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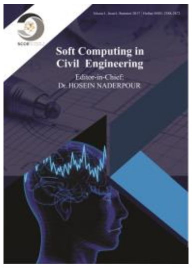

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Comparative Analysis of Rigid Pavement using Westergaard Method and Computer Program

I. H.H. Al-Ghafri[1], and M. A. Javid[1*]

1. College of Engineering and Architecture, University of Nizwa, Initial Campus at Birkat-al-Mouz, 616, Nizwa, Oman

Corresponding author: *ma.javid@hotmail.com*

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ABSTRACT

Country's economic, social and cultural development is mainly dependent on performance of its highway structure. Selection of appropriate pavement type and related design method are vital for the improvement of pavement performance and its service life, and reduction in the initial and maintenance cost. The rigid pavement exposed to many distresses during its service life resulted due to variation of traffic loading, material properties and climatic conditions. The main objective of this project is to make comparison between manual and computer design for rigid pavement structure under different loading, material properties and temperature regimes. For manual design and computer design, "Westergaard Method" and "KENPAVE software" were used respectively. The stress analysis results revealed that edge stresses are higher as compared with interior and corner location, and stresses estimated at all locations with Westergaard method are significantly lower than stresses estimated with KENPAVE software. Results of sensitivity analysis showed that change in pavement thickness, material properties and wheel load has significant impact on developed stresses at different slab locations.

1. Introduction

Currently, many highway Projects are under construction in Oman, for Example, BATINAH EXPRESSWAY CONSTRUCTION PROJECT and BIDBID - SUR DUAL CARRIAGEWAY PROJECT. Generally, highway projects are high cost projects and consume a large amount of country's development budget. In addition, country's economic, social and cultural development is mainly dependent on performance of its highway structure. Selection of appropriate pavement type and related design method are vital for the improvement of pavement performance and its service life, and reduction in the initial and maintenance cost. Pavement is an artificial surface laid over the ground to simplify the travel. The pavement structure must be durable and serviceable in order to resist the imposed traffic loading. The top surface of rigid pavement structure usually consists of Portland cement concrete (PCC). PCC has a high modulus of elasticity and rigidity, and do not flex noticeably under the application of traffic loading [1].

The rigid pavement exposed to many types of distresses during its service life that include warping cracks, joint faulting and punch-out's failure. The continuously variation in traffic loading, material properties and climatic conditions mainly contributes towards such distresses and results in reduced pavement performance and its service life. To improve the performance of pavement, it is required to evaluate the behavior of pavement structure under varying loading, material properties and climatic conditions. The main objective of this study is to make a comparison for stresses and deflections at various locations between Westergaard method and KENPAVE software.

2. Literature Review

Concrete pavement is susceptible to combination of thermal and traffic stress. When the load applied on the surface of rigid pavement, it causes flexure of the slab that produces tensile and compressive stresses. There are three types of traffic loading in concrete slab: loading at corner, edge loading, and interior loading. According to Westergaard equation the highest stress level were caused by traffic induce stress is edge loading stress due to lower thickness of the grouted macadam layer, which is less than half of the concrete thickness [2].

Traffic load is one of the major factors that affect pavement performance. Equivalent single axle load (ESAL) provides a typical value of the traffic loading experienced by a pavement structure in its whole life [3]. Temperature stresses developed in cement concrete due to daily variation in slab temperature gradient along the slab thickness, and seasonal temperature variation due to overall change in slab temperature. Khana et al. (2014) state that cement concrete assumed to be identical and have uniform elastic properties with subgrade. The main factor considered in the design of rigid pavements is the structural strength of the concrete, therefore; slight differences in subgrade strength have little influence upon the structural capacity of the pavement [4]. Pavements are designed to distribute traffic induced stresses to the subgrade. For this reason, subgrade condition is consider as a principal factor in selecting the pavement structure and before pavement is plotted, the quality of the subgrade soils must be evaluated to ensure that it has sufficient strength to carry the expected traffic loads during the design life of the pavement. The pavement must also be plotted to limit the expansion and loss of density of the subgrade soil [5].

Arora (2003) has reported that the Westergaard's analysis is used for design of rigid pavements. The stresses in the concrete slab are determined using Westergaard's theory. Westergaard considered the rigid pavement as a thin elastic plate resting on soil subgrade. The slab deflection depends on the stiffness of the subgrade and the flexural strength of the slab. Therefore, the stress-deformation characteristics of a rigid pavement depend on the relative stiffness of the slab and the subgrade. There are other methods used to calculate rigid pavement stresses other than using Westergaard method. Finite element method is suggested as an alternative method, which can provide optimum and economical design because of the procedure of FEM, which calculate stresses at each node. This method can estimate accurately the performance of rigid pavement under the design load [6].

3. Research Methodology

Figure 1 shows the design framework of this research work. It starts with the selection of design input variables. These variables include traffic, subgrade soil properties, PCC properties and climatic data of the selected site. Using these input pavement structure is designed using Westergaard method and computer program.

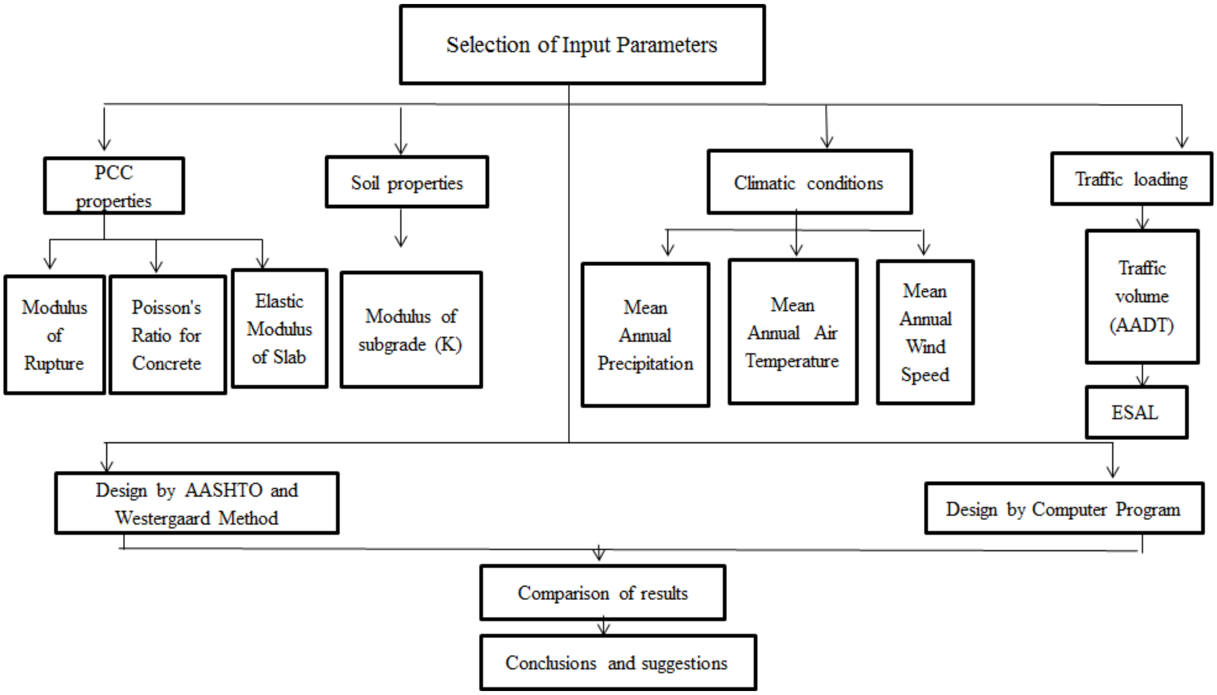


Fig.1. Design framework.

Initially pavement was design using AASHTO method and obtained results were used as reference for other methods.

AASHTO Method: In this method, empirical equation is used to related observed or measurable phenomena with the required outcomes. The equation-1 is widely used for design of rigid pavement and has the following form.

$$\log_{10}(W_{18}) = Z_R \times S_o + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624\times 10^{7}}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \times \log_{10}\left[\frac{(S'_c)(C_d)(D^{0.75}-1.132)}{215.63(J)\left(D^{0.75}-\frac{18.42}{\left(E_c/k\right)^{0.25}}\right)}\right] \quad (1)$$

In above equation:

W_{18} = predicted number of 80 KN (18,000 lb) ESALs

Z_R = standard normal deviate

S_0 = combined standard error of the traffic prediction and performance prediction

D = slab depth

p_t = terminal serviceability index

ΔPSI = difference between the initial design serviceability index, p_o, and the design terminal serviceability index, p_t

Cd = drainage coefficient

J = load transfer coefficient

E_c = elastic modulus of PCC

k = modulus of subgrade reaction

ESAL: in pavement design it is a common practice to convert the damage from wheel loads of various magnitudes and repetitions of mixed traffic to damage for an equivalent number of "standard single axle" loads. This conversion makes the design calculations simple. The most commonly used equivalent load in the U.S. is the 18,000 lb (80 KN) [7]. The equation-2 is used to calculate ESAL for the design period at a growth rate of 4% [8].

$$ESAL_D = (AADT)_i \; x \; (L_{Fi}) \; x \; T_{24} \; x \; D_F \; x \; E_F \; x \; 365 \qquad (2)$$

Where;

AADT = average annual daily traffic

L_{Fi} = Lane Factor, converts directional trucks to the design lane trucks

T_{24} = Percent heavy trucks during a 24-hour period with six tires or more

D_F = directional distribution factor

E_F = Equivalency Factor, which is the damage caused by one average heavy truck measured in 18-KIP (80-kN) ESALs

Westergaard Method: Westergaard assumed a pavement slab to be a thin plate resting on a special subgrade, which is considered elastic in a vertical direction only. The pressure-deformation characteristics of a rigid pavement depend upon the relative stiffness of the slab and the subgrade [9].

In this method equation are available for three loading conditions i.e. interior, edge and corner. In addition, curling stresses are calculated at edge and interior location only. These equations are given below for each location. In this method, the wheel load is assumed circular with radius ‘a’.

Equation for interior stress (σ_i) due to circular load (radius = a):

$$\sigma_i = \frac{3P(1+\mu)}{2\pi h^2}\left[\ln\frac{2l}{a} + 0.5 - \gamma + \frac{\pi}{32}\left(\frac{a}{l}\right)^2\right] \tag{3}$$

Equation for interior deflection (δ_i) due to circular load:

$$\delta_i = \frac{P}{8kl^2}\left[1 + \left(\frac{1}{2\pi}\right)\left(\ln\left(\frac{a}{2l}\right) + \gamma - 1.25\right)\left(\frac{a}{l}\right)^2\right] \tag{4}$$

Edge Stress (Semi Circular) Westergaard Equations:

Equation for edge stress (σ_e) due to semi-circular load:

$$\sigma_e = \frac{3(1+\mu)}{\pi(3+\mu)h^2}\left[\ln\frac{Eh^3}{100ka_2^4} + 3.84 - \frac{4\mu}{3} + 0.50(1+2\mu)\left(\frac{a_2}{l}\right)\right] \tag{5}$$

Equation for edge deflection (δ_e) due to semi-circular load:

$$\delta_e = \frac{P(2+1.2\,\mu)^{0.5}}{(E\,h^3\,k)^{0.5}}\left[1 - (0.323 + 0.17\,\mu)\left(\frac{a_2}{\ell}\right)\right] \tag{6}$$

$$a_2 = a\sqrt{2}$$

Edge Stress (Circular) Westergaard Equations:

Equation for edge stress (σ_e) due to circular load:

$$\sigma_e = \frac{3(1+\mu)P}{\pi(3+\mu)h^2}\left[\ln\frac{Eh^3}{100ka^4} + 1.84 - \frac{4\mu}{3} + \frac{1-\mu}{2} + 1.18(1+2\mu)\left(\frac{a}{\ell}\right)\right] \tag{7}$$

Equation for edge deflection (δ_e) due to circular load:

$$\delta_e = \frac{P(2+1.2\,\mu)^{0.5}}{(E\,h^3\,k)^{0.5}}\left[1 - (0.76 + 0.4\,\mu)\left(\frac{a}{\ell}\right)\right] \tag{8}$$

Corner Stress Westergaard Equations:

Equation for Corner stress (σ_c) due to circular load (radius = a):

$$\sigma_c = \frac{3P}{h^2}\left[1 - \left(\frac{\sqrt{2}\,a}{\ell}\right)^{0.6}\right]$$

(9)

Equation for Corner deflection (δ_c) due to circular load:

$$\delta_c = \frac{P}{k\ l^2}\left[1.1 - 0.88\left(\frac{\sqrt{2}\ a}{\ell}\right)\right]$$

(10)

Where in equation 3 to 10:

γ = Euler's constant (0.577215)

P = wheel load

k = modulus of subgrade reaction

μ = Poisson ratio

a = radius of circular load

l = length of slab

h = slab thickness

E = elastics modulus of pcc

Curling Stress Westergaard Equations:

Exterior $$\sigma_e = \frac{C\,E\,\alpha_T\,\Delta T}{2}$$ (11)

$$\sigma_i = \frac{E\,\alpha_T\,\Delta T}{2}\left[\frac{C_1 + \mu C_2}{1-\mu^2}\right]$$

Interior (12)

Where;

$$C = 1 - \frac{2\cos\lambda\cosh\lambda}{\sin 2\lambda + \sinh 2\lambda}(\tan\lambda + \tanh\lambda)$$

(13)

$$\lambda = \frac{L}{\ell\sqrt{8}}\quad (Edge) \qquad \lambda = \frac{W}{\ell\sqrt{8}}\quad (Interior)$$

L, W = Length and Width of PCC Slab

C, C_1, C_2 = coefficients for interior stress for the desired direction

ΔT = Temperature differential in degree F

a_T = Coefficient of thermal expansion

KENPAVE SOFTWARE: Kenpave program is used to determine stresses, strains and deflections at different points in the pavement structure subjected to traffic loading and taking into account the material properties. General information is assigned to the program like; the number of slab layers to be designed and the data of materials in each layer e.g. thickness, poisons ratio, unit weight and elastic modulus. In addition, type of foundation used whether it is liquid, solid, or Winkler foundation, number of periods per year and number of load groups. In addition loading data is entered. Finally, the program is run to get the output (stress and deflection).

4. Results and Discussion

Accumulative ESAL is calculated for arterial urban rigid pavement based on 8662 AADT, which projected for 30 years from 2016 until 2047. The opening year of the project is 2017. Since it is two-way traffic the directional distribution factor (DF) taken as 0.5 and the percent of heavy trucks during 24-hour period (T24) = 25. The lane factor=75 and the EF for arterial urban rigid pavement = 2.02.

Table 1.
Calculation of ESAL

Year	AADT	ESAL	Accumulative ESAL	D_F	T_{24}	LF	EF
---	Veh/day	---	---	---	%	---	---
2016	8662	598762	---	0.5	25	0.75	2.02
2017	9009	622712	622712	0.5	25	0.75	2.02
2018	9369	647621	1270333	0.5	25	0.75	2.02
2019	9744	673526	1943859	0.5	25	0.75	2.02
2020	10134	700467	2644325	0.5	25	0.75	2.02
2021	10539	728485	3372811	0.5	25	0.75	2.02
2022	10961	757625	4130436	0.5	25	0.75	2.02
2023	11399	787930	4918365	0.5	25	0.75	2.02
2024	11855	819447	5737812	0.5	25	0.75	2.02
2025	12329	852225	6590037	0.5	25	0.75	2.02
2026	12822	886314	7476351	0.5	25	0.75	2.02
2027	13335	921766	8398117	0.5	25	0.75	2.02
2028	13869	958637	9356754	0.5	25	0.75	2.02
2029	14424	996982	10353737	0.5	25	0.75	2.02
2030	15000	1036862	11390598	0.5	25	0.75	2.02
2031	15601	1078336	12468935	0.5	25	0.75	2.02
2032	16225	1121470	13590404	0.5	25	0.75	2.02
2033	16874	1166328	14756733	0.5	25	0.75	2.02
2034	17548	1212982	15969715	0.5	25	0.75	2.02
2035	18250	1261501	17231215	0.5	25	0.75	2.02
2036	18980	1311961	18543176	0.5	25	0.75	2.02

2037	19740	1364439	19907616	0.5	25	0.75	2.02
2038	20529	1419017	21326633	0.5	25	0.75	2.02
2039	21350	1475778	22802410	0.5	25	0.75	2.02
2040	22204	1534809	24337219	0.5	25	0.75	2.02
2041	23093	1596201	25933420	0.5	25	0.75	2.02
2042	24016	1660049	27593469	0.5	25	0.75	2.02
2043	24977	1726451	29319920	0.5	25	0.75	2.02
2044	25976	1795509	31115429	0.5	25	0.75	2.02
2045	27015	1867329	32982759	0.5	25	0.75	2.02
2046	28096	1942023	34924782	0.5	25	0.75	2.02
2047	29219	2019704	36944485	0.5	25	0.75	2.02

4.1. DESIGN BY AASHTO METHOD

The values of input variables were taken from AASHTO design guide and other references and pavement thickness was calculated. The input data includes: reliability = 90%, combined standard Error (S_0) = 0.4, initial Serviceability Index (p_o) = 4.5, Terminal serviceability index (p_t) = 3, Elastic modulus of PCC (Ec) = 4,000,000 psi (27586 MPa), Modulus of Rupture (S) = 700 psi (4.826 MPa), Drainage coefficient (Cd) = 1, Load transfer coefficient (J) = 3.2, Modulus of subgrade reaction (k) from CBR% = 304.5 pci (82.76 KPa/mm), Standard normal deviate (Z_R) = - 1.282, and ΔPSI = 1.5. The calculated thickness using equation-1was 300 mm and this thickness was used as reference for analysis using Westergaard method and Computer Program.

4.2. Stresses and Deflections Calculation by Westergaard Method and KENPAVE

Table 2 presents the summary of stresses and deflection of Westergaard method and KENPAVE analysis. For base case, using Westergaard's method Curling stresses are higher at interior of the slab as compared with slab edge. Traffic induced stresses are higher at edge are higher in comparison to other locations. In addition, for KENPAVE analysis results show that edge stresses are higher than interior and corner stresses that are similar to manual method.

Table 2.
Westergaard method and KENPAVE software results for Stresses and Deflections

	Westergaard method			KENPAVE software		
Position of Load	Traffic Induced Stresses (MPa)	Curling Stresses (MPa)	Deflection (mm)	Traffic Induced Stresses (MPa)	Curling Stresses (MPa)	Deflection (mm)
Interior	0.598	1.198	0.057	0.815	1.256	0.232
Edge	1.139	1.081	0.214	1.462	1.170	0.386
Corner	0.787	---	0.361	0.873	---	0.285

Figure 2 shows the comparison between Westergaard method and KENPAVE software results for stresses at different locations. The estimated stresses with Westergaard method are lower than the computer method at all locations. Traffic induced interior, edge, and corner stresses are lower by 36.3%, 28.35, and 11%, respectively. The difference for curling stresses is less. These results implied that Westergaard method underestimate the stresses. This is due to its limitation in considering the subgrade supporting conditions for different locations. As Bartosova mentioned in his study that the highest load stress done by westergaard method and finite element method occurs at longitudinal and transverse edges of slab, and Westergaard method results lower stresses in comparison to Finite element method [10].

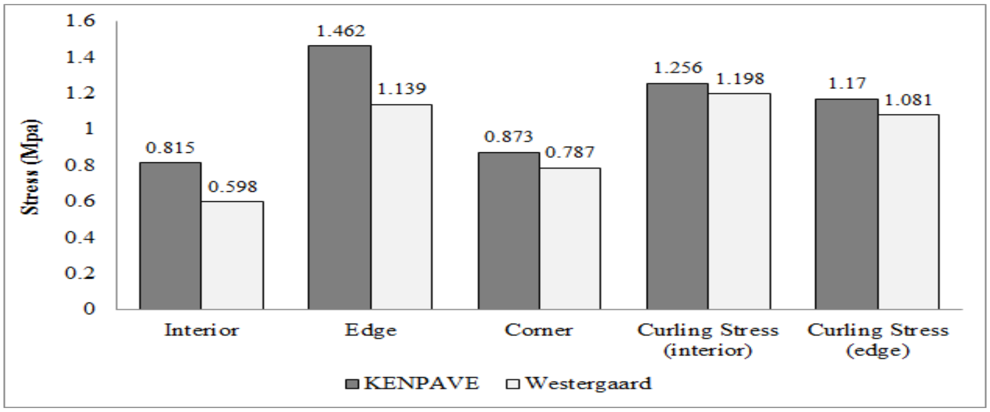


Fig. 2. Comparison of stresses between Westergaard and KENPAVE method.

4.3. SENSITIVITY ANALYSIS FOR STRESSES

The sensitivity analysis was conducted in order to assess the variation in stresses at different level of material properties and traffic loading. This analysis was conducted using westergaard's method.

Stresses at Different Pavement Thickness:

Stresses were calculated at different locations (interior, edge and corner) under various slab thicknesses. Figure 3(a) shows that increase in slab thickness results significant reduction in stresses at all locations. Figure 3(b) shows the relation between curling stresses and pavement slab thickness. Curling stresses are maximum at slab depth of 200 mm and stresses decreases with the increase of slab depth. Curling stresses are resulted due to temperature difference at top and bottom of slab. This temperature variation across slab thickness is usually non-linear and this variation is more at top and little at bottom of slab [11]. Thus differential temperature change results reduction in curling stresses with the increase of slab depth.

Stresses at Different PCC Modulus of Elasticity:

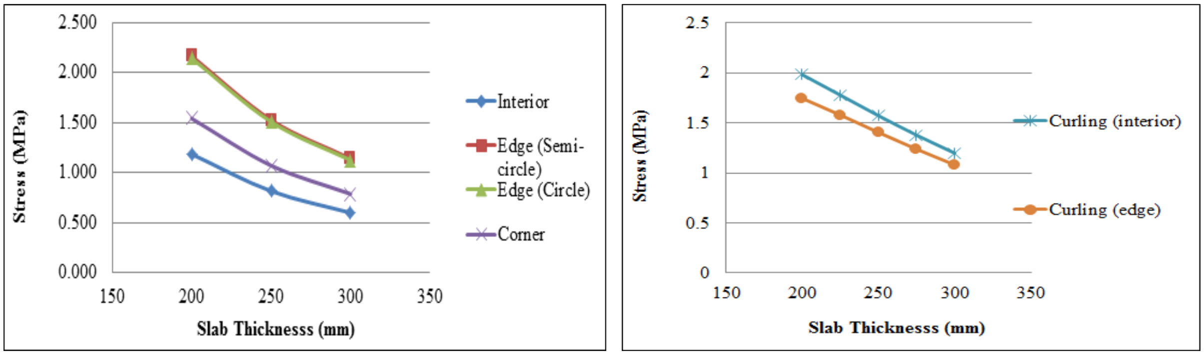
Result of loading and curling stresses at different PCC modulus of elasticity with slab thickness = 12in (300mm) are presented in Figure 3(c). Results show that change in different stresses with increase of PCC modulus of elasticity is linear. As modulus of elasticity increases stresses also increases and it has impact that is more significant on traffic-induced stresses at interior location and curling stresses at edge location.

Stresses at Different PCC Thermal Coefficient of Expansion:

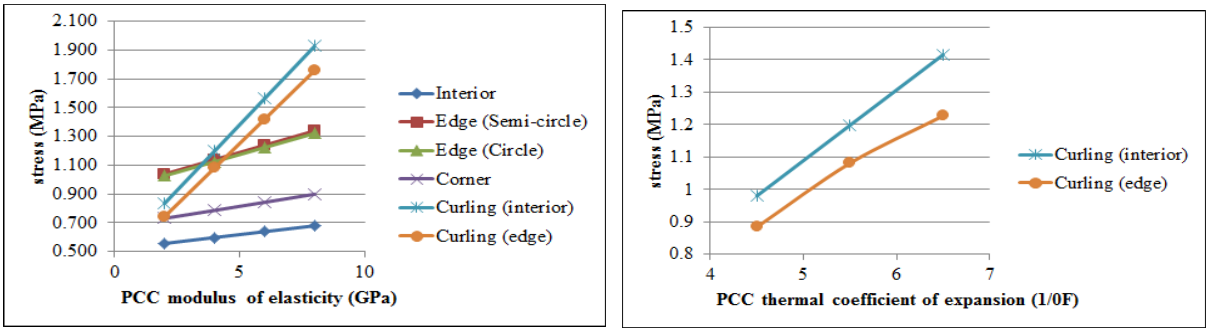
Stresses were calculated under different PCC thermal coefficient of expansion. There was no significant change in loading stresses. Increase in thermal expansion coefficient increases the curling stresses within the pavement structure. The results are shown below in figure 3(d).

Stresses at Different Slab Length:

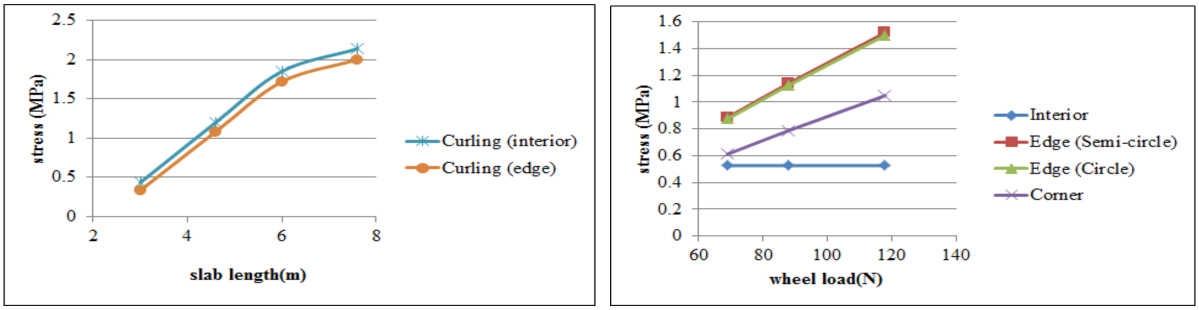
Figure 3(e) show that curling stresses increases with the increase of slab length. This is, because slab geometric dimensions are one of governing parameters in resulting curling stresses along with material thermal properties. Temperature differential is also affected with the increase of slab length, which results higher stresses. These results imply that in order to minimize the curling stresses appropriate length needed to be selected.



(a) Loading stresses versus slab thickness (b) Curling stresses verses slab thickness



(c) Loading stresses versus PCC modulus of elasticity (d) Stresses versus PCC thermal coefficient of expansion



(e) Stresses versus slab length (f) Stresses versus wheel load

Fig. 3. Results of sensitivity analysis for stresses at different locations.

Stresses at Different Wheel Loads:

The stresses were calculated with respect to 7000, 9000, 12000 lb wheel loads. Figure 3(f) shows that by increasing the wheel load the corner and edge loading stresses increase but the interior stresses remain constant. This may be due to different supporting conditions at bottom of slab at interior, edge and corner. There is no significant effect on curling stresses, as they remain constant under different wheel loads.

5. CONCLUSIONS

- The maximum loading stress calculated is 1.139MPa, which occurs at the edge.
- The maximum curling stress occurs at interior, which is 1.198MPa.
- For both Westergaard and sensitivity analysis the critical loading stress appear at the edge and critical curling stress occurs at the interior.
- For both Westergaard and sensitivity analysis the critical loading stress appear at the edge and critical curling stress occurs at the interior.
- Computed stresses with Westergaard method are significantly lower than KENPAVE software stresses for traffic loading whereas the difference for curling stresses is less.
- Sensitivity analysis is significant tool in finding the optimum design of rigid pavement structure.
- It is recommended that the optimum thickness of slab is 300 mm for selected values of input parameters as loading and curling stresses are minimum at this depth.
- KENPAVE software program provides more accurate results for stress analysis as Westergaard method has certain limitation while considering underneath support to concrete slab.

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