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Comprehensive evaluation of transverse joint spacing in jointed plain concrete pavement

Orhan Kaya[1*]

[1] Department of Civil Engineering, Adana Alparslan Türkeş Science and Technology University, Adana (Türkiye)
*Correspondence: okaya@atu.edu.tr,

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Abstract: Transverse joint spacing is one of the fundamental input parameters in structural design of jointed plain concrete pavement (JPCP). It has to be determined considering many factors to produce a well-performing and cost-effective JPCP. In this study, a comprehensive evaluation of transverse joint spacing in JPCP was carried out based on the followings: (1) guidelines based on previous studies, the Federal Highway Administration and the American Concrete Pavement Association recommendations were summarized; (2) empirical and mechanistic-empirical (M-E) pavement design methodologies were reviewed; (3) current state highway agency practices in USA were surveyed as part of this study and the survey results were documented; (4) effects of joint spacing on JPCP performance were evaluated based on field observations; and (5) lastly, an economic analysis was performed to evaluate effects of joint spacing on life-cycle costs. This study demonstrated that a joint spacing between 15-18 ft (4.6-5.5 m) seems to be provide a safe zone for both performance and cost effectiveness.

Keywords: Transverse joint spacing, JPCP, concrete pavement, economic analysis, pavement design.

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1. Introduction

Concrete pavement develops internal stresses because of not only mechanical loads but also environmental loads such as drying shrinkage, temperature and moisture differences in the body of a concrete slab which controls the amount and possible location of the cracks, if there will be any. Rather than waiting for uncontrolled cracks to occur at the locations where internal stresses exceed flexural strength of the concrete, locations and patterns of these cracks should be pre-determined by pavement designers. Transverse joints, joints perpendicular to traffic direction, are needed in jointed plain concrete pavement (JPCP) for several reasons such as: (1) controlling the location, appearance and width of slab cracks; (2) allowing normal slab movements by relieving internal stresses; (3) accommodating load transfer between the cracked slabs; and (4) minimizing performance loss (slab cracking, faulting and roughness etc.) of concrete pavement because of random cracks.

Therefore, JPCP should be jointed at intervals less than the intervals where concrete cracks naturally occur to control cracking. There are many factors that should be considered while determining optimum transverse joint spacing in JPCP such as concrete characteristics (e.g., temperature and moisture response, elasticity and flexural strength), concrete slab thickness, foundation support, environmental conditions, pavement performance expectations and economic considerations etc. Therefore, it is extremely challenging and overwhelming to consider and quantify relative impact of each factor in determining optimum joint spacing in JPCP to obtain the best performing, at the same, cost-effective joint design option. That is why, most of the literature related to transverse joint spacing design in JPCP focuses only on one or very few numbers of factors but lacks providing a comprehensive evaluation of all factors affecting joint spacing design in JPCP (AASHTO, 1998; Darter, 1997; FHWA, 1990; FHWA, 1998; Grosek, et al., 2019).

In this study, a comprehensive evaluation of transverse joint spacing in JPCP was carried out. First, guidelines and rule-of-thumbs in determining joint spacing in JPCP based on previous studies, the Federal Highway Administration (FHWA) and the American Concrete Pavement Association (ACPA) recommendations were summarized. Then, whether joint spacing has been used as an input parameter in empirical and mechanistic-empirical (M-E) pavement design methodologies; and if so, how it has been used, were reviewed. As part of this paper, ACPA Chapter/State Association representatives were surveyed in October 2018 by the author of this paper and Iowa Concrete Paving Association (ICPA) for their agency designs/best practices related to joint spacing design. The survey results were summarized and discussed in this paper to identify the latest US States practices on joint spacing design. Then, effect of joint spacing on JPCP performance was evaluated based on field observations obtained from LTPP InfoPave. Lastly, an economic analysis was carried out to evaluate the effects of joint spacing on JPCP construction, maintenance, and rehabilitation costs. Using the findings and comprehensive literature review of this paper, useful and practical recommendations and in-depth discussion on determining optimum joint spacing were provided for practitioners and pavement design professionals.

2. Literature review on transverse joint spacing

2.1. *Guidelines based on previous studies, FHWA and ACPA recommendations*

Previous studies showed that environmental and traffic conditions, concrete material properties, slab thickness and dimensions, base stiffness, loss of support and level of built-in curling are the most important parameters controlling the maximum anticipated joint spacing of JPCP to minimize transverse (mid-panel) cracking potential. Generally, JPCP with thinner slabs produces higher curling stresses so as higher transverse cracking potential (FHWA, 1990). Therefore, for thinner slabs, shorter joint spacing should be used. Similarly, slabs exposed to higher temperature gradient exhibit higher level of curling stresses so as higher transverse cracking potential (FHWA, 1990).

Therefore, for such cases, shorter joint spacing should be used. Curling stresses are also directly related to coefficient of thermal expansion of (CTE) of concrete. As CTE of concrete increases, level of shrinkage and expansion of concrete also increases. CTE of each material used in concrete is also directly affecting CTE of concrete; the most dominant component of concrete in determining CTE of concrete is coarse aggregate. Studies showed that slabs made with sandstone or quartz generally have higher CTE compared to the ones made with limestone (FHWA, 1990). Other two factors that should be considered in the design of joint spacing is loss of support and built-in curing. Beckemeyer, et al. (2002) observed top-down cracks occurred mostly due to excessive upward built-in curling and loss of support. Therefore, reducing joint spacing might be considered for such cases.

Along with slab thickness, climate and base stiffness are other important parameters in determining JPCP joint spacing. Darter, et al. (1997) recommended maximum joint spacing values for different climatic regions based on various modulus of subgrade reaction (k) and slab thickness values (Figure 1). As can be seen in Figure 1, as slab thickness increases, recommended maximum joint spacing generally increases. Note that the highest recommended maximum joint spacing values were reported for the pavement sections located in wet-freeze/dry freeze climatic regions compared to the ones located in dry-nonfreeze and wet-nonfreeze climatic regions. It can be also seen in Figure 1 that, as subgrade stiffness values increase, maximum recommended joint spacing values decrease.

This is because, as pavement foundation gets stiffer, curling stresses on slab increase, so maximum joint spacing should be reduced to prevent transverse cracking and transverse joint faulting. FHWA (1990) also highlights that there is a relationship between joint spacing and radius of relative stiffness (l), a parameter relating stiffness of slab to pavement foundation. It recommends the ratio between joint spacing and radius of relative stiffness (L/l) not to exceed “5” to limit transverse cracking.

ACI (2002) also recommends L/*l* to be less than “4.4”. This is because as stiffness of pavement foundation increases, curling stresses on slab also increase, so joint spacing should be limited accordingly.

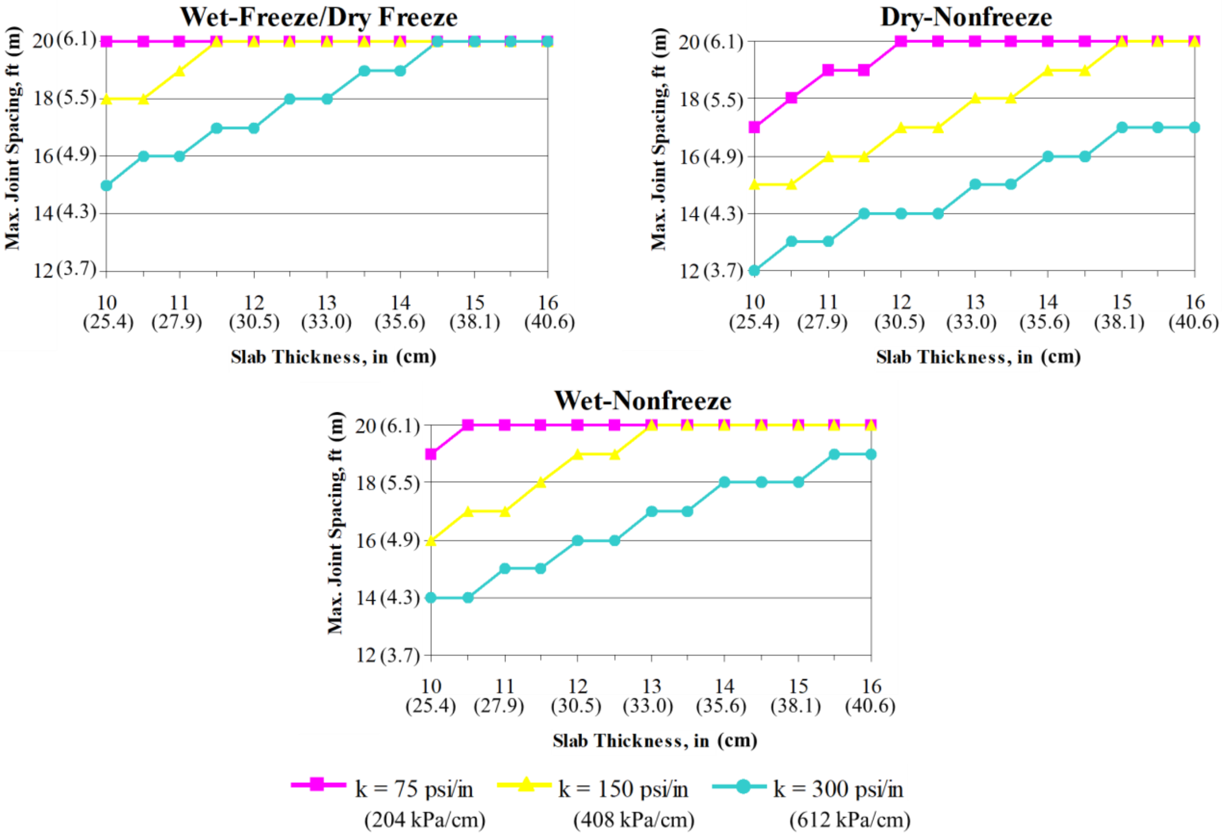


Figure 1. Recommended maximum JPCP joint spacings based on climatic region, base type, and slab thickness (adapted from Darter. et al., 1997).

FHWA (2019) recommends that joint spacing should not exceed 19 to 24 times the slab thickness to prevent uncontrolled slab cracking. ACPA (2019) and FHWA (2019) also recommend that aspect ratio of concrete slabs (ratio between slab length and slab width) should not exceed “1.5”.

Darter, et al. (2006) demonstrated that joint spacing has a significant impact on transverse cracking of JPCP by comparing performance of two road sections (each road section includes concrete slabs with various joint spacings) in terms of percent-slabs-cracked, one in Minnesota and the other one in Michigan (each of these sections has 8 in (20.3 cm) slab thickness). They found that after 10-years of service for the Minnesota section and 15-years of service for the Michigan section, as joint spacing increases, observed percent slabs cracked values significantly increase, rate of increase is the highest in joint spacing between 6.0 and 7.0 m. Around the joint spacing of 9.0 m, cracking curve starts to level-off, where around 21% of all slabs in the Minnesota section and 15% of all slabs in the Michigan section crack after corresponding service years.

2.2. *Transverse joint spacing in pavement design methodologies*

In the AASHO Road Tests, joint spacing was not examined and varied: For JPCP, a 15 ft (4.6 m) joint spacing with no reinforcement steel (JPCP); and for jointed reinforced concrete pavement (JRCP), a 40 ft (12.2 m) joint spacing with mild reinforcement were used (AASHTO, 1993). In 1993 AASHTO Rigid Pavement Structural Design Methodology (AASHTO, 1993), joint spacing is not a direct input in JPCP structural design, but the design methodology is only providing some general guidelines in terms of joint spacing design: ‘The joint spacing (in feet) for plain concrete pavements should not greatly exceed twice the slab thickness (in inches)' and 'As a general guideline that the ratio of slab width to length should not exceed 1.25' (AASHTO, 1993). A supplement to AASHTO (1993) was released in 1998 (AASHTO, 1998) based on the findings of NCHRP Project 1-30 report (NCHRP, 1994), where design charts are used to determine slab thickness for various joint spacing values along with other parameters.

In AASHTO mechanistic-empirical pavement design guide (MEPDG)/AASHTOWare Pavement ME Design (the latest name of MEPDG), joint spacing is a direct input in JPCP structural design (NCHRP, 2004). In NCHRP 1-47 report (NCHRP, 2011), cracking and faulting predictions of MEPDG were found to be very sensitive to joint spacing.

3. US State practices survey on joint spacing

A survey was conducted in October 2018 by the author of this paper and Iowa Concrete Paving Association (ICPA) of ACPA Chapter/State Association representatives for their agency designs/best practices related to joint spacing. They were asked to answer the following question: "What typical transverse joint spacing is used on interstates and divided highways? 26 ACPA Chapter/State Association representatives responded to the survey question: Alabama (AL), Arkansas (AR), Colorado (CO), Delaware (DE), Florida (FL), Idaho (ID), Illinois (IL), Indiana (IN), Kansas (KS), Kentucky (KY), Louisiana (LA), Maryland (MD), Michigan (MI), Minnesota (MN), Missouri (MO), New York (NY), North Carolina (NC), Ohio (OH), Oklahoma (OK), Pennsylvania (PA), South Carolina (SC), South Dakota (SD), Virginia (VA), Washington (WA), West Virginia (WV), Wisconsin (WI). Responses to the joint spacing survey were summarized in Figure 2. As can be seen in Figure 2, 22 out of 26 (85%) responders stated that their agency designs/best practices related to joint spacing is using a 15 ft (4.6 m) joint spacing. Among the responders:

- South Dakota representative stated that joint spacing in South Dakota is determined depending on slab thickness: for the slab thicknesses of 10 in (25.4 cm) and above (typical slab thickness for divided highways), a 20 ft (6.1 m) of joint spacing for concrete slabs made of limestone aggregate and a 15 ft (4.6 m) of joint spacing for concrete slabs made of quartzite are used. The representative also stated that current design is quite new as joint spacing was 20 ft (6.1 m) for all concrete pavement designs not so long ago. The representative further stated that joint spacing was recently shortened in South Dakota due to curling issues with the quartzite.
- Pennsylvania representative stated that, since 2004, non-skewed transverse joints with a 15 ft (4.6 m) joint spacing has been the common practice in Pennsylvania. However, from about 2000 to 2004, non-skewed transverse joints with a 20 ft (6.1 m) joint spacing were used. Prior to 2000, skewed joints with a 20 ft (6.1 m) joint spacing had been used.
- Indiana representative stated that typical joint spacing for Indiana used to be 20 ft (6.1 m). As Indiana moved to MEPDG designs and optimizing pavement thickness design, joint spacing became 15-16 ft (4.6-4.9 m) in Indiana.
- Michigan representative stated that joint spacing in Michigan is determined based on slab thickness: (1) for slab thicknesses from 6.0 in to 8.75 in (15.2 cm to 22.2 cm), a 12 ft (3.7 m) joint spacing; (2) for slab thicknesses from 9.0 in to 11.75 in (22.9 cm to 29.8 cm), a 14 ft (4.3 m) joint spacing; and (3) for slab thicknesses above 12 in (30.5 cm), a 16 ft (4.9 m) joint spacing are used.
- South Carolina representative stated that South Carolina has been using a 15 ft (4.6 m) joint spacing for the last 20 years. Prior to mid-1990s, South Carolina had been using 20 ft (6.1 m), 25 ft (7.6 m) and 30 ft (9.1 m) joint spacings.

Overall, there seems to be a general trend among state highway agencies (SHA) in USA that most of them are currently using a 15 ft (4.6 m) joint spacing and some of the SHAs previously using longer joint spacing than 15 ft (4.6 m) started reducing their joint spacing designs to proximity of 15 ft (4.6 m).

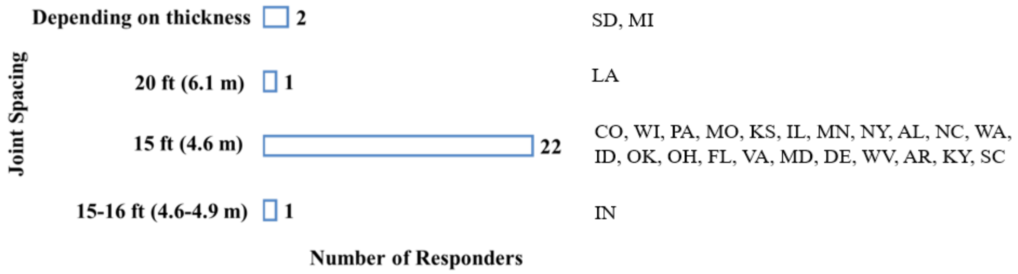


Figure 2. Distribution of joint spacing survey responses.

4. Effect of joint spacing on pavement performance – LTPP data analysis

Long-Term Pavement Performance Program (LTPP) was created as part of the Strategic Highway Research Program (SHRP) in 1987 and has been managed by FHWA since 1992. The creation of this program was to study performance of pavements and understand the mechanisms behind the performance of pavements based on field data. Under LTPP, data for 2,509 pavement sections throughout US and Canada have been collected since 1989. The collected data have been made available to public via the Web through the data portal system, LTPP InfoPave, in 2014 (FHWA, 2015).

In this part of the paper, effect of joint spacing on pavement performance was evaluated based on field data obtained from LTPP InfoPave. Performance of pavement sections with very similar structural designs, annual average daily truck traffic (AADTT) values, climatic regions but having different joint spacings were evaluated. Details related to the selected pavement sections and their performance changes over time were presented.

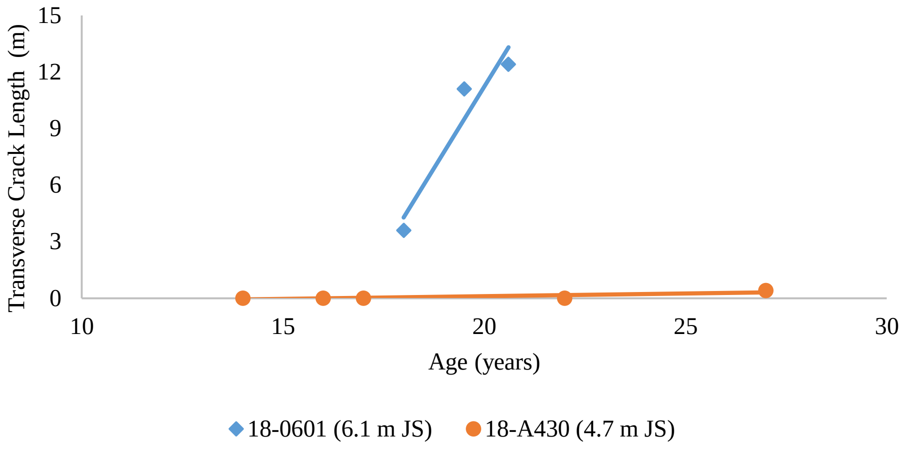
4.1. Indiana JPCP sections

Performance of two JPCP sections in the State of Indiana were compared here. Detailed information regarding location, structural design, climatic and traffic information of these pavement sections are presented in Table 1. As shown in Table 1, these pavement sections are located in the same climatic region; they have very similar structural designs (one having 10 in (25.4) and the other one having 10.3 in (26.2 cm) slab thickness; slabs are laying on a bound treated base with the same thickness); they have very similar traffic conditions (Table 1). However, joint spacing of these pavement sections differs: The section with the section ID of 18-0601 has a joint spacing of 20 ft (6.1 m); while the section with the section ID of 18-A430 has an average joint spacing of 15.5 ft (4.7 m).

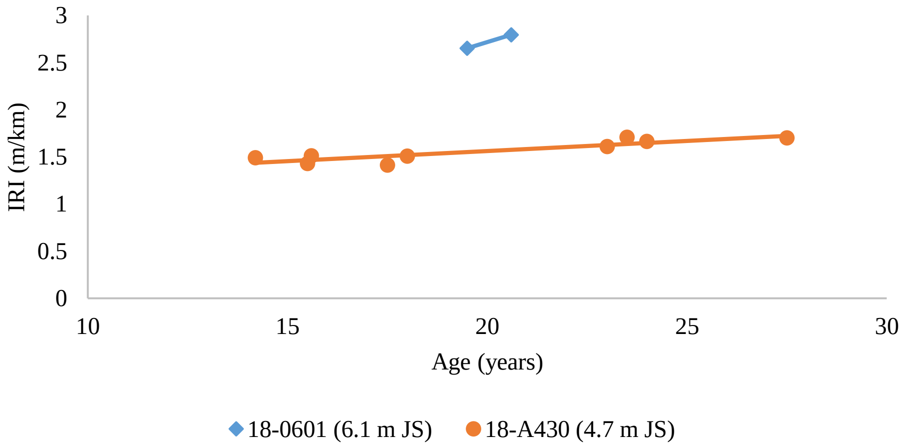
Table 1. Information of two Indiana JPCP sections.

Section ID	18-0601	18-A430
Location	Marshall County, US-31, Northbound	Posey County, State-62, Westbound
Number of lanes	2	2
Climatic zone	Wet, freeze	Wet, freeze
Structure Information	• A PCC layer, thickness, 10 in (25.4 cm) • A bound treated base, thickness, 4 in. (10.2 cm) laying on subgrade	• A PCC layer, thickness, 10.3 in (26.2 cm) • A bound treated base, thickness, 4 in. (10.2 cm) laying on subgrade
Joint Spacing	20 ft (6.1 m)	15.5 ft (4.7 m)
Date of construction	January 1972	July 1977
AADTT	924 (Average AADTT of 20 years of service)	926 (Average AADTT of 29 years of service)

Performance changes of these two JPCP sections over the time are presented in Figure 3 in terms of (a) transverse cracking length, and (b) international roughness index (IRI). As can be seen in Figure 3a, the pavement section with a 20 ft (6.1 m) joint spacing (18-0601) exhibits significantly higher level of transverse cracking (as high as 12.4 m) compared to the pavement section with a 15.5 ft (4.7 m) joint spacing (18-A430). This is an expected result because as joint spacing increases, risk for transverse cracking also increases in JPCP. Similarly, the pavement section with a 20 ft (6.1 m) joint spacing (18-0601) exhibits significantly higher level of IRI compared to the pavement section with a 15.5 ft (4.7 m) joint spacing (18-A430) (Figure 3b). This result is also expected as higher surface distresses as well as higher level of curling and warping cause concrete slabs to produce rougher surfaces.



(a) Transverse crack length



(b) IRI

Figure 3. Performance comparisons of pavement sections with 20 ft (6.1 m) joint spacing (18-0601) and 15.5 ft (4.7 m) joint spacing (18-A430) in terms of (a) transverse cracking length, and (b) international roughness index (IRI).

4.2. South Dakota JPCP sections

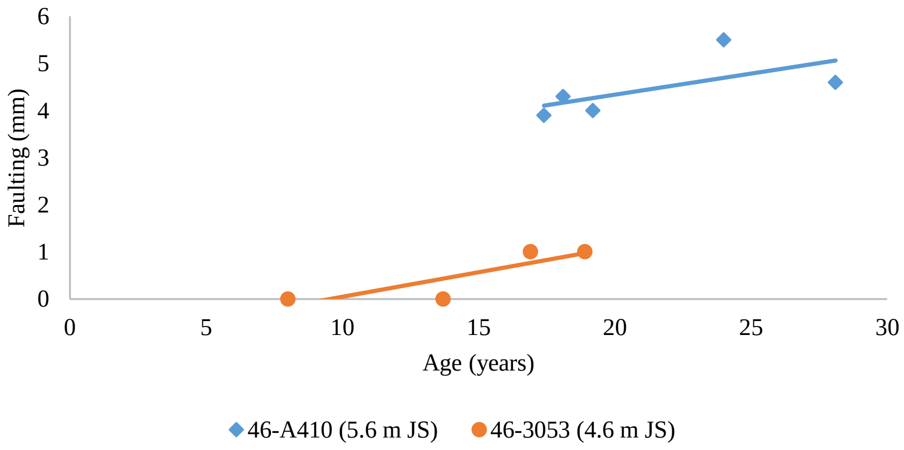
Performance of two JPCP sections with two different joint spacings in the State of South Dakota were compared here. Detailed information regarding location, structural design, climatic and traffic information of these pavement sections are presented in Table 2. As shown in Table 2, these pavement sections are in the same climatic region; they have very similar structural designs and traffic conditions (Table 2). However, joint spacings of these pavement sections differs: The section with the section ID of 46-A410 has a joint spacing of 18.5 ft (5.6 m); while the section with the section ID of 46-3053 has an average joint spacing of 15 ft (4.6 m).

Table 2. Information of two South Dakota JPCP sections.

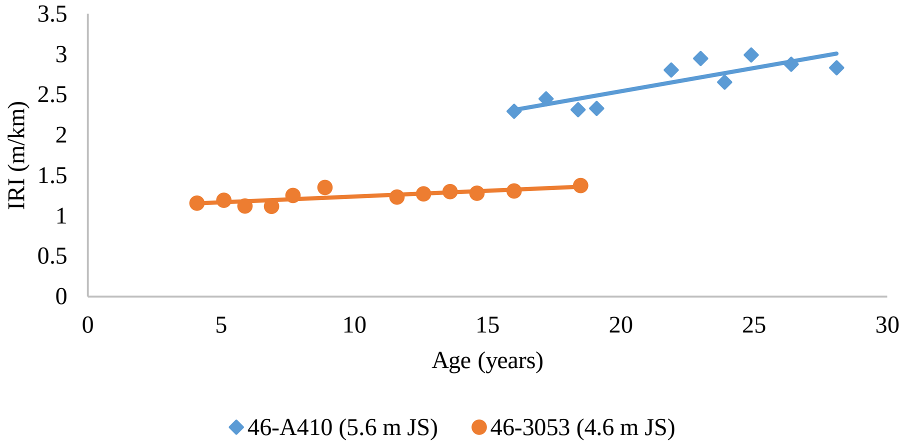
Section ID	46-A410	46-3053
Location	Clay County, State-50, Eastbound	Pennington County, U. S.-16, East-bound
Number of lanes	2	1
Climatic zone	Wet, freeze	Wet, freeze
Structure information	• A PCC layer, thickness, 8 in (20.3 cm) • A granular base, thickness, 3 in. (7.6 cm) laying on sub-grade	• A PCC layer, thickness, 8.2 in (20.8 cm) • A granular base, thickness, 1.3 in. (3.3 cm) laying on sub-grade
Joint spacing	18.5 ft (5.6 m)	15 ft (4.6 m)
Date of construction	June 1975	October 1985
AADTT	213 (Average AADTT of 25 years of service)	171 (Average AADTT of 25 years of service)

Performance changes of South Dakota JPCP sections with different joint spacings over the time are presented in Figure 4 in terms of (a) transverse joint faulting, (b) IRI and (c) load transfer efficiency (LTE) of transverse joints. Similar to the results of earlier-presented Indiana JPCP sections, as joint spacing of the presented South Dakota JPCP sections increases, higher level of transverse joint faulting and IRI are observed (Figure 4).

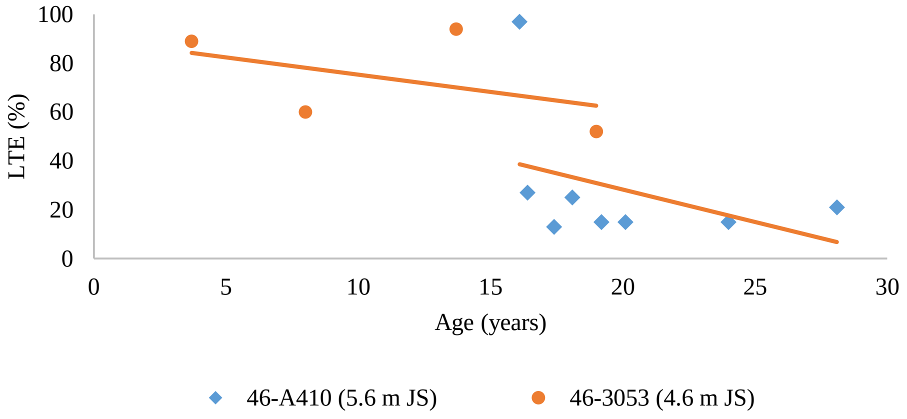
Load is transferred from one slab to another through joints. Load transfer capabilities of joints are quantified by LTE values. LTE is commonly calculated as the ratio of deflections on leave and approach slabs. LTE could also be calculated based on stress or strain ratios but use of deflection in the calculation of LTE is more common because deflections in concrete slabs can be easily measured. As part of LTPP, JPCP sections are tested time to time by the falling weight deflectometer (FWD) and LTE values of transverse joints in these sections are calculated using the deflections measured by FWD equipment. Figure 4c compares calculated LTE values of transverse joints in the selected sections. As shown in Figure 4c, the pavement section with a 5.6 m joint spacing (46-A410) have significantly lower LTE values compared to the pavement section with a 4.6 m joint spacing (46-3053). Higher LTE values mean higher level of load transfer between adjacent slabs. Transverse joints with lower LTE values have higher risk for concrete slabs to exhibit faulting and transverse cracking (NCHRP, 2004).



(a) Transverse joint faulting.



(b) IRI



(c) LTE

Figure 4. Performance comparisons of pavement sections with an 18.5 ft (5.6 m) joint spacing (46-A410) and a 15 ft (4.6 m) joint spacing (46-3053) in terms of (a) transverse joint faulting, (b) IRI and (c) LTE of transverse joints.

5. Economic analysis of transverse joint spacing

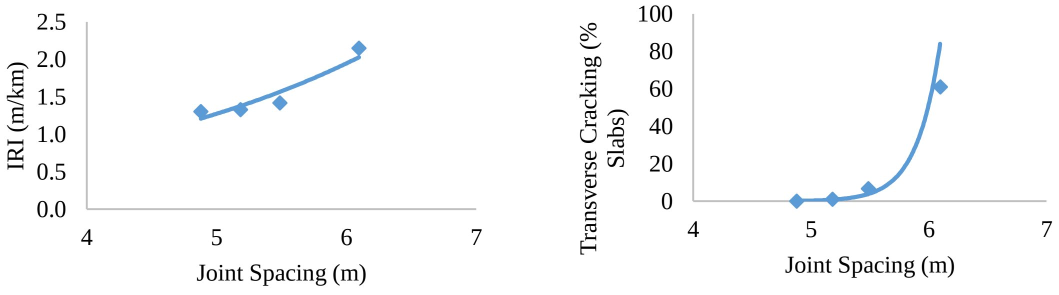
To evaluate the effect of transverse joint spacing on JPCP construction, maintenance and rehabilitation costs, an economic analysis was carried out. First, a JPCP section with various transverse joint spacing scenarios (all inputs are the same for all scenarios except for joint spacing) was analyzed using AASHTOWare Pavement ME Design software (version 2.5.3) to obtain performance predictions of these pavement design scenarios. Then, construction, maintenance and rehabilitation cost estimations considering various joint spacing and performance predictions were evaluated.

In AASHTOWare Pavement ME Design runs, a JPCP section located in Montgomery, Alabama was chosen. Other input parameters related to design are as follows:

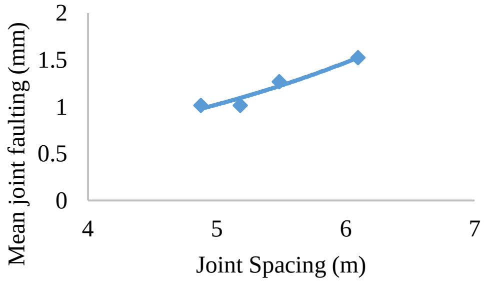
- General information: Design life: 20 years; Pavement construction month: July/2019; Traffic opening month: August/2019; Initial IRI: 63 in/mile (0.99 m/km)

- Traffic information: Initial two-way AADTT:5,000; Number of lanes in design direction:2; Percent of trucks in design direction: 50%; Percent of trucks in design lane: 95%; Operating speed: 60 mph (96 kmh)
- Pavement structure and material-related information: Pavement layers: 3-layers (JPCP/Non-stabilized base/Subgrade):
    - JPCP thickness: 10 in (25.4 cm)
    - Non-stabilized base thickness: 8 in (20.3 cm) (Type of granular base material: A-1-a)
    - Subgrade thickness: Semi-infinite (Type of subgrade material: A-6)
    - Transverse Joint Spacing: Various
    - Dowel diameter: 1.25 in (3.2 cm)

For other input parameters, AASHTOWare Pavement ME Design defaults were used. For calibration coefficients, national defaults were used. Performance predictions of AASHTOWare Pavement ME Design for various joint spacing cases at 50% reliability are presented for the following performance criteria: a) IRI, b) transverse cracking (percent slabs) and c) mean joint faulting (Figure 5). As can be seen in Figure 5, as joint spacing increases; transverse cracking predictions increase significantly especially after use of a 18 ft (5.5 m) joint spacing: while using a 20 ft (6.1 m) joint spacing, transverse cracking predictions were as high as 61%. IRI and faulting predictions also increase as joint spacing increases, although the increase rate for these performance indicators was not as high as the one for transverse cracking (Figure 5).



(a) IRI (b) transverse cracking (percent slabs)



(c) mean joint faulting

Figure 5. Performance predictions of AASHTOWare Pavement ME Design for various joint spacing cases in terms of a) IRI, b) transverse cracking (percent slabs) and mean joint faulting.

An economic analysis was carried out considering construction, maintenance and rehabilitation costs of a two-lane (12 ft (3.66 m) wide) one-mile-long (1.61 km) JPCP road section with various joint spacings. Considered JPCP road section has a slab thickness of 10 in (25.4 cm), laying on a non-stabilized base (8 in (20.3 cm) thickness), laying on a subgrade (the same inputs used in AASHTOWare Pavement ME Design runs). In the economic analysis, only agency costs were considered; user costs are not considered; and estimations of construction, maintenance and rehabilitation costs were derived from TxDOT (2012) report. One of the reasons that cost estimations from TxDOT (2012) report are used is that Texas is located near

Alabama, where AASHTOWare Pavement ME Design runs were carried out for, so cost of materials, labor and equipment should be similar in both cases. Cost estimations of some of the items used in this study were summarized below:

- Items related to construction cost:

Coarse aggregate for concrete: \$22.65/ton; concrete without coarse aggregate: \$45/cubic-yard (\$59/cubic-meter); dowel bars: \$11.25/each; saw-cutting: \$4.96/lane-feet (\$16.27/lane-meter); joint clean and seal: \$1.97/lane-feet (\$6.46/lane-meter); steel reinforcement (#5, #6, tie bars): \$2,125/ton; labour, equipment & overhead: \$15.30/square-yard (\$18.30/square meter)

- Items related to maintenance and rehabilitation:

Routine maintenance (crack clean and seal): \$1.97/lane-feet (\$6.46/lane-meter)
Full-depth repair: \$157.41/square-yard (188.26/square-meter)

Construction cost of JPCP sections varies as joint spacing varies. As joint spacing increases, number of joints in a one-mile-long (1.6 km) JPCP section decreases. Table 3 compares number of joints in a one-mile-long (1.6 km) road section for different joint spacings. As can be seen in Table 3, number of joints increase by 33% when a joint spacing of 15 ft (4.6 m) is used compared to when a joint spacing of 20 ft (6.1 m) is used. As joint spacing increases, construction cost of the pavement decreases. This is because, number of dowel-bars, saw-cutting, joint sealing and amount of labor and equipment required for the construction of JPCP decrease as number of joints decreases. It was found out in this study that construction cost decreases by 4.89% if a 20 ft (6.1 m) joint spacing is used compared to the case if a 15 ft (4.6 m) joint spacing is used.

Table 3. Number of joints for different joint spacings.

Joint Spacing	15 ft (4.6 m)	16 ft (4.9 m)	17 ft (5.2 m)	20 ft (6.1 m)
Number of Joints (per mile) (1.6 km)	352	330	311	264
% Change in Number of Joints	33	25	18	0

The economic analysis was carried out for an analysis period of 20 years. It was assumed that there would be three major stages of spending during this 20 year of analysis period: construction cost will be used as initial cost at year zero; a routine maintenance cost (crack clean and seal) at year 10; and a rehabilitation cost at year 20. In the calculation of the routine maintenance cost, it was assumed that number of cracked slabs estimated from transverse cracking predictions of AASHTOWare Pavement ME Design software at year 10 will be cleaned and sealed. AASHTOWare Pavement ME Design produces transverse cracking predictions in terms of percent-slabs-cracked; however, unit cost for crack clean and seal is provided by TxDOT (2012) in terms of lane-feet. Equation 1 is used to convert transverse cracking predictions unit form percent slabs-cracked to lane-feet:

$$TC_{lane-feet} = TC_{\%-slabs-cracked} \times \frac{12\times5280}{Joint\ Spacing*100} \qquad (1)$$

where,
$TC_{lane-feet}$ = transverse cracking (lane-feet)
$TC_{\%-slabs-cracked}$= transverse cracking (percent-slabs-cracked)
Joints spacing = joint spacing (feet)

In the calculation of the rehabilitation cost, two scenarios were considered:

- Rehabilitation scenario 1: 5% of the cracked slabs based on AASHTOWare Pavement ME Design transverse cracking predictions at year 20 (Figure 6) will be rehabilitated using full-depth repair and the rest of the cracks will be cleaned and sealed
- Rehabilitation scenario 2: 10% of the cracked slabs based on AASHTOWare Pavement ME Design transverse cracking predictions at year 20 (Figure 6) will be rehabilitated using full-depth repair and the rest of the cracks will be cleaned and sealed

Once all cost calculations were finished, net present values (NPV) of JPCP section scenarios with various joint spacings were calculated for comparisons. In the calculation of NPV values, a discount rate of 7% was used based on US Office of Management and Budget (OMB) Circular No. A-94 (Darman, 1992). Figure 6 compares NPV estimations of constructions costs, option 1 (sum of NPV values of construction, routine maintenance and rehabilitation scenario 1) and option 2 (sum of NPV values of construction, routine maintenance and rehabilitation scenario 2) for JPCP sections with various joint spacings. As can be seen in Figure 6, as stated earlier, as joint spacing increases, construction cost also decreases. Furthermore, as joint spacing increase, NPV values of both option 1 and option 2 decrease until around a joint spacing value of 5.5 m, then increase.

This might be because, AASHTOWare Pavement ME Design transverse cracking predictions significantly increase after a joint spacing of 5.5 m (Figure 5) so required routine maintenance and rehabilitation costs also increase. Therefore, as recommended by FHWA (FHWA, 1998), while designing a JPCP section, not only construction cost but also maintenance and rehabilitation costs during the design life of a pavement section should be considered.

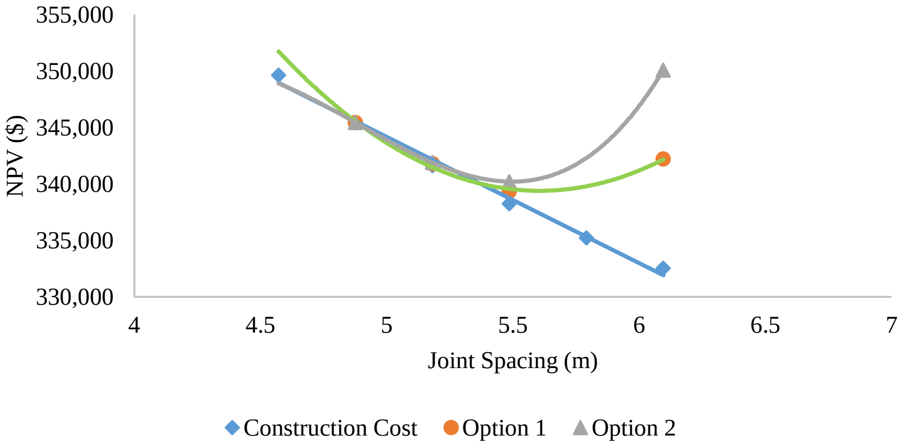


Figure 6. NPV estimations of construction cost, option 1 and option 2.

6. Conclusions, discussion and recommendations

In this study, a comprehensive evaluation of transverse joint spacing in JPCP was carried out.

First, guidelines and rule-of-thumbs in determining joint spacing in JPCP based on previous studies, FHWA and ACPA recommendations were summarized as follows:

1. JPCP with thinner slabs, higher level of temperature gradient and CTE have higher level of curling stresses so as higher potential for transverse cracking. Therefore, joint spacing could be reduced for such pavement sections to reduce transverse cracking risk.
2. Slabs sitting on a stiffer foundation experience higher level of curling stresses compared to less stiff foundations. Therefore, as pavement foundation gets stiffer, maximum recommended joint spacing values decrease.
3. FHWA (1990) found a relationship between joint spacing (L) and radius of relative stiffness (*l*). FHWA (1990) and ACI (2002) recommend L/*l* ratio not to exceed “5” and “4.4”, respectively, to limit transverse cracking. FHWA (2019) also recommends that joint spacing should not exceed 19 to 24 times the slab thickness (non-dimensionally) to prevent uncontrolled slab cracking. Moreover, ACPA (2019) and FHWA (2019) recommend that aspect ratio of concrete slabs (ratio between slab length and slab width) should not exceed “1.5”.

Reviewing empirical and M-E pavement design methodologies, it was realized that in recent design methodologies, joint spacing has been used as an important input parameter in the structural design of JPCP, although in AASHTO 1993 and earlier design methodologies, it had not been considered in the design. In NCHRP 1-47 report (NCHRP, 2011), cracking and faulting predictions of MEPDG were found to be very sensitive to joint spacing.

As part of this paper, ACPA Chapter/State Association representatives were surveyed in October 2018 for their agency designs/best practices related to joint spacing design. 22 out of 26 (85%) responders stated that their agency designs/best practices related to joint spacing design is using a 15 ft (4.6 m) joint spacing. It was also realized based on responses that some of the SHAs previously using longer joint spacing than 15 ft (4.6 m) started reducing their joint spacing designs to proximity of 15 ft (4.6 m).

Effect of joint spacing on JPCP performance was also evaluated based on field observations obtained from LTPP InfoPave. There was a general trend in the field observations that pavement sections with longer joint spacings tend to perform worse compared to the sections with shorter joint spacings. However, it should be noticed that structural design of a pavement section is not the only parameter controlling performance of JPCP. In some cases, construction quality becomes more prominent factor for a successful product rather than structural design.

An economic analysis was also carried out to evaluate the effect of joint spacing on JPCP construction, maintenance and rehabilitation costs. It was found out in this study that construction cost decreases by 4.89% if a 20 ft (6.1 m) joint spacing is used compared to the case if a 15 ft (4.6 m) joint spacing is used. Considering sum of construction, maintenance and rehabilitation costs, total NPV significantly increases for the JPCP scenarios having joint spacing value of 5.5 m and above. This might be because, AASHTOWare Pavement ME transverse cracking predictions significantly increase after a joint spacing of 5.5 m so required routine maintenance and rehabilitation costs also increase.

Overall, it was concluded that as joint spacing increases, overall performance of JPCP tend to decrease. However, reducing joint spacing increases number of joints required in a pavement section. Increasing number of joints also increases construction cost of a pavement. Decrease in performance of a pavement also increases user-costs. Therefore, a balance between cost and performance is recommended. Based on the findings of this study, a joint spacing between 15-18 ft (4.6-5.5 m) seems to be provide a safe zone for both performance and cost effectiveness.

Conflicts of interest: The author would like to declare that the author does not have any potential conflict of interest regarding this research.

References

AASHTO. (1993). AASHTO guide for design of pavement structures. Washington, D.C., USA.

AASHTO. (1998). Supplement to the AASHTO guide for design of pavement structures. Washington, D.C., USA.

ACPA. (2019). Web Application “Max joint spacing”. http://apps.acpa.org/applibrary/MaxJointSpacing/ (Accessed:01.09.2021).

American Concrete Institute (ACI). (2002). Guide for design of jointed concrete pavements for streets and local roads (ACI 325.12R-02). Report by ACI Committee 325. American Concrete Institute. Farmington Hills, MI.

Beckemeyer, C. A., Khazanovich, L., & Yu, H. T. (2002). Determining amount of built-in curling in jointed plain concrete pavement. Transportation Research Record Journal of the Transportation Research Board 1809(1):85-92.

Darman, R. (1992). Guidelines and discount rates for benefit-cost analysis of federal programs (OMB Circular No. A-94 Revised). Office of Management and Budget, Washington, DC.

Darter, M. I., Von Quintus, H., Jiang, Y. J., Owusu-Antwi, E. B., & Killingsworth, B. M. (1997). Catalogue of recommended pavement design features (Final Report, NCHRP Project 1-32). Transportation Research Board, Washington, DC.

Darter, M. I., Mallela, J., Larson, G. E., Rao, C., Titus-Glover, L., & Khazanovich, L. (2006). Use of mechanistic-empirical procedures for design of long-life concrete pavements. Proceedings of the international conference on long-life concrete pavements, Chicago, Illinois.

FHWA. (1990). Concrete pavement joints (Technical Advisory T 5040.30). Federal Highway Administration, Washington, DC. Retrieved from: https://www.fhwa.dot.gov/pavement/t504030.cfm (Accessed:01.09.2021).

FHWA. (1998). Life-cycle cost analysis in pavement design (Technical Bulletin). Federal Highway Administration, Washington, DC. Retrieved from: (https://www.fhwa.dot.gov/infrastructure/asstmgmt/013017.pdf) (Accessed:01.09.2021).

FHWA. (2015). The long-term pavement performance program. Federal Highway Administration Washington, DC.

FHWA. (2019). Concrete pavement joints. Federal Highway Administration Washington, DC.

Grosek, J., Zuzulova, A., & Brezina, I. (2019). Effectiveness of dowels in concrete pavement. Materials (Basel, Switzerland), 12(10), 1669. doi:10.3390/ma12101669.

NCHRP. (1994). Support under Portland cement concrete pavements (NCHRP Project 1-30 report). University of Illinois, Urbana-Champaign, IL, USA.

NCHRP. (2004). Guide for mechanistic–empirical design of new and rehabilitated pavement structures. final report (NCHRP Project 1–37A). TRB, National Research Council, Washington, D.C. Retrieved from: http://trb.org/mepdg/guide.htm (Accessed:01.09.2021).

NCHRP. (2011). Sensitivity evaluation of MEPDG performance prediction. Final report, (NCHRP Project 1-47). TRB, National Research Council, Washington, D.C.

TxDOT. (2012). Optimizing concrete pavement type selection based on aggregate availability (Research project 0-6681) Texas Department of Transportation.