2D ANALYSIS OF STRESSES AND DISPLACEMENTS OF ROLLER COMPACTED CONCRETE PAVEMENTS (RCCP) FOR LOW VOLUME ROADS UNDER VEHICULAR LOADING

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Abstract

The American Concrete Institute (ACI) 116R defines RCC as "Concrete compacted by roller compaction; concrete that in its unhardened state will support a roller while being compacted". RCC as a pavement material has been gaining acceptance over the past years. RCC can combat the problems often encountered with flexible bituminous pavements. RCC is the commercial name used for concrete placed with conventional hot mix bituminous paving equipment then compacted with vibratory rollers. This early stiffness makes the compaction process of RCC a feasible construction method and therefore eliminates the need for forms, finishing, dowels and steel reinforcement. The main objective of pavement design is to calculate the optimal thickness of different structural layers. In the design of rigid pavements, it is important to determine the thickness of slab in case of rigid slab taking most of the load carrying capacity. Roller Compacted Concrete Pavement belongs to the family of rigid pavements. Therefore the methods used for jointed plain concrete pavements are used for analyzing and designing of Roller Compacted Concrete Pavement. These methods primarily depend on "WESTERGAARD's" analytical solution, which determines the mechanical response of a concrete slab under vehicular loading. Analysis of rigid pavements consists of determination of stresses, strains and displacements in a slab induced by vehicular and/or environmental loading. The model pavement will be analyzed under a tire load of 30kN with tire pressure of 0.5N/mm^2, tire load of 51kN with a tire pressure of 0.7N/mm^2, tire load of 65kN with a tire pressure of 0.74N/mm^2; applied at three different locations namely, the pavement center, the pavement corner and the pavement edge using ALIZE, IAONNIDES and PORTLAND CEMENT ASSOCIATION (PCA) equations. For the applied tire load relative stresses and displacements will be calculated at three different locations. IRC: SP-62-2004 guidelines have been followed.

Keywords: *Wheel Load, Roller Compacted Concrete Pavement, Tire Pressure, Modulus of Sub grade Reaction.*

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1. INTRODUCTION

Roller Compacted Concrete is the commercial name used for concrete placed with conventional hot-mix asphalt paving equipment, then compacted with rollers[5]. The basic ingredients used for conventional concrete are used for RCC; but RCC is a drier mix made with low water-cement ratio, but with same cement content as that of a conventional concrete. Therefore, RCC is well renowned as a "ZERO-SLUMP" concrete. Hence, there will be early stiffness in the concrete & thus the compaction process of RCC is quite easier compared to conventional concrete & thus construction of RCC pavements is simple, fast & economical. In addition, RCC pavements are highly rigid, due to this reason; there is no problem of deformation that usually occurs in flexible pavements.

The main objective of pavement design is to calculate the optimal thickness of its different structural layers; therefore several design methods for rigid pavements were developed to determine the necessary concrete slab thickness[8]. Determination of the pavement response to vehicular loadings evolved also over time from using simple closed-form formulae, to the use of influence charts, to the use of finite-element method.

2. APPLICATION OF 2D MODELS FOR ANALYSIS OF RCC PAVEMENTS

Analysis of rigid pavements includes determination of stresses, strains & displacements in the slab induced due to vehicular and/or environmental loadings. The first theoretical solutions to the problem of a tire load on a concrete slab laid over a supporting sub grade were proposed by Westergaard in early 1920's[9]. Further research was carried out by some other researchers &Westergaard's solutions were further developed & some more closed-form formulae & influence charts were presented to solve the 2D problem shown in below figure[10,11,12].

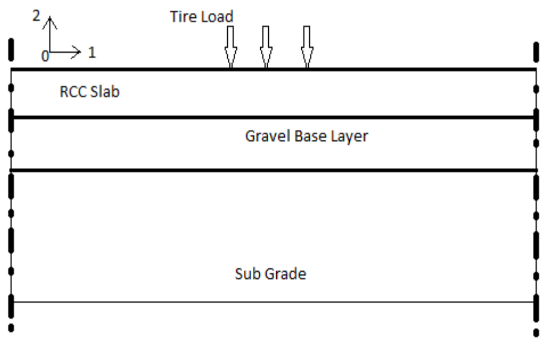


Fig. 1 2D Model Adopted for a RCC Pavement under a Tire Load

2.1 Corner Loading

In case of corner loading, on bottom surface of slab, the equations proposed by Westergaard to calculate the tensile stress (σ) & vertical displacement (Δ) are:

$$\sigma=\frac{3P}{h^2}\left[1-\left(\frac{a\sqrt{2}}{l}\right)^{0.6}\right] \quad (1)$$

$$\Delta=\frac{P}{kl^2}\left[1.1-0.88\left(\frac{a\sqrt{2}}{l}\right)\right] \quad (2)$$

Where, 'l' is radius of relative stiffness (m) given by equation (3), 'a' is the contact radius (m), 'P' is the concentrated load (N), 'h' thickness of RCC slab (m), 'k' is the modulus of sub grade reaction (MPa/m);

$$l=\left[\frac{Eh^3}{12(1-v^2)k}\right]^{0.25} \quad (3)$$

Where, 'E' is elastic modulus of RCC slab, 'v' is Poisson's ratio

Further research was carried &Westergaard's (1926) equations were modified by Ioannides (1985) & he suggested the equations;

$$\sigma=\frac{3P}{h^2}\left[1-\left(\frac{c}{l}\right)^{0.72}\right] \quad (4)$$

$$\Delta=\frac{P}{kl^2}\left[1.205-0.69\left(\frac{c}{l}\right)\right] \quad (5)$$

Where, c=1.772*a

A comparison was made between these different equations presented by Westergaard[9] (1926) &Ioannides[10] (1985) with three different load cases:

Case (I): A tire load of P=30kN, with a tire pressure[13] of 0.5N/mm^2
Case (II): A tire load of P=51kN, with a tire pressure of 0.7N/mm^2
Case (III): A tire load of P=65kN, with a tire pressure of 0.74N/mm^2

And in common, having a slab thickness of h=0.20m, three cases for the modulus of sub grade reaction (k=21, 62, 140) and calculated stress & deformation were tabulated in table1.

Table-1: Stresses and displacements for the corner loading case using Westergaard and Ioannides equations

Case (I):

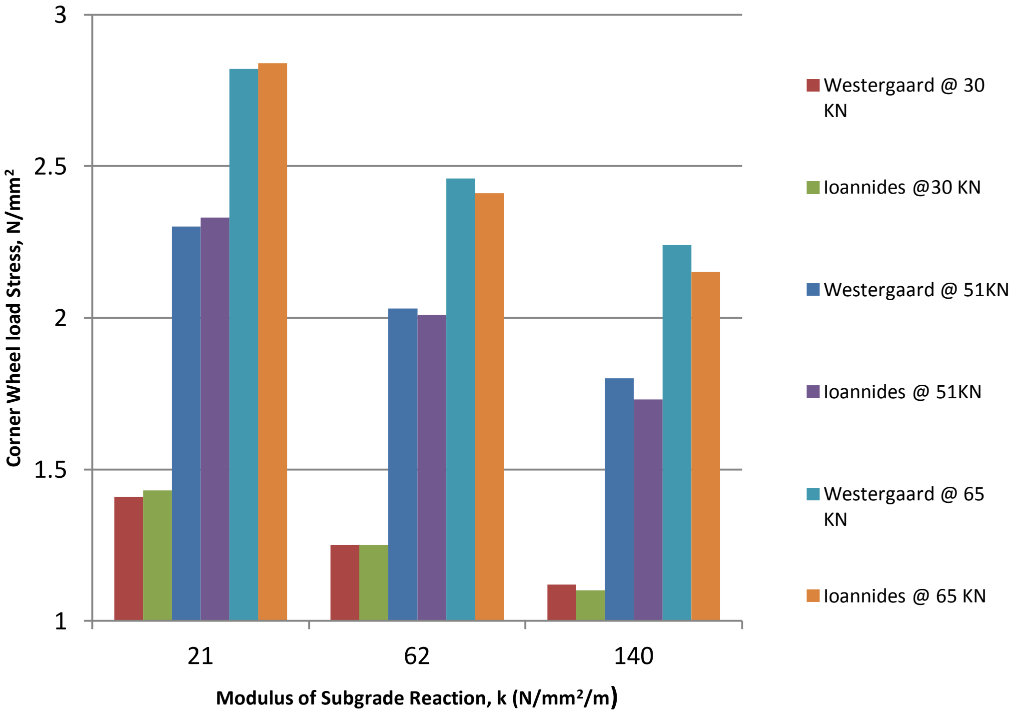
Wheel Load	(N)	30000		
$E_{FOUNDATION}$	(MPa)	30	150	500
CBR		2	15	50
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.622
$\sigma_{WESTERGARDS}$	(MPa)	1.41	1.25	1.12
$\sigma_{Ioannides}$	(MPa)	1.43	1.25	1.10
$\Delta_{WESTERGARDS}$	(mm)	1.32	0.72	0.45
$\Delta_{Ioannides}$	(mm)	1.48	0.82	0.57

Case (II):

Wheel Load	(N)	51000		
$E_{FOUNDATION}$	(MPa)	30	150	500
CBR		2	15	50
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.622
$\sigma_{WESTERGARDS}$	(MPa)	2.30	2.03	1.80
$\sigma_{Ioannides}$	(MPa)	2.33	2.01	1.73
$\Delta_{WESTERGARDS}$	(mm)	2.2	1.2	0.74
$\Delta_{Ioannides}$	(mm)	2.4	1.36	0.85

Case (III):

Wheel Load	(N)	65000		
$E_{FOUNDATION}$	(MPa)	30	150	500
CBR		2	15	50
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.662
$\sigma_{WESTERGARDS}$	(MPa)	2.82	2.46	2.24
$\sigma_{Ioannides}$	(MPa)	2.84	2.41	2.15
$\Delta_{WESTERGARDS}$	(mm)	2.7	1.49	0.83
$\Delta_{Ioannides}$	(mm)	3.09	1.66	0.95



Corner Loading:

For all the 3 loads cases, Ioannides stress for modulus of sub grade reaction $21 N/mm^2/m$ is increasing compared to Westergaard stress.

2.2 Interior Loading

In case of interior loading, on bottom surface of slab, the equations proposed by Westergaard to calculate the tensile stress (σ) & vertical displacement (Δ) are:

$$\sigma=\frac{3(1+v)P}{2\pi h^2}\left[Ln\frac{l}{b}+0.6159\right] \quad (6)$$

$$\Delta=\frac{P}{8kl^2}\left\{1+\frac{1}{2\pi}\left[Ln\left(\frac{a}{2l}\right)+0.673\right]\left(\frac{a}{l}\right)^2\right\} \quad (7)$$

With b=a, if a≥1.724h

$b=\sqrt{1.6a^2+h^2}-0.675h$, if a<1.724h

On further research carried out by Portland Cement Association (PCA), in their procedure of design "Design of Airport Concrete Pavement" [11] ,equation (8) was adopted to calculate the tensile stress in the bottom fiber of the pavement in the slab centre caused by the load of a given axle.

$$\sigma=\frac{0.316P}{h^2}\left(4log\frac{l}{b}+1.069\right) \quad (8)$$

Using the above equations i.e., eqs. (6), (7), (8) with three treated cases, the values of stress and displacement were tabulated in table 2.

Table2: Stresses and displacements for the Interior loading case using Westergaard and Portland Cement Association (PCA) equations

Case (I):

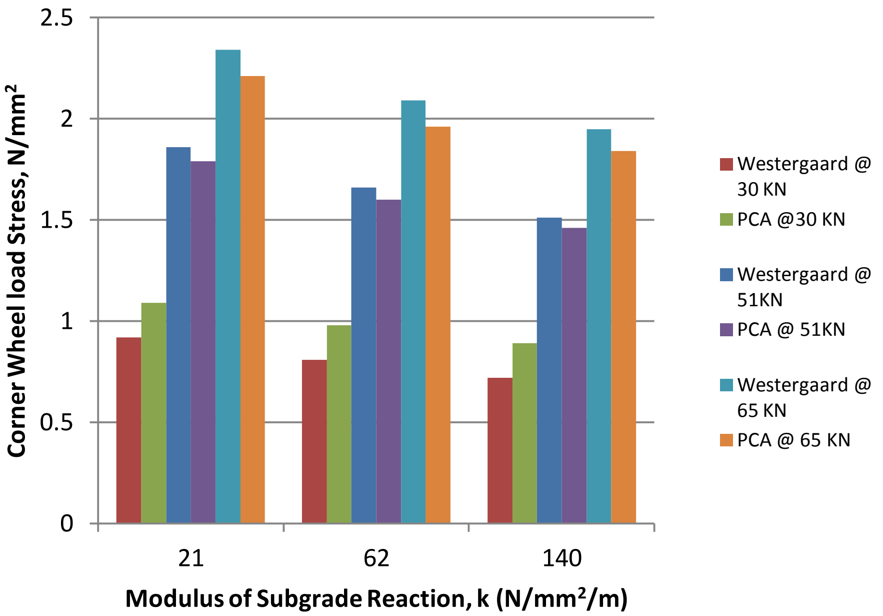
Wheel Load	(N)	30000		
$E_{FOUNDATION}$	(MPa)	30	150	500
a	(m)	0.138	0.138	0.138
b	(m)	0.130	0.130	0.130
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.662
$\sigma_{WeSTERGARDS}$	(MPa)	0.92	0.81	0.72
σ_{PCA}	(mm)	1.09	0.98	0.89
$\Delta_{Westergards}$	(mm)	0.17	0.09	0.067

Case (II):

Wheel Load	(N)	51000		
$E_{FOUNDATION}$	(MPa)	30	150	500
a	(m)	0.152	0.152	0.152
b	(m)	0.142	0.142	0.142
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.662
$\sigma_{WeSTERGARDS}$	(MPa)	1.86	1.66	1.51
σ_{PCA}	(mm)	1.79	1.60	1.46
$\Delta_{Westergards}$	(mm)	0.29	0.17	0.11

Case (III):

Wheel Load	(N)	65000		
$E_{FOUNDATION}$	(MPa)	30	150	500
a	(m)	0.167	0.167	0.167
b	(m)	0.155	0.155	0.155
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.662
$\sigma_{WeSTERGARDS}$	(MPa)	2.34	2.09	1.95
σ_{PCA}	(mm)	2.21	1.96	1.84
$\Delta_{Westergards}$	(mm)	0.38	0.22	0.12



Interior Loading:

PCA stress for 30kN Wheel load with modulus of sub grade 21N/mm^2/m is increased compared to Westergaard stress.

2.3 Edge Loading

For the edge loading case, equations (9), (10) were proposed by Westergaard to calculate the tensile stress and vertical displacement on the bottom surface. These equations are used for calculation of maximum stresses and displacement produced by loads applied on the edges of a rigid slab.

$$\sigma=\frac{3(1+v)P}{\pi(3+v)h^2}\left[Ln\frac{Eh^3}{100ka^4}+1.84-\frac{4v}{3}+\frac{1-v}{2}+\frac{1.18(1+2v)a}{l}\right] \quad (9)$$

$$\Delta=\frac{\sqrt{2+1.2vP}}{\sqrt{Ekh^3}}\left[1-\frac{(0.76+0.4v)a}{l}\right] \quad (10)$$

In the French mechanistic-empirical procedure to design pavements (programmed in the ALIZE software), the above formula was further modified and the maximum tensile stress at the bottom fibers at the edge of the slab is calculated using equation (11).

$$\sigma=\frac{0.572P}{h^2}\left(4log\frac{l}{b}+0.359\right) \quad (11)$$

Using the above equations i.e., eqs. (9), (10), (11) with three treated cases, the values of stress and displacement were tabulated in table 3.

Table3: Stresses and displacements for the CORNER loading case using Westergaard and Alize[12] equations

Case (I):

Wheel Load	(N)	30000		
$E_{Foundation}$	(MPa)	30	150	500
a	(m)	0.138	0.138	0.138
b	(m)	0.130	0.130	0.130
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.662
$\sigma_{Westergard}$	(MPa)	2.14	1.85	1.63
σ_{ALIZE}	(MPa)	1.67	1.47	1.32
$\Delta_{Westergard}$	(mm)	1.10	0.61	0.39

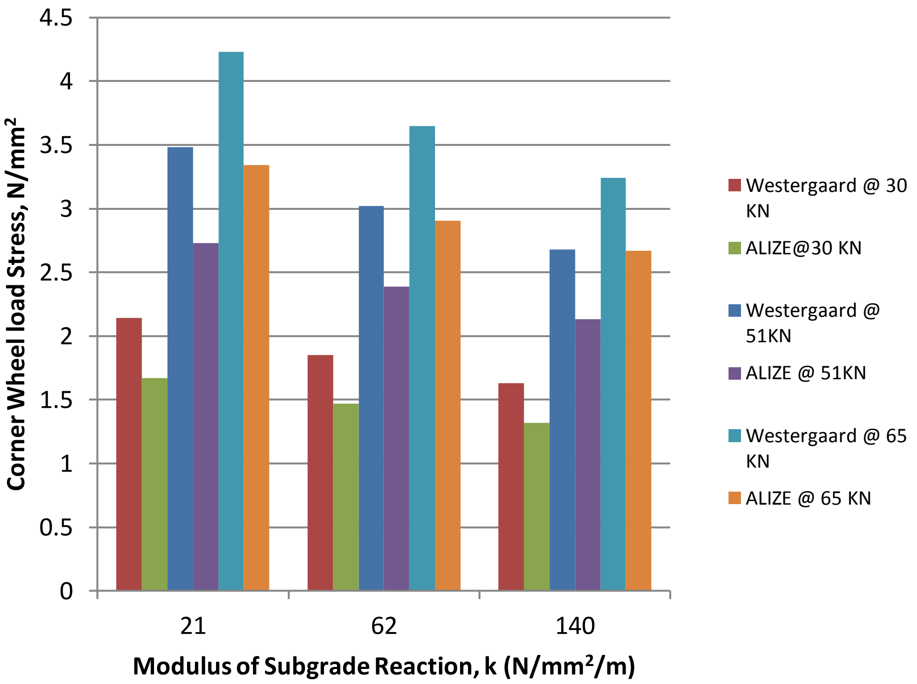
Case (II):

Wheel Load	(N)	51000		
$E_{Foundation}$	(MPa)	30	150	500
a	(m)	0.138	0.138	0.138
b	(m)	0.130	0.130	0.130

E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.662
$\sigma_{Westergard}$	(MPa)	3.48	3.02	2.68
σ_{ALIZE}	(MPa)	2.73	2.39	2.13
$\Delta_{Westergard}$	(mm)	1.42	0.79	0.50

Case (III):

Wheel Load	(N)	65000		
$E_{Foundation}$	(MPa)	30	150	500
a	(m)	0.167	0.167	0.167
b	(m)	0.155	0.155	0.155
E_{RCC}	(MPa)	30000	30000	30000
k	(MPa/m)	21	62	140
l	(m)	1.0	0.762	0.662
$\sigma_{Westergard}$	(MPa)	4.23	3.65	3.24
σ_{ALIZE}	(MPa)	3.34	2.905	2.67
$\Delta_{Westergard}$	(mm)	1.33	0.68	0.419



Edge Loading

Alize stress is decreased compared to Westergaard stress at all loads cases & at all modulus of sub grade reaction values.

3. INTERPRETATION

3.1 Corner & Interior

The calculated displacements for the interior loading case were found to be lower compared to corner loading. Stresses due to interior loading were about 65% of that due to corner loading & deflections were about 13%.

3.2 Corner & Edge

The calculated displacements for edge loading case were found to be lower compared to corner loading. Stresses due to corner loading were about 65% of that due to edge loading & the deflection were about 85%.

3.3 Interior & Edge

The displacements for interior loading were found to be lower compared to edge loading. Stresses due to Interior loading were about 45% of that due to edge loading & deflections were about 15%.

4. DISCUSSION

From the above studies, stresses due to edge loading case were higher than those for interior & corner loading cases. On the other hand, displacements calculated for interior loading is lower compared to corner & edge loading cases.

5. CONCLUSION

The comparison of the stresses & displacements were predicted using different 2D models. All methods used with all cases analyzed shows that the edge loading case induces higher stresses than interior and corner loading cases and corner loading case induces high deformation than interior and edge loading cases.

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