Research Article

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The role of temperature differential and subgrade quality on stress, curling, and deflection behavior of rigid pavement

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Abstract: To determine performance of rigid pavement, pavement engineers should not only conduct stress, curling, and deflection analysis, but also understand weather conditions and subgrade quality effects on rigid pavement performance well. This study aims to analyze and visualize the mechanical behaviors of rigid pavement in terms of stress, curling, and deflection using the KENPAVE Program under different curling temperature and subgrade quality. Besides, this study also evaluated temperature differential and k-value effects on the stress, curling, and deflection behavior of concrete pavement. The findings revealed that there is a linear correlation between stress and both k-value and curling temperature, with the latter having more significant impact in controlling stress than the former. However, even though curling is not affected by subgrade quality, it significantly depends on the temperature differential since a higher curling temperature produces higher curling behavior. Lastly, a higher temperature differential produces greater deflection, but a higher k-value produces smaller deflection. Nevertheless, deflection behavior has a more significant curve and the position of the highest deflection shifted towards the center of the slab as the curling temperature and subgrade quality increase.

Keywords: curling, deflection, KENPAVE, modulus of subgrade reaction, rigid pavement, stress

1 Introduction

In this modern era, the phenomenon of increasing environmental heat become a crucial issue. It is characterized by a

higher temperature in dense regions such as an urban area compared to the surrounding rural areas [1]. According to Solecki *et al.* [2] and Romeo and Zinzi [3] in Carpio *et al.* [1], a high percentage of shortwave solar radiation could be absorbed by concrete materials during the day. Moreover, during the summer season, solar radiation tends to be stored and evaporative cooling tends to be blocked by concrete pavement [4–6]. Such a condition can affect the properties of concrete materials in rigid pavement.

A study on the application of reflective pavement in an urban square with a total area of 4,500 m², in Athens (Greece) had been reported by [7]. They revealed that there was a reduction in air temperature in the square by 1.9°C on a summer's day due to the application of cool pavement. At the same time, the surface temperature decreased by 12°C. Moreover, according to [6], temperature distribution across a pavement slab is affected more by the daily temperature amplitude during the daytime rather than during night-time. Pavement in areas with more significant daily temperature amplitude experience higher negative temperature gradients during the night-time hours.

Temperature has a significant effect on the design and performance of both rigid and flexible pavement. Variations in temperature within a pavement structure contribute to pavement distress and possible failure in several ways [6]. A study into the effect of temperature is necessary to determine the type and frequency of maintenance required throughout the service life of a pavement structure. Pavement's structural performance are extremely reliant on the temperature to which they are exposed. In establishing thermal stress and design parameters of flexible pavement and rigid pavement, daily and seasonal variations in the maximum, minimum, average, and gradient temperature across the pavement depth need to be considered. The principal element is not the actual temperature at or near the surface, but the temperature gradients within the slab that can create cracks in the rigid pavement slab [8–12] and rutting in the asphalt pavement [13]. Significant thermal stress and deformations in the concrete pavement with laterally-fixed concrete slabs can result from daily change

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in temperature. This stress is vital for the dimensioning of pavement and is significantly contingent on concrete slab temperature difference [14]. In rigid pavement, stress caused by environmental factors such as temperature is much more critical compared to in flexible pavement. This stress can be calculated easily after determining environmental and materials properties. However, semi-static nature makes them complicated to superimpose on dynamic traffic stresses [15].

In concrete slab pavement, temperature difference between the top and bottom of the PCC layer results in temperature gradients across the concrete slab depth, which in turn leads to a tendency to curl and differential expansions [11, 16, 17]. Concrete slab weight controls this curling tendency, making thermal stress induced in concrete materials. Vehicle load stress, together with thermal stress, may produce cracking in the pavement structure. Furthermore, in case of curling stress due to a positive thermal gradient, a critical stress condition will occur in a rigid pavement. A positive thermal gradient means that the surface temperature is higher than the temperature at the bottom [11, 18]. Also, Shoukry *et al.* [19] and Siddique *et al.* [20] in Hernandez and Al-Qadi [21] found that curling resulting from a positive temperature differential is slightly higher than that caused by a negative one.

According to Mackiewicz [14], curling stress occurs due to linear thermal difference in the whole thickness of the slab. He also assumed that temperature remains constant in the typical middle plane of the pavement, whereas temperature at the top of the slab is different from that at the bottom. To obtain the overall stress of the slab due to temperature variations, these two primary components of thermal stress are combined using algebraic addition.

Regarding the solution for temperature curling, Westergaard [22, 23] has assumed a linear temperature change through the depth of concrete pavement slabs [24]. However, in contrast to Westergaard's research outputs, other authors concluded that the actual temperature profiles through the rigid slab thickness are nonlinear [24–27]. Moreover, Choubane and Tia [28] recommended to consider the non-linear temperature distribution throughout the whole concrete slab thickness rather than temperature difference between extreme slab fibres.

A model to analyze the impact of non-linear temperature distribution had been developed by [29]. Although temperature difference between the top and bottom surfaces of pavement slabs is the fundamental parameter in the analysis of linear temperature distribution, they concluded that the real temperature distribution along the slab depth was more important to analyze the effect of temperature variation.

According to O'Mahony *et al.* [30], there are differences in bearing capacity, deformability, and stability of weak foundations such as peat soil under changing time frames and weather conditions. These variations will pose a considerable challenge to the maintenance and serviceability of rigid pavement structures constructed on weak soil. Roads on peat foundations will deform easily under vehicle loading, which speeds up their degradation and enforces high maintenance and rehabilitation costs. Furthermore, previous studies conducted by Joshi *et al.* [8] have shown that for particular joint spacing and rigid slab thickness, a higher modulus of subgrade reaction can result in higher curling stress due to temperature difference. Higher curling stress can lead to higher loading and curling stress in pavement.

Finite element modeling of flexible pavement on soft soil subgrades had been developed by [31] to study the effect of wheel pressure and configuration, as well as axle load variations of a standard truck on the mechanical performance of flexible road pavement with a thin asphalt surfacing layer. They concluded that a finite element method could be used to assess potential distress efficiently. Finite element simulation could be conducted as well to analyze pavement under response to various parameters [32–34]. In the last two decades, there are several 2- and 3-dimensional finite element models developed and used around the world, such as KENPAVE [36, 37], ISLAB [33], ILLI-SLAB [37–40], JSLAB [41], WESLAYER [42], FEACONS IV [43, 44], and ISLAB2000 [45].

KENSLAB program was developed by Huang [46] and simulates slabs using 2D medium-thick plate elements as either beam elements or linear and torsion springs. Even though the program can neither simulate stress distribution through the depth of the slab nor include a non-linear gradient, it helps pavement engineers to visualize the mechanical behavior of a pavement structure by some modification and additional work and it supports computer programs such as Microsoft Excel that can provide a 3-dimensional graphical design. In a rigid pavement system, stress and deflection analysis is essential to determine the response of the structure due to loading (curling, corner, interior, and edge).

Curling temperature

Due to variation in temperature between the top and bottom of a concrete slab, curling stress develops along rigid pavement (Figure 1). Even though curling stress may not be as significant as vehicular loading stress, it usually re-

sults in increased cracking potential and, therefore, reduces pavement serviceability [21, 23].

Figure 1: Curling condition in rigid pavement: (a) Negative temperature gradient, the temperature at the top < temperature at the bottom; and (b) positive temperature gradient, the temperature at the Top > temperature at the bottom

Modulus of subgrade reaction (k-Value)

The k-value is an essential design input that describes the response of the subgrade material [19, 47]. It is defined as:

$$k = -p/\Delta$$

Where a foundation of width “b” is subject to a load per unit area of “p” and the corresponding settlement is “Δ”. The value of k can be stated in pci or kN/m³ and depends on several factors like the length, width, and depth of the foundation. Therefore, the k-value is not constant for soil [19, 47, 48].

In this study, the analysis was conducted by assuming that the temperature change through the depth of concrete pavement is linear, and using a positive temperature differential. The analysis was also conducted by assuming that the type of foundation is liquid foundation based on the k-value (modulus of subgrade reaction).

Figure 2: PCC temperature profile [49]

Figure 3: Soil property (k-Value) adjustment [49]

As can be seen in Figures 2 and 3 above, the PCC temperature profile and soil properties (k-value) change over time. Temperature and moisture gradients in the top PCC layer can significantly affect stress and deflection, and result in damage and distress in the pavement. Also, k-value will be higher in the winter season and lower in the summer season. Pavement engineers need to understand the behavior of rigid pavement by considering different PCC temperature profiles and k-values. Therefore, this study aims to visualize the mechanical behaviors of rigid pavement using KENPAVE Program (stress, curling, and deflection behavior) under various temperature differentials, ΔT (10°F, 20°F, 30°F) and different subgrade qualities, k (100 pci, 200 pci, and 300 pci) in order to gain more understanding of the effects of the temperature differential and modulus of subgrade reaction on the stress, curling, and deflection behavior of concrete pavement.

However, this study only considered stress and deflection due to Interior Loading and Curling and does not consider stress due to Friction as well as joints, steel reinforcements, tie bars, dowel bars, and the gap that may happen between the bottom of the slab and the subgrade when exposed to curling temperature. Therefore, in this study there is no loss of subgrade support.

2 Research method

This study used 10-inch thick slabs supported by a subgrade with modulus of subgrade reaction, k. A dual-tandem wheel load (of 9,800 lb each) was applied to the interior of the slab, as shown in Figure 5 below. The contact pressure is 80 psi. Assume that the Young's modulus

is 4,000,000 psi, Poisson's ratio for the slab is 0.15, and $\alpha_t = 5 \times 10^{-6}$ in/in/°F.

The following table (Table 1) shows nine (9) combinations of the modulus of subgrade reaction (k) and temperature difference (ΔT) for the KENPAVE analysis.

Table 1: Combinations for KENPAVE Analysis

k & ΔT	10°F	20°F	30°F
100 pci	10°F & 100 pci	20°F & 100 pci	30°F & 100 pci
200 pci	10°F & 200 pci	20°F & 200 pci	30°F & 200 pci
300 pci	10°F & 300 pci	20°F & 300 pci	30°F & 300 pci

Figure 4 presents the contact area between tires and the pavement surface and its equivalent contact area.

Figure 4: (a) Contact area between tires and the pavement surface; (b) equivalent contact area [46, 50]

Since L is 15.30 in, 1 wheel has the rectangular area conversion of $0.5227 L^2$, with a length of 13.3 and a width of 9.2 in. This study also considered the wheel configuration based on truck class 9. Moreover, the wheel configuration on the slab and part of the slab that modeled in KENSLAB (inside the red rectangle) can be seen in Figure 5. Besides, Figure 6 presents data on load areas for each wheel.

Figure 5: Wheel configuration on the slab [50]

Unit	LS	X1	X2	Y1	Y2	Q
1	1	12	25.3	23.8	33	80
2	1	12	25.3	37.8	47	80
3	1	67.1	80.4	23.8	33	80
4	1	67.1	80.4	37.8	47	80

Figure 6: Data on load areas in KENSLAB

3 Results and discussion

Figure 7 presents the slab design and wheel configuration in KENSLAB as well as the highest stress position in each row of nodes (red points).

Figure 7: Slab design, wheel configuration in KENSLAB, and the highest stress position in each row of nodes

As illustrated in Figure 8 (a-f), there are two peaks in each line. These two peaks are below the wheel positions. Furthermore, in Figure 8a, a k -value of 100 pci and an increase in the curling temperature by 10°F (i.e. from 10°F to 20°F and from 20°F to 30°F) will cause stress to rise by approximately 14 psi. For example, from 150 psi (10°F) to 164 psi (20°F) and from 164 psi (20°F) to 178 psi (30°F). Then, a k -value of 200 pci and an increase in the curling temperature by 10°F will cause stress to rise by approximately 25-26 psi (Figure 8c). Lastly, a k -value of 300 pci and an increase in the curling temperature by 10°F will cause stress to rise by approximately 35 psi (Figure 8e). Also, a higher k -value tends to result in a greater gap between the lines.

In Figure 8b, a curling temperature of 10°F and an increase in the k -value by 100 pci (i.e. from 100 pci to 200

Figure 8: Stress in the center line of the slab

pci and from 200 pci to 300 pci) will result in increased stress by approximately 3-4 psi, meaning that stress rises from 150 psi to 153 psi in the event of an increased k-value from 100 pci to 200 pci and, likewise, it rises from 153 psi to 157 psi in the event of an increased k-value from 200 pci to 300 pci. Then, a curling temperature of 20°F and an increase in the k-value by 100 pci will cause stress to rise by approximately 13-15 psi (Figure 8d). Lastly, a curling temperature of 30°F and an increase in the k-value by 100 pci will lead to increased stress by approximately 23-26 psi (Figure 8f). Besides, a higher curling temperature leads to a greater gap between the lines.

Table 2: Combinations for KENPAVE analysis

k & ΔT	10°F	20°F	30°F
100 pci	150 psi	164 psi	178 psi
200 pci	153 psi	179 psi	204 psi
300 pci	157 psi	192 psi	228 psi

Figure 9 exhibits the line graph for all combinations of curling temperature and k-value, while Table 2 shows the summary of the highest stress in rigid pavement for each combination. It can be concluded that stress in rigid pave-

Figure 9: Stress for all combinations of curling temperature and k-Value

Table 3: Comparisons of curling

k & ΔT	10°F	20°F	30°F
100 pci	0.01684	0.03368	0.05052
200 pci	0.01684	0.03368	0.05052
300 pci	0.01684	0.03368	0.05052

ment is affected by both the modulus of subgrade reaction and curling temperature. Based on Figure 9 and Table 2, the highest stress was generated in the simulation with $k = 300$ pci and $\Delta T = 30^\circ\text{F}$, while the lowest stress was generated in the simulation with $k = 100$ pci and $\Delta T = 10^\circ\text{F}$.

The following discussion concerns curling analysis and visualizations. Figure 10 illustrates the results of curling analysis using the same k-value for three different curling temperatures. At first, the k-value used amounted to 100 pci. By increasing the curling temperature from 10°F to 20°F , the curling behavior will rise from 0.01684 inch to 0.03368 inch. Then, an increase in the curling temperature from 20°F pci to 30°F will raise the curling behavior from 0.03368 inch to 0.05052 inch. More results of the curling analysis using the same k-value (200 pci and 300 pci) and different ΔT (10°F , 20°F , and 30°F) can be seen in Table 3, where the results show the same increment. The results accord with the findings of [14] that a higher ΔT results in greater curling.

Figure 11 shows the output of the curling analysis using the same curling temperature of 10°F for three different k-values (i.e. 100 pci, 200 pci, and 300 pci). In the first simulation, the three different k-values showed the same curling behavior, i.e. 0.01684 inch, at the same curling temperature of 10°F . More results of the curling analysis at the same ΔT (20°F and 30°F) with different k-values (100, 200, and 300 pci) can be seen in Table 3, which suggest that ΔT at 20°F and 30°F produce a higher curling value than the

previous ΔT at 10°F , but the curling value is the same for a k-value of 100, 200, and 300 pci at ΔT of 20°F and 30°F .

Table 3 displays the summary of the highest curling condition in each combination. An increase in the temperature difference from 10°F to 20°F will increase curling behavior two times. Then, an increase in the temperature difference from 10°F to 30°F will increase curling behavior three times.

Figure 12 presents results of the deflection analysis and visualizations. Initially, the analysis focused on the use of the same k-value for three different curling temperatures. The first simulation used a k-value of 100 pci and increased the curling temperature from 10°F to 20°F , which resulted in increased deflection from 0.0811 inch in the 1st row to 0.0819 inch in the 2nd row (an increase of 1%). Then, using the same k-value, the curling temperature was increased from 20°F pci to 30°F , which generated increased deflection from 0.0819 inch in the 2nd row to 0.0835 inch in the 3rd row (an increase of 2%). More results of the deflection analysis at the same k-value (200 pci and 300 pci) with different ΔT (10°F , 20°F , and 30°F) can be seen in Table 4, where the results show different increments. As for the simulation with a k-value of 200 pci and an increase in the curling temperature from 10°F to 20°F , it led to an increase in deflection from 0.0392 inch in the 2nd row to 0.0409 inch in the 4th row (an increase of 4.3%). Then, the curling temperature was raised from 20°F pci to 30°F , which also resulted in increased deflection from 0.0409 inch in the 4th row to 0.0444 inch in the 5.5th row (an increase of 8.6%). Lastly, a k-value of 300 pci with an increase in the curling temperature from 10°F to 20°F increased the deflection from 0.0256 inch in the 3.5th row to 0.0285 inch in the 5.5th row (an increase of 11.3%). Then, the curling temperature was raised from 20°F pci to 30°F and it generated increased deflection from 0.0285 inch in the 5.5th row to 0.0322 inch in the 6th row (an increase of 13%). The results agree with [14], that a higher ΔT generates greater deflection.

Figure 13 shows results of the deflection analysis and visualizations using the same curling temperature for three different k-values. The first simulation used a curling temperature of 10°F . An increased k-value from 100 pci to 200 pci reduced deflection from 0.0811 inch in the 1st row to 0.0392 inch in the 2nd row (a reduction of 51.7%). Then, an increase in the k-value from 200 pci to 300 pci reduced deflection from 0.0392 inch in the 2nd row to 0.0256 inch in the 3.5th row (a reduction of 34.7%). More results of the deflection analysis at the same ΔT (20°F and 30°F) with different k-values (100, 200, and 300 pci) can be seen in Table 4, where the results show different decrements. As for the simulation using a curling temperature of 20°F and an increase in the k-value from 100 pci to 200 pci caused

Figure 10: Curling at the same $k = 100$ pci with different ΔT (10°F , 20°F , and 30°F)

Figure 11: Curling at the same $\Delta T = 10^\circ\text{F}$ with different k -value (100, 200, and 300 pci)

Figure 12: Deflection at the same k -value = 100 pci with different ΔT

Figure 13: Deflection at the same $\Delta T = 10^\circ\text{F}$ with different k -value

deflection to decrease from 0.0819 inch in the 2nd row to 0.0409 inch in the 4th row (a reduction of 50%). Then, an increase in the k-value from 200 pci to 300 pci reduced deflection from 0.0409 inch in the 4th row to 0.0285 inch in the 5.5th row (a reduction of 30.3%). Lastly, a curling temperature of 30°F and an increase in the k-value from 100 pci to 200 pci led to reduced deflection, *i.e.* from 0.0835 inch in the 3rd row to 0.0444 inch in the 5.5th row (a reduction of 46.8%). Then, an increase in the k-value from 200 pci to 300 pci reduced deflection from 0.0444 inch in the 5.5th row to 0.0322 inch in the 6th row (a reduction of 27.5%). Based on the foregoing, it is evident that as the k-value rises, the shape of deflection visualization has a greater curve both in X and Y direction, while the position of the highest deflection shifted towards the center of the slab.

Table 4 shows the summary of the critical deflection point in each combination. It can be concluded that unlike curling temperature that has a minor effect, the modulus of subgrade reaction exercises a significant effect on deflection.

Table 4: Comparisons of deflection (inch) and its node row position

k & ΔT	10°F	20°F	30°F
100 pci	0.0811 (1)	0.0819 (2)	0.0835 (3)
200 pci	0.0392 (2)	0.0409 (4)	0.0444 (5.5)
300 pci	0.0256 (3.5)	0.0285 (5.5)	0.0322 (6)

Although there are other finite element programs such as three-dimensional finite element programs NIKE3D and ABAQUS [50, 51] used to design and analyze pavement thickness, the output of KENPAVE program is only the values of curling and deflection at the nodes. Therefore, this paper briefly describes research on the optimization of the KENPAVE program output by visualizing the curling and deflection behavior in a three-dimensional shape.

4 Conclusions

Based on the results obtained in this study, the following conclusions can be drawn. A higher modulus of subgrade reaction and curling temperature lead to higher stress on rigid pavement. Moreover, curling temperature has more significant impact compared to the modulus of subgrade reaction in maintaining stress in rigid pavement. Curling is not affected by the subgrade quality, but it significantly depends on the temperature differential. A higher temperature differential will result in higher curling behavior and

more significant deflection that has a greater curve shifting more towards the center of the slab. On the contrary, a higher modulus of subgrade reaction causes smaller deflection, but still has a more significant curve shifting more towards the center of the slab.

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