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Comparison of Isotropic and Cross-anisotropic Analysis of Pavement Structures

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Abstract: In most existing pavement design methods, pavements are analyzed using linear elastic multilayer theory, with the assumption that isotropic conditions are present in the structural layers of the pavement section. There are however numerous researchers that disagree with this assumption and their research have proven that there are inherent and induced cross-anisotropic material behaviors in the structural layers of a pavement section. The problem facing the South African Mechanistic Design Method (SAMDM) is that this cross-anisotropic behavior of material may reduce the predicted life of pavement sections as described in the Technical Recommendations for Highway (TRH4). The objective of this study was to quantify the effect of cross-anisotropic conditions induced in the pavement layer on the predicted life based on the SAMDM approach.

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***Key words**: Anisotropy; Isotropy; Pavement response.*

Introduction

The purpose of a pavement structure is to distribute and reduce stresses obtained from traffic loading to acceptable levels for the subgrade to handle. It is thus essential to know the actual stresses in the structure as it is loaded. By utilizing appropriate transfer functions, these stresses and accompanying strains give an indication of the predicted life of a pavement section. In pavement analysis there are two approaches of describing material behavior and its properties, isotropy and cross-anisotropy. These approaches influence the methods of determining the stresses in the pavement structure. Isotropic behavior is defined as an assumption that all material properties are the same in all directions, while anisotropic behavior is an assumption that material properties are different in each direction i.e. the elastic modulus of a layer in the horizontal direction differs from that of the elastic modulus in the vertical direction. These two approaches affect the estimation of stresses in layer. The two methods differ in complexity with isotropic analysis having two variables against the five variables of cross-anisotropic analysis [1].

A mathematical model is only as good as the initial assumptions made to derive it. This is an important concept to understand, as models will attain answers that are mathematically correct but do not conform to reality. An example of this is in the isotropic approach to unbound granular material behavior. The model attains a tensile stress that is mathematically correct but from an engineering perspective is incorrect. According to Hooke's Law a stress can only be obtain if there is an accompanying strain in the material, which is not true for unbound granular material moving away from each other. It can thus be argued that cross-anisotropic approach may provide responses that are more realistic.

The objective of this paper is to compare the predicted lives calculated for typical South African pavement structures under isotropic and cross-anisotropic conditions. In South Africa, classical transfer functions where individual layer life (in terms of permanent deformation and/or cracking together with occurrence of crushing in cemented layers (when present)) are usually used to predict ultimate pavement bearing capacity or pavement life [2]. The paper is restricted to variation of the parameters of the mathematical models.

Background

Analyzing a pavement structure is a complex and time intensive exercise. It is thus common for the engineering fraternity to devise ways and means to simplify the methods used in obtaining a solution. Simplification to any method will limit its uses and thus it is important to determine whether the assumptions made in the simplification process will not doom the method to failure. The two methods that are examined in this paper are isotropic and cross-anisotropic analysis. In South Africa the general consensus in the design of the road network is that the pavement structure can be defined as a thinly surfaced flexible structure. This causes a major problem in using linear isotropic analysis which has erroneous prediction of tensile stresses in the bottom aggregate layers [3].

Anisotropy and Cross-Anisotropy

Anisotropy is described by a material having different properties and characteristics in varying directions [4]. A true characterization of anisotropic has twenty-one variables which account for all the material behaviors in all the different directions. Cross-anisotropy is a simplification of the material properties into five variables under axial symmetry. Fig. 1 illustrates the variables and the means in which it is simplified for use in pavement structures [5].

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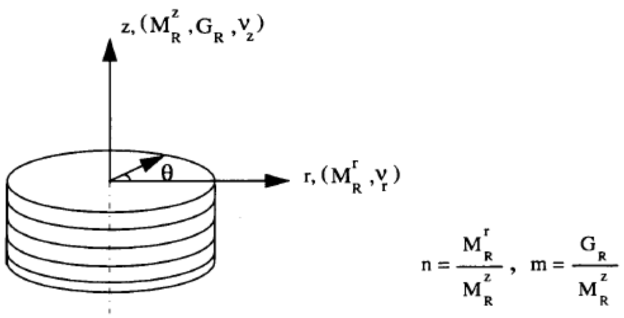


Fig. 1. Stratified Cross-anisotropy Under Axial Symmetry [5].

Theoretical Analysis

Derivation for the case of axi-symmetric (circular) loading is presented hereunder. By neglecting internal forces and similar to the isotropic case, the equilibrium equation may be written as follows:

$$\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \tag{1a}$$

$$\frac{\partial \tau_{rz}}{\partial r} + \frac{\partial \sigma_z}{\partial z} + \frac{\tau_{rz}}{r} = 0 \tag{1b}$$

Deflection in r for axi-symmetric case may be represented as $u = u(r,z)$, whereas deflection in z may be represented as $w = w(r,z)$. Circumferential (θ) deflection is zero. Normal stresses in r, θ and z directions may be represented as σ_r, σ_θ, and σ_z, respectively. Shear stress in $r-z$ section will be τ_{rz}. Strains corresponding to these stresses are ε_r, ε_θ, ε_z, and γ_{rz}. Strains-deflection relationship is similar to the case where material properties are assumed to be isotropic and may be written shown below:

$$\varepsilon_r = \frac{\partial u}{\partial r}, \quad \varepsilon_\theta = \frac{u}{r}, \quad \varepsilon_z = \frac{\partial w}{\partial z}, \quad \gamma_{rz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} \tag{2}$$

The difference between cross-anisotropic and isotropic material properties is in the expressions of strains in terms of stresses. In this regard, strain-stress relationship for cross-anisotropic material may be written as follows:

$$\begin{Bmatrix} \varepsilon_r \\ \varepsilon_\theta \\ \varepsilon_z \\ \gamma_{rz} \end{Bmatrix} = \begin{bmatrix} 1/E_h & -\nu_h/E_h & -\nu_v/E_v & 0 \\ -\nu_h/E_h & 1/E_h & -\nu_v/E_v & 0 \\ -\nu_v/E_v & -\nu_v/E_v & 1/E_v & 0 \\ 0 & 0 & 0 & 1/G \end{bmatrix} \begin{Bmatrix} \sigma_r \\ \sigma_\theta \\ \sigma_z \\ \tau_{rz} \end{Bmatrix} \tag{3}$$

where

E_h : elastic modulus in horizontal direction

E_v : elastic modulus in vertical direction

ν_h : Poisson's ratio for effect of horizontal stress on horizontal strain

ν_v : Poisson's ratio for effect of vertical stress on vertical strain

G : shear elastic modulus

Whereas, strain-stress relationship for isotropic material may be written as follows:

$$\begin{Bmatrix} \varepsilon_r \\ \varepsilon_\theta \\ \varepsilon_z \\ \gamma_{rz} \end{Bmatrix} = \begin{bmatrix} 1/E & -\nu/E & -\nu/E & 0 \\ -\nu/E & 1/E & -\nu/E & 0 \\ -\nu/E & -\nu/E & 1/E & 0 \\ 0 & 0 & 0 & 1/G \end{bmatrix} \begin{Bmatrix} \sigma_r \\ \sigma_\theta \\ \sigma_z \\ \tau_{rz} \end{Bmatrix} \tag{4}$$

where

E : elastic modulus

ν : Poisson's ratio

G : shear elastic modulus

Eqs. (3) and (4) show that in case of cross-anisotropic material, five parameters are used to express strain-stress relationship, namely, moduli of elasticity in horizontal and vertical directions, Poisson's ratios for effects of stresses on strains in vertical and horizontal directions and shear elastic modulus, whereas in case of isotropic material, strains and stresses may be expressed using only two parameters, namely elastic modulus and Poisson's ratio.

Stresses and deflections may be determined by adapting Hankel transform and based on strain-stress relationship, strains may also be determined. By using the procedure explained above, software known as me-CRAMES (CRoss-anisotropic Analysis of Multi-layered Elastic Systems), which is capable of analyzing the effect of cross-anisotropic material for both circular and rectangular loads, was developed and is used in the analyses in this paper. Me-CRAMES is a based on MLLE theory.

Multi-layer (ML) analysis was originally developed [6, 7] to determine stresses, strains and displacements of a two layer system. Multi-layer linear elastic systems are founded upon assumptions that include [8]:

- Homogeneous material properties;
- Isotropic material properties;
- Full friction between layer;
- No surface shearing forces;
- Layers infinite in the horizontal direction;
- Materials are characterized by Poisson's ratio and elastic moduli, and
- Bottom layer is infinite in vertical direction.

By the expansion of the above equations, a complete multi-layered system can be fully determined. The layers in the system can be quantified under ideal conditions. These quantifications of stresses and strains can be used to determine the layer thicknesses and their subsequent elastic moduli to ensure the subgrade stays between its allowable behavioral conditions e.g. not displaying great amounts of distress. By using multi-layered analysis a pavement structure is normally designed by increasing the elastic moduli of successive layers from the bottom (subgrade) upwards. This increase in elastic modulus of the layers decreases the deflections and stresses on the subgrade dramatically which is a direct result of the better load-spreading capabilities of the upper layers. The stiffer layers may decrease the level of distress on the subgrade but this introduces new complications into the system. The stiffer layers are now inducing larger tensile stresses at the bottom of the stiffer layers and increased horizontal shear stresses [6]. This introduces the need for further design analysis to ensure the correct construction of a pavement structure to resist all the inducted stresses. The Finite Element Method (FEM) can be used to determine the tensile and compressive stresses and their subsequent strains.

FEM is a numerical analysis method in which complex loading, boundary conditions and material properties can be handled through the use of matrix methods [9]. The pavement is considered a solid continuum and subdivided into smaller finite elements with varying properties. A nodal system is attached to the elements and complex analysis can be performed. The small elements interact with each other as a load is applied. The element boundaries are set according to different conditions [10]. The elements deform according to Poisson's ratio and inter-element shear forces are created. The elements on the edges of the element under consideration provide confining forces up to the point where they also start to deform and thus the complex behavior of the material can be simulated. Intricate pavement structures can be analyzed by using FEM with high level of accuracy to obtain solutions for stresses and elastic moduli in varying directions.

Cross-Anisotropic Behavior of an Unbound Granular Layer

One or more pavement layers usually consist of an unbound granular material. The main purpose of the material is to receive a concentrated load from above and distribute it sufficiently to decrease the deflections and thus stresses and strains on the following layer. The behavior of the material is important in the estimation of the stresses and strains. If the material behaves differently than assumed by the models, an accurate estimation of remaining lifespan cannot be made.

Cross-anisotropic behavior in an unbounded granular material is inherent because of physical material properties, the way in which material is deposited and the method of compaction of the material in a pavement structure [3]. The physical material properties are particle form, angularity, texture and gradation. Form provides an indication of elongation of the particles, while angularity represents the shape of the particles and texture indicate the surface roughness of particles. Gradation describes the particle sizes present in the material. These parameters affect the load carrying capacity of a pavement structure and thus the lifespan. Deposition of the material affects the initial location and orientation of the particles. The elongated directions of the particles tend to align with the horizontal direction. Compaction influences the contact areas between the particles and increases the packing factor of the particles. Regression models of nonlinear cross-anisotropic properties were developed to indicate how the level of cross-anisotropy is influenced by the different material properties [4, 11]. Application of the models indicates that a well graded granular material with angular and highly textured particles has less inherent levels of cross-anisotropy.

Cross-Anisotropic Behavior of a Cemented Layer

A cemented layer consists of granular material bound into a random lattice structure through portlandite crystals and ettringite needle matrix formed by a cementitious material. The layer's elastic modulus is thus a function of the strength and quantity of these bonds and the aggregate stiffness. Cross-anisotropic behavior of this layer can be apparent due to the same reasons than for granular layers. This is due to the fact that the layer mainly consists of granular material. There is evidence that these layers undergo a cracking phase due to shrinkage and facture of the cementitious matrix under loading, with post-cracking behavior similar to that of unbound granular layer which is intrinsically cross-anisotropic.

Cross-Anisotropic Behavior of Asphalt Surfacing

It can be argued that asphalt surfaces act in a cross-anisotropic way. This is mainly due to the bonded internal structure of the asphalt. The bitumen used in the manufacture of the surfaces is visco-elastic or visco-elastic-plastic. These two material properties differ in the way the material recovers from deformations. Visco-elasticity is characterized by a smooth nonlinear function that shows that when stress is applied and removed the material will have some immediate recovery followed by a slow strain recovery over a period of time. Visco-elastic-plasticity has the same characteristics as visco-elasticity with the added exception that not all the strain is recovered [12].

In traditional asphalt surface analyses an isotropic simplification method is used. The main concern is that by using such simplified methods, stresses and subsequent strains can be underestimated at the critical location. The implications of using cross-anisotropy versus isotropy for asphalt surfacings was evaluated [13] and the Boussinesq's solution and FEM analysis of the pavement model with sufficient boundary conditions and material properties measured in a true triaxial (cubical) testing device compared. It was concluded that an asphalt surfacing does in fact have cross-anisotropic properties. This is significant because using the traditional approach of isotropic analysis, the stresses and strains are underestimated.

Pavement Structural Behavior

The layers of a pavement structure can behave in a cross-anisotropic manner. It is then a logical conclusion that the method of analyzing the structure must also be cross-anisotropy allowing for a more accurate estimate of the pavement responses. By using cross-anisotropic analysis the vertical compressive stresses in a pavement structure can be shown to be larger than that obtained from the isotropic analysis, implying that the lifespan of that specific structure is overestimated [13]. In some instances horizontal tensile stresses where obtained in unbound granular layers by using isotropic methods. This is an obvious limitation of the isotropic simplification. By using cross-anisotropic methods, these horizontal tensile stresses in unbound granular layer can be eliminated [4]. Currently, true 3-dimensional characterization of the Eh/Ev ratio in either the laboratory or field is still not well developed. It is therefore difficult to recommend values for practical use as these are influenced by pavement structure and interaction between layers, loading and types of materials.

Methodology

This paper focuses on comparing the solutions obtained from undertaking an isotropic and cross-anisotropic analysis of a pavement structure with regards to the estimation of remaining lifespan. The South African Mechanistic Design Method (SAMDM) typically analyzes a pavement in a static, linear elastic multi-layered manner. Two pavement structures were evaluated. They were selected from the TRH4 design catalogue [14], and consisted of a granular base Class A and a granular base Class B pavement structure.

The elastic moduli and Poisson's ratios of the different structural layers as per acceptable design values [1] were used for the two TRH4 structures. The data were analyzed by populating the mathematical models of isotropic analysis and cross-anisotropic analysis. From here a variety of parameters can be changed such as the interlayer frictions of the pavement structure, boundary conditions and elastic modulus variations in the layers. The software package that was used in determining the predicted life of a pavement section under consideration is me-CRAMES.

TRH 4 Pavement Structures

A Class A road (which has a granular base layer and cemented subbase layer, with a predicted life falling in the range of ES3 (1.0 to 3.0 x 10^6 standard axles)) and a Class B road (which has a granular base and subbase layer, with a predicted life falling in the range of ES10 (3.0 to 10.0 x 10^6 standard axles)) were investigated. The physical properties of the structures are shown in Table 1. Values for the elastic moduli and Poisson's ratios were selected from published values for South African roads [1]. The data analysis discussion in this paper focuses on the Class A structure, with similar outcomes observed for the Class B structure.

The different types of analysis yield different stresses and strains in the layers which are used in the remaining life predictions using the relevant transfer functions. These predictions are divided into two concepts, remaining life of a specific layer and the remaining life of the pavement structure as whole. The predicted lives of the two analysis types are compared.

Data Analysis

Isotropic analysis is currently used in the SAMDM to predict remaining life of a pavement structure. There are set ranges in the SAMDM to show how a structure must be designed to allow for the predicted life of a pavement structure. These ranges where empirically determined through the vast experience of the pavement engineering fraternity. By using cross-anisotropic analysis the stresses obtained in the layers may differ significantly, which can result in vastly reduced predicted life. If the differences is such that it is in a different range conclusions can be made that will favor cross-anisotropic analysis.

Pavement Layer Characteristics

The pavement structures are introduced into the software package and parameters of layer type, thickness, elastic moduli in vertical and horizontal directions and Poisson's ratios in both directions are integrated into the software. The loads on the pavement structure are selected to be either circular or rectangular and spaced to coincide with standard axle dimensions. The contact pressure on the surface is selected as 520 kPa and terminal rut conditions is selected to be 20 mm. The program is executed and data are logged for variations of elastic moduli in terms of Level of Cross-Anisotropy. The Level of Cross-Anisotropy is the horizontal elastic moduli divided by the vertical elastic moduli. By varying the Level of Cross-Anisotropy the data in Fig. 2 to 4 were obtained. Validation of the Eh/Ev results discussed in this paper is part of a major current evaluation of pavement behavior in South Africa, as reliable field data of this parameter is not currently available.

Fig. 2 shows how the structure reacts as the continuously graded asphalt surface layers' Level of Cross-Anisotropy is varied from 0.1 to 2.0. It should also be noted that the elastic modulus is defined as a ratio of tensile stress to tensile strain. In Fig. 2 (top), as the level of Cross-Anisotropy decreases (meaning a decrease in the horizontal elastic modulus of the surfacing layer due to vertical

Table 1. Test Sections' Physical Characteristics.

TRH4 Class A Granular Base ES3 Structure					
Layer	Thickness [mm]	E-Modulus		Poisson's	
		Ev [MPa]	Eh [MPa]	Muz	Muh
Asphalt (AC)	40	3500	3500	0.44	0.44
Granular Base (G2)	125	250	250	0.35	0.35
Cemented Subbase (C3)	150	1500	1500	0.35	0.35
Granular Upper Selected (G7)	150	120	120	0.35	0.35
Granular Lower Selected G9	150	85	85	0.35	0.35
Subgrade	Semi-infinite	60	60	0.35	0.35
TRH4 Class B Granular Base ES10 Structure					
Layer	Thickness [mm]	E-Modulus		Poisson's Ratio	
		Ev [MPa]	Eh [MPa]	Muz	Muh
Asphalt (AC)	30	3500	3500	0.44	0.44
Granular Base (G2)	150	250	250	0.35	0.35
Granular Subbase G5	200	200	200	0.35	0.35
Granular Upper Selected (G7)	150	120	120	0.35	0.35
Granular Lower Selected G9	150	85	85	0.35	0.35
Subgrade	Semi-infinite	60	60	0.35	0.35

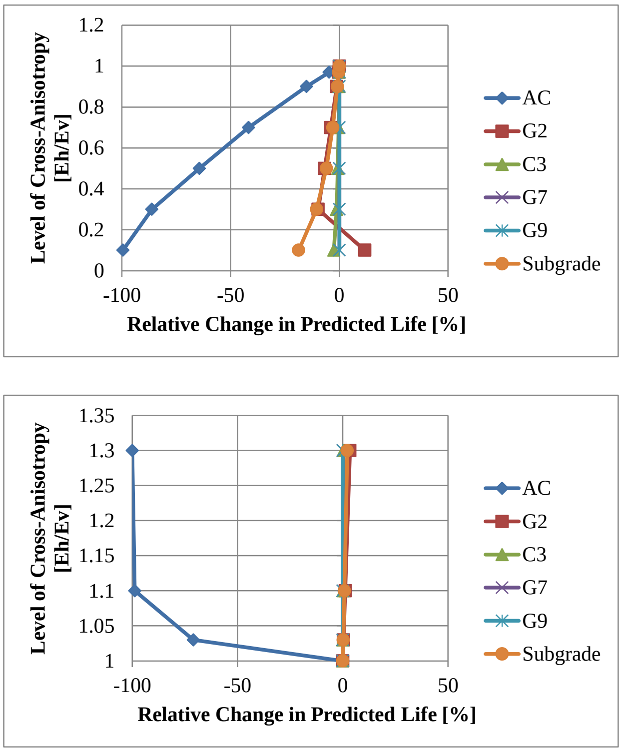


Fig. 2. TRH4 Structure Asphalt Cross-anisotropy Results (Vertical Cracking of Layer (top), Delamination in Layer (Bottom)).

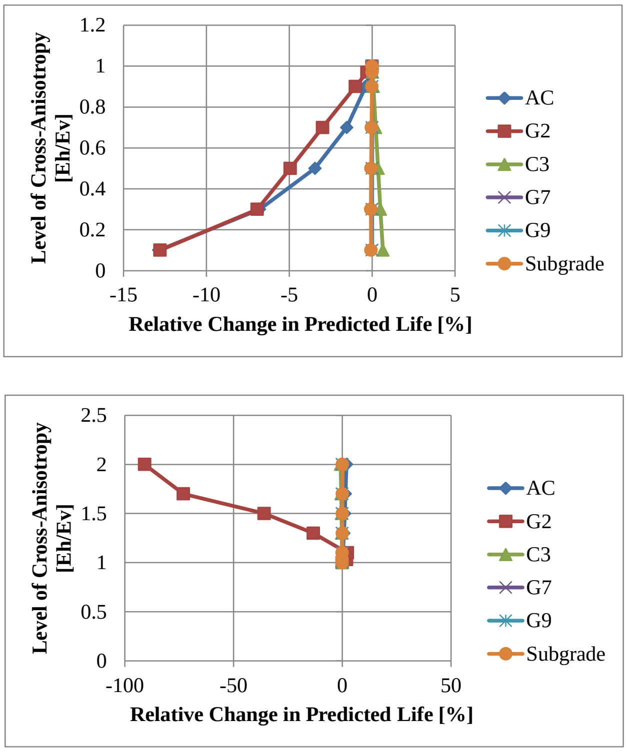


Fig. 3. TRH4 Structure Granular Cross-anisotropy Results (Vertical Cracking of Layer (top), Delamination in Layer (Bottom)).

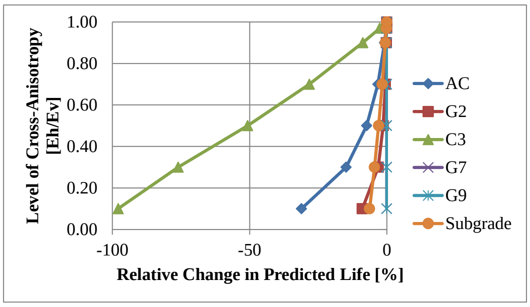
cracks through that layer) there is a linear decrease in the predicted life of the surfacing layer, granular layer and the subgrade. The effects on the cemented layer and the selected layer are negligible. On the other hand, Fig. 2 (bottom) simulates the behavior under delamination within the layer. This phenomenon appears to significantly affect the surface layer only as a small percentage decrease in the horizontal elastic modulus reduces the predicted life of the surfacing layer significantly. Furthermore, this effect does not influence predicted lives of all the underlying layers.

In Fig. 3 the granular base's elastic modulus was varied. It is notable that as the cross-anisotropy increased from 1 (isotropic conditions) to 2 which means the horizontal elastic modulus is twice the vertical elastic modulus and the layer is delaminating, the granular base's predicted life increased by 2.9 percent and then drastically decreases to 91 percent. This decrease in relative predicted life can be equated to the fact that the layer delaminates into smaller layers which in turn increases stresses induced in the layer. The rest of the layers compensate marginally to the relative extreme variation in bearing capacity of the G2 base layer.

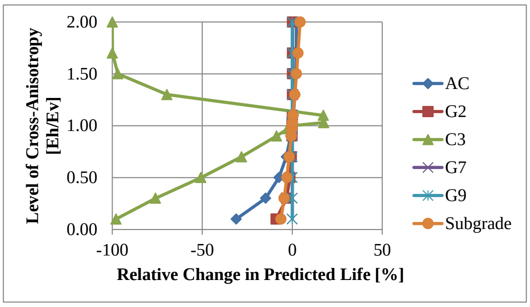
In Fig. 4 (left, top to bottom) the cemented subbase's Level of Cross-Anisotropy was varied and only the cemented life (phase 1) of the layer was plotted. The layer underwent relatively large amounts of change in the predicted life. In case of the vertical cracking (horizontal elastic modulus less than vertical elastic modulus) these changes tend to be linear (Fig. 4 (top)). However, in case of the delamination (horizontal elastic modulus greater than vertical elastic modulus) there is an increase of 17.5 percent in predicted life and then drastic decrease to negligible strength (Fig. 4 (middle)). This is due to the layers of delamination getting extremely small and the induced stresses becoming larger. The stresses induced in the layer breaks the bonds between the aggregates created by the cementitious material and the layer enters the post-cracked phase where the relative elastic moduli are significantly reduced. The bonds are caused by portlandite crystals and fine needles of ettringite in a matrix around the aggregate. The starting condition elastic moduli were 1 500 MPa, and after cracking the relative moduli reduced to 100 MPa, assuming a good parent material in this theoretical pavement section.

In Fig. 4 (right, top to bottom) the predicted life of each layer is illustrated, including the phasing of the cemented layer to an equivalent granular layer and the relative behavioral characteristics. The subbase layer under both conditions of vertical cracking and delamination experiences reduced predicted life (Fig. 4 (right, bottom)).

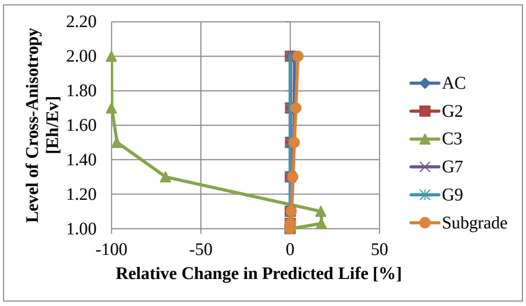
As the cemented subbase reduces in strength, the rest of the structure responds by relative reduction in predicted life. This can be seen as a balancing phenomenon. The pavement structure is thus shifting its balance lower down into the remaining layers of the pavements. Initially this pavement is called "shallow" (strength situated in the upper layers). As the cemented subbase reduces bearing capacity the rest of the layers compensate and the pavement "deepens" (strength is distributed lower down). The granular base layer's relative strength and thus bearing capacity increase which causes larger stresses induces in the layer, according to Hooke's Law. These larger stresses are transferred to the cemented subbase across the friction boundary between the layers and causes higher fatigue rates in that layer. The interlayer boundary is thus assumed to have full friction and no slip. The increased stresses in the cemented subbase layer causes the portlandite crystals and fine needles of ettringite matrix to fracture around the aggregate and



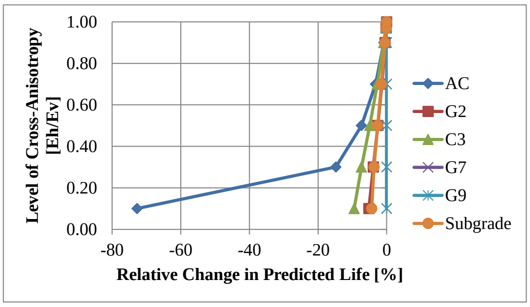
Class A C3 Varied Vertical Cracking



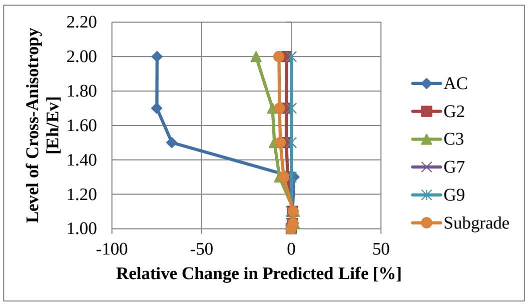
Class A C3 Varied Vertical Cracking



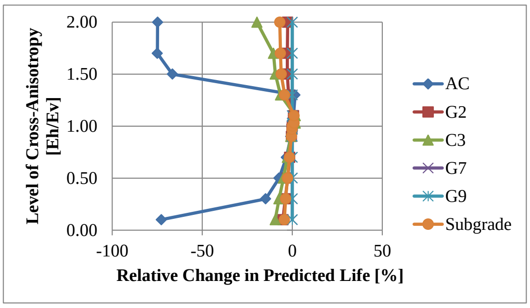
Class A C3 Varied Delamination



Class A C3 Varied Delamination



Class A C3 Varied Combined



Class A C3 Varied Combined

Fig. 4. TRH4 Structure C3 Subbase Cross-anisotropy Results.

thus the layer enters the post-cracked phase earlier, where it has granular layer characteristics. This results in a strength decrease and deflection increase of layer which in turn causes reduced predicted life. The high level of Cross-Anisotropy may also induce in the granular layer a column or cylinder of material underneath the load which increases confinement of the material thus increase the strength of the layer.

In Fig. 5 the Level of Cross-Anisotropy was varied in the upper selected layer (G7), using a 40 kN circular load at a pressure of 520 kPa. The selected layer is a granular layer of reduced bearing capacity relative to the upper layer of the pavement structure. In the vertical cracking arena there is an apparent increase in predicted life as shown in Fig. 5 (top). This is mainly due to the fact that the layer's resistance to deflections is vastly diminished. The induced stresses in the layer are subsequently reduced (Hooke's Law) and the predicted life increases. In the delamination area (Fig. 5 (bottom)), the vertical elastic modulus of the layer increases, thus increasing resistance to deflection and increasing induced stresses in the layer. This is due to the fact that there is now interlayer movement relative to the rest of the structure and the stresses cannot be transferred to the next layer. These increased stresses causes larger damage per loading cycle and thus predicted life is reduced. The rest of the structure's behavior remains relatively constant. This further illustrates the fact the initially this pavement is "shallow."

Conclusion and Recommendations

The objective of this paper was to indicate the potential effect of introduction of cross-anisotropic conditions in pavement structural analysis on the estimation of predicted life. Data from one in-service pavement structure and two typical South African catalogue design structures were used. Analysis was conducted using me-CRAMES that allows for cross-anisotropic analysis to be done. Analysis of the TRH4 theoretical pavements showed that an asphalt surfacing layer is extremely sensitive to cross-anisotropic conditions. This layer's predicted life has a tendency to reduce with any level of cross-Anisotropy. It can thus be concluded that the current values of predicted life in the TRH 4 for asphalt surface layers are erroneous. This is of great concern because the planned maintenance actions on surfacing layers are overestimated and will result in functional failure earlier in the life of the pavement. Cross-Anisotropic analysis methods are thus more favorable when determination of predicted life of asphalt surfacing layers.

The granular base layers yield results that have tendencies of

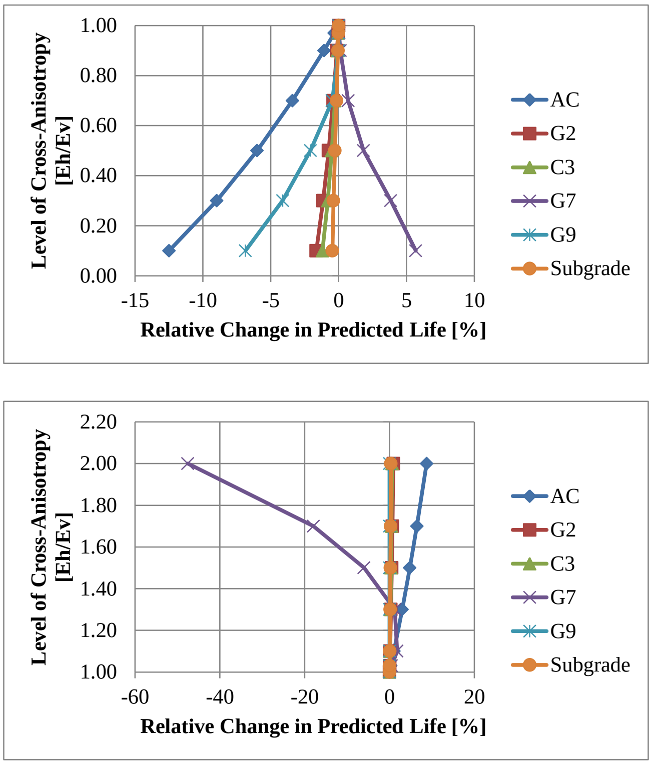


Fig. 5. TRH4 Structure Upper Selected Layer Cross-anisotropy Results.

reduced predicted life values. This was noted in the theoretical pavement sections and validated using the test sections with laboratory values for elastic modulus. It thus appears as if the granular layers tend to have reduced predicted life using cross-anisotropy, relative to that calculated by isotropic conditions. There can thus be vastly overestimated values of predicted life in the current design catalogues.

Cemented layers have two phases. An initial bonded phase and a post-cracked phase. The phases have different values of elastic modulus and thusly different behaviors. In the analysis, the level of Cross-Anisotropy was varied by the same degree for each phase. The results obtained where divided into two groups. The first group of results showed the behavior of the cemented phase life of the layer. There is an increase of 17.5 percent predicted life in the vertical cracking arena then a sudden decrease. In the delamination phase there is only a linear decrease in predicted life. The cemented life of the layer is thus overall reduced. The second group is the overall predicted life of the layer including the cemented and equivalent granular phase. In this group the predicted life tends to be negative. This was noted in the TRH 4 sections. This allowed for a third phase in the analysis of the cemented layer. The results were remarkably similar to those of the theoretical sections. It can be concluded that the cemented layer has a reduced predicted life when cross-anisotropic analysis was done. This illustrates an over-estimation of these layers in the current design methods.

During the analysis of pavement structures with induced cross-anisotropic conditions it was evident that the predicted life of the structure changes dramatically. The change in predicted life is so extensive in some cases that the pavement moves from its traffic class (ES) range. This is clearly evident in cross-anisotropic conditions induced in granular bases and subbases. A reason is that the strength of the pavement in concentrated in the upper portion of the structure and as the layer becomes weaker, the lower layers cannot compensate for the larger induced stresses and the pavement fails earlier. The introduction of cross-anisotropic conditions on a structure of this category has an overall negative effect on the pavement structure, with large reductions in predicted life of the layer. This is mainly due to the fact that there are inducted compressive stresses in the bottom of the granular base as illustrated by [5] and [11]. Pavements of this class can be vastly underestimated in respect to bearing capacity. This underestimation is due to the degree of cross-anisotropy induced in the layer by the construction process and material factors. A larger emphasis must be placed in the quality control of pavements that are constructed of material that fall into the danger zones. These danger zones are material of high degrees of elongation, low angularity and incorrect compaction processes. There exist standard tests such as Flakiness Index and Average Least Dimension (ALD) that where developed to determine theses danger factors and must be adhere to. The compaction of a pavement section induces cross-anisotropy due to the one dimension compaction directions. There are cross-anisotropic conditions in a pavement and the design approach must include a structural analysis method which takes anisotropy into account.

A recommendation from this paper is to initiate research into determining the amount of induced anisotropy in a pavement structure and to calibrate the existing design catalogue to include this estimated reduced predicted life of the pavement structures. This may increase the initial construction cost of some pavements, but a reliable estimation of predicted life will be more economical with regard to underperforming pavement sections currently in South Africa.

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