CRUSHING DAMAGE ESTIMATION FOR PAVEMENT WITH LIGHTLY CEMENTITIOUS BASES

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ABSTRACT

Crushing (or compression) failure and associated surface deformation of lightly cementitious (stabilised) materials used for base/sub-base course layers in pavements has been well established in the South African pavement design practice since the 1990s. Typically, crushing failure starts at the surface of the cementitious base layer, and could extend to 50 mm deep, depending on tyre load/stress conditions. Recently developed crushing damage relationships for 2, 5, 10, 15 and 20 mm level of deformation ("rut") were proposed for practical application on these pavements. The aim of this paper is the practical application of these relationships for an un-surfaced and surfaced pavement with a typical stabilised (C3 – quality) base layer. Currently there are up to 15 standard pavement designs with cementitious base layers proposed in TRH 4 (1996). This paper demonstrates the impact of four different tyre models (including overloading) used in the mechanistic-empirical design of these pavements. In particular, the importance of adequate surface protection is demonstrated with reference to the vertical tyre contact stresses expected on these cementitious layers. The impact of the findings extends to the use (or not) of C3 - quality bases and associated surfacings on all categories of pavements carrying up to 10 million E80s. This is considered important towards the upgrading of secondary (or alternative) road pavements using cementitious stabilisers in the base layer, especially in the light of the potential future attraction of heavily loaded vehicles - with or without overloading on the tyres.

1 INTRODUCTION

Lightly cementitious pavement materials (road aggregate treated with not more than 3 to 4 % of hydraulically based binders such as cement, lime, etc.) are commonly used in South African pavements. Previous research works to evaluate the failure mechanism of these materials dates back in 1990s. Lightly cementitious pavement material exhibits two traffic associated failure modes; the fatigue cracking and the crushing or compression failure (De Beer, 1990). The fatigue cracking is controlled by the maximum horizontal tensile strain at the bottom of the layer; whereas the crushing damage is controlled by the maximum vertical compressive stress at the top of the cementitious layer (which is defined by it's unconfined compressive strength (UCS)). The focus of this paper is on the crushing damage of these cementitious layers.

Over the past few years, extensive research studies have been conducted in South Africa to support the revision of the South African Pavement Design Method (SAPDM) which is currently at its final stage (SAPDM, 2014). Such research studies included the development of new crushing damage relationships for lightly cementitious pavement materials (Litwinowicz and De Beer., 2013; De Beer., 2013). The newly developed crushing damage relationships are proposed for practical application at *in situ* as-built moisture conditions.

The objective of this paper is to present results of practical application of the newly developed crushing damage relationships for lightly cementitious base layers. The study investigates crushing potential of lightly cementitious base layer of C3 - quality (TRH 14, 1985) on three types of pavement structures using four different tyre-road contact stress models, including overloading. The pavement responses in terms of applied vertical tyre compressive stresses and the resulting crushing life of the cementitious base layer were compared for a combination of pavement structures and tyre-road contact stress models.

2 CRUSHING FAILURE OF LIGHTLY CEMENTITIOUS MATERIALS

Extensive research works to develop empirical transfer functions for crushing damage of lightly cementitious pavement material in South Africa dates back in 1990s. A comprehensive review of the historical development of empirical relationships for crushing damage of lightly cementitious pavement material in South Africa, in a chronological order can be found in a recently published paper by Litwinowicz and De Beer (2013).

The original crushing damage relationships took a form of Equation 1.

$$\mathrm{N_c} = 10^{\mathrm{k_1(1-(\sigma_V/k_2*UCS))}} \quad (1)$$

where, N_c is the number of load cycles to crushing failure; k_1 and k_2 are regression constants; *UCS* is in situ unconfined compressive strength (UCS) of the cementitious layer; σ_V is the applied vertical stress. From Equation 1, the stress ratio (SR) can be defined as ratio of the applied vertical stress to UCS of the cementitious layer (Equation 2).

$$SR = \frac{\sigma_V}{UCS} \quad (2)$$

It is important to mention that the vertical contact stress (σ_V) in Equation 2 was assumed to be equal to the tyre inflation pressure. Recent studies using Stress-In-Motion (SIM) technology have shown that the tyre inflation pressure does not necessary be equal to the vertical contact stresses (De Beer, 2008; De Beer *et al.,* 2012; Maina *et al,* 2013).

Substituting Equation 2 into Equation 1, Equation 1 can be simplified into Equation 3.

$$\mathrm{N_c} = 10^{\mathrm{k_1(1-(SR/k_2))}} \quad (3)$$

The original work in South Africa using accelerated pavement testing, with Heavy Vehicle Simulator (HVS), resulted to the development of two crushing damage relationships namely; "*crush initiation*" which was considered as 2 mm surface deformation and "*advanced crushing*" which was defined as 10 mm surface deformation of lightly cementitious pavement layer. The original crushing damage relationships have undergone through series of revisions; the 1995 revision resulted into Equations 4 and 5 for crush initiation (N_{ci}) and advanced crushing (N_{ca}) respectively (Theyse et al., 1995).

$$\mathrm{N_{ci}} = 10^{8.316(1-(\mathrm{SR}/1.223))} \quad (4)$$

$$\mathrm{N_{ca}} = 10^{8.994(1-(\mathrm{SR}/1.322))} \quad (5)$$

Recently, Litwinowicz and De Beer (2013) evaluated the crushing damage relationships for lightly cementitious pavement layer with two objectives; to reconfirm the crush initiation (N_{ci}) relationship for *as-built* moisture conditions, and to develop advanced crushing (N_{ca}) relationship for various deformation depths and for *as-built* moisture conditions. The work resulted into development of updated relationship for crush initiation (Equation 6) and four advanced crushing relationships for 5, 10, 15 and 20 mm levels of deformation (Equations 7 to 10).

$$\mathrm{N_{ci}} = 10^{8.2218(1-(SR/1.2450))} \quad (6)$$

$$\mathrm{N_{ca5}} = 10^{8.0160(1-(SR/1.6223))} \quad (7)$$

$$\mathrm{N_{ca10}} = 10^{8.1759(1-(SR/1.7984))} \quad (8)$$

$$\mathrm{N_{ca15}} = 10^{8.0614(1-(SR/1.9785))} \quad (9)$$

$$\mathrm{N_{ca20}} = 10^{7.9941(1-(SR/2.1410))} \quad (10)$$

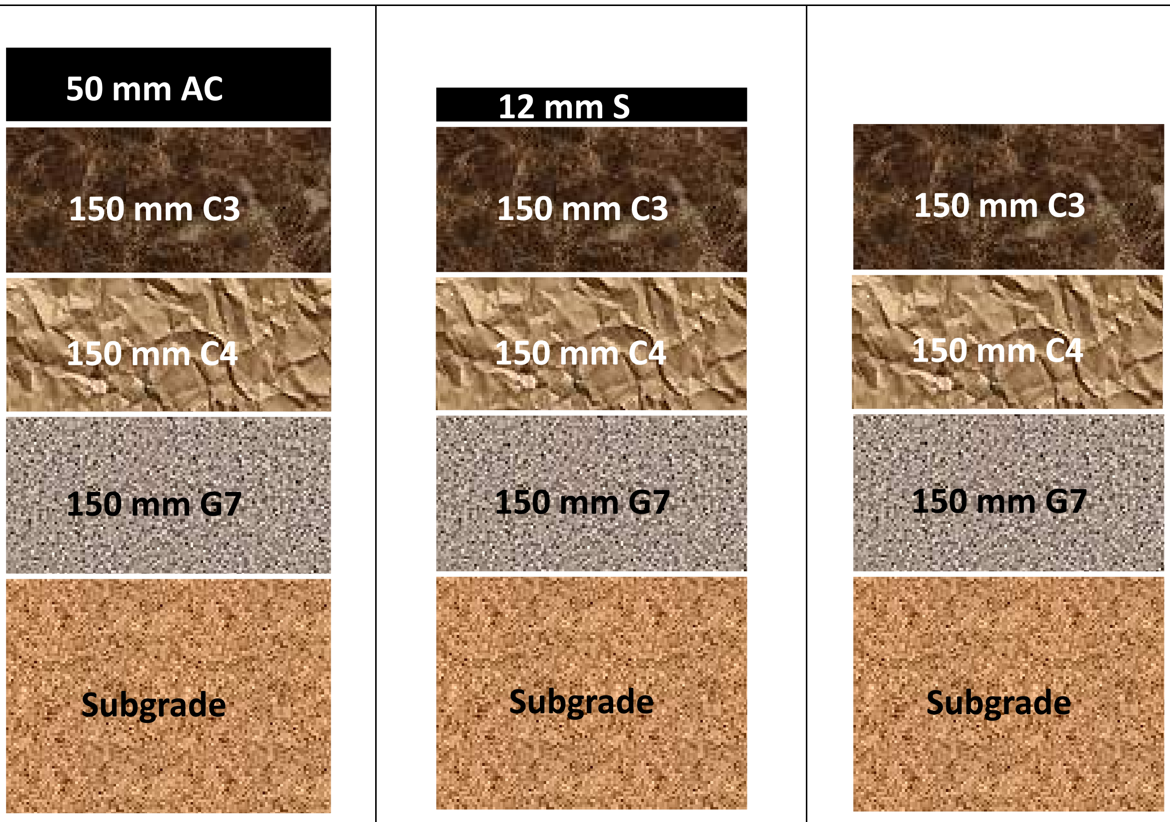
According to the work by Litwinowicz and De Beer (2013), the newly developed damage relationship for crush initiation (Equation 6) does not differ significantly with the original relationship (Equation 4). However, the newly developed relationship for advanced crushing (Equation 8) differs significantly with original relationship for 10 mm deformation (Equation 5). Therefore, the newly developed crushing damage relationships are proposed to be used in South African pavement design procedures. In this paper, the new crushing damage relationships are used to investigate failure of lightly cementitious base layer of C3 – quality (TRH 14, 1985), aiming at the protection of these layers against these crushing failures.

3 PAVEMENT ANALYSIS

3.1 Pavement structures

Three pavement structures (PS1, PS2 and PS3) with lightly cementitious base material (C3) were considered in this paper as illustrated in Figure 1. The material type, properties and thicknesses of base, sub-base, selected and subgrade layers were similar for the three pavement structures; the only difference was the surfacing layers. The first pavement structure had 50 mm asphalt surfacing (Figure 1a); the second pavement structure had 12 mm seal surfacing as recommended in TRH 4 1996 (Figure 1b) and the third pavement structure had no surfacing layer (Figure 1c), which was the reference case. Material properties (Elastic modulus and Poisson’s ratio) were estimated based on recommendations by Theyse et al., (1996). Table 1 presents a summary of material properties used during the multi-layer linear elastic (MLLE) pavement analysis.

Crushing failure of lightly cementitious materials is governed by the imposed vertical compressive stress at the surface of the base/sub-base course. Therefore, it was expected that different protective surfacings will result in different stress conditions at the surface of base/sub-base course which will ultimately result in different crushing life estimations.



(a) Pavement Structure 1 (PS1): 50 mm AC

(b) Pavement Structure 2 (PS2): 12 mm S

(c) Pavement Structure 3 (PS3): No surfacing

Figure 1. Pavement structures

Table 1. Material properties used during MLLE pavement analysis

Material	Elastic modulus (MPa)	Poisson's ratio
Asphalt (AC)/Seal (S)	3500	0.44
Cementitious Base (C3)	1500	0.35
Cementitious Sub-Base (C4)	1000	0.35
Selected layer (G7)	120	0.35
Subgrade	100	0.35

3.2 Tyre-road contact stress models

Traditionally, an assumption of uniform tyre-road contact stress has been used for mechanistic-empirical (ME) pavement modelling. The developments of advanced technologies such as Stress-In-Motion (SIM) have made it possible to model pavements by using more realistic non-uniform tyre-road contact stress (De Beer, 2008; De Beer *et al.,* 2012; Maina *et al.,* 2013). SIM measurements have been successfully used for modelling and analysis of pavements by using software such as General Analysis for Multi-layered Elastic Systems (GAMES) (De Beer *et al.,* 2012 and Maina *et al.,* 2013). In this paper, the CSIR's meGAMES software[1] was used to investigate crushing damage failure of lightly cementitious pavement material, using the newly developed South African crushing damage relationships (Litwinowicz and De Beer., 2013). Four types of tyre-pavement contact stress models were used. For each tyre-pavement contact stress model, only tyre contact stresses in the vertical direction were used in the analysis presented in this paper. The tyre-pavement contact stress models used in this paper are the following:

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[1] Note: meGAMES at CSIR Built Environment – Build Date: meGAMES New Crushing: 29 Jan 2014.

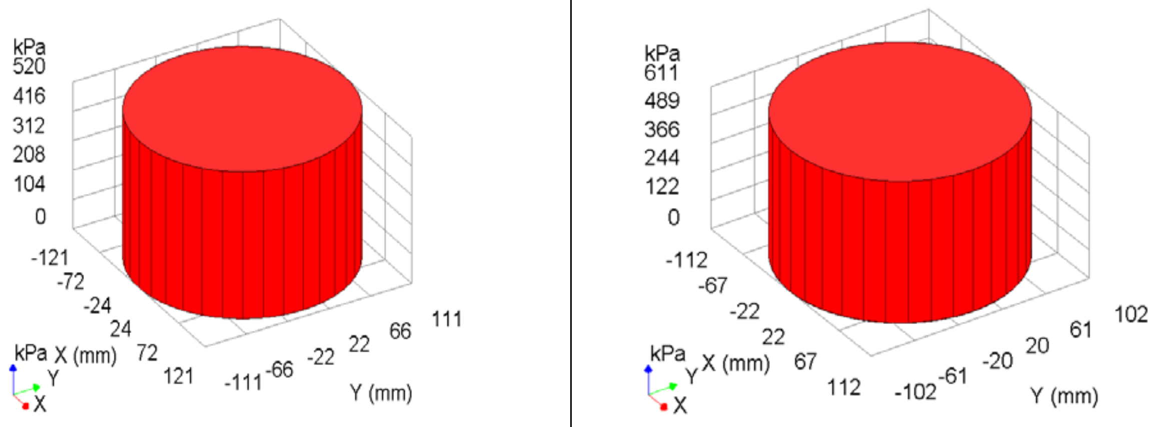
Tyre-road contact-Stress Model 1: Single uniform load on a circular area - conventional 20 kN tyre load at 520 kPa inflation pressure [Traditional Model] (Figure 2a).

Tyre-road contact-Stress Model 2: Single uniform load on circular area - 20 kN tyre load at 520 kPa inflation pressure with fixed width[2] [Limit on tyre width = 204 mm] (Figure 2b).

Tyre-road contact-Stress Model 3: SIM interpolated tyre load of 20 kN load at 520 kPa inflation pressure, showing "*n-shaped*" with multiple circular discs [210 circular discs] (Figure 2c).

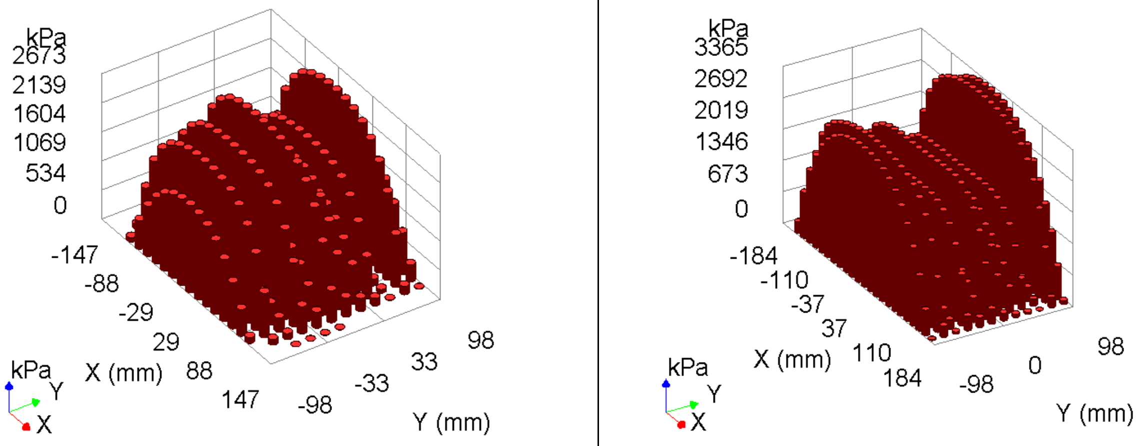
Tyre-road contact-Stress Model 4: SIM interpolated tyre load of 35 kN load at 520 kPa inflation pressure, showing "*m-shaped*" with multiple circular discs (overloading) [285 circular discs] (Figure 2d).

It should be mentioned that the tyre inflation pressure of 520 kPa was use in this paper for illustration purposes only, the actual tyre inflation pressure in South Africa is currently more than 520 kPa (SAPDM, 2014).



(a) Tyre Model 1 [Traditional Model]

(b) Tyre Model 2 [Limit on tyre width=204 mm]



(c) Tyre Model 3 [210 circular discs]

(d) Tyre Model 4 [285 circular discs]

Figure 2. Tyre-road contact stress models used in this study

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[2] Specific tyre used: SA06-Tyre 18 Firestone 12 x R22.5 G391 (SA-HVS)-2004 Caravan side (SAPDM, 2014).

4 RESULTS AND DISCUSSIONS

4.1 Magnitude and position of the maximum vertical stress

Mechanistic analysis software packages are commonly used for multi-layer linear elastic (MLLE) pavement analysis to obtain critical parameters and subsequently compute the life of pavement layers (Theyse et al., 1996). The critical parameter governing the crushing failure of lightly cementitious pavement materials is the maximum vertical compressive stress at the top of the cementitious layer. During pavement analysis and design, an engineer normally selects the position at which the critical design parameters are to be computed. For a conventional single circular load, the maximum vertical compressive stresses have always been assumed to occur directly underneath the tyre at the centre of the circular tyre contact patch (i.e. X = 0 and Y = 0). Findings from this study indicate that, this is not always the case, especially when non-uniform tyre-road contact stress models are considered (i.e. Tyre Models 3 and 4 in this paper). In order to gain better understating of the magnitude and the position of the maximum compressive vertical stresses for the three pavement structures and the four tyre models used in this paper, it was decided to perform mechanistic analysis and compute magnitude *and* the X, Y - position of the maximum vertical compressive stress from the top of the pavement to directly on the surface of C3 - base layer at depth intervals of 5 mm. The results are presented in Table 2.

From the results in Table 2, the following conclusions are drawn:

- For uniform (circular) tyre-road contact stress (i.e. Tyre Models 1 and 2, the maximum vertical compressive stress occur directly underneath the tyre at centre of the circular contact patch (i.e. X = 0 and Y = 0), and
- For non-uniform tyre-road contact stress[3] (i.e. Tyre Models 3 and 4), the maximum vertical compressive stress may not necessary occur in the centre of the patch directly underneath the tyre. However, for pavement structure with thick surfacing layer (Pavement Structure 1 in this paper), the maximum vertical stress at the bottom of the surfacing layer (top of the C3 - base layer) occurred directly underneath the tyre at the tyre centre (i.e. X = 0 and Y = 0). Therefore, computation of crushing life by using vertical compressive stresses directly underneath the tyre at the geometric centre of the contact patch may lead to overestimation of crushing life of cementitious layer for some pavement structures, especially for pavements with thin surfacing layer.

Based on the findings in Table 2, the current CSIR's meGAMES software was improved by implementing a routine search for identifying the magnitude and X, Y - position of the maximum vertical compressive stress so that it can be used for computation of the crushing life of lightly cementitious C3 - layer. This is an improvement compared to the traditional practice where by an engineer is required to specify design location, which may not necessarily correspond to the position of the maximum vertical compressive stress on the C3 – base layer. This could potentially result in an over prediction of the crushing life, and hence premature failure of the C3 – base layer.

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[3] Obtained from TyreStress-Internal software: Build Date: 6 Feb 2014

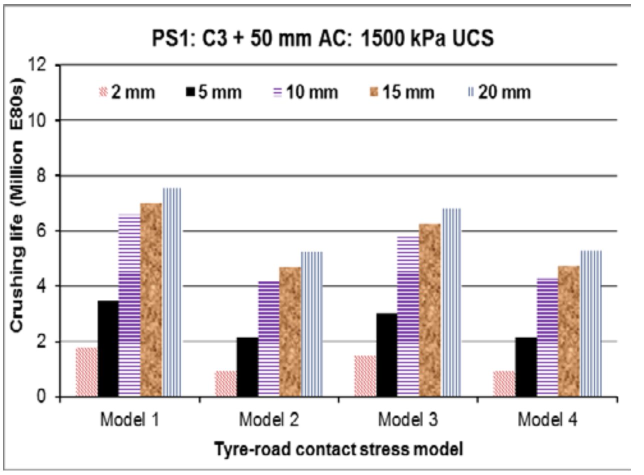
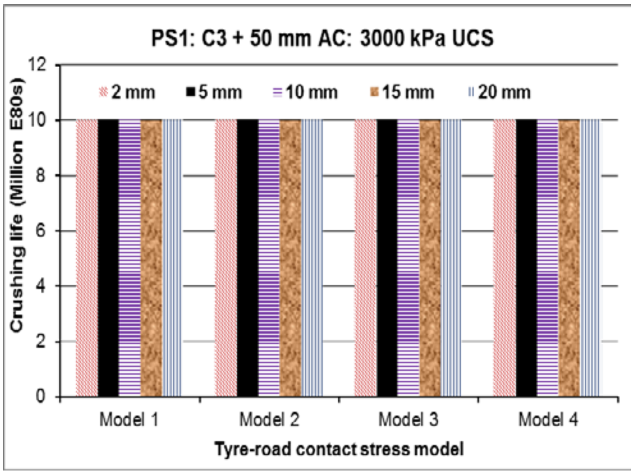
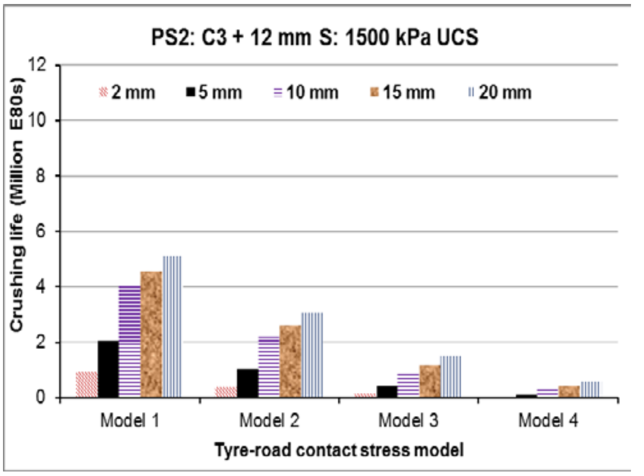
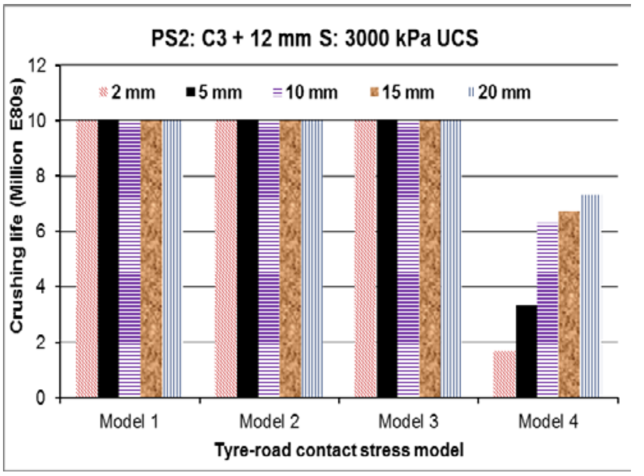
Table 2. Magnitude and X, Y - position of maximum vertical stress at different z – depths. (Shaded cells indicate X, Y positions *not* in the centre of contact patch).

		Tyre Model 1			Tyre Model 2			Tyre Model 3			Tyre Model 4		
	Z (mm)	X (mm)	Y (mm)	Max stress (kPa)	X (mm)	Y (mm)	Max stress (kPa)	X (mm)	Y (mm)	Max stress (kPa)	X (mm)	Y (mm)	Max stress (kPa)
Pavement Structure 1 (PS1)	0	0	0	520	0	0	611	0	76.5	2673	-7.4	76.5	3365
	5	0	0	519	0	0	610	0	76.5	1632	-7.4	76.5	2059
	10	0	0	517	0	0	607	-14.7	-8.5	898	-7.4	76.5	1138
	15	0	0	513	0	0	602	-14.7	-8.5	701	-7.4	76.5	865
	20	0	0	508	0	0	594	0	-8.5	630	-7.4	85	778
	25	0	0	501	0	0	584	0	0	592	-7.4	85	700
	30	0	0	493	0	0	572	0	0	563	-7.4	85	629
	35	0	0	483	0	0	559	0	0	536	-7.4	76.5	573
	40	0	0	472	0	0	544	0	0	510	0	0	541
	45	0	0	461	0	0	528	0	0	487	0	0	525
	50	0	0	448	0	0	511	0	0	466	0	0	510
Pavement Structure 2 (PS2)	0	0	0	520	0	0	611	0	76.5	2673	-7.4	76.5	3365
	5	0	0	520	0	0	611	0	76.5	1601	-7.4	76.5	2028
	10	0	0	518	0	0	609	-14.7	-8.5	839	-7.4	76.5	1051
	12	0	0	517	0	0	607	-14.7	-8.5	734	-7.4	76.5	907
Pavement Structure 3 (PS3)	0	0	0	520	0	0	611	0	76.5	2673	-7.4	76.5	3365

4.2 Impact of tyre-road contact stress model on crushing life

As indicated earlier, the maximum vertical compressive stress at the top of the cementitious layer of a certain UCS controls the crushing failure. The maximum vertical compressive stress at the top of the C3 - layer was used to predict the crushing life of the layer by using crushing damage relationships for 2, 5, 10, 15 and 20 mm levels of deformation. The prediction of crushing life was performed by using two different unconfined compressive stress (UCS) values of the C3 - material; 1 500 kPa (representing lower margin) and 3 000 kPa (representing upper margin). The analysis to predict the crushing life of the C3 - layer for the three pavement structures studied was performed by using each of the four tyre-road contact stress models. Considering that the data used to develop the current advanced crushing damage relationships is limited to 10 million E80s (Litwinowicz and De Beer., 2013), the maximum crushing life for the analysis presented in this paper was also limited to 10 million E80s. Figure 3 shows the results of the crushing life of the C3 - layer. From the figure, the following conclusions are drawn:

- Using 1 500 kPa UCS of C3 - layer; PS 1 (50 mm surfacing) shows that Tyre Model 1 results in higher crushing life, followed by Tyre Model 3. Tyre Models 2 and 4 have relatively similar crushing life. For PS 2 (12 mm seal) and PS 3 (without protective surfacing layer), the crushing life decreases from Tyre Model 1 to 4. Tyre Models 3 and 4 results in zero crushing life for unsurfaced pavement structure (PS 3). It is further observed that the crushing life increases with increasing damage criterion i.e. less crushing life is obtained when using crushing damage relationships for 2 mm compared to damage case of 20 mm;
- Using 3 000 kPa UCS of C3 - layer; PS 1 has a maximum crushing life of 10 million E80s for all four tyre models. PS 2 had a maximum crushing life of 10 million E80s for Tyre Models 1 to 3, whereas the crushing life for tyre Model 4 is less that 10 million E80s. PS 3 has maximum crushing life of 10 million E80s for Tyre Models 1 and 2, and zero crushing life Tyre Models 3 and 4, and
- Overall, higher crushing life was obtained when using 3 000 kPa UCS compared to 1 500 kPa UCS, except for PS 3 where zero crushing life were obtained using Tyre Models 3 and 4 regardless of the UCS value of the C3 - base layer.

1 500 kPa UCS	3 000 kPa UCS
	
	

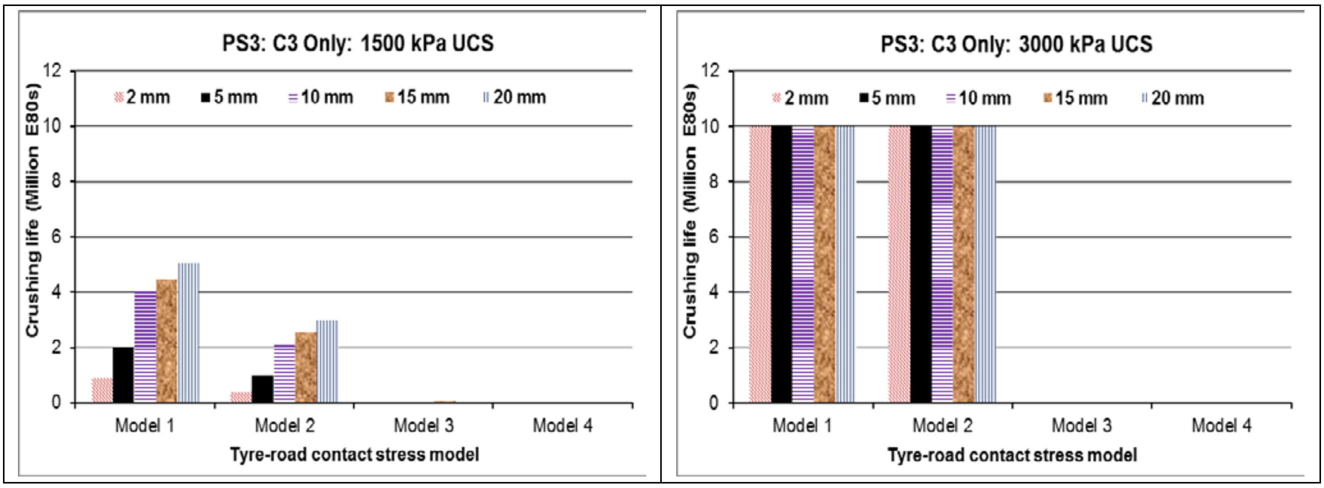


Figure 3. Crushing life estimations for the three pavement structures – this study

4.3 Optimising crushing life of lightly cementitious layer

The crushing life of lightly cementitious layer may be improved by increasing the UCS of the cementitious materials. This is evident from Figure 3 whereby increasing the UCS of the C3 - base layer from 1 500 to 3 000 kPa resulted in significant increase in the crushing life of the C3 - base layer. Alternatively, the desired crushing life may also be achieved by adjusting the thickness of the protective surfacing layer, which will alter the contact stress at the top of the cementitious base layer and subsequently the crushing life. Assuming that the desired crushing life of lightly cementitious base layer is 10 million E80s; from Figure 3 the crushing life of C3 - base layer with UCS of 1 500 kPa did not get close to 10 million E80s, despite the 50 mm thickness of the surfacing layer. This means that in order to achieve the desired crushing life with a minimum thickness of surfacing layer, the UCS of the C3 - material needs to be improved (say at least to 3 000 kPa as used in this paper). After improving the UCS, the thickness of the surfacing layer (i.e. protection) may then be altered to achieve the desired crushing life. This approach is demonstrated in Figure 4 by using Tyre Model 4 and C3 - base material with 3 000 kPa UCS. From Figure 4, it can be seen that a minimum protective surfacing thickness of 20 mm is required to ensure that the desired crushing life of 10 million E80s is achieved for all crushing damage relationships (2, 5, 10, 15 and 20 mm).

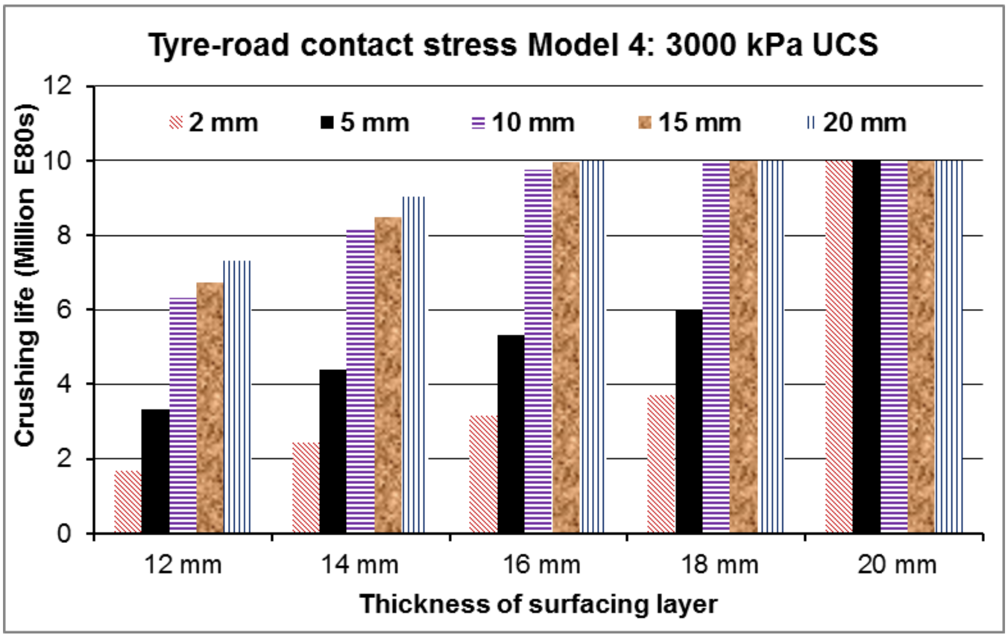


Figure 4. Optimizing crushing life of cementitious layer

5 CONCLUSIONS AND RECOMMENDATIONS

The paper presented results of practical application of the newly developed South African crushing damage relationships for lightly cementitious road pavement material. Based on the results presented in this paper, the following conclusions and recommendations can be drawn:

- The maximum vertical compressive stress does not necessary occur at the centre of the tyre contact patch directly underneath the wheel load. A search routine was introduced to the current CSIR's meGAMES software to identify the magnitude and X, Y - position of maximum vertical stress to be used for computation of crushing life of lightly cementitious base material;
- The conventional circular tyre-road contact stress model results in higher crushing life relative to other tyre models, which could be overestimating the crushing life of lightly cementitious base layers (i.e. increased potential for premature failure);
- Approaches for optimizing the crushing life of lightly cementitious base material with an adequate protective surfacing have been presented, and
- Limited pavement structures and tyre-road contact stress models were considered in this paper, it is recommended that future studies should cover various range of pavement structures and tyre-road contact stress models.

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