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A critical review of the PCA and IRC methods of thin white topping pavement design

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Abstract

The concept of Thin White Toppings (TWT) is gaining momentum across the nations as an economical and durable rehabilitation technique for the bituminous roads in distress compared to repairs or rehabilitations done with bituminous mixes. On the other hand, constructing a completely new cement concrete (CC) pavement in these stretches by removing the existing pavement structure is a very costly alternative. So, Portland Cement Association (PCA) constructed some test sections of TWT and developed the performance equations based on the performance of the test sections. Indian Roads Congress (IRC) adopted these equations and simplified them with minor changes for calculating the stresses. These changes lead to overestimation of stresses and subsequent reduction in cost saving for TWT compared to constructing a new concrete pavement. The present study examines the differences between IRC and PCA design methods for TWT by considering various parameters. Both methods consider 8 T single axle load and 16 T tandem axle load for estimating the stresses in CC layer. The stresses estimated with IRC equations are higher compared to the stresses estimated with PCA equations of the order of 40 to 50 percent for 8 T single axle load and of the order of 0 to 22 percent for 16 T tandem axle load.

Keywords: Thin white topping; rehabilitation; performance;

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1. Introduction

Pavements constructed all over the world are predominantly black top roads (bituminous roads). Cement concrete pavements are constructed only in places where there is huge truck traffic or weak subgrade and where maintenance of bituminous roads is challenging. The major reason for not preferring cement concrete (CC) pavements by the highway agencies is the higher initial cost of the CC pavements. But once constructed the CC pavements practically need no maintenance and overall life cycle cost of a well designed and constructed CC pavement is less compared to that of a bituminous pavement.

For the bituminous roads the reduction in serviceability is quick and high. The aging and rutting due to heat pose problems at top surface apart from the fatigue damage initiated at the bottom of bituminous layer, thereby necessitating frequent overlays either from functional or structural aspect. This leads to the build-up of thick bituminous layers over time and the overlay will become part of the ever increasing thickness of bituminous layer which adds more and more cost while offering the same level of service with same drawbacks. This is where the thin white topping (smaller panel size concrete overlay over existing bituminous pavement) comes into picture with its reduced thickness of concrete layer with very little or no requirement of base preparation as done in the case of thick concrete pavements.

When a thin concrete overlay of thickness 100 to 150 mm (or even lesser for ultra-thin white toppings) is provided over the existing bituminous pavement (which is profile corrected for surface cracks and rutting) with a smaller panel size of the order of 1.0 m X 1.0 m or 2.0 m X 2.0 m, it is likely to perform well without any need for maintenance for a long time as the cement concrete (CC) panels distribute the load before transferring it onto the bituminous (base) layer and hence rutting is eliminated. The aging effect of bitumen will not be an issue as there is a layer of concrete above the bituminous layer. The smaller panels which reduce the flexural stresses substantially and transfer the loads through compressive force (4-way vertical punching shear on base), will prove to be more cost effective in construction and are also practically maintenance free and long lasting. This thin white topping (TWT) is as good as a new rigid pavement with no cost for removing older bituminous pavement and constructing new sub-base, and Dry Lean Concrete (DLC) base and higher thickness of Concrete layer. So, the cost of TWT will be only 50 to 60 % of the cost of construction of conventional CC pavement.

The main principle involved in white topping that lead to reduced thickness requirement of CC are:

- Presence of a strong base (higher effective modulus of subgrade reaction)
- Smaller panel size reduces the flexural stresses due to reduced bending moment as a result of short span (Bending Moment for slab varies with square of span)
- Bonding of Base and CC layers leads to increase in the combined flexural stiffness and as a result flexural tensile stress in CC layer decreases (due to shifting of neutral axis towards lower layer)

2. Overview of design methodology adopted in IRC and PCA

Concrete pavement design can be done in many ways with different analysis tools available currently. The early rational approach for rigid pavement design was proposed by Westergaard (1926) as a thin slab resting on Winkler foundation. It was subsequently updated by many researchers. It is the basis for concrete pavement design in Indian Roads Congress (IRC): 58 – 2002 guidelines used in India until IRC: 58 – 2011 guidelines came into circulation. IRC : 58 -2011 and subsequent revision in 2015 both used Finite Element Analysis tools for calculating stresses and for which stress charts were developed. These methods and guidelines are suitable for design of conventional concrete pavement where the slab sizes are typically 3.5 m X 4.5 m. There is no design methodology or performance equations available for smaller slab sizes until the PCA equations were published for designing thin white topping with smaller panel sizes. IRC: SP: 76-2015 used these PCA equations and simplified them with minor approximations which provided guidelines for design of thin white topping in India.

The white topping design equations (stress analysis) presented in IRC: SP: 76-2015 are adopted from PCA design procedure, with little modifications. The PCA equations were originally developed by Mack et al. (1997) and Wu et al. (1998) for bonded concrete over asphalt (BCOA) based on 3D-FEM models and field data from UTW sites in Missouri and Colorado, USA.

Equations 1 and 2 presented here are the PCA equations for calculating corner stresses under 18 kips single axle load and 36 kips tandem axle load respectively.

$$\log_{10}(\sigma_{PCC,18k,SAL}) = 5.025 - 0.465\log_{10}k + 0.686\log_{10}\left(\frac{L_{adj}}{l_e}\right) - 1.291\log_{10}l_e \quad (1)$$

$$\log_{10}(\sigma_{PCC,36k,TAL}) = 4.898 - 0.599\log_{10}k + 1.395\log_{10}\left(\frac{L_{adj}}{l_e}\right) - 0.963\log_{10}l_e - 0.088\left(\frac{L_{adj}}{l_e}\right) \quad (2)$$

The terms L_{adj}, l_e are explained in equations 7 and 10.

Equation 3 represents PCA equation for stress due to temperature differential in concrete.

$$\Delta\sigma_{PCC,\Delta T} = 28.037 - 3.496\alpha_{PCC}\Delta T + 18.382\left(\frac{L_{adj}}{l_e}\right) \quad (3)$$

IRC: SP: 76 - 2015 equations for corner stress under 8 Tonne (18 kips) single axle load and 16 Tonne (36 kips) tandem axle load are presented in equations 4 and 5 respectively.

$$\log_{10}(\sigma_8) = 3.6525 - 0.465\log_{10}k + 0.686\log_{10}\left(\frac{L}{l_{e*}}\right) - 1.291\log_{10}l_{e*} \quad (4)$$

$$\log_{10}(\sigma_{16}) = 3.249 - 0.599\log_{10}k + 1.395\log_{10}\left(\frac{L}{l_{e*}}\right) - 0.963\log_{10}l_e - 0.088\left(\frac{L}{l_{e*}}\right) \quad (5)$$

Where 'L' is the length of square panel, and l_{e*} is radius of relative stiffness of CC panel as calculated from equation 9.

IRC: SP: 76 - 2015 equation for stress in PCC due to temperature differential is shown as equation 6.

$$\sigma_T = 1.933 - 241000(\alpha\Delta T) + 1.267\left(\frac{L}{l_{e*}}\right) \quad (6)$$

PCA and IRC equations are essentially same except for the units of input and output parameters.

The key factors considered in calculating stresses in both methods are:

i. k value of subgrade
ii. radius of relative stiffness of slab
iii. length of the panel
iv. Temperature differential

However, there is a difference in the way these parameters are used in calculating stresses in concrete and/or bituminous layer and these differences are explained in the following text.

The stresses were calculated for 18 kips / 8 T single standard axle and for other single axle loads the stresses are linearly extrapolated. Similarly, stresses are calculated for 36 kips /16 T tandem axle load and extrapolated for other tandem axle loads linearly. The design procedure appears to be similar in IRC and PCA methods, except for the following differences:

i. The ‘k’ value considered in PCA method is modulus of subgrade reaction of soil where as in IRC method ‘k’ value on top of bituminous layer is considered, which is estimated either from American Concrete Pavement Association (ACPA) charts or from Portaland Cement Association (PCA) chart depending on the available data (Benkelman beam deflection data or from layer thicknesses). Hence, the ’k’ value used in IRC code is higher than what is taken in PCA.

ii. Radius of relative stiffness value used in IRC is calculated from only concrete layer thickness, as ‘k’ on top of bituminous layer is taken into account, where as in PCA method the effective radius of relative stiffness of combined section of cement concrete and asphalt concrete is considered. So, the ‘le’ value estimated in PCA method is higher than that taken in IRC.

iii. The effective radius of relative stiffness as calculated in PCA method is shown in equation 7 along with equation 8 that is used for calculating position of neutral axis.

$$l_e = \sqrt[4]{E_{PCC}\frac{\left[\frac{t_{PCC}^3}{12} + t_{PCC}\left(NA - \frac{t_{PCC}}{2}\right)^2\right]}{[k(1-\mu_{PCC}^2)]} + E_{HMA}\frac{\left[\frac{t_{HMA}^3}{12} + t_{HMA}\left(t_{PCC} - NA + \frac{t_{HMA}}{2}\right)^2\right]}{[k(1-\mu_{HMA}^2)]}} \qquad (7)$$

Where $$NA = \frac{\frac{E_{PCC}t_{PCC}^2}{2} + E_{HMA}t_{HMA}\left(t_{PCC} + \frac{t_{HMA}}{2}\right)}{(E_{PCC}t_{PCC} + E_{HMA}t_{HMA})} \qquad (8)$$

The terms E_{PCC} ,t_{PCC}, μ_{PCC} and E_{HMA} , t_{HMA}, μ_{HMA} are elastic moduli, thicknesses and poissons ratios of Plain Cement Concrete (PCC) and Hot Mix Asphalt (HMA) layer respectively.

The radius of relative stiffness term used in IRC: SP: 76 -2015 is presented in equation 9

$$l_{e*} = \sqrt[4]{\frac{[E_{PCC}t_{PCC}^3]}{[12\,k(1-\mu_{PCC}^2)]}} \qquad (9)$$

iv. The panel dimension is directly taken in IRC method where as in case of PCA, the panel dimension is converted into a factor and that is taken as ‘L_{adj}’

The L_{adj} taken in PCA method is given in equation 10

$$L_{adj} = 12\left\{8 - \left[24/\left(\frac{L}{12} + 2\right)\right]\right\} \qquad (10)$$

v. The PCA method considers white topping as bonded concrete overlay as effective radius of relative stiffness ‘le’ is calculated; where as in IRC the design is for un-bonded concrete overlay as the ‘k’ on top of bituminous layer is considered.

The calculation of strains in HMA layer are not considered in the present study.

In-spite of these differences in the approach and parameters considered in design, IRC still uses the same equations (only with unit conversions and corresponding constants) to calculate the stresses at the corners of the panels, as corner cracking is considered critical for thin white toppings. But, the IRC equations overestimate the stresses in CC layer leading to over design of CC layer thickness. This in turn leads to low acceptability of TWT as the cost saving does not seem to be substantial. Even though there is higher factor of safety for CC layer due to overdesign, it cannot be quantified. The differences in design thicknesses obtained from both PCA and IRC methods are presented through a sample calculation with the following parameters.

$k_{subgrade}$ = 20 MPa/m, Thickness of granular layer = 300 mm, and thickness of Bituminous Layer = 100 mm with modulus of resilience of 1000 MPa.

$k_{\text{on top of bituminous layer}}$ = 55 MPa/m as estimated from ACPA charts.

The stress in PCC layer of thickness 150 mm for different panel sizes is estimated for 8 T single axle load and 16 T tandem axle load using both IRC and PCA equations and the results are plotted as shown in Figures 1 and 2.

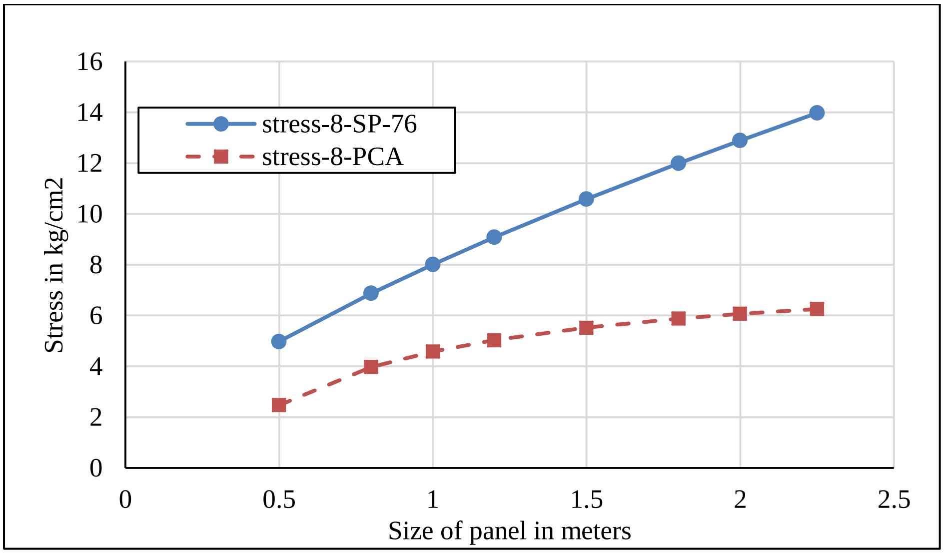

Figure 1: Variation of stress with panel size for 8 T single axle load

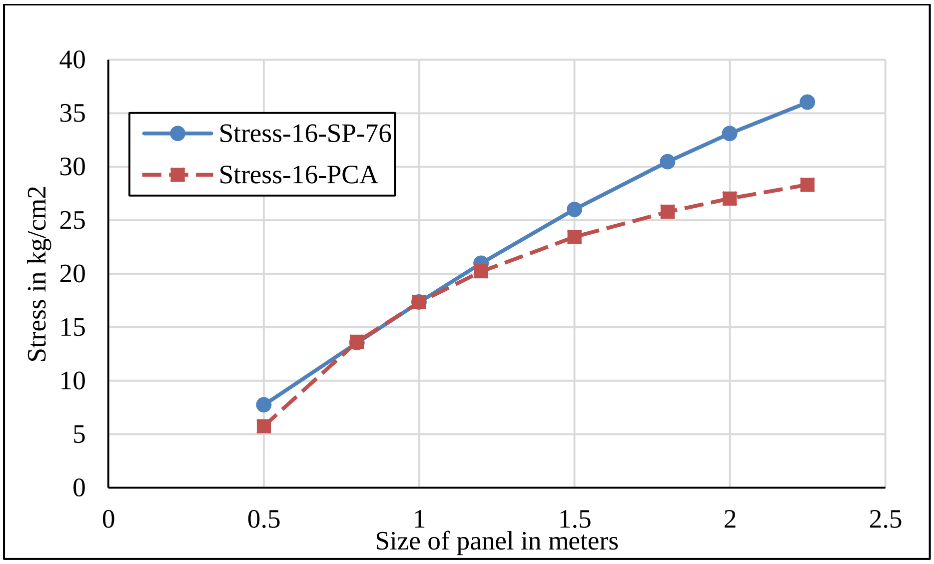

Figure 2: Variation of stress with panel size for 16 T tandem axle load

There is a difference in stress estimated by PCA and IRC equations of the order of 40 to 50 % due to 8 T single axle load as shown in Figure 1. The difference in stresses from both methods due to 16 T tandem axle load are of the order of 0 to 22% with 1 m panel size having both values matched as can be seen in Figure 2. However, a tandem axle may not be accommodated on a 1 m long panel as the centre to centre tandem axle spacing is of the order of 1.2 to 1.3 m. This explains the variation in stresses estimated from both methods and also that IRC is over estimating stresses. Similar trend was observed for other thicknesses as well. The over-estimation of stress may provide an extra factor of safety to balance the effects of vehicular overloading and the poor quality control practices followed in India as some researchers argue. However, the vehicular overloading is considered in calculating stresses from the axle load spectrum and the quality control practices in India are now on par with the world standards. So, the IRC method is clearly over-estimating stresses.

3. Conclusions

The stresses estimated with IRC equations are higher compared to the stresses estimated with PCA equations of the order of 40 to 50 percent for 8 T single axle load and of the order of 0 to 22 percent for 16 T tandem axle load. This increases the thickness requirement for TWT. When thickness requirement is more, the cost saving compared to conventional concrete pavement may not appear substantial. This may not encourage adoption of TWT technology. At the same time; the PCA equations are developed for the traffic conditions prevalent in USA where there is little or no overloading and hence may or may not be completely suitable for Indian traffic conditions of overloading. So, there is a need for evaluating performance of TWT for Indian conditions and developing performance equations for designing new TWT pavements.

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