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THE EFFECTS OF NON-LINEAR MATERIAL PARAMETERS ON THE SHAPE OF THE DEFLECTION BASIN FOR FLEXIBLE PAVEMENTS: A PARAMETRIC STUDY

M DE BEER

Division of Roads and Transport Technology, CSIR, P O Box 395, Pretoria, 0001

SUMMARY

This paper summarises some of the main effects of non-linear, ie. stress stiffening (in this case) behaviour of resilient elastic moduli of typical granular base pavement structures on the calculated deflection basin. The basin was characterized by associated parameters such as maximum deflection (Ymax), radius of curvature (R), surface curvature index (SCI), area (A), base damage index (BDI), base curvature index (BCI), shape factors (F1 and F2) and outer deflections. The evaluation is based on a parametric study where the constants (K1 & K2) in the stress stiffening model of the granular material (layer) are varied. The effect of Poisson's ratio on the basin parameters is also investigated.

OPSOMMING

In hierdie referaat word 'n opsomming gegee van die primêre effekte van die nie-lineêre, dws spanningsverstywende gedrag (in hierdie geval) van die veerkragtigheids-elastisiteitsmodulus van tipiese granulêre kroonlaagplaveisels op die berekende defleksiekom. Die defleksiekom word gekarakteriseer deur verskeie komparameters soos maksimum defleksie (Ymaks), krommingstraal (R), oppervlakkromming-indeks (SCI), area (A), kroonlaagskade-indeks (BDI), vormfaktore (F1 en F2) en buiterand defleksies. Die evaluasie is op 'n parametriese studie gebaseer waar die konstantes (K1 & K2) van die spanningsverstywende model van die granulêremateriaal (laag) gevarieer is. Die effek van die Poisson verhouding op die komparameters word ook bestudeer.

INTRODUCTION

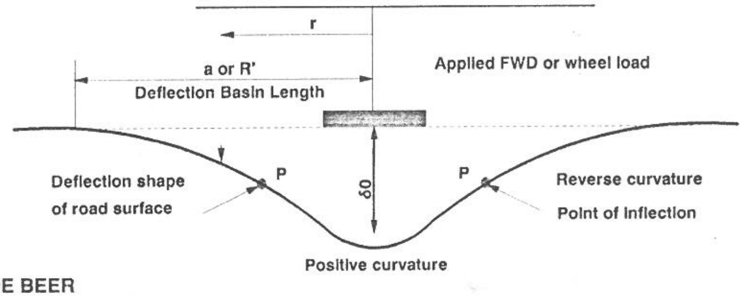
For more than a decade maximum surface deflection (Ymax or δ_0) and maximum depth deflection (measured with the Multi-depth Deflectometers (MDD)) were the main pavement response parameters used to evaluate pavements structurally in South Africa. Internationally, Ymax is still one of the main parameters used, but with the advent of the Falling Weight Deflectometer (FWD) or Impulse Deflectometer (IDM) (as it is called in South Africa), more use is made of the full deflection basin which can also be measured with either the IDM, the Lacroix Deflectograph or the Road Surface Deflectometer (RSD). Various basin parameters are defined[6], which are used together with Ymax as pavement response parameters. A summary of the most important parameters is given in Table 1. Experience and continued research have shown that many characteristics of the layered system of the pavement and material properties may be extracted from the *shape* of the measured surface deflection basin. Care, however, should be exercised when the mathematical model for elastic pavement response is based purely on "fitting" the full deflection basin indiscriminately. Numerous studies have shown that, for example, the multi-layer linear elastic solution (a set of elastic moduli values for the pavement system reproducing the measured deflection basin) is ***not*** unique for a specific deflection basin, and that, in fact, many solutions are possible for a single basin[1,2,3,4,5]. In order to derive the "correct" answer, the intervention of an expert is normally needed.

The aim of this paper is to highlight to practitioners and researchers some of the important effects that, for example, non-linearity of the elastic moduli (non-linear stress-strain relationship) of a granular base material can have on the shape of the deflection basin. Various basin parameters are used to quantify these effects in a parametric study in this paper. Some of the extreme values, however, used in the analysis may not be practically appropriate, but merely serve as indicators to the overall context of the study.

TABLE 1 - SUMMARY OF DEFLECTION BASIN PARAMETERS

PARAMETER			FORMULA
1. MAXIMUM DEFLECTION	δ0	=	δ0
2. RADIUS OF CURVATURE (DEHLEN,1962)	R	=	$\frac{r^2}{2\delta o\,(1-{}^{\delta r}/_{\delta o})}$ where r = 127 mm or r = 200 mm
3. SPREADABILITY	S	=	$\frac{[(\delta 0+\delta 1+\delta 2+\delta 3)/5]100}{\delta 0}$ δ1...δ3 SPACED 305 mm
4. AREA	A	=	$6[1+2(\delta 1/\delta 0)+2(\delta 2/\delta 0)+\delta 3/\delta 0]$
5. SHAPE FACTORS	F1 ,F2	=	$F1 = (\delta 0-\delta 2)/\delta 1; F2 = (\delta 1-\delta 3)/\delta 2$
6. SURFACE CURVATURE INDEX	SCI	=	δ0 - δr where r = 305 or 500 mm
7. BASE CURVATURE INDEX	BCI	=	δ610 - δ915
8. BASE DAMAGE INDEX	BDI	=	δ305 - δ610
9. DEFLECTION RATIO	Qr	=	δr/δ0 where δr=δ0/2
10. BENDING INDEX	BI	=	δ0/a where a = deflection basin length
11. SLOPE OF DEFLECTION	SD	=	$TAN^{-1}[(\delta 0-\delta r)/r]$ where r = 610 mm
12. TANGENT SLOPE	ST	=	(δ0-δr)/r where r = distance to inflection point
13. RADIUS OF INFLUENCE	RI	=	R'/δ0 where R' is the distance from δ0 to where basin is tangent to horizontal
14. E-AASHTO	E_1	=	$6158,3/\delta_{1500}$
15. E-SUBGRADE	E2	=	$10\ (-1,063\ X\ LOG\ (\delta_{1200})) + 4,297$

TYPICAL DEFLECTION BASIN



PAVEMENT MODEL

The parametric study was performed on a granular base pavement structure with two cementitious subbase layers. The pavement model is illustrated in Figure 1. The elastic modulus of the granular base material was modelled as non-linear, using the well known $K1\Theta^{K2}$ stress (or resilient moduli) stiffening behaviour, with:

K1, K2 and μ the parametric variables,
with K1, K2 constants determined from laboratory testing
μ = Poisson's Ratio, and
Θ = sum of principle stresses, $\sigma_1 + \sigma_2 + \sigma_3$

The parametric variables were varied according to Table 2. The rest of the layers in the pavement were modelled as linear elastic, ie with constant elastic moduli and Poisson's ratios. The actual values for these layers are given separately in Figure 1. The analysis was done with a PC-based finite element computer code called MICH-PAVE [11]. A total of 80 runs was done to generate the data, which in general is given graphically as it is relatively easy to interpret.

Table 2: Parametric variables used for the granular base layer

K1 (MPa)	6.9	34.5	69	138	207
K2 (MPa/MPa)	0.2	0.4	0.6	0.8	-
μ	0.1	0.2	0.3	0.4	-

Deflection basin parameters studied

The following basin parameters extracted from Table 1 were used in the study, viz maximum deflection (Ymax, δ_0 or D1); area, A; radius of curvature (R); surface curvature index (SCI); base damage index (BDI); base curvature index (BCI); shape factors F1 and F2 (dimensionless) and outer deflection D6. Definitions of these parameters are also given in Figures 2 and 3. Normally, the upper

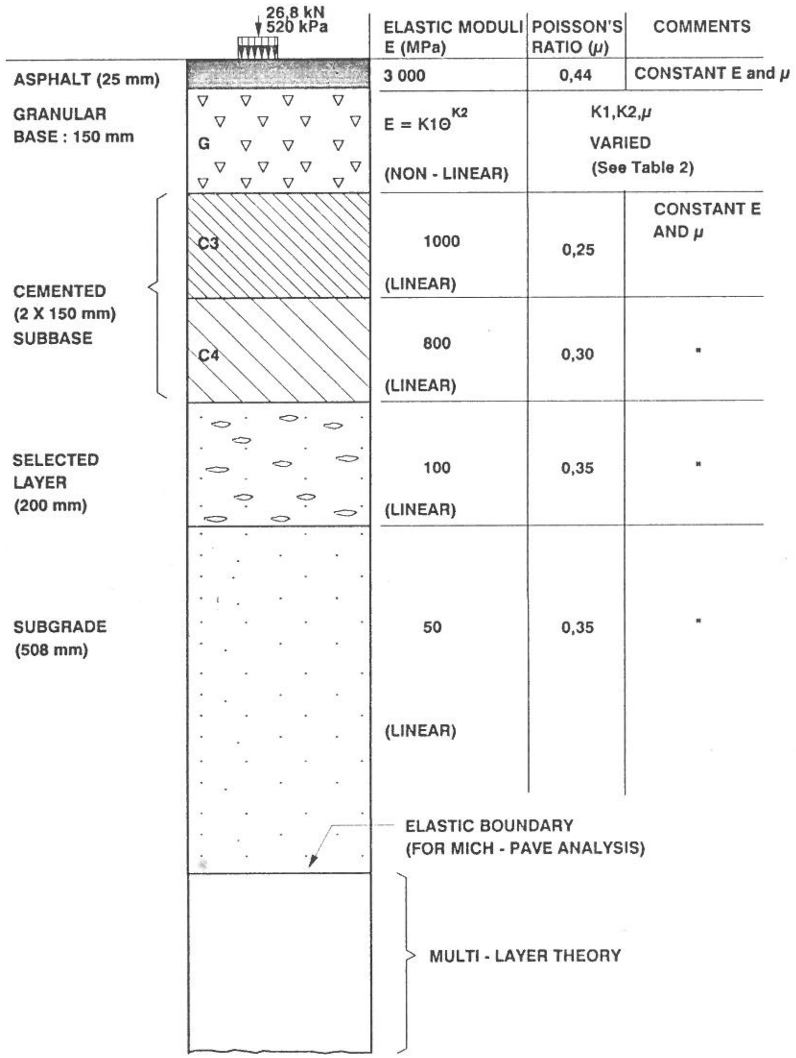


FIGURE 1
PAVEMENT MATERIAL AND LOAD CONFIGURATION FOR THE NON-LINEAR ANALYSIS USING MICH-PAVE

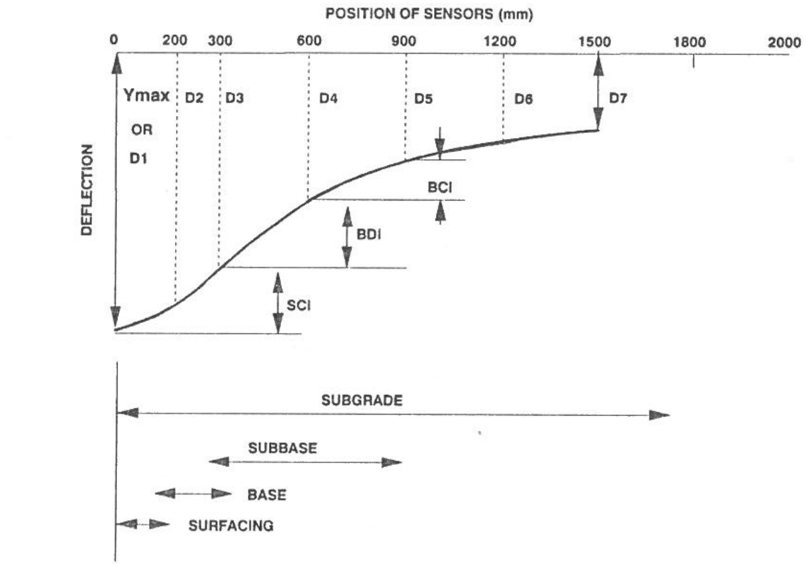
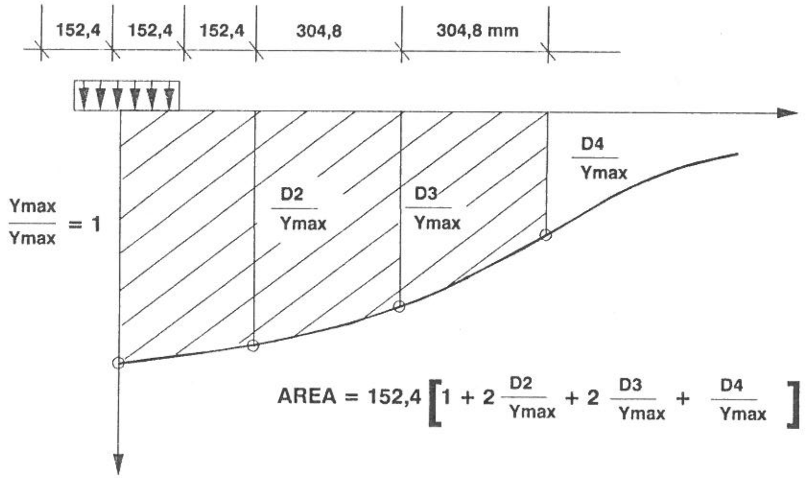


FIGURE 2 : SOME DEFLECTION BASIN PARAMETERS



$$\frac{Ymax}{Ymax} = 1$$

$$AREA = 152{,}4\left[1 + 2\frac{D2}{Ymax} + 2\frac{D3}{Ymax} + \frac{D4}{Ymax}\right]$$

FIGURE 3: DEFLECTION BASIN CHARACTERIZATION IN TERMS OF AREA

pavement layers influence the deflection basin closer to the load application, and the lower subgrade layer(s) the vertical position of full basin (See Figure 2). The deflection basin area (A) ranges from a calculated practical minimum of 279 mm (according to Boussinesq approximation) to a maximum of 914 mm. Also the area increases with increasing pavement stiffness. The basin shape factors (F1 and F2) are analogous to a derivative of the deflection basin curves, which represent the variation of surface deflection with lateral distance from the centre line of the load. In general, stiff pavements have lower shape factors[2].

RESULTS

Deflection basin

In Figure 4 the effect of K2 on some of the calculated deflection basins for the various K1-values at a Poisson's ratio, $\mu = 0.1$, is illustrated. In general, the "stiffer" the granular base material, ie higher K1 and K2-values, the shallower the basin, as well as a smaller basin radius. For relatively low K1-values, the effects of K2 are significant. K1 can be viewed as a "modulus number", with stress units, and K2 is an indication of the rate at which the moduli increases with an increase in stress on a log-log scale, with units stress/stress. However, high K1-values are normally associated with low K2-values [2,4,]. In this example it is clear that for all practical purposes the stress dependent granular base layer influences only the basin up to approximately 500 mm from the load. The effects however of variable Poisson's ratio on the results in Figure 4 are insignificant.

Maximum Deflection, Ymax

In Figure 5 the effects of K1 and K2 on Ymax at different Poisson's ratios are illustrated. As expected, K1 and K2 have a major influence on Ymax, with K1 being the predominant parameter, especially on weaker "low moduli" (low K1) materials. From this result it appears that Ymax is an important basin parameter if used in a non-linear material elastic moduli back-calculation as well as in the pavement evaluation processes. It is therefore critical to measure Ymax as

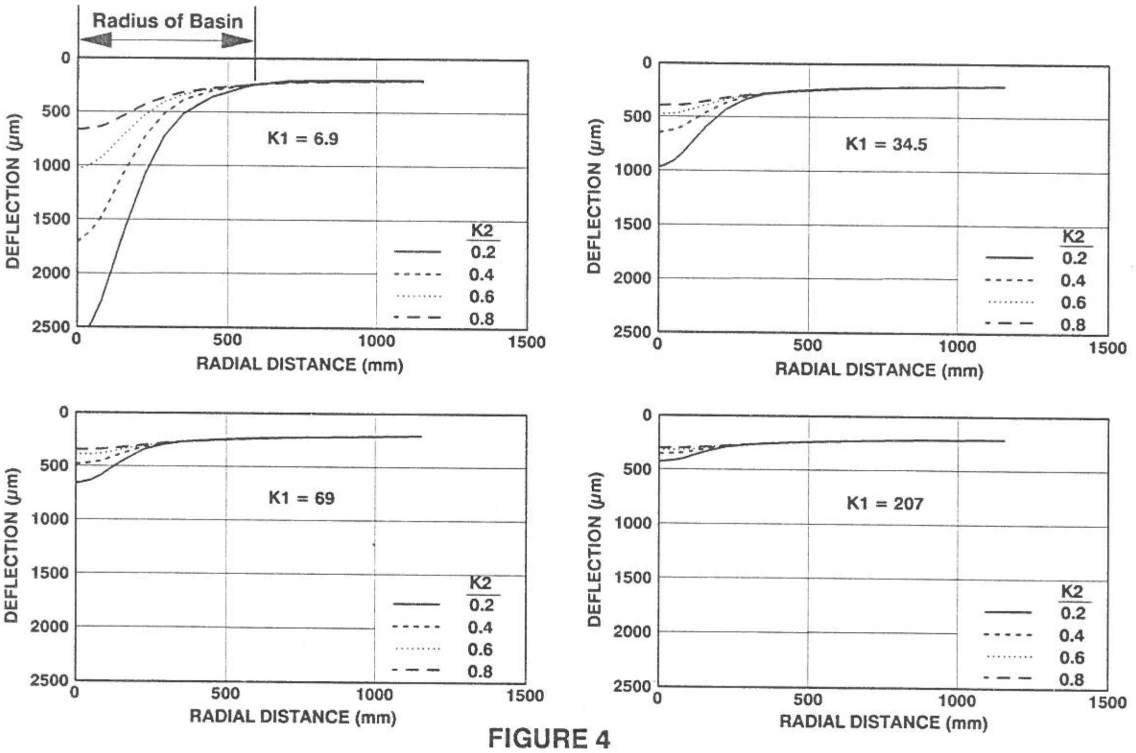


FIGURE 4

EFFECT OF K2 ON THE DEFLECTION BASIN FOR VARIOUS K1 - VALUES AT POISSON'S RATIO OF $\mu = 0.1$

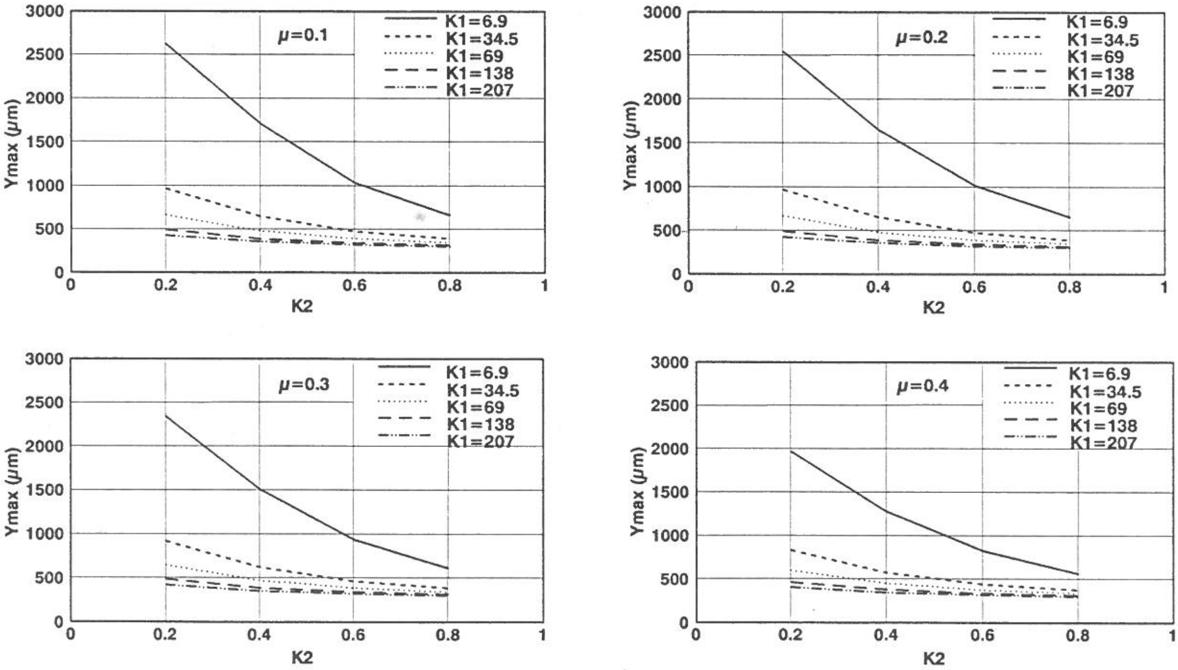


FIGURE 5

EFFECT OF K1 AND K2 ON Ymax AT DIFFERENT POISSON'S RATIOS, μ

accurately as possible in the field. In general, an increase in Poisson's ratio results in slightly lower maximum deflections, especially at lower K2-values.

Area, A

By definition the upper layers in the pavement predominantly influences the area. In Figure 6 the effects of K1 and K2 on the area of the basin at different Poisson's ratios are illustrated. In this case both K1 and K2 appear to influence the area, with K1 predominant. The stiffer the upper pavement layers, the higher the area. Therefore area is also an important basin parameter for evaluation and back-calculation of non-linear material properties of especially base layers. However, the effect of varying Poisson's ratio on area appears to be insignificant.

Radius of Curvature, R

In Figure 7 the effects of K1 and K2 on the radius of curvature at different Poisson's ratios are illustrated. An increase in both K1 and K2 result in an increase in R (stiffer pavement), which implies that R is also an important parameter for back-calculation of non-linear base moduli and pavement evaluation. Traditionally, R indicates the state of the upper layers in the pavement. An increase in Poisson's ratio results in slightly lower R, especially at higher K2-values.

Surface Curvature Index, SCI

The effects of K1 and K2 on SCI at different Poisson's ratios are illustrated in Figure 8. An increase in both K1 and K2 results in a decrease in SCI, ie stiffer pavement. In this case, an increase in Poisson's ratio results in a decrease in SCI, especially at low K1 and K2-values. Therefore SCI appears to be an important basin parameter for the evaluation and back-calculation of non-linear base material properties of granular pavements, which, in this case, include K1, K2 and μ.

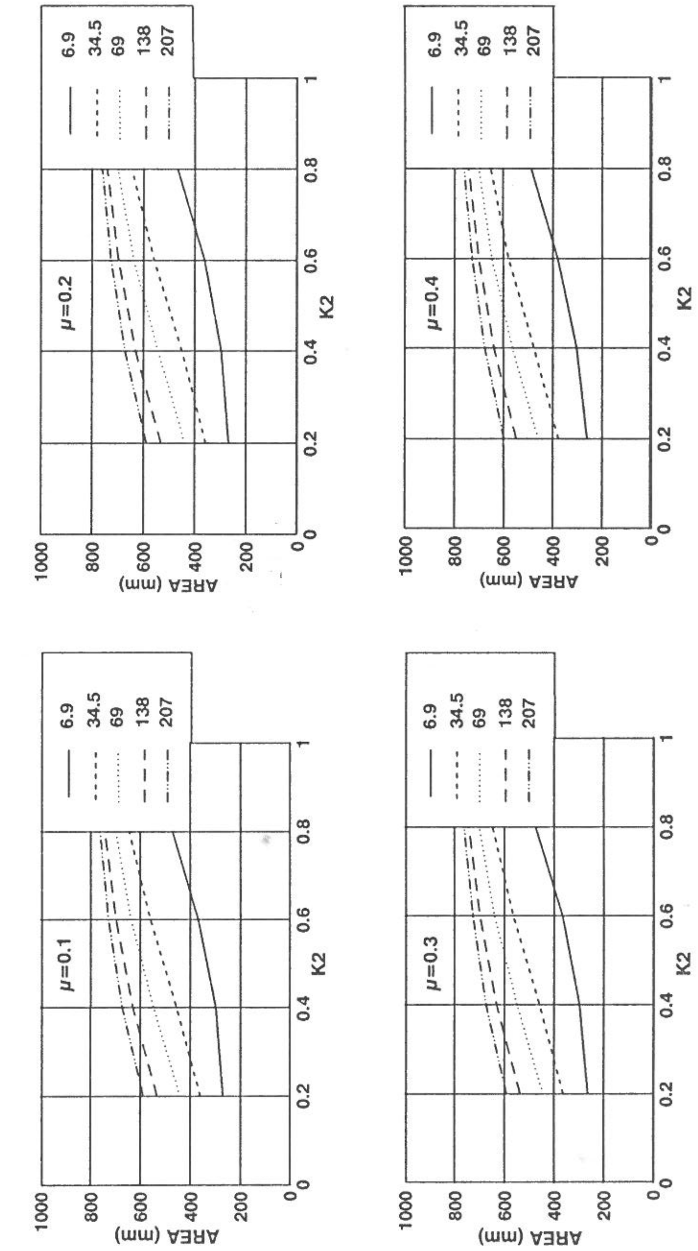


FIGURE 6
EFFECT OF K1 AND K2 ON THE AREA OF THE BASIN AT DIFFERENT POISSON'S RATIOS, μ

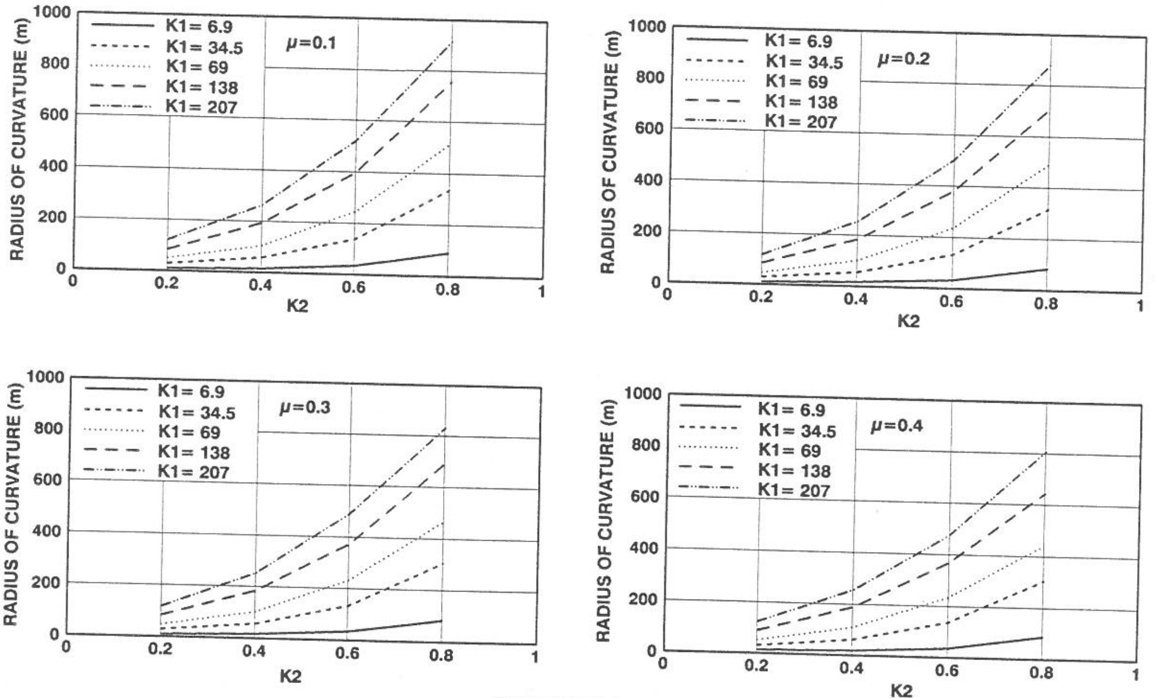


FIGURE 7

EFFECT OF K1 AND K2 ON THE RADIUS OF CURVATURE AT DIFFERENT POISSON'S RATIOS, μ

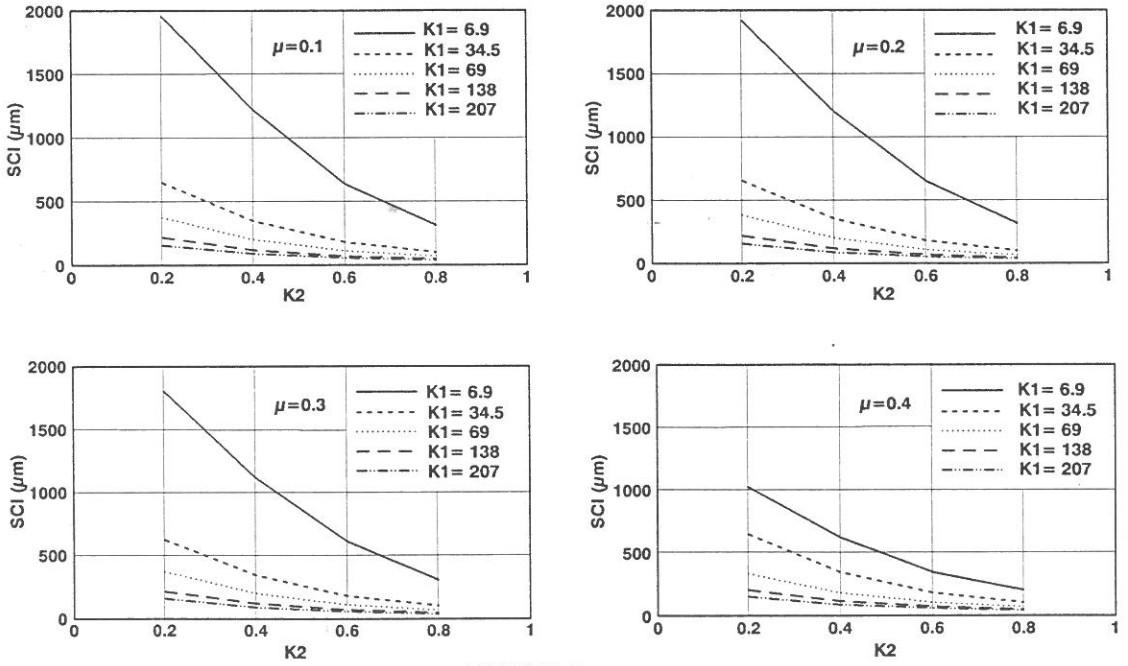


FIGURE 8

EFFECT OF K1 AND K2 ON SCI AT DIFFERENT POISSON'S RATIOS, μ

Base Damage Index, BDI and Base Curvature Index, BCI

The effects of K1 and K2 on BDI and BCI at different Poisson's ratios were also investigated. In general, these parameters decrease with an increase in both K1 and K2. However, at higher K1-values, the influence of K2 decreased. Both BDI and BCI appear to be insignificant basin parameters for evaluation or back-calculation of non-linear base material properties. A slight reduction in these parameters occurred with an increase in Poisson's ratio, especially with relatively low K1 values.

Shape factors, F1 and F2

The effects of K1 and K2 on the basin shape factor, F1, are illustrated in Figure 9. F1 decreased with an increase in K1 and K2, and is more sensitive for the relatively lower K1 values investigated here. F2 appears to be relatively insensitive to variation in K2, especially at relatively high K1-values. Only F1 appears to be an important basin parameter for back-calculation of non-linear base material parameters.

Outer deflection, D6

An attempt was also made to analyze the deflection at the basin extremities, D6, at a distance approximately 1200 mm from the load was used. (Normally D7 is used for this purpose, but owing to the MICH-PAVE programme code default limitations, only deflections up to 1153 mm from the load could be calculated, which is approximately D6 at 1200 mm). As expected, the non-linear granular base material properties in this pavement configuration have minimal influence on the outer deflections. The effect of varying Poisson's ratio was also found to be insignificant.

EFFECTS ON PAVEMENT LIFE

Asphalt Horizontal Tensile Strain

With the effects on the deflection basin of non-linear material properties known, the effects on expected pavement life predictions were also studied. The critical

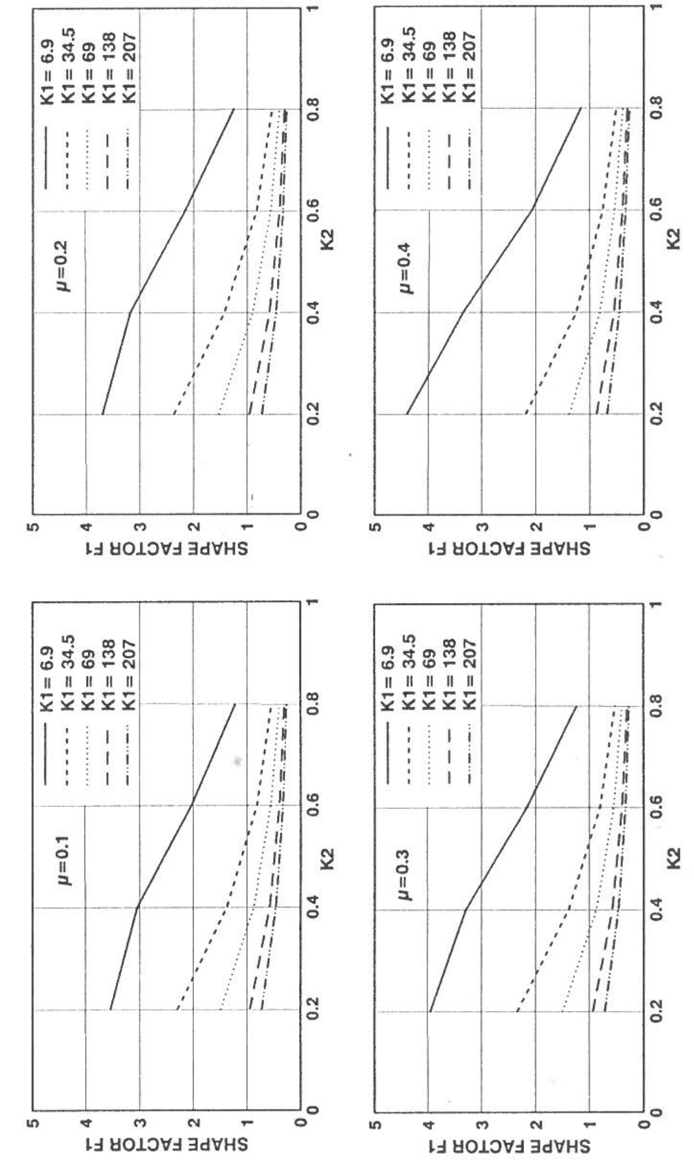


FIGURE 9
EFFECT OF K1 AND K2 ON THE SHAPE FACTOR F1
AT VARIOUS POISSON'S RATIOS, μ

parameter for relatively thin asphalt surfacing layers is the maximum tensile strain at the bottom of the asphalt layer, and is directly influenced by the type of support from the base layer. The stiffer the support, the lower the strain, hence longer fatigue life. In Figure 10 the effects of K1 and K2 on the maximum tensile strain at the bottom of the asphalt layer are indicated for a Poisson's ratio, $\mu = 0.3$. In general, the higher K1 and K2 (stiffer base), the lower the tensile strain in the asphalt layer, hence longer fatigue life.

Granular Base Layer

The granular base layer was modelled as a stress stiffening (elastic moduli stiffening) layer, and therefore the moduli reduces with radial distance from the load. Figure 11 illustrates this reduction in moduli for a specific case in the parametric study, with $\mu = 0.3$ and K2=0.8. The figure illustrates the change in moduli as a function of radial distance from the load for the various values of K1. From a radial distance of approximately 400 mm the moduli appear to be constant for all values of K1 investigated. It is however accepted that a modulus of 6400 MPa for a granular layer appears to be approximately ten times higher than a "normal" modulus of a good quality granular layer. In this particular case, relatively high values of K1 and K2 were used. Nevertheless, the purpose of the figure is to illustrate the importance of stress dependency of the resilient elastic moduli in granular pavement materials and not the actual modulus value, per sè.

In Figure 12 the effects of K1 and K2 on the calculated life of the granular base layer at a Poisson's ratio, $\mu = 0.3$, are illustrated. The safety factor approach against shear failure proposed by Maree [4] was used for the calculations, with varying cohesion, c, and internal friction angles, ϕ. The figure indicates that shear failure potential is predominantly controlled by K1, and to a lesser extent by K2. A minimum life for the granular layer was computed at K2=0.6 for most K1-values. This may be related to the specific c and ϕ values assumed in this study, and the minima must not be interpreted as purely a function of K1 and/or K2.

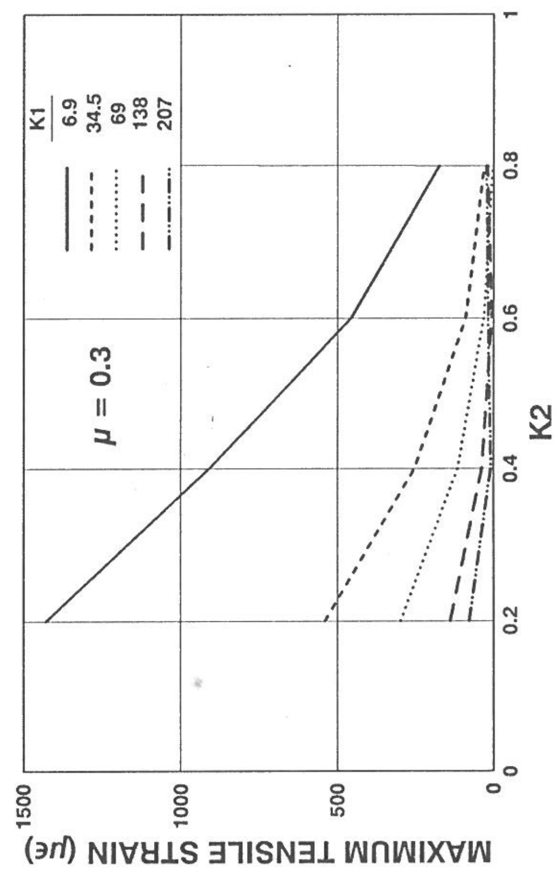


FIGURE 10
EFFECT OF K1 AND K2 ON THE MAXIMUM ASPHALT STRAIN AT THE BOTTOM OF THE ASPHALT LAYER

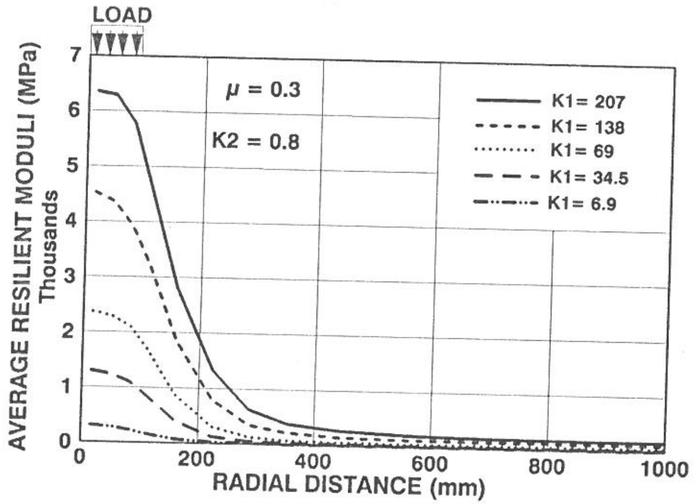


FIGURE 11

VARIATIONS IN THE RESILIENT MODULI OF THE GRANULAR BASE LAYER AS A FUNCTION OF RADIAL DISTANCE FROM THE LOAD

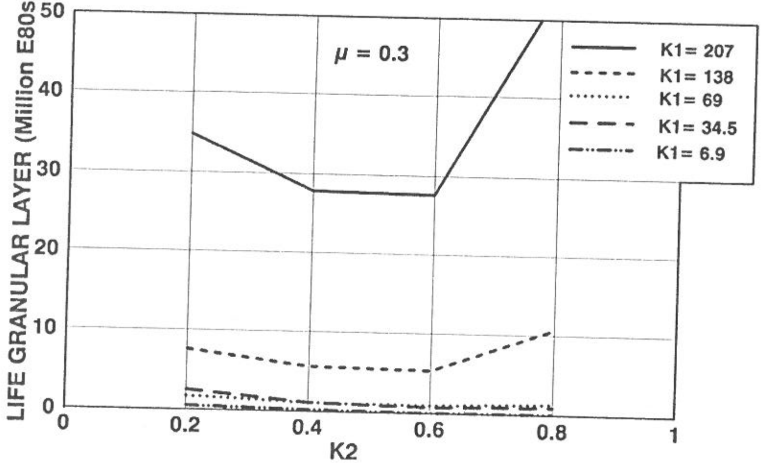


FIGURE 12

EFFECT OF K1 AND K2 ON THE CALCULATED LIFE OF THE GRANULAR BASE LAYER AT A POISSON'S RATIO, $\mu = 0.3$

DISCUSSION

Deflection basin parameters are gaining popularity in both research and practical application because of the relative ease of measuring a full deflection basin with, for example, the IDM. Not only are these parameters valuable for the structural evaluation of in-service pavements, both on the network management level and project level detail evaluations, but also in the research environment where latest developments include the extraction of non-linear material layer properties from the deflection basin and its parameters[1,2,6,7,10,12]. The advantage of such an approach is that laboratory tests (mainly on disturbed or laboratory manufactured specimens) will be limited, so that the important material or layer properties (linear and/or non-linear) may be back-calculated from the measured deflection basin[7,8]. Some information for the back-calculation of elastic moduli for pavement materials are discussed elsewhere[10]. In addition, the material is evaluated in its structural and functional condition as part of the full pavement system. The stresses and strains calculated from appropriate pavement behavioural models based on the full deflection basin are much more valid and accurate than those, for example, based on Ymax only. Stresses and strains outside the loading area are also more accurate if this method is adopted and can therefore also be used optimally. Care, however, should be taken in the use of suitable transfer functions between the pavement response parameters, such as stresses and strains, and pavement life, as most of the current South African transfer functions are basically linear elastic model dependent, based on Ymax[9]. Improvement of the current transfer functions is an area for future research. For the interim it is proposed that the existing transfer functions be used. Some of these are summarised in Ref. 9.

The results of this study indicate that certain basin parameters are more important than others, depending on the layer being evaluated. Typically, for the upper pavement layers, the parameters describing the basin characteristics close to the load (such as Ymax, A, R, SCI and F1) will be more important. On the other hand, for selected and subgrade layers, the outer basin parameters (such as BCI, D6 or D7) are more important[7]. Similar parametric studies could be done on other typical pavements and load configurations to address a specific need, or to increase knowledge of, for example, stress dependency in lower (subgrade) pavement layers.

CONCLUSIONS

This paper describes a parametric study done on a specific type of pavement, viz. 150 mm granular base on two 150 mm cementitious subbase layers. This study concentrates on the effects of the stress (or resilient moduli) stiffening behaviour of the granular base material on the *shape* of the deflection basin calculated on the surface of the pavement. This is done through a series of deflection basin parameters.

It is concluded that the following basin parameters are the most important with regard to the non-linear behaviour of the granular base layer:

(i) maximum deflection, Ymax
(ii) area, A
(iii) radius of curvature, R
(iv) surface curvature index, SCI
(v) shape factor, F1

It is believed that material (layer) property extraction or elastic moduli back-calculation should incorporate the above parameters, or some combination of these, in order to reproduce the measured basin. Similar studies to this one are recommended on other typical pavement types, such as those with non-linear subbases (advanced cracked cementitious layers) and/or stress (moduli) softening cohesive subgrades.

ACKNOWLEDGEMENT

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