

Effect of Nonuniform Foundation Support on Concrete Slab Responses

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Abstract

The ability to spatially map the stiffness of the foundation layers under concrete pavements with intelligent compaction has created a need to define limits on the allowable stiffness variations in a given construction area as well as the maximum size of a non-complaint area which does not require remedial action. In order to work towards this goal, a two-dimensional finite element analysis was completed to determine the effects of four nonuniform subgrade support conditions (relative to uniform support) on the tensile stresses in a concrete slab under tandem axle loading and temperature curling. The slab responses showed that certain nonuniform subgrade support conditions have a greater impact on the slab tensile stresses relative to the uniform support irrespective if the slab is experiencing curling. A soft support along the longitudinal slab edge and a subgrade with randomly assigned 9 ft² (0.84 m²) soft and stiff areas were found to decrease the slab performance relative to a uniform subgrade assumption. In the most extreme case, the nonuniform support with soft longitudinal edges had a maximum stress that was 63 percent greater than the uniform soft support. In this analysis, subgrade nonuniformities produced the potential for bottom-up or top-down fatigue cracking depending on the interaction of the axle location, temperature differential, and local support condition.

Key words: nonuniform support, concrete slab, finite element analysis, intelligent compaction, foundation layer

Introduction

Intelligent compaction (IC) technology has existed in various forms for several years. The desire for agencies to extend the performance life of pavement systems has resulted in an interest to implement IC technologies in order to more effectively and efficiently compact roadway subgrades and bases. IC works by adjusting roller drum characteristics, such as amplitude and frequency, in attempt to uniformly compact the soil (Van Hampton 2009). A National Cooperative Highway Research Program report has recently been published on IC technology (Mooney et al. 2010) but there is still significant research required to continue to advance construction specifications to incorporate IC technology. The Federal Highway Administration reports that state

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agencies in Colorado, Florida, Iowa, Michigan, Minnesota, Texas, and Wisconsin are currently investigating the possibility of implementing IC technology (FHWA 2011).

One advantage of using IC technology is the ability to rapidly find soft, weak, or nonuniform locations in the compaction area (Petersen 2005, Hossain et al. 2006, Petersen and Peterson 2006, White et al. 2006, White et al. 2007, Mooney and Rinehart 2007, Sebesta et al. 2009). Subgrade nonuniformity is an important consideration since it can cause stress concentrations in the bound pavement layers which could result in premature distresses and failures (White et al. 2005). A study by Facas et al. (2010) documented spatial anisotropy in the soil stiffness through IC roller measurements, which occurs under existing construction and earthwork handling processes. The effect of such nonuniform support conditions and/or loss of support on slab responses has undergone some study (Leonards and Harr 1959, Richart and Zia 1962, Hudson and Matlock 1966, Levey and Barenberg 1970, Barenberg et al. 1976). Levey and Barenberg (1970) found that slab responses are dependent on the statistical differences in adjacent material stiffness. They also noted that slab responses were more affected by a larger area with slightly less than average stiffness versus a small area with larger difference in stiffness.

Given that IC technology has the capability to determine the areas of nonuniformity, the objective of this initial study was to quantify if nonuniformities in the subgrade would significantly affect concrete slab stresses and deflections relative to the traditional assumption of a uniform soil support layer. The response analysis was conducted using the two-dimensional finite element program ISLAB2000 (Version 2.0).

Nonuniform Foundation Soil k-Value Experimental Design

Table 1 lists the input variables included in the finite element analysis, including six subgrade support conditions and three temperature differentials for one type of axle configuration. The following three linear temperature differentials were considered to check the sensitivity of the slab responses to nonuniform support and curling: 0°F, +20°F, and -20°F (0°C, +11°C, and -11°C). The input variables held constant in the ISLAB2000 runs are summarized in

Table 2 including the configuration for the 36-kip (16000 kg) tandem axle. The contact area for each wheel was 100 in² (645 cm²) or 10 by 10 inches (25 by 25 cm) square. The slab was idealized with plate bending elements and the subgrade with a Winkler foundation model. The slab was placed directly on the subgrade without any frictional interaction, but was allowed to separate under temperature loading. In order to minimize the number of variables (e.g., adjacent slabs or load transfer efficiency), only a single slab was considered.

Six different subgrade support conditions (cases) were considered, as shown in

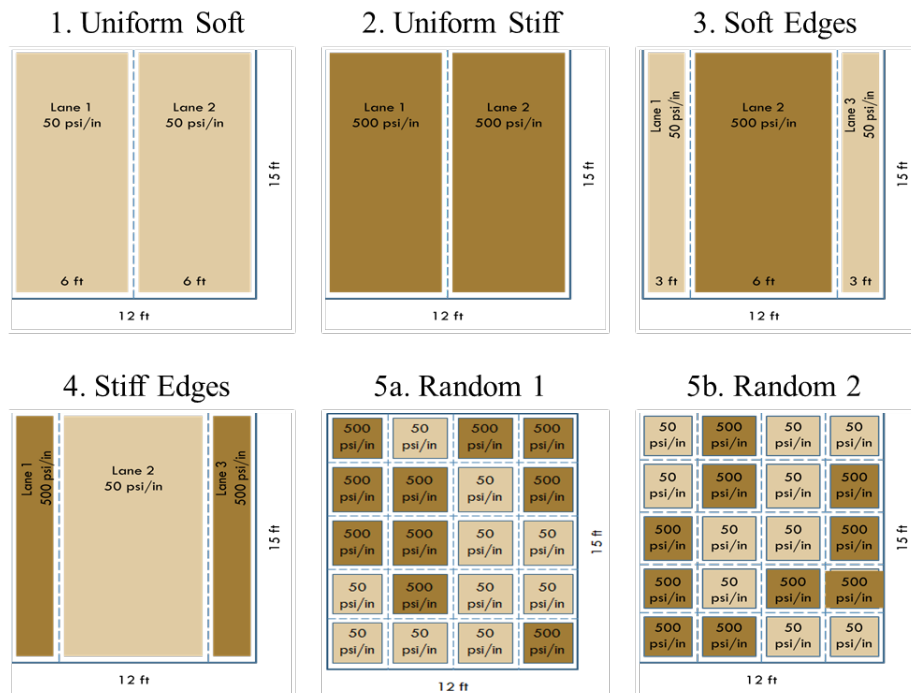


Figure 1. For each subgrade support condition, the stiffness was either soft (50 psi/in or 13.5 MPa/m) or stiff (500 psi/in or 135 MPa/m), which represented extreme soil stiffness values. There were two uniform subgrade conditions: uniform soft and uniform stiff. Two different edge support conditions were considered: one stiff with soft edges and one soft with stiff edges. The soft or stiff edges along the longitudinal edge were 3 feet (0.9 m) in width. Two additional nonuniform cases were also examined which had equal proportions of soft to stiff sections that were randomly assigned. In these random cases, each 3 by 3 foot (0.9 by 0.9 m) area was defined by a uniform k-value.

For each subgrade support condition and temperature differential, the tandem axle was moved in 10 inch (25 cm) increments from the transverse edge to the middle of the slab (called mid-slab edge) with zero offset from the longitudinal edge, as illustrated in Figure 2 for a single axle. Table 1 lists the locations of the tandem axle as it was moved along the slab. However, for a single slab analysis, the load center cannot be placed directly on the transverse edge, so the first loading location is at 5 inches (13 cm) from the joint. At each axle position, the maximum principal stress (tensile), stress spatial location (x,y,z), and maximum deflection were recorded.

Table 1. Input Variables for Finite Element Analysis

Subgrade Support Condition	Uniform soft; uniform stiff; soft edges; stiff edges; and two random distributions (Soft = 50 or Stiff = 500 psi/in; 13.5 MPa/m or 135 MPa/m)
Axle Configuration	Tandem (36 kip; 16000 kg)
Axle Location	10-inch (25-cm) increments from transverse edge to mid-slab edge
Temperature Differential	-20, 0, 20 °F (-11, 0, 11°C)

Table 2. Fixed Inputs for Finite Element Analysis

Slab Size	12x15ft (144x180 in)	3.7x4.6 m
Slab Thickness	8 in	20 cm
Elastic Modulus	4.00×10^6 psi	27.5 GPa
Poisson Ratio	0.15	0.15
Coefficient of Thermal Expansion	$5.5 \times 10^{-6}/^{\circ}\text{F}$	$9.9 \times 10^{-6}/^{\circ}\text{C}$
Unit Weight	0.087 pci	2410 kg/m ³
Tire Pressure	90 psi	620 kPa
Tire Contact Aspect Ratio	1	1
Element Mesh Size	2x2 in ²	5x5 cm ²
Wheel Spacing	96 in (8 ft)	244 cm
Axle Spacing (Tandem Axle)	48 in (4 ft)	122 cm

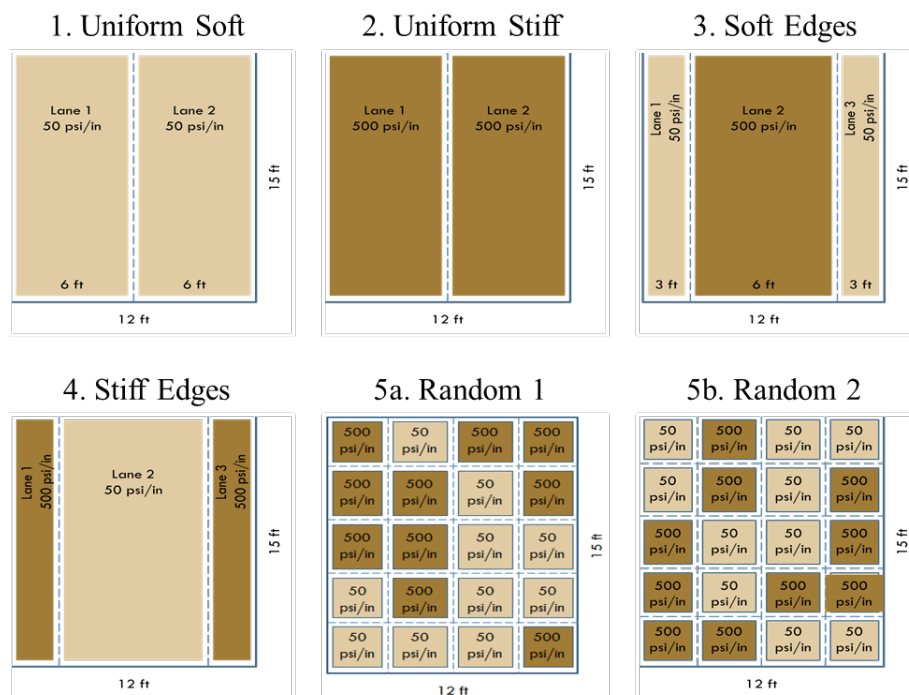


Figure 1. Six subgrade support conditions analyzed with ISLAB2000. The soft or stiff edges were 3 feet (0.9 m) in width. Random cases were 3 by 3 feet (0.9 by 0.9 m). The tandem axle traversed from bottom-right corner and moved along the longitudinal edge until the mid-slab edge at 7.5 feet (2.3 m).

Conversions: 50 psi/in = 13.5 MPa/m, 500 psi/in = 135 MPa/m, 1 ft = 0.3 m.

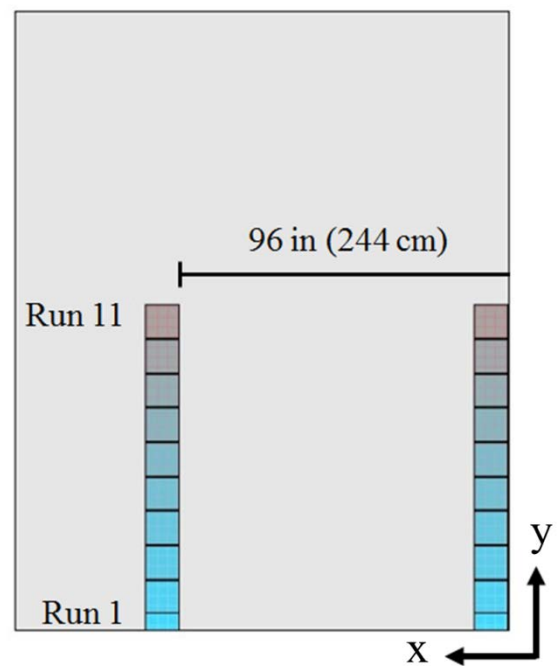


Figure 2. Rear axle (illustrated as a single axle) moved in 10-inch (25-cm) increments from the transverse edge to the mid-slab edge. The first position was at a 5-inch (13 cm) offset from the transverse edge. The transverse edge is the x-axis and the longitudinal edge is the y-axis.

Table 3. Tandem Axle Locations Along the Slab Longitudinal Edge

Run Number	Rear Axle Wheel Center Location (X,Y)*	Front Axle Wheel Center Location (X,Y)*
1	(0,5)	(0,53)
2	(0,10)	(0,58)
3	(0,20)	(0,68)
4	(0,30)	(0,78)
5	(0,40)	(0,88)
6	(0,42)	(0,90)
7	(0,50)	(0,98)
8	(0,60)	(0,108)
9	(0,70)	(0,118)
10	(0,80)	(0,128)
11	(0,90)	(0,138)

*Relative to the longitudinal slab edge

Results and Discussion

Cases Without Temperature Curling The maximum tensile stress for each tandem axle position along the longitudinal edge was recorded from the transverse edge to the mid-slab edge, as seen in Figure 2, for the no temperature differential case. Subgrade Case 3 (Soft Edges) produced the highest tensile stress, which occurred at the top of the slab with the axle at the transverse edge location. The stresses for Case 3 diminish as the tandem axle was moved toward the mid-slab edge. Case 5a (Random 1) has the

greatest tensile stresses near the mid-slab load location followed closely by Case 1 (Uniform Soft).

Without curling, Case 2 (Uniform Stiff) produced low tensile stresses throughout the tandem axle movement, demonstrating that a uniform subgrade support with proper stiffness can result in low slab stresses. Case 4 (Stiff Edges) also resulted in relatively low tensile stresses except at the transverse edge load position. Case 5b (Random 2) also resulted in very low tensile stresses as the tandem axle moved towards the interior of the slab. The extreme difference in behavior for Cases 5a and 5b demonstrates that random nonuniformities could be detrimental (Case 5a) or have limited effect on the slab (Case 5b). Overall, construction processes that limit the size of random nonuniformities in the foundation layer could significantly lower the risk of premature failures.

Most of the maximum tensile stresses for the no curling condition occurred at the bottom of the slab except for near the transverse edge load position where almost all cases produced tensile stresses at the top of the slab. The maximum tensile stresses increased 34 percent and 9 percent for Cases 3 and 5a, respectively, relative to the uniform soft soil (Case 1), and the increases were 88 percent and 53 percent for Cases 3 and 5a, respectively, relative to the uniform stiff soil (Case 2).

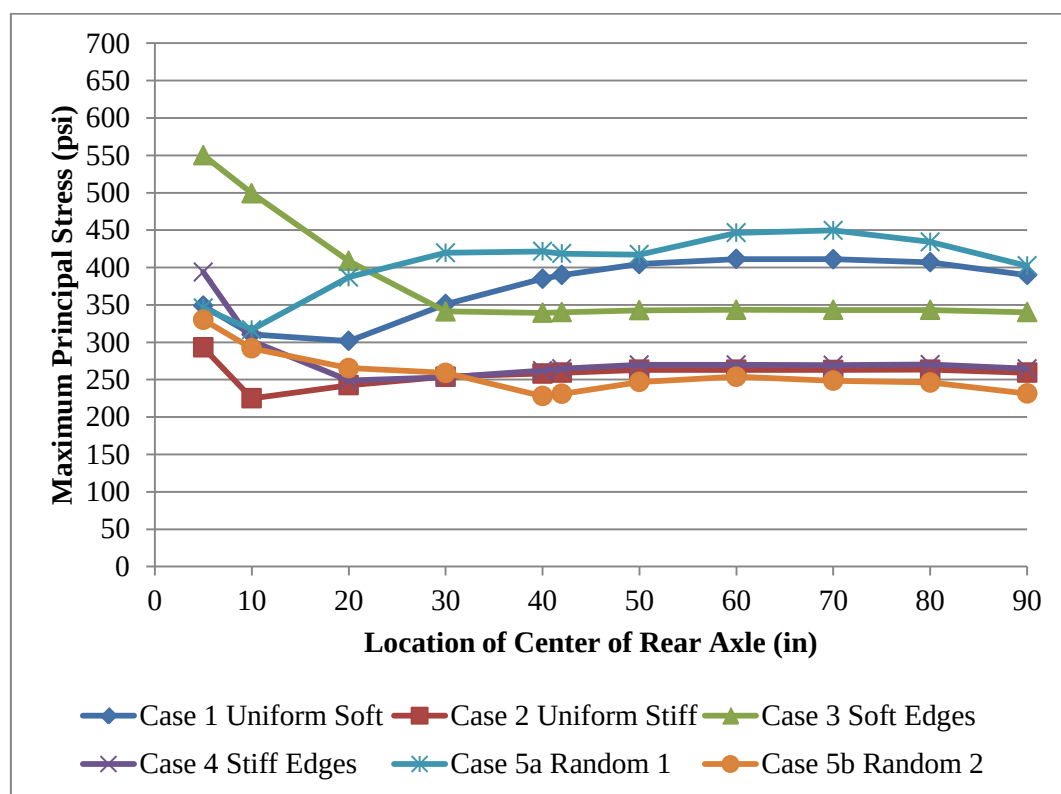


Figure 2. Maximum tensile stress at each tandem axle position from the transverse edge to the mid-slab edge for 0°F (0°C) temperature differential.

Conversions: 1 inch = 2.54 cm; 1 psi = 6.9 kPa

High deflections may lead to other types of slab failure besides cracking, such as pumping and erosion of the support layers. The maximum slab deflections for the

no temperature differential analyses versus the tandem axle position are shown in Figure 3. The trends for maximum deflection do not necessarily map with the results from the stress analysis. Case 1 (Uniform Soft) produced the largest deflections for each axle position, followed by Case 3 (Soft Edges). Case 5a (Random) produced the second highest tensile stresses (see Figure 2) but its deflections were relatively lower. Cases 2 (Uniform Stiff) and 4 (Stiff Edges) had the smallest deflections. The deflection trends do not vary with the nonuniformities, which suggests that existing falling-weight deflectometer (FWD) test patterns on a concrete slab would not be very effective in locating nonuniformities in the foundation layers.

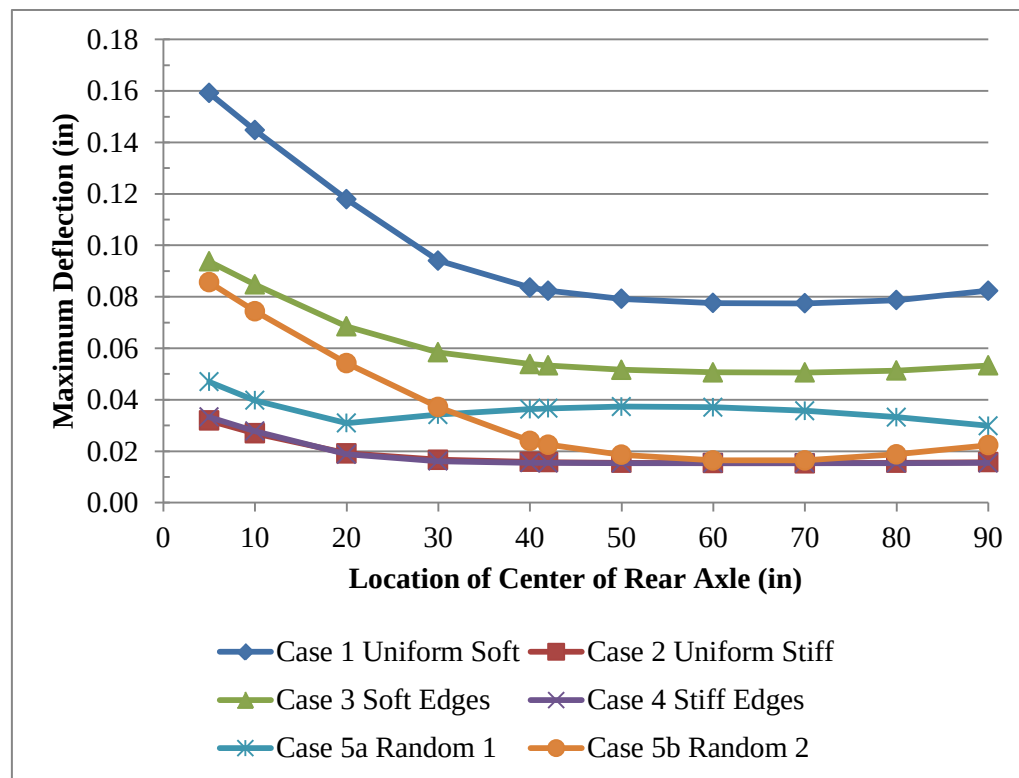


Figure 3. Maximum slab deflection at each tandem axle position from the transverse edge to the mid-slab edge for 0°F (0°C) temperature differential. Conversions: 1 inch = 2.54 cm.

Positive Temperature Differential Cases As seen in Figure 4, the inclusion of a +20°F (+11°C) temperature differential significantly increased the maximum tensile stresses for all subgrade support conditions. Cases 3 and 5a produced the greatest tensile stress at the transverse edge and mid-slab edge, respectively. In fact, the two random nonuniform cases produced the largest difference in maximum tensile stresses. Case 5a resulted in the highest tensile stresses at each load position while Case 5b resulted in the lowest tensile stresses for all but one load position, as seen in Figure 4. Furthermore, Case 5b produced lower stresses than the uniformly soft soil (Case 1). Without a temperature differential, the largest tensile stress difference

between Cases 5a and 5b was 200 psi (1400 kPa), but with a +20°F (+11°C) temperature differential the greatest difference was 315 psi (2200 kPa).

As expected, the tensile stresses are comparatively higher at the mid-slab edge for positive temperature differentials as seen most notably in Figure 4 for Cases 1 and 5a. Within 60 inches of the mid-slab edge, Cases 1, 2, 3, and 4 have similar tensile stresses. Cases 1, 2, 5a, and 5b all have lower stresses at the transverse edge and then increase towards the interior of the slab. Case 3 (Soft Edges) produced the largest transverse edge stresses, followed closely by Case 4 (Stiff Edges), providing evidence that the edge condition is critical for nonuniform support, regardless if the slab is curled.

All of the maximum principal stresses with the +20°F (+11°C) temperature differential occurred at the bottom of the slab. The only exceptions were the top stresses at the transverse edge for Cases 1 and 3. Compared to a uniform soft subgrade support (Case 1), the maximum tensile stresses for Cases 3 and 5a increased 11 percent and 32 percent, respectively. Similarly compared to a uniform stiff subgrade support (Case 2), the increases in maximum stress were 15 percent and 37 percent for Cases 3 and 5a, respectively.

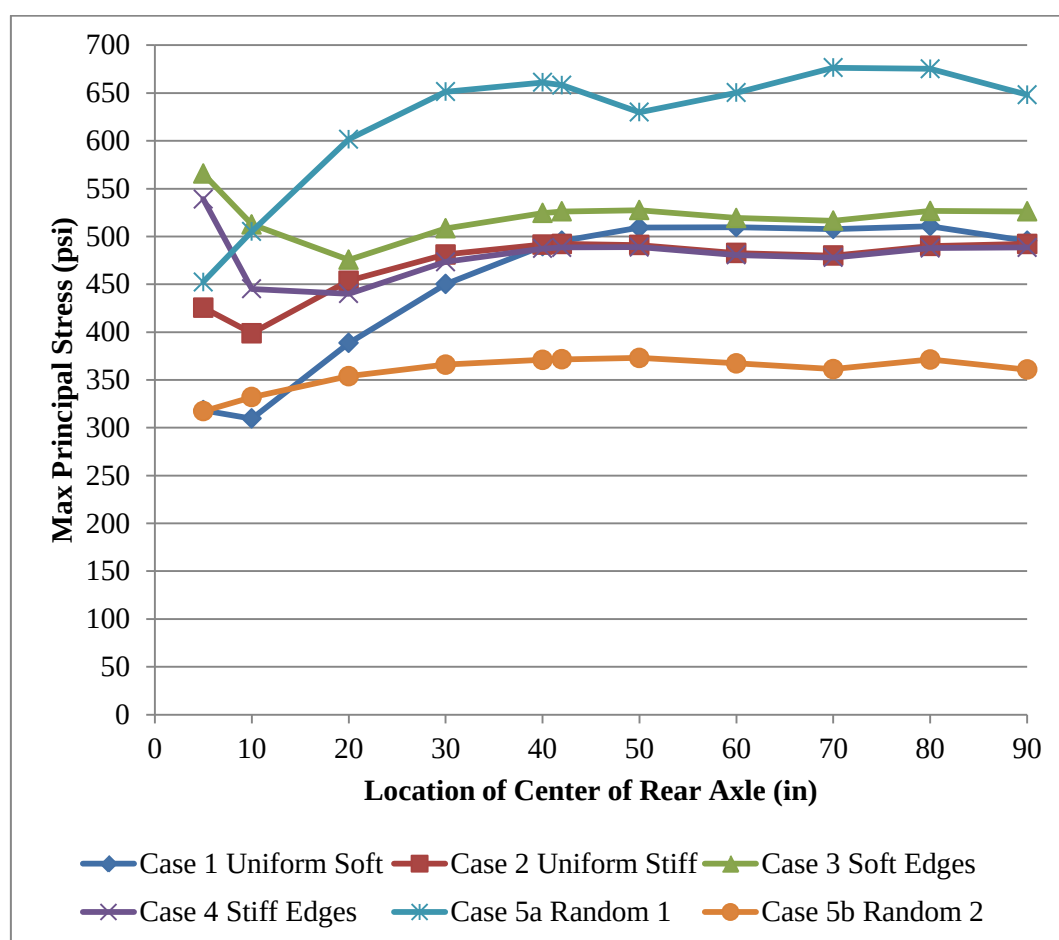


Figure 4. Maximum tensile stresses versus axle location for the +20°F (+11°C) temperature differential. Conversions: 1 inch = 2.54 cm; 1 psi = 6.9 kPa.

Negative Temperature Differential Cases With a -20°F (-11°C) temperature differential, the concrete slab curls upward, which should lead to higher tensile stresses near the transverse edge. **Error! Reference source not found.** clearly demonstrates that a negative temperature differential under all subgrade support conditions produced the greatest tensile stresses at the transverse edge. The soft edge support (Case 3) is significantly greater than the other subgrade support conditions and is nearly 200 psi (1400 kPa) greater than Case 5b at the transverse edge load position. The greatest difference in tensile stress values was approximately 300 psi (2100 kPa) between Cases 3 and 4, soft and stiff edge support, respectively.

Case 5a produced the second highest tensile stress near the mid-slab edge whereas Case 5b resulted in the second highest tensile stresses at the transverse edge load position. Compared to a uniform subgrade (Cases 1 and 2), the subgrade nonuniformity either increased (Cases 3 and 5b) or decreased (Cases 4 and 5a) the maximum tensile stresses in a slab subjected to a negative temperature differential. The maximum tensile stress for Case 3 increased 63 percent and 59 percent versus Cases 1 and 2, respectively. The maximum tensile stresses for Case 5b were approximately 13 percent and 10 percent greater than the maximum tensile stresses for Cases 1 and 2, respectively. The majority of maximum tensile stresses for a -20°F (-11°C) temperature differential occurred at the top of the slab except for Cases 1 and 5a which had critical bottom tensile stresses at axle position locations from 30 to 90 inches (76 to 229 cm).

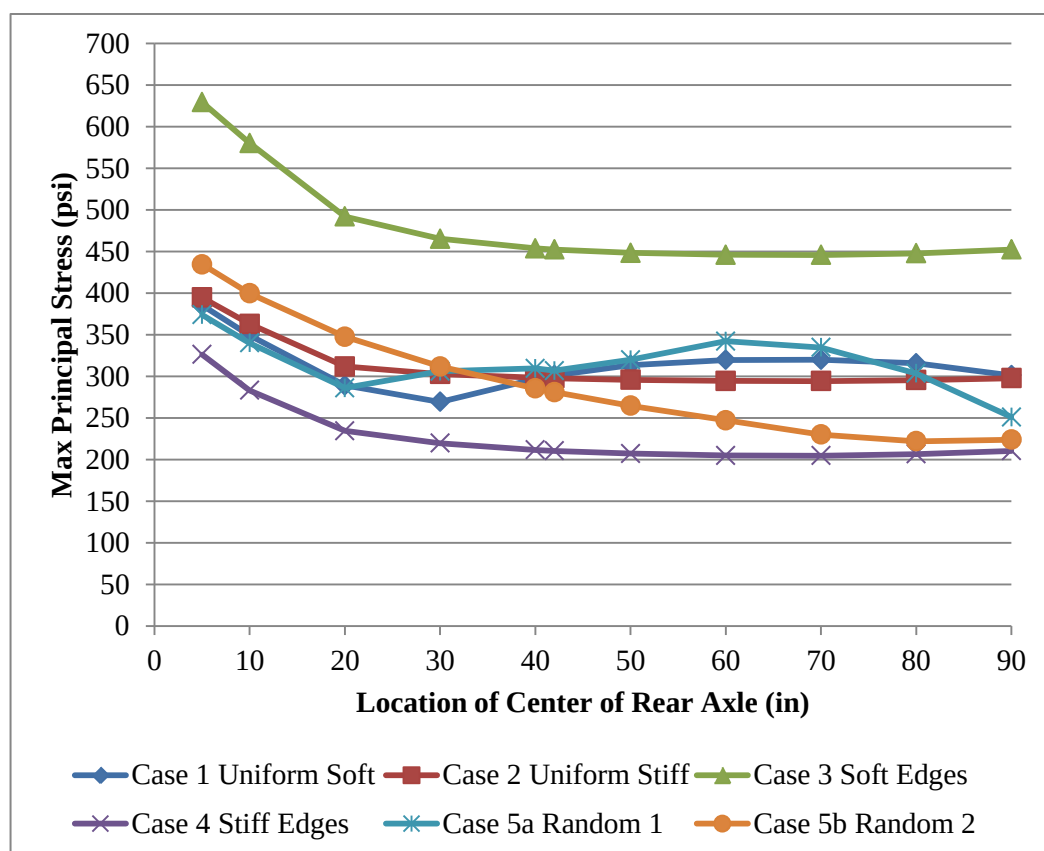


Figure 5. Maximum tensile stresses versus axle location for the -20°F (-11°C) temperature differential. Conversions: 1 inch = 2.54 cm; 1 psi = 6.9 kPa.

Maximum Tensile Stresses and Locations A summary of the maximum tensile stress values for each subgrade support condition and temperature differential can be seen in Figure 6. The magnitude and location of the highest tensile stress for each case is also listed in Table . Overall the magnitude of the tensile stresses depended on the specific nonuniform support condition as well as the temperature differential in the slab. As seen in Figure 6, the soft edge support (Case 3) was the most critical nonuniform subgrade support condition analyzed, having the highest tensile stresses for negative temperature differential and no curling as well as the second highest tensile stresses for the positive differential. Conversely, Case 4 with stiff edge support had significantly lower tensile stresses for all temperature conditions.

Subgrade support conditions with nonuniform areas placed randomly (Cases 5a and 5b) may produce the critical tensile stresses for all cases, as seen in Case 5a, or the lowest tensile stress (Case 5b) for a given temperature differential (i.e. +20°F). Therefore, random nonuniform subgrade conditions increase the risk of a premature failure. The results in Figure 6 and Table suggest it is much better to have a uniformly soft or stiff soil over a wide range of expected temperature differentials rather than accepting nonuniform support conditions with a wide difference in spatial stiffnesses. Table shows that the critical location depends on the nonuniform support, temperature condition, and location of the axle. Most cases produced maximum tensile stresses along the bottom of the longitudinal slab edge for the positive and no temperature differentials while a negative temperature differential resulted in critical top tensile stresses near the transverse load positions.

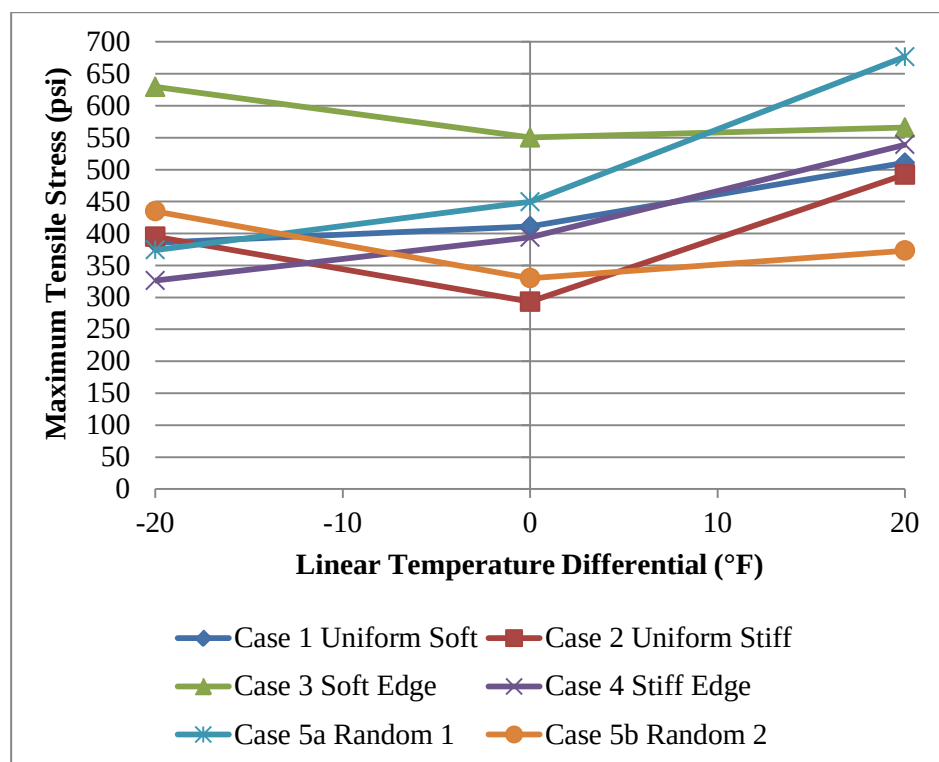


Figure 6. Maximum principal stress (tensile) achieved for tandem axle versus temperature differential. Conversions: 1 psi = 6.9 kPa.

Table 4. Magnitude and Locations of the Maximum Principal Stress (Tensile) for Each Foundation Support Case and Temperature Differential

Case	Temperature Differential (°F)	Maximum Principal Stress for All Load Locations (psi)	Max Stress Location (x,y)	Rear Axle Location at Max Stress (x,y)	Top or Bottom Stress
1	20	511	0, 80	0, 80	Bottom
	0	411	0, 108	0, 60	Bottom
	-20	385	46, 0	0, 0	Top
2	20	492	0, 90	0, 90	Bottom
	0	293	102, 0	0, 0	Bottom
	-20	395	48, 0	0, 0	Top
3	20	566	48, 0	0, 0	Top
	0	550	48, 0	0, 0	Top
	-20	629	52, 0	0, 0	Top
4	20	539	100, 0	0, 0	Bottom
	0	394	100, 0	0, 0	Bottom
	-20	326	30, 0	0, 0	Top
5a	20	676	0, 70	0, 70	Bottom
	0	450	0, 60	0, 60	Bottom
	-20	374	32, 0	0, 0	Top
5b	20	373	0, 98	0, 50	Bottom
	0	330	32, 42	0, 5	Top
	-20	435	38, 52	0, 0	Top

Table explicitly shows the percent differences in maximum tensile stresses in all cases compared to the uniform soft (Case 1) and uniform stiff (Case 2) subgrade conditions. The differences from uniform to nonuniform subgrades can result in significantly greater tensile stresses which can lead to premature cracking under certain loading and curling conditions. Especially Case 3 (Soft Edges) consistently results in significantly greater tensile stresses versus the uniform subgrade conditions (Cases 1 and 2) across all temperature differentials.

Table 5. Percent Difference in Maximum Tensile Stresses
from Uniform to Nonuniform

Case	Temperature Differential, °F (°C)	Maximum Principal Stress for All Load Locations (psi)	Percent Difference in Value from Case 1	Percent Difference in Value from Case 2
No Temperature Differential				
1	0 (0)	411	--	40%
2		293	-29%	--
3		550	34%	88%
4		394	-4%	34%
5a		450	9%	53%
5b		330	-20%	13%
Positive Temperature Differential				
1	+20 (+11)	511	--	4%
2		492	-4%	--
3		566	11%	15%
4		539	6%	10%
5a		676	32%	37%
5b		373	-27%	-24%
Negative Temperature Differential				
1	-20 (-11)	385	--	-2%
2		395	2%	--
3		629	63%	59%
4		326	-15%	-17%
5a		374	-3%	-5%
5b		435	13%	10%

Conclusions

Intelligent compaction technology offers great potential to spatially characterize the stiffness variation of the foundation layer under concrete pavements and the ability to produce a higher quality support system for concrete slabs. Several limiting factors in their widespread implementation have been defining the effects of nonuniformity on concrete pavement performance and determining the allowable stiffness variation and size of area that could be permitted. A two-dimensional finite element analysis has been conducted for six subgrade support conditions (two uniform and four nonuniform) subjected to a moving tandem axle load including flat and curled slab conditions in order to assist in better defining ranges of allowable soil stiffness, size of area for acceptable nonuniformity, and potentially critical support areas underneath the slab. Based on the stress analysis, the nonuniform subgrade support can lead to higher tensile stresses at certain locations in the slab that would cause premature fatigue cracks to occur that were not part of the original design assumptions of a uniform subgrade support condition. The maximum deflection trends for a flat slab condition do not follow the maximum tensile stress trends and thus existing deflection testing strategies would not be particularly reliable in detecting nonuniformities in the support layers.

The analysis showed that the nonuniform subgrade support conditions produced the first and second highest tensile stresses for all three temperature differentials, verifying the need to monitor pavement construction for nonuniformities in the support layers. A subgrade with a soft longitudinal edge support produced the greatest tensile stress for a flat slab condition and a negative temperature differential. The soft longitudinal edge support resulted in tensile stresses that were 34 percent and 63 percent greater than the uniform soft subgrade in the no temperature and negative temperature differential loadings, respectively. Nonuniform subgrade support areas placed randomly were shown to produce critical tensile stresses for a given set of inputs, while another random nonuniform distribution produced some of the lowest tensile stresses. One of the random subgrade support conditions resulted in the highest tensile stress with a positive temperature differential, which was 32 percent greater than the uniform soft subgrade. Depending on the temperature condition, location of the axle, and subgrade support condition, the maximum tensile stress could be on the top or bottom of the slab. The analysis demonstrates that certain nonuniform support conditions can be detrimental to the concrete pavement performance, and implementing intelligent compaction should reduce the risk of premature failures associated with the foundation layer.

Acknowledgments

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