Controlling Cracking in Concrete Pavements Loaded with 18-Wheelers

This whitepaper details the number of fully loaded 18-wheelers that different jointed plain concrete pavement (JPCP) configurations can carry before experiencing structural fatigue cracking. It is shown that a 6" thick doweled TCPavements JPCP with 6' joint spacing can be a longer performing design than a 8" thick doweled JPCP with 15' joint spacing. Also shown is that a 6" thick undoweled TCPavements JPCP with 6' joint spacing is approximately as crack resistant as an undoweled 8" thick x 15' joint spacing or a doweled 7" thick x 15' joint spacing. Thus, dowels are shown to mechanically allow for a thickness reduction of 1" while shortening of joint spacing from 15' to 6' according to a TCPavements system design allows for a 2" thickness reduction for doweled or undoweled pavements. Also illustrated, concrete pavement performance models that only include bottom-up cracking (e.g., ACPA's StreetPave) greatly over predict load carrying capacity versus a more complete model that also includes the impact of curl and top-down cracking (e.g., TCPavements' OptiPave or AASHTOWare Pavement ME).

Response of 6’ vs. 15’ Joint Spacing to an 18-Wheeler Loaded to the Legal Limit

To investigate the crack prevention equivalence of JPCP designed with traditional 15’ joint spacing versus a TCPavements system design with 6’ joint spacing, the tractor of an 18-wheeler loaded to the legal limit (80,000 lb) was modeled on these two systems. The 6’ joint spacing TCPavements design was 6” thick while the 15’ joint spacing was modeled at both 7” and 8” thick. All three of these designs were modeled with either engineered load transfer dowel devices (e.g., PNA’s PD3 Basket Assembly and Diamond Dowel systems) with 90% load transfer efficiency (LTE) or the assumption of undoweled joints with aggregate interlock load transfer of 15% LTE. Maximum top and bottom stresses on the concrete slab were mechanistically determined using ISLAB2000 for conditions of 1) only the curl applied to the concrete pavement, 2) only the 18-wheeler being applied and no curl (e.g., flat slabs), or 3) a combination of the curl and 18-wheeler simultaneously. Results of this investigation are presented in Figure 1.

Appendix A details the derivation of the concrete slab capacity, which is shown as the red lines in Figure 1, and cracking fatigue capacity. Appendix B details the assumptions made in the mechanistic finite element analysis (FEA) conducted using ISLAB2000, with Appendix C providing the detailed output of the FEA as visually presented in Figure 1.

For the curl only scenario, top stress increases with joint spacing whereas bottom stresses are effectively zero, with most of the bottom of the slab in compression due to the curl and slab self-weight. For the 18-wheeler only (e.g., loaded on flat slabs), bottom stresses are higher than top stresses, with thicker section and the inclusion of dowels reducing stresses. Lastly, for the 18-wheeler and curl loading simultaneously, bottom stress trends are like as with the 18-wheeler only but with reduced induced stresses whereas the top stresses are now typically higher than bottom stresses and, thus, are the controlling cracking mode.

Figure 1. Top and bottom slab stress responses (blue bars) for varying JPCP configurations under curl only loading, 18-wheeler only loading, or 18-wheeler and curl loading simultaneously and the estimated top-down or bottom-up slab capacity (e.g., red lines).

Superposition of Curl Only and 18-Wheeler Only Does Not Equal 18-Wheeler + Curl

The net result of loading with the 18-wheeler and curled slabs cannot be predicted by summing stresses from curl only with those from the 18-wheeler only. Figure 2 shows the percent error in the stress prediction if such an assumption of superposition of the stresses from the top two parts of Figure 1 (CURL ONLY and 18-WHEELER ONLY) to estimate the bottom (18-WHEELER + CURL). With such high errors on these examples, it is inappropriate to simplify to a superposition; curl and loads must be modeled simultaneously with a JPCP configuration to realistically predict slab stresses to control slab cracking.

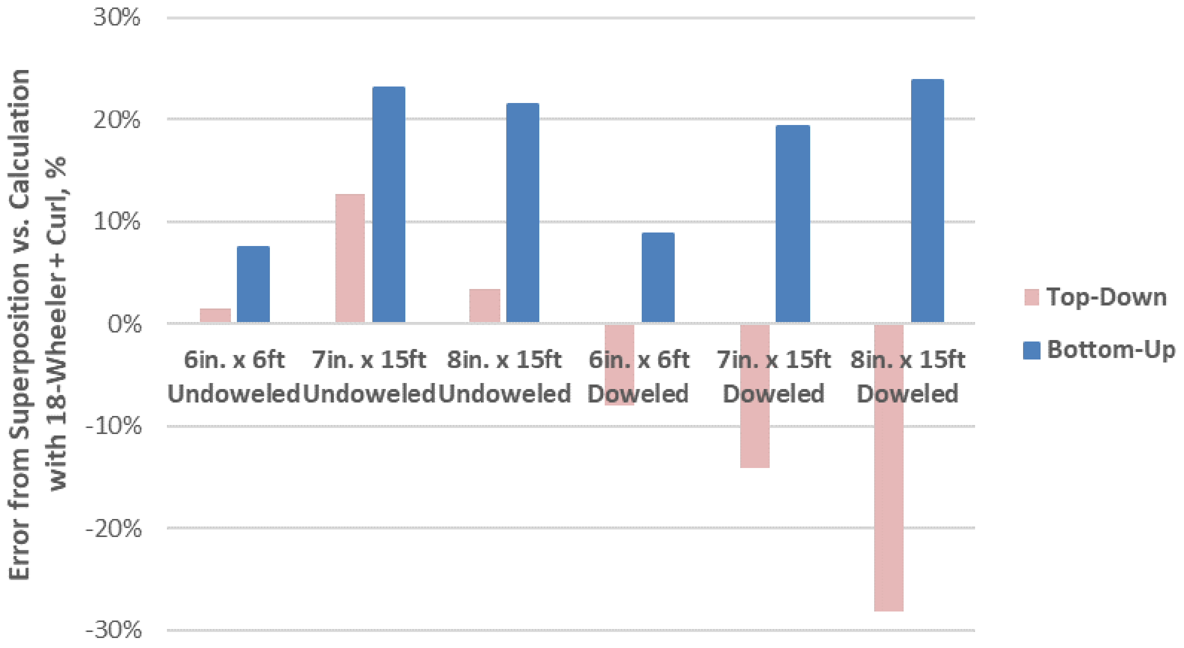

Figure 2. Error from superposition of stresses from the curl only load and 18-wheeler only load versus the stresses calculated with the 18-wheeler and curl loading simultaneously.

18-Wheelers Carried until Slab Fatigue Cracking Failure

The StreetPave fatigue equation developed by ARA can be used to estimate the total number of 18-wheelers a JPCP configuration can carry until slab fatigue cracking failure. This equation is supplemented with slab stresses as mechanically developed with ISLAB 2000 and slab capacity as estimated by a series of equations given in Appendix A.

The total number of 18-wheelers that can be carried until slab fatigue cracking failure for each JPCP configuration are shown in Figure 3. For simplicity, a design is considered infinite fatigue with a stress ratio of 0.54, allowing for over 100,000,000 repetitions, or over 9,000 18-wheelers per day for 30 years.

If 18-wheeler only loading is considered (e.g., curling is ignored), the capacity of the traditional joint spacing (e.g., 15’) is predicted to be effectively infinite, with or without the use of dowels. In reality, far fewer 18-wheelers can be carried before cracking when including curl and its interaction with loading in determining the system capacity. Thus, **the 18-wheeler capacity suggested by a JPCP model built on flat slabs is overly optimistic in practice; a more realistic model is produced by considering the 18-wheeler and curl simultaneously.**

The results from the combination loading of the 18-Wheeler + Curl also revealed that the doweled 6” x 6’ JPCP has the highest 18-wheeler carrying capacity, even exceeding the doweled 8” x 15’ JPCP. Also shown is that the value of a dowel is about 1” thickness reduction (8” x 15’ undoweled vs. 7” x 15’ doweled) and that the value of the panel size reduction from the traditional 15’ to TCPavements’ 6’ is about 2” thickness reduction (6” x 6’ undoweled vs. 8” x 15’ doweled).

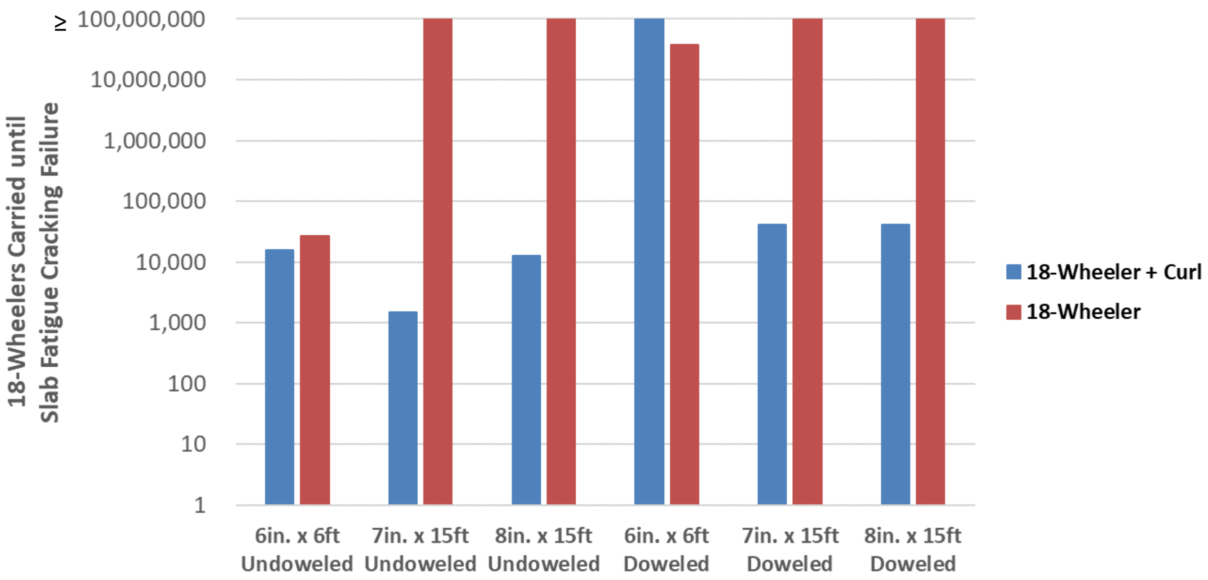

Figure 3. 18-wheelers carried until slab fatigue cracking failure when loading with just an 18-wheeler (red bars) versus an 18-wheeler and curl loading simultaneously.

Complete, Modern Design of Concrete Pavements

While this whitepaper focuses on slab fatigue cracking failures under the loading of an 18-wheeler, a more complete, modern design requires more inputs than those assumed here plus consideration for additional failure modes, including surface roughness and faulting of joints or cracks. TCPavements' OptiPave and AASHTOWare Pavement ME provide the most complete, modern concrete pavement performance predictions, including each of these potential failure modes and both bottom-up and top-down cracking. ACPA's StreetPave and pavementdesigner.org present a limited and incomplete analysis of bottom-up cracking and faulting only. More details are available in PNA's whitepaper, "Comparison of Modern Concrete Pavement Performance Predictions, Thickness Requirements, and Sensitivity to Joint Spacing."

For More Information

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Appendix A. Concrete Slab Capacity and Fatigue

The following is a simplistic approach to estimating the design 18-wheelers for the JPCP configurations modeled; software such as TCPavements' OptiPave and AASHTOWare Pavement ME undergo much more complex and field-calibrated equation sets in their effort to manage stresses to control slab cracking.

The maximum strength of a concrete slab in the field is greater than the flexural strength of an unsupported lab-cured concrete beam tested at 28-days. The slab capacity can be approximated as:

$$\sigma_{max}=(MOR_{avg}+t*MOR_{SD}) x\ F_e\ x\ C_1 x\ C_2$$

where:

- σ_{max} = allowable concrete tensile strength, psi
- MOR_{avg} = specified concrete flexural strength, psi | specified strength minimum compressive strength of 4,000 psi is approximately 474 psi flexural per the ACI 318 conversion equation
- t = standard normal deviate (z-score) | at 80% reliability on MOR tests, z-score = 0.84
- MOR_{SD} = standard deviation (SD) on concrete flexural strength, psi | coefficient of variation (COV) of ready-mixed concrete is approximately 15%, thus SD = 15% * MOR_{avg} = 71 psi
- F_e = 28-to-90 day strength correction factor | approximately (1.235*(1-COV)) = 1.05
- C_1 = beam-to-slab correction factor | 1.0 for top-down cracking and for bottom-up cracking:

  $$C_1 = 0.0086\ x\ T_{slab}^2 - 0.1997\ x\ T_{slab} + 2.3535$$

  where:

  T_{slab} = thickness of the concrete slab or pavement, in.

- C_2 = fiber factor, assumed equal to 1 for concrete without macrosynthetic or steel fibers

Thus, the slab capacity for bottom-up cracking for a 6" slab is:

$$\sigma_{max}^{bottom\text{-}up} = (474\ psi + 0.84\ x\ 71\ psi)\ x\ 1.05\ x\ 1.4649\ x\ 1.0 = 821\ psi$$

And the capacity for top-down cracking for a 6" slab is:

$$\sigma_{max}^{top\text{-}down} = (474\ psi + 0.84\ x\ 71\ psi)\ x\ 1.05\ x\ 1.0\ x\ 1.0 = 560\ psi$$

The Factor of Safety (FOS) in design against cracking is the ratio of slab capacity to maximum stress (e.g., output from ISLAB2000 analysis) under a given slab configuration and loading. A stress ratio is taken as a reciprocal of the FOS, so there is a maximum bottom-up stress ratio and a maximum top-down stress ratio. The design stress ratio is the larger of these two stress ratios because the design is operating closer to the fatigue stress limit.

The number of allowable load repetitions until slab fatigue cracking failure is modeled per Darter, et al. "Enhanced PCC Fatigue Model for StreetPave," 2004, Applied Research Associated, Inc. (ARA) as:

$$\log N = \left[\frac{-SR^{-10.24} long(1-p)}{0.0112}\right]^{0.217}$$

where:

N = number of load repetitions

SR = design stress ratio

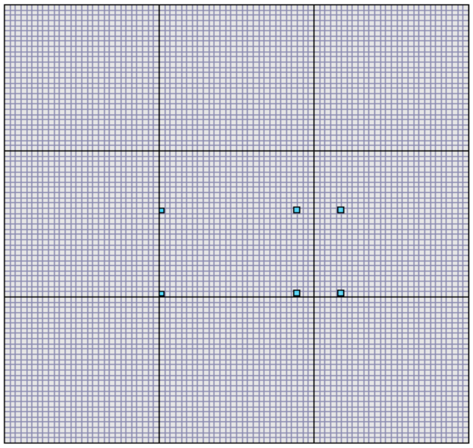
p = probability of failure, set to 50% for this paper to model average expected performance

(1 – *p*) = probability of survival

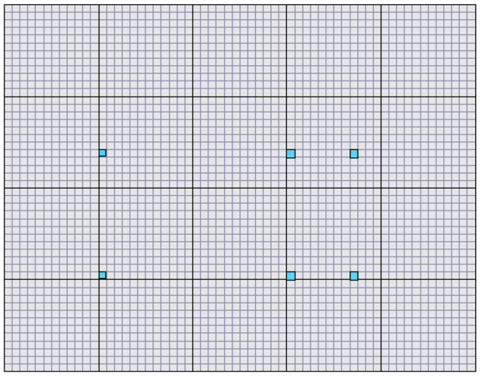
Appendix B. ISLAB Design Variables

- Slab Thickness and Joint Spacing Combinations:
  - 6” thick x 6’ joints
  - 7” thick x 15’ joints
  - 8” thick x 15’ joints
- Design Vehicle:
  - Legal Limit 18-wheeler
    - Tractor front single axle load = 16,000 lb
    - Tractor rear dual axle load = 32,000 lb
    - Trailer dual axle load = 32,000 lb
    - Total weight = 80,000 lb
    - Tire width = 10”
    - Tire pressure = 150 psi
    - Front axle width (center-to-center) = 96”
    - Rear axle width (center-to-center) = 96”
    - Spacing between wheels = 48”
- Pavement Structure:
  - Concrete materials:
    - Modulus of elasticity = 4,000,000 psi
    - Poisson’s ratio = 0.15
    - Coefficient of thermal expansion and contraction: 5.5 x 10^{-6} / °F
    - Unit weight = 150 lb/ft^3
  - Support stiffness (k-value) = 200 psi/in.
  - Joint load transfer efficiency = 90%
  - Effective build-in temperature gradient = -30°F
  - Design vehicle on an interior corner, as worst-case in an industrial pavement case:

15’ x 15’ joints with 18-Wheeler Tractor



6’ x 6’ joints with 18-Wheeler Tractor



Appendix C. Detailed Results

Slab Configuration	Max Top Stress, psi	Top-Down Capacity, psi	Top-Down Factor of Safety	Max Bottom Stress, psi	Bottom-Up Capacity, psi	Bottom-Up Factor of Safety	Max Curl, in.
CURL ONLY							
6 in. x 6 ft | 15% LTE	32.0	560.4	17.5	1.0	820.9	812.8	-0.034
7 in. x 15 ft | 15% LTE	225.8	560.4	2.5	3.2	771.7	241.2	-0.132
8 in. x 15 ft | 15% LTE	190.7	560.4	2.9	2.7	732.1	271.1	-0.123
6 in. x 6 ft | 90% LTE	32.0	560.4	17.5	1.0	820.9	812.8	-0.034
7 in. x 15 ft | 90% LTE	225.8	560.4	2.5	3.2	771.7	241.2	-0.132
8 in. x 15 ft | 90% LTE	190.7	560.4	2.9	2.7	732.1	271.1	-0.123
18-WHEELER ONLY							
6 in. x 6 ft | 15% LTE	379.0	560.4	1.5	579.0	820.9	1.4	-0.097
7 in. x 15 ft | 15% LTE	292.0	560.4	1.9	392.0	771.7	2.0	-0.046
8 in. x 15 ft | 15% LTE	232.1	560.4	2.4	304.8	732.1	2.4	-0.040
6 in. x 6 ft | 90% LTE	151.0	560.4	3.7	455.0	820.9	1.8	-0.032
7 in. x 15 ft | 90% LTE	107.4	560.4	5.2	300.0	771.7	2.6	-0.017
8 in. x 15 ft | 90% LTE	88.3	560.4	6.3	241.4	732.1	3.0	-0.015
18-WHEELER + CURL							
6 in. x 6 ft | 15% LTE	405.0	560.4	1.4	540.0	820.9	1.5	-0.123
7 in. x 15 ft | 15% LTE	459.0	560.4	1.2	321.0	771.7	2.4	-0.032
8 in. x 15 ft | 15% LTE	409.0	560.4	1.4	253.0	732.1	2.9	-0.137
6 in. x 6 ft | 90% LTE	199.0	560.4	2.8	419.0	820.9	2.0	-0.073
7 in. x 15 ft | 90% LTE	388.0	560.4	1.4	254.0	771.7	3.0	-0.040
8 in. x 15 ft | 90% LTE	388.0	560.4	1.4	197.0	732.1	3.7	-0.134
Error in FEA Response from Superposition vs. Calculation with 18-Wheeler + Curl							
6 in. x 6 ft | 15% LTE	1%			7%			7%
7 in. x 15 ft | 15% LTE	13%			23%			450%
8 in. x 15 ft | 15% LTE	3%			22%			18%
6 in. x 6 ft | 90% LTE	-8%			9%			-10%
7 in. x 15 ft | 90% LTE	-14%			19%			268%
8 in. x 15 ft | 90% LTE	-28%			24%			3%