0206 section (September 12, 2006).

Figure 30. Longitudinal cracking near the shoulder in Washington-0206 section (May 23, 2013).

Details of the structural factors and climatic conditions of these sections are presented in table 3. The table shows that the pattern of longitudinal cracking was only exhibited in thinner pavements (design depth: 203 mm). By contrast, other sections with thick slabs (design depth: 279 mm) did not exhibit such longitudinal cracking. The table also shows that this pattern of longitudinal cracking occurred mainly in sections constructed with wide slabs (with the exception of section 08-0218). This longitudinal cracking pattern (single cracking near the shoulder) occurred for soil types, shoulder types, and climatic conditions.

Table 3. The structural factors and climate conditions of the 10 sections shown in figure 6.						
	PCC Slab		Base			
Section Number	Design Depth (mm)	Design Width (m)	Type	Soil Type	Shoulder	Climatic Conditions
04-0213	203	4.27	DGAB	Coarse-grained	PCC	Dry and non-freeze
04-0262	203	4.27	DGAB	Coarse-grained	PCC	Dry and non-freeze
05-0213	203	4.27	DGAB	Fine-grained	AC	Wet and non-freeze
05-0217	203	4.27	LCB	Fine-grained	AC	Wet and non-freeze
08-0217	203	4.27	LCB	Coarse-grained	PCC	Dry and freeze
08-0218	203	3.66	LCB	Coarse-grained	PCC	Dry and freeze
38-0217	203	4.27	LCB	Fine-grained	AC	Dry and freeze
19-0217	203	4.27	LCB	Fine-grained	PCC	Wet and freeze
39-0206	203	4.27	LCB	Fine-grained	PCC	Wet and freeze
53-0206	203	4.27	LCB	Coarse-grained	AC	Dry and freeze

AC = Asphalt concrete.

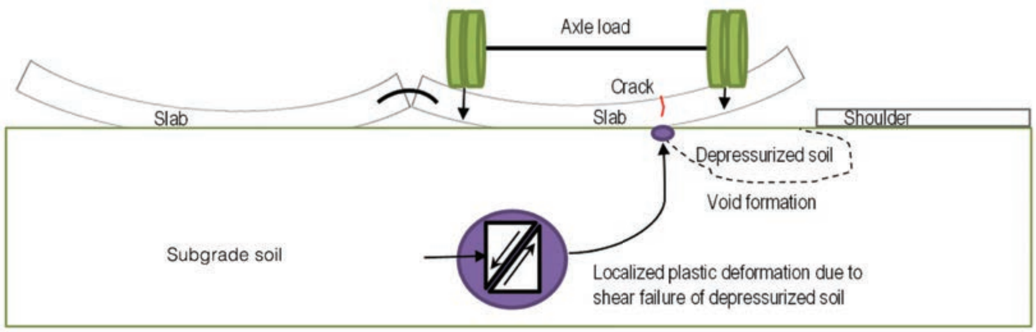
Mechanism of Premature Cracking

Hypothesis

The shear strength of granular materials is dependent on the effective mean stress or hydrostatic confining pressure.[14,15] The material becomes weaker as the confining pressure decreases. It is hypothesized that premature longitudinal cracking of pavement slabs could be caused by slab curl interacting with wheel loading as described as follows and shown in figure 31 (the mechanism for premature transverse cracking is thought to be similar):

1. Slabs curl upward at the edges during the night because of temperature through their thickness. They can also curl because of moisture gradients (though with a longer time period). This reduces the hydrostatic pressure on the subgrade soil under lifted areas of the slab. This effect is labeled as "depressurization" in the following discussion.
2. The curled slab is loaded by wheel loads, and parts of the lifted sections are pressed back down. The curvature of the slab causes the foundation to be loaded along a line adjacent to the depressurized area. This means that the subgrade soil yields easily and is deformed transversely (pushed out of the way) into the depressurized area. On repeated loading, this creates a void along the edge of the slab adjacent to the shoulder.
3. Reloading the slabs into the newly created void by wheel loads causes high tensile stress on the surface about 1 m in from the edge of the slab. The high transverse bending stress causes the slab to crack from the top down.
4. In wet regions, water ingress under the edge of the slab can cause foundation material to be pumped out of the voided area to accelerate the voiding and slab-cracking process. However, pumping is not necessary for the mechanism to work. The fact that slabs in dry regions crack earlier indicates that dry soils (with low cohesive strength) are more susceptible to being deformed in this way than more cohesive wet soils.

Figure 31. Hypothesized mechanism of void and crack formation due to interaction between slab curl and axle loading.



Numerical Simulation

A two-dimensional plane strain finite element model of a transverse section through the pavement was created using ABAQUS 6.12 to examine the void creation hypothesis described in the Hypothesis section. The system was assumed to be symmetrical at the centerline of the slab, so the model consisted of one-half of the elastic concrete slab resting upon the subgrade soil (see figure 32). The foundation soil was modeled using a linear elastic–perfectly plastic Mohr-Coulomb (M-C) constitutive model, which captured its pressure-sensitive yield behavior as shown in figure 33.

Figure 32. Plane strain model of the slab and foundation subjected to vehicle axle loading.

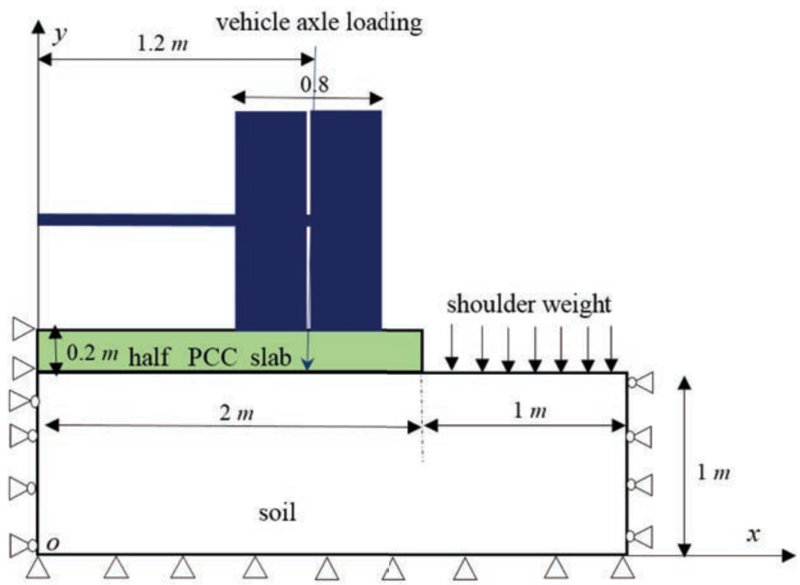


Figure 33. M-C constitutive model.

$$\tau = \sigma tan\emptyset + C$$

Where:

τ = The shear strength of the soil.
σ = The normal (hydrostatic) stress.
ϕ = The angle of internal friction, assumed to be 30 degrees.
C = The cohesion stress.

The soil was assumed to have a typical elastic modulus of 40 MPa and a dilation angle of 0.1 degree. Contact between the slab and soil foundation was assumed to have a coefficient of tangential friction of 0.5.

Vertical pressure was applied to the surface of the foundation under the shoulder to account for the weight of the shoulder material above. The slab was assumed to be clamped along its longitudinal centerline, and the foundation was clamped along its edges as shown in figure 32. The slab could optionally be curved as a result of temperature and moisture gradients, and it was loaded by a vertical wheel load. Four cases were simulated, as shown in table 4. Two different subgrade soils were used. Cases I and III had high cohesive stress (C = 8 kPa), nominally representing soils in wet regions. Cases II and IV had soils with low cohesive stress, nominally representing sandy soils in dry regions. Slab curl was switched on and off by optionally applying an upward deflection of 0.5 mm along the shoulder edge of the slab. Cycles of axle loading and unloading were applied, with the permanent soil deformation the result of each load cycle being multiplied by 100 to accumulate the void growth due to 100 axle load passes. This was repeated 100 times to simulate the soil deformation due to 10,000 axle passes.

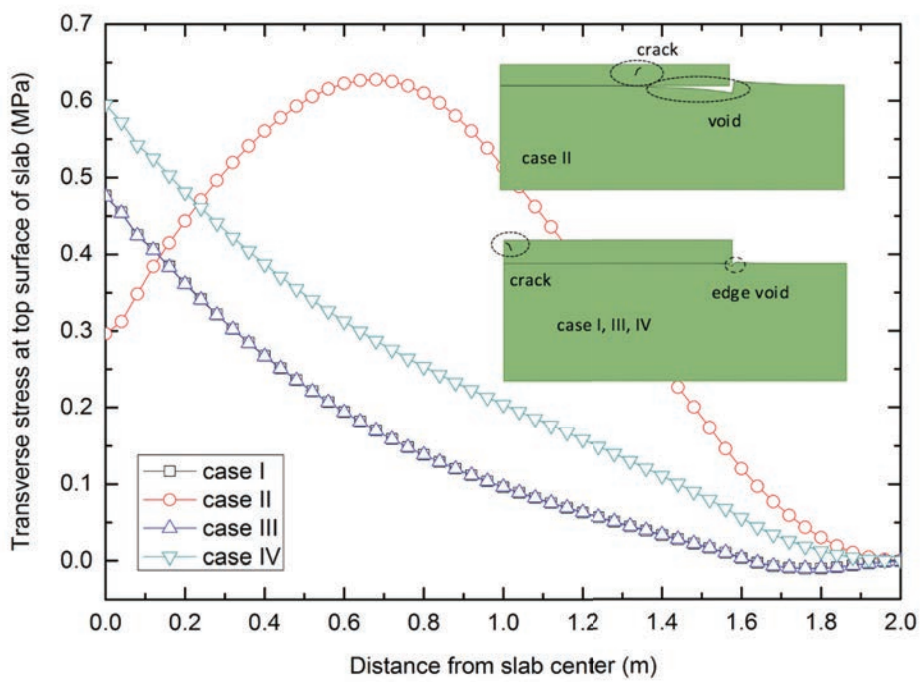
Figure 34 shows the transverse stress at the top surface of the slab after 10,000 load cycles for the four load cases. The peaks of transverse stress in cases I, III, and IV are all located at x = 0, the centerline of the full slab, about 2 m from the shoulder. Only small edge voids were generated underneath the shoulder edge of the slab. In these three cases, any longitudinal cracking would be expected to occur along the centerline of the slab between the wheels. In case II, the peak of transverse stress is significantly higher and is located at about x = 0.7 m (i.e., 1.3 m from the shoulder), with significant voids generated underneath the slab. This position is consistent with the measurements of crack locations on the test pavements (see figure 20).

Therefore, it appears that the prerequisites for this mechanism of premature cracking to occur are soils with low cohesive strengths (e.g., in dry regions) and slabs with some curl (which is more prevalent in thinner slabs). If the soils have low cohesive strengths but the slabs do not curl (case IV), then longitudinal cracking is more likely to occur in the middle of the slab, as predicted by conventional elastic analysis of a slab on an elastic foundation. The model provides convincing evidence that the main cause of premature longitudinal cracking is not inadequate compaction but depressurization of the foundation due to slab curl.

Table 4. Simulation load cases.

Load Case	Slab Curl	Cohesive Stress (*C*)
I	Yes	8 kPa
II	Yes	0.5 kPa
III	No	8 kPa
IV	No	0.5 kPa

Figure 34. Transverse stress at top surface of the slab for four cases.



Conclusions

LTPP SPS-2 is an excellent resource for studying long-term performance of jointed concrete pavements because of the availability of data for pavement performance, material properties, environmental data, and traffic data. The investigation points to a mechanism that explains the patterns of premature cracking of plain jointed concrete pavements involving interaction of slab curl, vehicle loading, and foundation soils with low cohesive strengths.

The major findings in this study are as follows:

- The severity of longitudinal and transverse cracking is sensitive to slab thickness and base type. Slab width and strength have a less clear effect.
- Cracks occur earlier and are more severe in dry zones.
- Longitudinal cracking occurs in two patterns: a single long crack about 1 m from the edge of the pavement slab adjacent to the shoulder and a short crack near the centerline of the slab.
- Most longitudinal cracks initiate from slab transverse edges, while most transverse cracks initiate from the slab longitudinal edge close to the shoulder.
- In Arkansas (wet zone), edge pumping occurred as a result of cracking rather than vice versa.
- A plausible explanation for premature cracking in plain jointed concrete pavements is the occurrence of voiding in the foundation soil due to localized plastic deformation. This can occur because of depressurization of the soil caused by slab curl. This mechanism is a particular problem for soils with low cohesive strength as found in dry regions.

References

1. Ardani, A., Hussain, S., and LaForce, R. (2003) "Evaluation of Premature PCC Pavement Longitudinal Cracking in Colorado." *Proceedings of the 2003 Mid-Continent Transportation Research Symposium*, Ames, IA.

2. Chen, D.H. and Won, M. (2007). "Field Investigations of Cracking on Concrete Pavements." *Journal of Performance of Constructed Facilities*, *21*(6), 450–458.

3. Yao, J.-I. and Weng, Q.-H. (2011). "Causes of Longitudinal Cracks on Newly Rehabilitated Jointed Concrete Pavements." *Journal of Performance of Constructed Facilities*, *26*(1), 84–94.

4. Hanna, A.N., Tayabji, S.D., and Miller, J.S. (1994). *SHRP-LTPP Specific Pavement Studies: Five-Year Report*, Report No. SHRP-P-395, National Research Council, Washington, DC.

5. Jiang, Y.J. and Darter, M.I. (2005). *Structural Factors of Jointed Plain Concrete Pavements: SPS-2—Initial Evaluation and Analysis*, Report No. FHWA-RD-01-167, Federal Highway Administration, Washington, DC.

6. Haider, S.W., Chatti, K., Buch, N., Lyles, R.W., Pulipaka, A.S., and Gilliland, D. (2007). "Statistical Analysis of In-Service Pavement Performance Data for LTPP SPS-1 and SPS-2 Experiments." *Journal of Transportation Engineering*, *133*(6), 378–388.

7. Hall, K.T. and Correa, C.E. (2003). *Effects of Subsurface Drainage on Performance of Asphalt and Concrete Pavements*, NCHRP Report 499, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC.

8. Suthahar, N., Ardani, A., and Morian, D.A. (2000). "Early Evaluation of Long-Term Pavement Performance Specific Pavement Studies-2, Colorado." *Transportation Research Record: Journal of the Transportation Research Board 1699*(1), 160–171.

9. Vongchusiri, K., Buch, N., Desaraju, P., and Salama, H. (2003) "An Evaluation of LTPP SPS-2 Sections in Michigan." *Proceedings of the 3rd International Symposium on Maintenance and Rehabilitation of Pavements and Technological Control*, Guimarães, Portugal.

10. Miller, J.S. and Bellinger, W.Y. (2003). *Distress Identification Manual for the Long-Term Pavement Performance Program*, Report No. PB2007-110362, National Technical Information Service, Alexandria, VA.

11. Walker, D. and Cebon, D. (2011). "The Metamorphosis of Long-Term Pavement Performance Traffic Data." *TR News 277—Transportation Research Board*, 9–17.

12. Long-Term Pavement Performance Program. (2002). *LTPP Table Navigator: Table View*, Federal Highway Administration, Washington, DC, obtained from: http://www.ltpp.org/cgi-bin/ltpp_tables.pl, last accessed September 30, 2016.

13. Craig, R.F. (1978). *Soil Mechanics*, Spon Press, New York, NY.

14. Terzaghi, K., Mesri, G., and Peck, R.B. (1996). *Soil Mechanics in Engineering Practice*, Wiley, New York, NY.

15. Xu, C. and Cebon, D. (2014). *Analysis of the Long Term Pavement Performance (LTPP) SPS-2 Experiment*. Cambridge University Engineering Department Technical Report CUED/C–MECH/TR.104, Cambridge, UK.

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