TABLE 6.7 AVERAGE DCP-NUMBERS OF THE TWO EXCESSIVELY LOADED TEST SECTIONS.

HVS-SECTION (HVS Wheel Load)	REPETITIONS	DCP NUMBER (mm/blow)		IN SITU MOISTURE
		DN_{112} *	$DN_{112-272}$ **	
337A4	0	1,5 (0,5)	2,9 (0,9)	DRY
(150 kN)	48 000	2,4 (0,4)	1,8 (0,1)	DRY
		DN_{64} *	DN_{64-120} **	
309A4	0	1,1 (0,2)	2,1 (0,4)	DRY
(150 kN)	19 000	1,1 (0,7)	1,8 (0,7)	DRY
	46 000	2,0 (0,1)	2,0 (0,1)	DRY
		$DN_{193-456}$ *	$DN_{456-800}$ **	
309A4 (cont.)	0	9,6 (2,2)	20,6 (3,9)	DRY
(150 kN)	19 000	3,3 (0,8)	6,2 (3,6)	DRY
	46 000	2,3 (0,2)	5,6 (2,6)	DRY

* DN_i = the average rate of penetration in the top i mm of the cemented base layer.
** DN_{i-r} = the average rate of penetration from a depth of i mm to a depth of r mm in the cemented base layer.
() = Standard deviation in the rate of penetration.

In Figures 6.14 and 6.15, the balance curves and layer strength diagrams at various stages of trafficking on the two sections are illustrated. Both these figures indicate a decrease in B, as a result of compaction of the lower layers, while fatigue and crushing failure occurred in the cemented base layers. In Table 6.8 the A and B parameters at various stages of trafficking on these section are given.

TABLE 6.8 AVERAGE A AND B PARAMETERS FOR THE TWO EXCESSIVELY LOADED TEST SECTIONS.

HVS-SECTION	TEST LOAD (kN)	REPETITIONS (ACTUAL)	A	B
337A4	150	0	1108	38
		48 000	3463	20
309A4	150	0	946	46
		19 000	2484	25
		46 000	2327	12

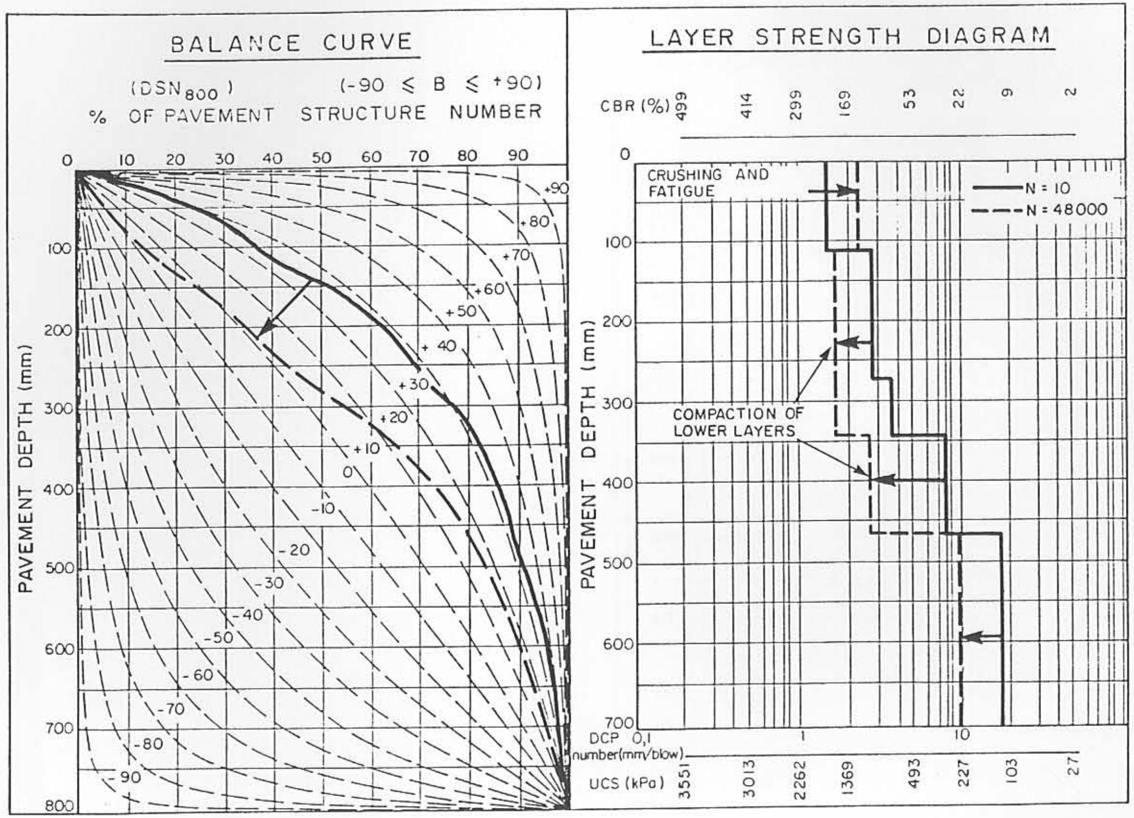


FIGURE 6.14

DCP BALANCE CURVES AND LAYER STRENGTH DIAGRAMS OF HVS SECTION 337A4
(INITIAL DCP-CATEGORY IV : WELL-BALANCED DEEP STRUCTURE - WBD)

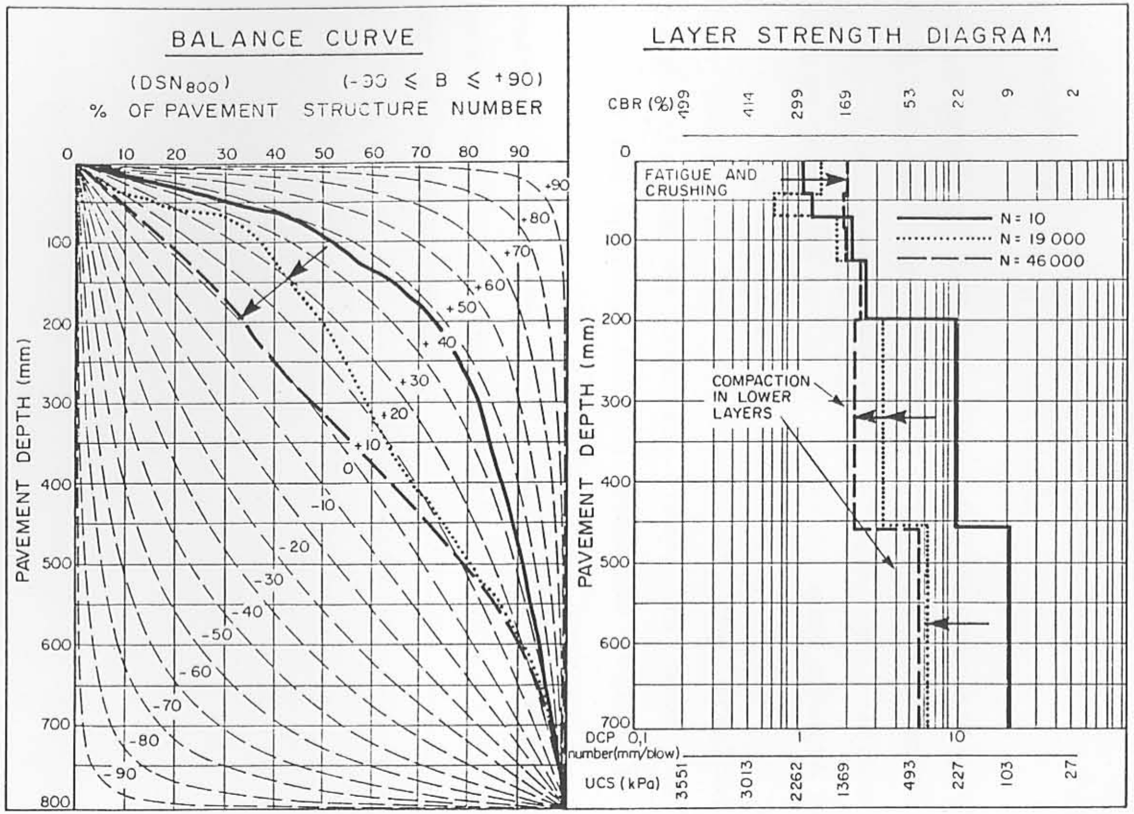


FIGURE 6.15

DCP BALANCE CURVES AND LAYER STRENGTH DIAGRAMS OF HVS TEST SECTION 309A4 (INITIAL DCP - CATEGORY I : WELL-BALANCED SHALLOW STRUCTURE (WBS))

The changes in A are also illustrated in Figure 6.16, indicating that these changes also occurred deeper in the pavement than those for the normal load tests (Figures 6.7 and 6.12). In Figure 6.17 the balance paths for these sections are plotted, and indicate a marked decrease in B, with an increase in A.

Section 337A4, although classified as a deep pavement (Chapter 3) before HVS trafficking, was shallower than the deep sections discussed previously (Paragraph 6.3.2). The initial B of this test section was much higher (B = 38), than those of the previously discussed test sections (B = 19) on the deep pavement. The main reason for this is possibly that this HVS section was situated in a valley area of this route, where relatively softer in situ layers may exist, thus causing it to be relatively shallower than the other sections on the deep pavement.

These two sections (337A4 and 309A4) are thus both relatively shallow and therefore the two balance paths are also similar (see Figure 6.17).

6.4 DCP - AIDED PREDICTION OF STRUCTURAL CAPACITY

6.4.1 Background

The first empirical DCP - based model for the prediction of structural capacity was developed by Kleyn (1984). This model is based on the DSN_{800} in blows and a moisture factor, Cm. Jordaan (1988) recently summarised this work and also suggested some changes to this model.

In this paragraph, an evaluation of the original model with the suggested changes by Jordaan (1988) is made to investigate its suitability and accuracy for the pavements studied in this dissertation.

Alternative models for the prediction of structural capacity for pavements with lightly cemented layers are also proposed and discussed in the following paragraphs.

DEVIATION FROM STANDARD PAVEMENT BALANCE CURVES (SPBCs) (DEVIATION, A_i)

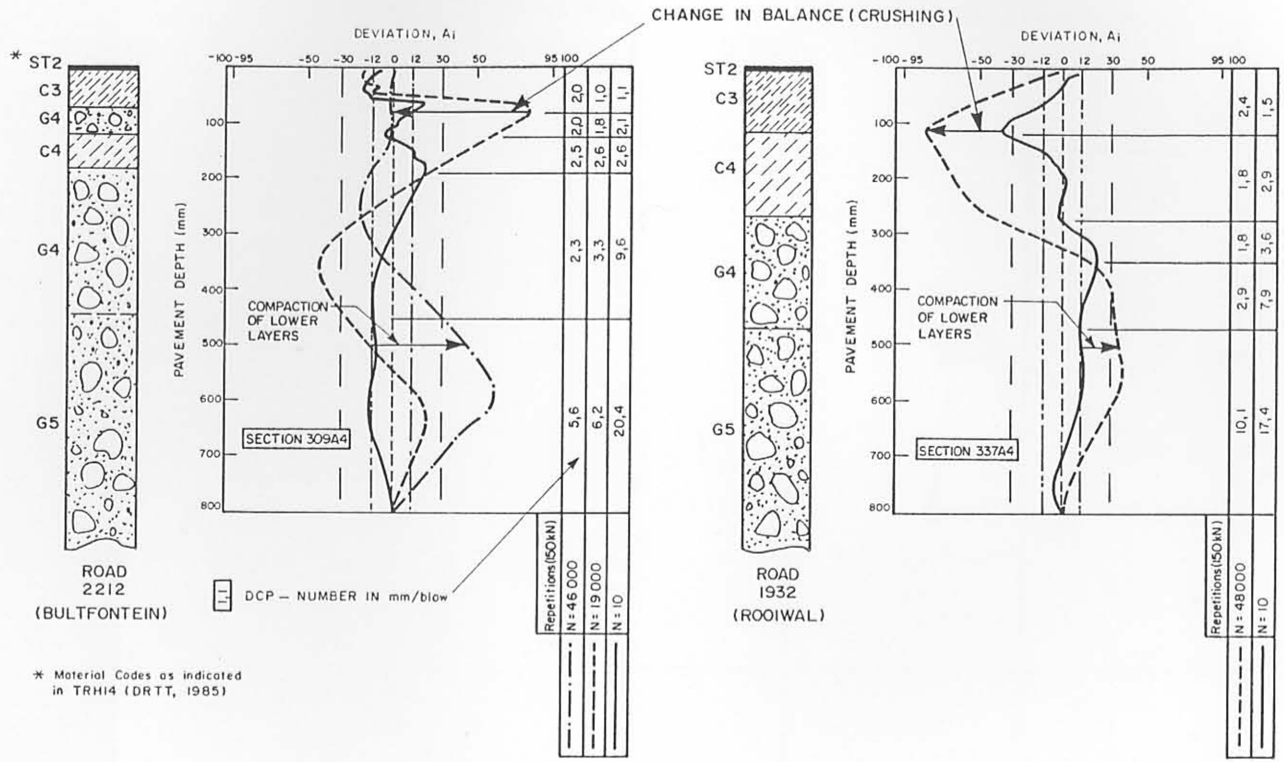


FIGURE 6.16

CHANGE IN DEVIATION FROM STANDARD BALANCE (A_i) AT VARIOUS STAGES OF HVS-TRAFFICKING (150 kN SINGLE WHEEL LOAD) ON SECTIONS 309A4 (SHALLOW) AND 337A4 (DEEP) PAVEMENT SECTIONS

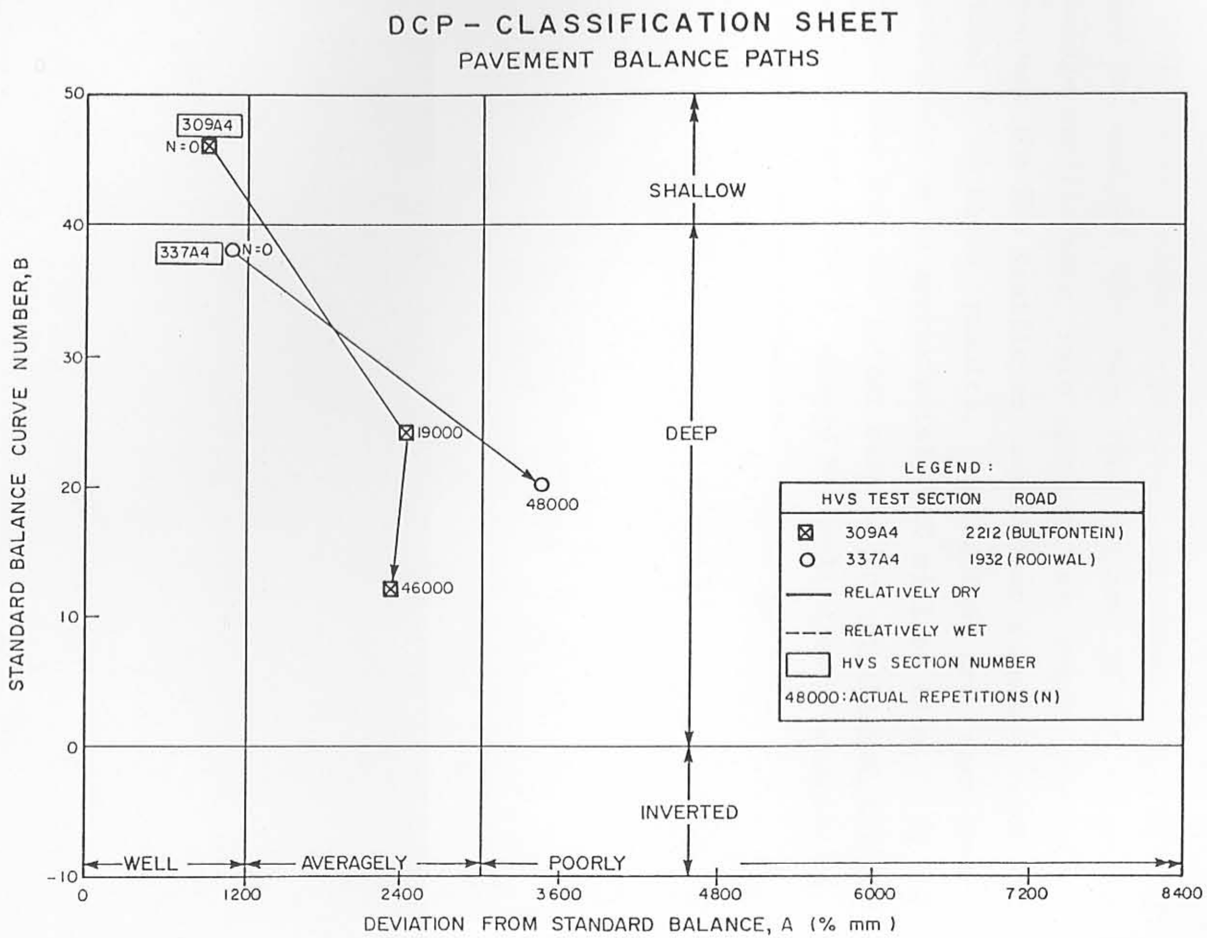


FIGURE 6.17

ILLUSTRATION OF THE BALANCE PATHS FOUND DURING ACCELERATED (HVS) TESTING FOR THE VARIOUS PAVEMENT SECTIONS TESTED

6.4.2 Original models

The original model (Kleyn, 1984), hereafter Model 1, is given below:

$$LIFE = Cm \times 10^{-9} (DSN_{800})^{3,5} \quad \text{..............6.1}$$

with LIFE = Number of standard 80 kN axles to produce 20 mm rutting on the surface of the pavement.
Cm = 6,5 for soaked
= 14 for wet
= 30 for optimum (average)
= 64 for dry conditions
DSN_{800} = Total number of blows to penetrate to a depth of 800 mm in the pavement.

Model 1 originated from the initial research work with the Transvaal HVS on light unbound pavements with gravel bases (Kleyn, 1984, Marais et al, 1982), and appears to predict the effective structural capacity to achieve 20 mm rutting on these pavements very accurately. In Figure 6.18, the correlation between predicted and measured repetitions on one of these pavements (Road P123/1) is illustrated. The figure indicates that a very accurate prediction resulted from the HVS tests on this pavement, irrespective of the test wheel load. The maximum structural capacity (only those tested at 40 kN dual wheel load), however, is relatively low, and is approximately 1×10^6 standard axles. Most of the work reported by Kleyn (1984) was also done at relatively low standard (40 kN) axle repetitions, and it is my opinion that Model 1 is accurate for the lower class pavements only, ie up to 1 million standard axles (E80s). Although pavements were also tested at higher wheel loads (60 kN and 100 kN) than the standard 40 kN (Figure 6.18), relative damage coefficients were <u>assumed</u> or, where possible, calculated to convert the HVS traffic to equivalent standard axles (E80s). Applying Model 1 to these results, indications are that this model predicts accurately up to approximately 10 million E80s. It must, however, be remembered that the latter case is for <u>equivalent traffic</u>, and it is my opinion that Model 1 should be applied with caution on the relatively stronger granular pavements.

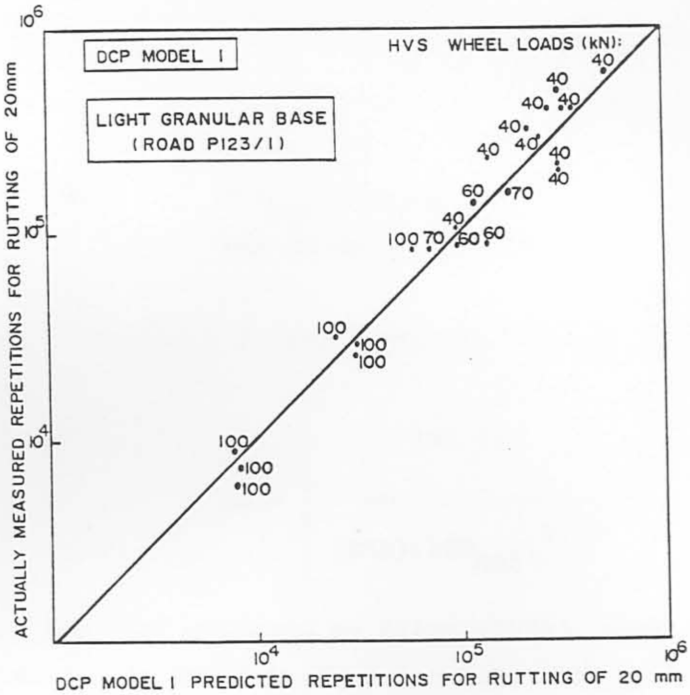


FIGURE 6.18

CORRELATION BETWEEN PREDICTED AND MEASURED REPETITIONS TO ACHIEVE A CHANGE OF 20mm IN THE RUTTING (MARAIS et al., 1982)

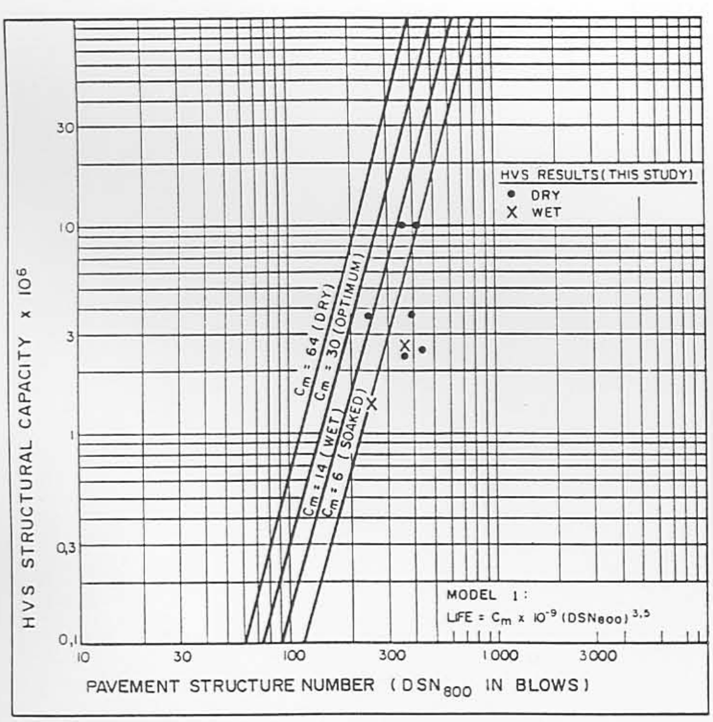


FIGURE 6.19

DCP MODEL 1 SUPERIMPOSED ON ACTUAL HVS MEASURED STRUCTURAL CAPACITY IN RELATION TO THE PAVEMENT STRUCTURAL NUMBER DSN_{800}

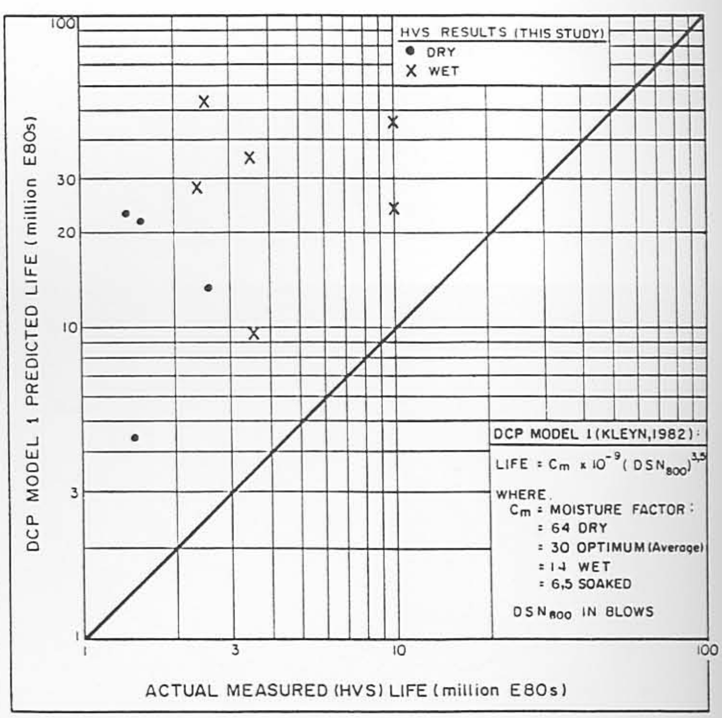


FIGURE 6.20

DCP MODEL 1 PREDICTION OF STRUCTURAL CAPACITY (LIFE) VERSUS ACTUAL MEASURED (HVS) LIFE TO ACHIEVE A CHANGE OF 20 mm IN THE PERMANENT DEFORMATION (RUTTING)

Applying Model 1, however, to the pavement sections tested in this chapter, the structural capacity is overestimated by a factor between 2 and 29, indicating that this model is <u>not</u> suitable for these pavements. See Figures 6.19 and 6.20 for the accuracy of Model 1, applied to the pavement sections investigated in this study.

Jordaan (1988) suggested the use of a combination of DSN_{800} and standard surface deflection (RSD, 40 kN) in order to calculate structural capacity. Following from this work of Jordaan (1988), the structural capacity may be calculated using Model 1, but with a "moisture" factor, Km, different from that of Cm proposed by Kleyn (1984). In Figure 6.21 the relations between deflection (RSD) and DSN_{800} are illustrated.

The relationships between DSN_{800} and deflection (RSD) are also given below (after Jordaan, 1988):

$$DSN_{800} = 339{,}8Km^{-0{,}28}(RSD)^{-1{,}17} \qquad \text{..........6.2}$$

$$RSD = 141{,}74Km^{-0{,}24}(DSN_{800})^{-0{,}85} \qquad \text{......6.3}$$

with DSN_{800} in blows
RSD in mm.

From Equations 6.2 and 6.3, the "moisture factor" is calculated:

$$Km = \left[\frac{141{,}74}{(RSD)(DSN_{800})^{0{,}85}}\right]^{4{,}1667} \qquad \text{..........6.4}$$

By replacing the "Cm" proposed by Kleyn (1984), with the "Km" calculated with Equation 6.4 in Model 1 (Equation 6.1), the structural capacity is then calculated. For the purpose of this dissertation the latter model is called Model 2. Model 2 overestimates the structural capacity even more than Model 1, by a factor between 1 and 950. This is unacceptable for the pavements in this study, and the need for an alternative model is evident.

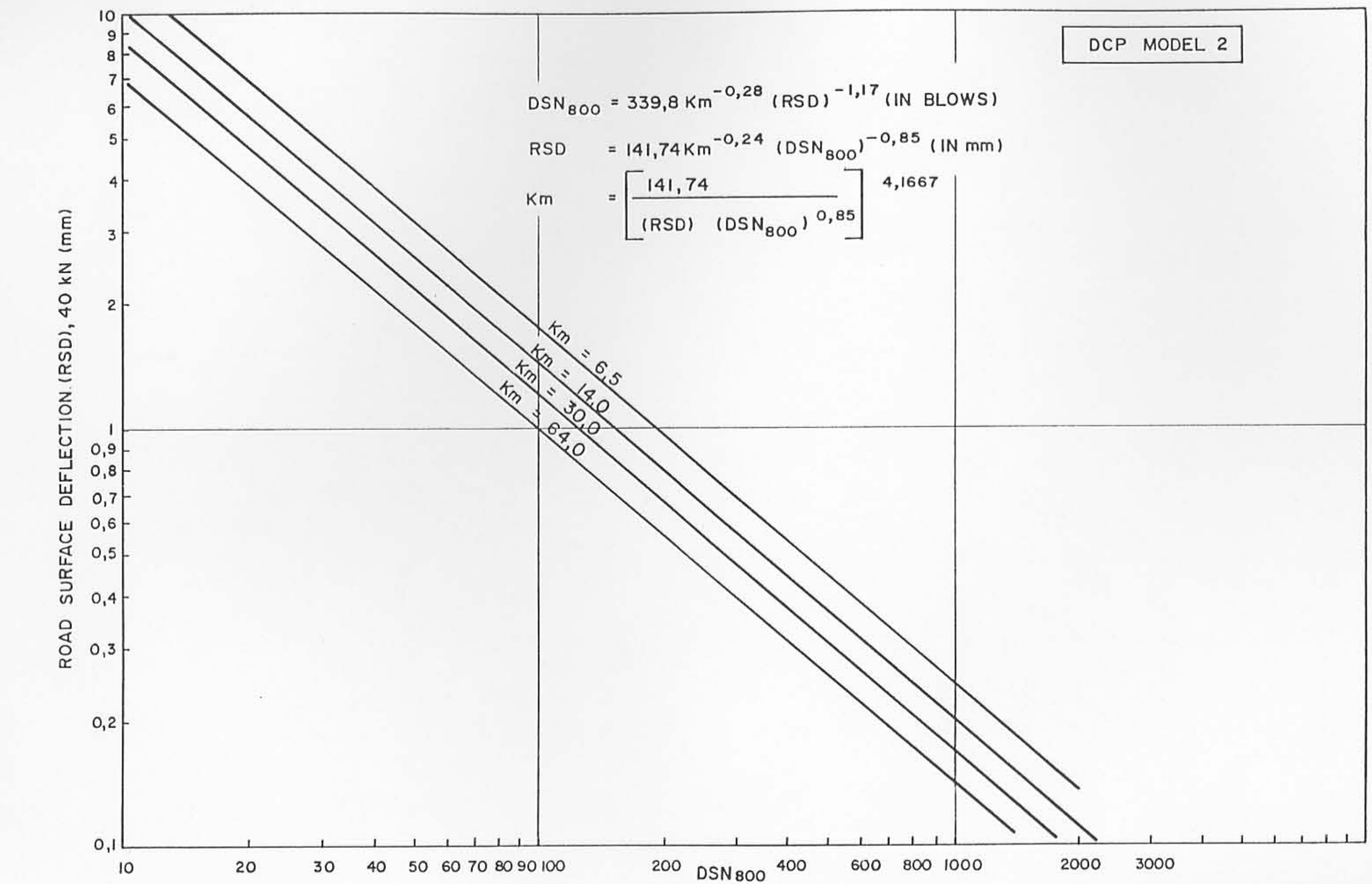


FIGURE 6.21

RELATION BETWEEN DEFLECTION (ASPHALT INSTITUTE) AND DCP STRUCTURE NUMBER DSN800 (JORDAAN, 1988)

It is believed that the underlying reasons for the overestimations of structural capacity by both Models 1 and 2 is strongly related to the fact that the basic DCP parameter, DSN_{800}, as well as the RSD, used in these models, is more representative of the total pavement depth (0 to 800 mm), especially the subgrade. If the majority of the permanent deformation originates from the subgrade layers or deeper down in the pavement, as is the case of the light unbound gravel pavements, Models 1 and 2 appear to be more accurate.

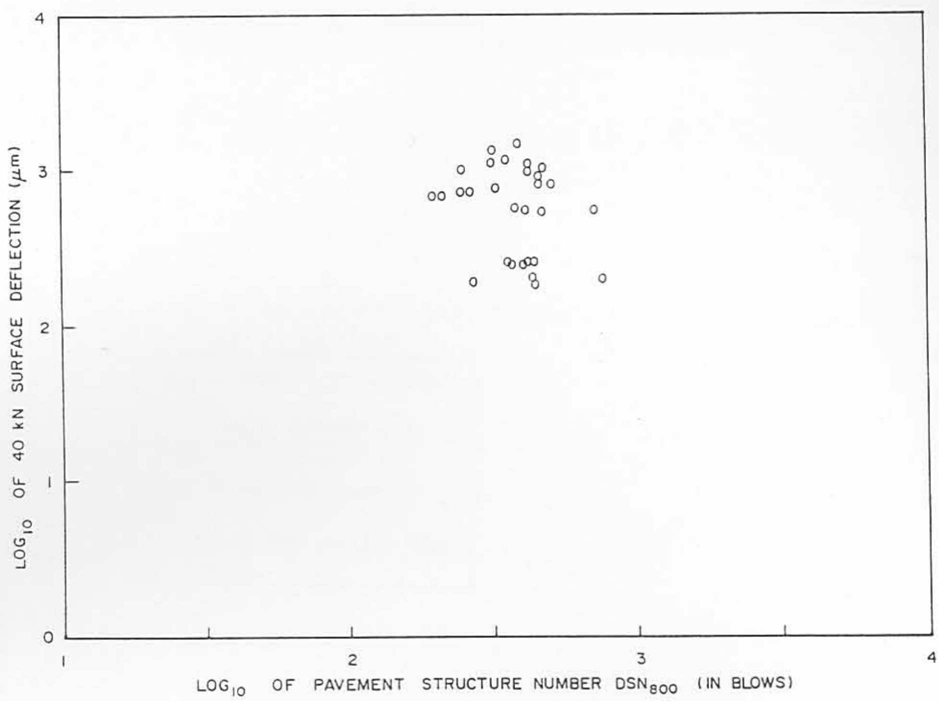
In Figure 6.22, the standard surface deflection (RSD) versus the DSN_{800} of the pavement sections studied here is illustrated. The figure illustrates that there is no correlation between the RSD and DSN_{800} for these sections. This is directly related to the fact that the majority of the RSD measured on the surface of these sections originates from the upper layers in the pavement, and not from the lower subgrade layers, and illustrates why Model 2 is incorrect for these pavements.

Both Models 1 and 2 are not recommended for use on pavements other than well- to averagely - balanced light unbound gravel bases, with structural capacity up to a maximum of 10 million E80s. These models appear to be fairly accurate for pavements with structural capacities less than one million E80s.

In Figure 6.23 various relationships between RSD and structural life for different type of bases, suggested by Kennedy et al (1978), are superimposed on the results found in this study. The figure indicates that although a similar trend appears, the results are scattered and do not conform to those published by Kennedy et al (1978), most probably for the reasons discussed above.

It is therefore necessary to investigate alternative parameters (in this case, DCP parameters) to be used in these pavements where the failures (usually deformation) originate in the upper layers of the pavement.

Figure 6.24 illustrates the relation between surface deflection (RSD) and DSN_{200} for the pavements studied here. DSN_{200} was selected because most of the deformation originated within the upper 200 mm of these pavements (both deep and shallow).



940-4-5915/5 BD

FIGURE 6.22

SURFACE DEFLECTION VERSUS THE PAVEMENT STRUCTURE NUMBER DSN_{800} AT VARIOUS STAGES OF HVS TRAFFICKING (THIS STUDY)

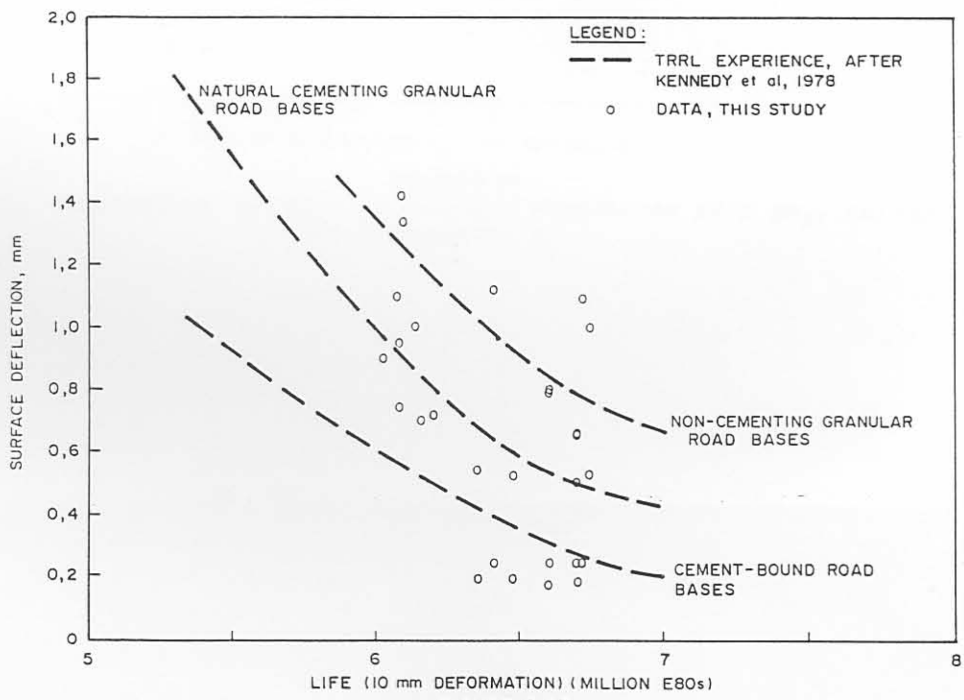


FIGURE 6.23

RELATIONS BETWEEN STANDARD (40 kN DUAL WHEEL) SURFACE DEFLECTION AND LIFE TO ACHIEVE A CHANGE OF 10 mm PERMANENT DEFORMATION ON VARIOUS TYPES OF ROAD BASES IN COMPARISON TO THE FINDINGS OF THIS STUDY

Although the accuracy of the relation is not very high (R^2=54 percent), a similar (promising) trend between deflection and a DCP parameter, suggested by Kleyn (1984) and Jordaan (1988) was found.

The relation is also given below:

$$RSD = 252041(DSN_{200})^{-1,22938} \quad \text{..........6.5}$$

where RSD in μm

DSN_{200} = Total number of blows needed to penetrate the upper 200 mm of the pavement.

The origin of the permanent deformations (and most of the deflection) in the pavements studied, was found to be in the upper layers owing to fatigue and crushing. Therefore an alternative model is needed for this situation, in which DCP parameters other than the DSN_{800}, are used.

6.4.3 Development of alternative models

In view of abovementioned limitations of the current DCP prediction models, alternative models were investigated based on the results of this study. It must, however, be remembered that these models are strictly applicable to the pavement situations as defined in this study, namely: averagely balanced deep and shallow lightly cemented base and subbase pavements.

As indicated in Chapter 4, the development of permanent deformation on pavements with lightly cementitious layers appears to be linear with HVS trafficking. The rate of deformation (R_L) with trafficking appears to be a reliable indicator of pavement behaviour. It is therefore my opinion that the DCP model for these pavements should be developed on the basis of the prediction of R_L. Because of the relatively "shallow" failures associated with these pavements, DCP parameters in these upper regions of the pavement should be used instead of DSN_{800}.

Various models were evaluated using different DCP parameters. The most significant models and their evaluations are summarised in Table 6.9.

940-4-5915/1 BD

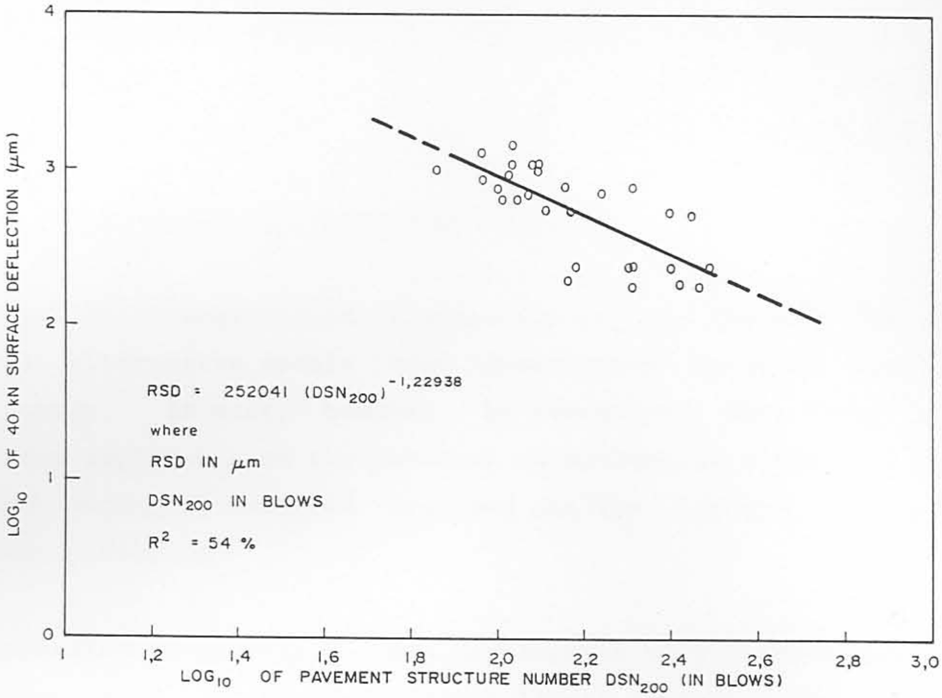


FIGURE 6.24

RELATION BETWEEN STANDARD (40 kN DUAL WHEEL) SURFACE DEFLECTION AND THE PAVEMENT STRUCTURE NUMBER DSN_{200} AT VARIOUS STAGES OF HVS TRAFFICKING

940-4-5914/3 BD

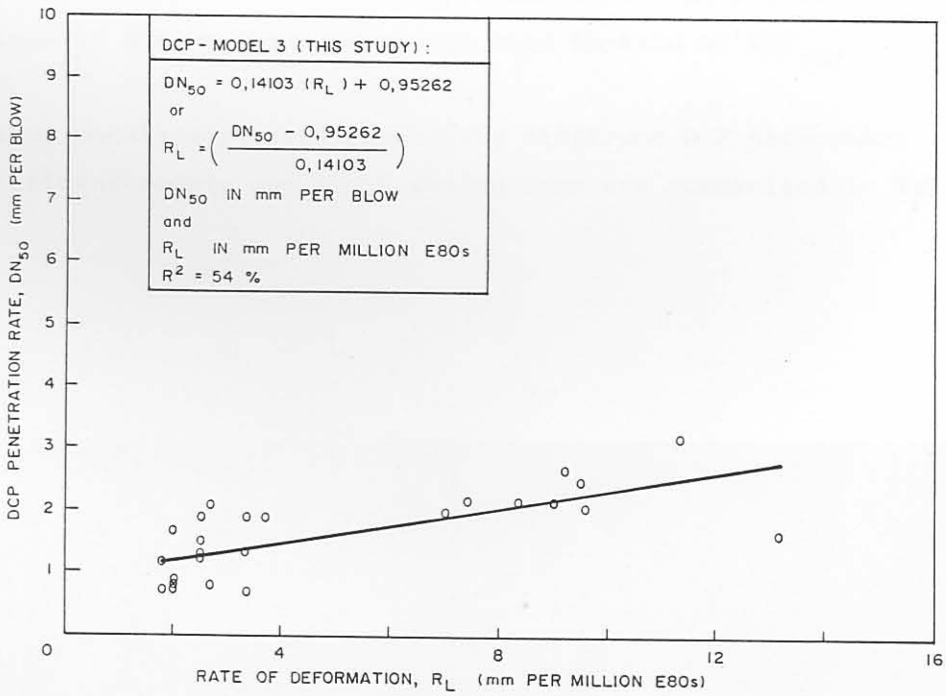


FIGURE 6.25

RELATIONSHIP BETWEEN AVERAGE DCP PENETRATION RATE DN_{50} AND RATE OF DEFORMATION, R_L

TABLE 6.9 EVALUATION OF THE VARIOUS DCP MODELS

REFERENCE	DCP PARAMETERS (VARIABLES)	R^2 (%)	REMARKS
Model 3	$R_L = f(DN_{50})$	54	Linear-linear
Model 4	$R_L = f(DN_{50}, DSN_{200})$	76	Linear-log
Model 5	$R_L = f(DSN_{200})$	36	Linear-log
Model 6	$LIFE_{10mm\ rut} = f(DSN_{200})$	38	Log-log
Model 7	$R_{Ldry} = f(DSN_{100}, DSN_{100-800})$	20	Linear-log
Model 8	$R_{Lwet} = f(DSN_{100}, DSN_{100-800})$	0,4	Linear-log

The table lists 6 models, of which only two appear promising, ie Models 3 and 4.

Model 3 is given below:

$$R_L = 7{,}091DN_{50} - 6{,}755 \quad \ldots\ldots\ldots\ldots\ldots 6.5$$

with R_L in mm per million E80s
DN_{50} = Average penetration rate of the upper 50 mm in the pavement base, in mm per blow.

Figure 6.25 shows Model 3, which is based on DN_{50}, which is the average penetration rate for the upper 50 mm of the pavement (base). Figure 6.26 shows the accuracy of Model 3 relative to HVS rate of deformation (R_L). In Figure 6.27 the random scatter of the residuals is illustrated. (The residuals are defined as the difference between the measured values and the predicted values, and residual plots are used to examine the assumptions made about the error terms and to check for model fit, Galpin, 1981).

940-4-5915/9 BD

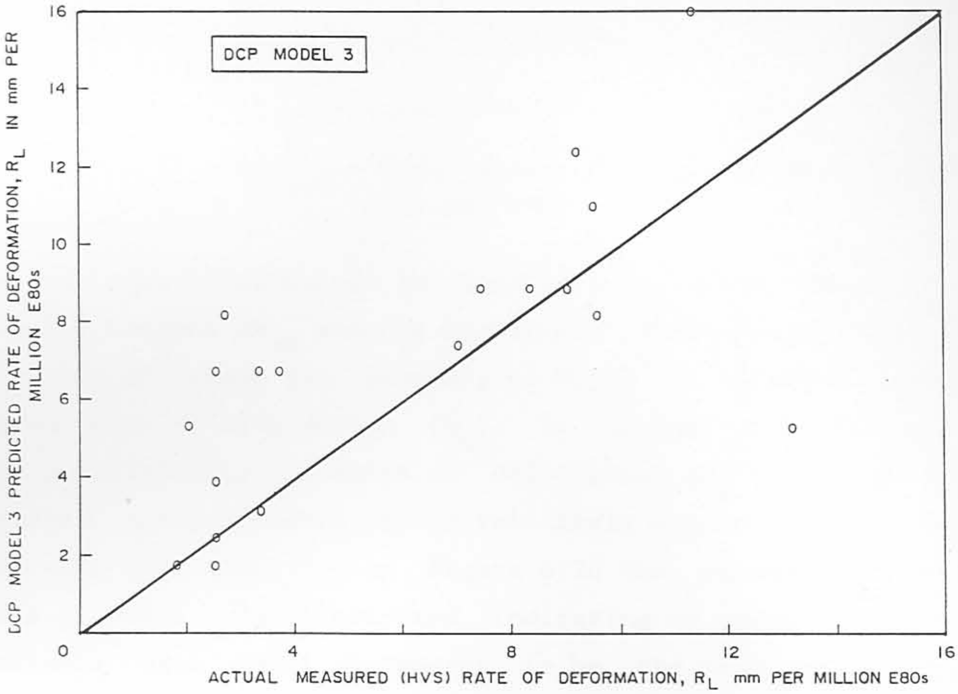


FIGURE 6.26

DCP MODEL 3 PREDICTION OF RATE OF DEFORMATION VERSUS ACTUAL MEASURED (HVS) RATE OF DEFORMATION

940-4-5915/7 BD

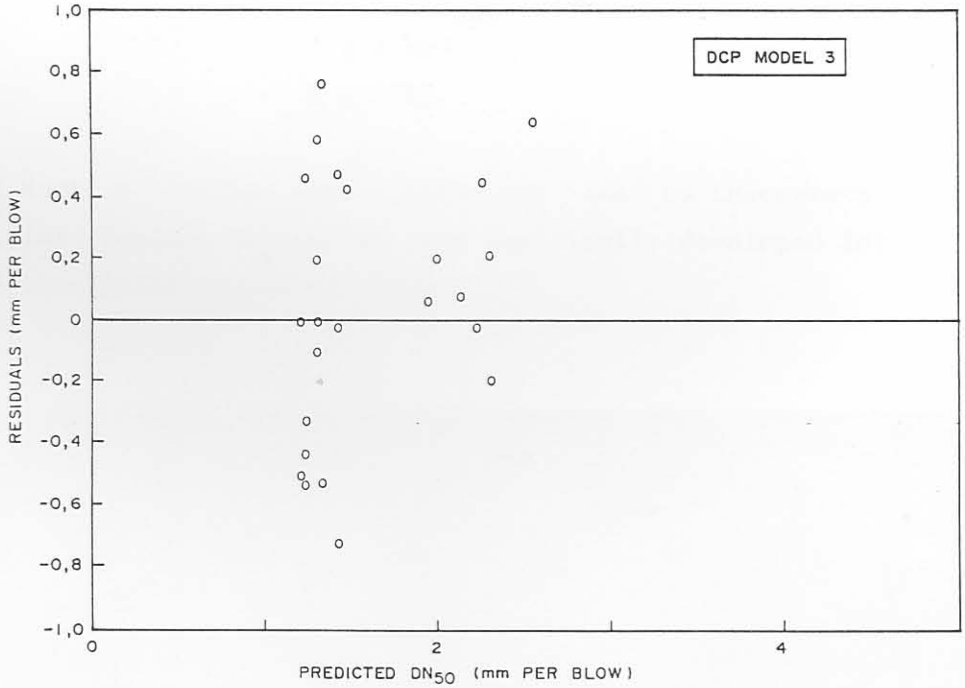


FIGURE 6.27

RANDOM SCATTER OF THE RESIDUALS OF DCP MODEL 3

Although the previous Figures 6.25 and 6.26 show a promising trend, it the accuracy of Model3 may be improved if additional DCP parameters (independent variables) are added. However, the models were kept as simple as possible.

Because the failures associated with the pavements in this study were limited to to the upper 200 mm, it was decided to incorporate the DSN_{200} (DSN_{200} = Total number of blows needed to penetrate the top 200 mm of the pavement) as another variable in addition to the DN_{50} of Model 3. This
model (Model 4) is given below:

$$R_L = \frac{DSN_{200}}{10^{((3,82806 - DN_{50})/(1,38572))}} \quad \text{........6.6}$$

with R_L in mm per million E80s

DN_{50} in mm per blow

DSN_{200} = Total number of blows in the top 200 mm of the pavement.

Model 4 is also illustrated in Figure 6.28, which shows a linear relationship between DN_{50} and the log of the ratio between DSN_{200} and R_L. Figure 6.29 shows the accuracy of Model 4, relative to the HVS determined rate of deformation (R_L). It appears that Model 4 over-predicts at relatively low rates of deformation (R_L < 5 mm per million repetitions), and under-predict at relatively higher rates. This was also the case for Model 3. In Figure 6.30 the random scatter of the residuals of Model 4 is illustrated, indicating no specific trend. With the available data, Model 4 appears to be the best model for these pavements, at this stage, and is only applicable to pavements with lightly cemented bases with the following DCP conditions:

$200 \leq DSN_{800} \leq 750$

$B \geq 0$ and

$A \leq 3000$.

Use of Model 4 outside these limits may lead to inaccurate structural capacities, because this model was empirically developed for pavements within the limits indicated above.

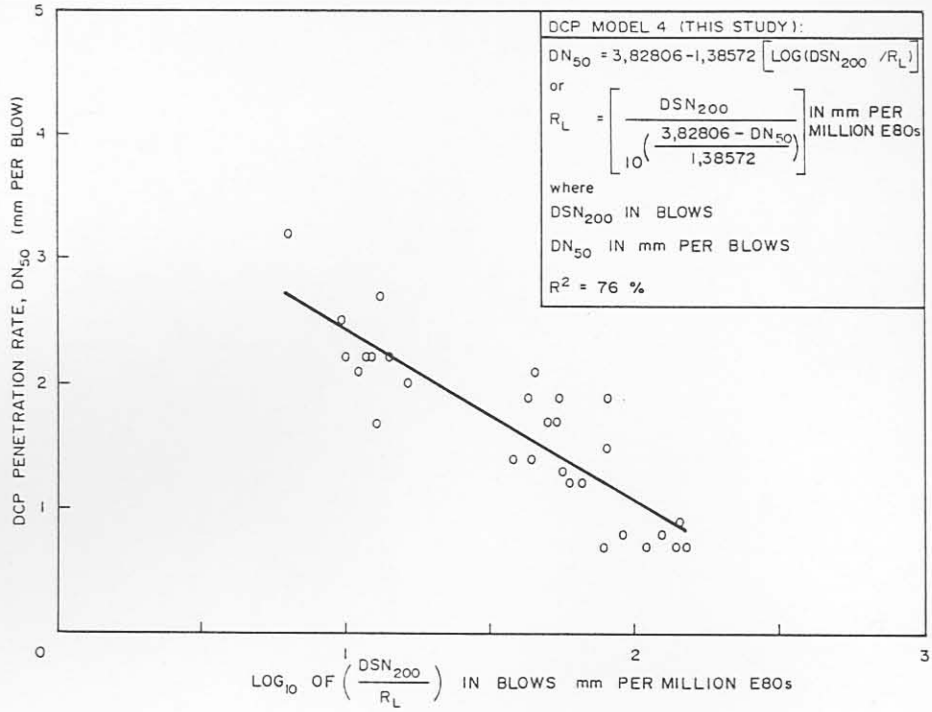


FIGURE 6.28

RELATIONSHIP BETWEEN DCP PENETRATION RATE DN_{50}, DSN_{200} AND THE RATE OF DEFORMATION, R_L

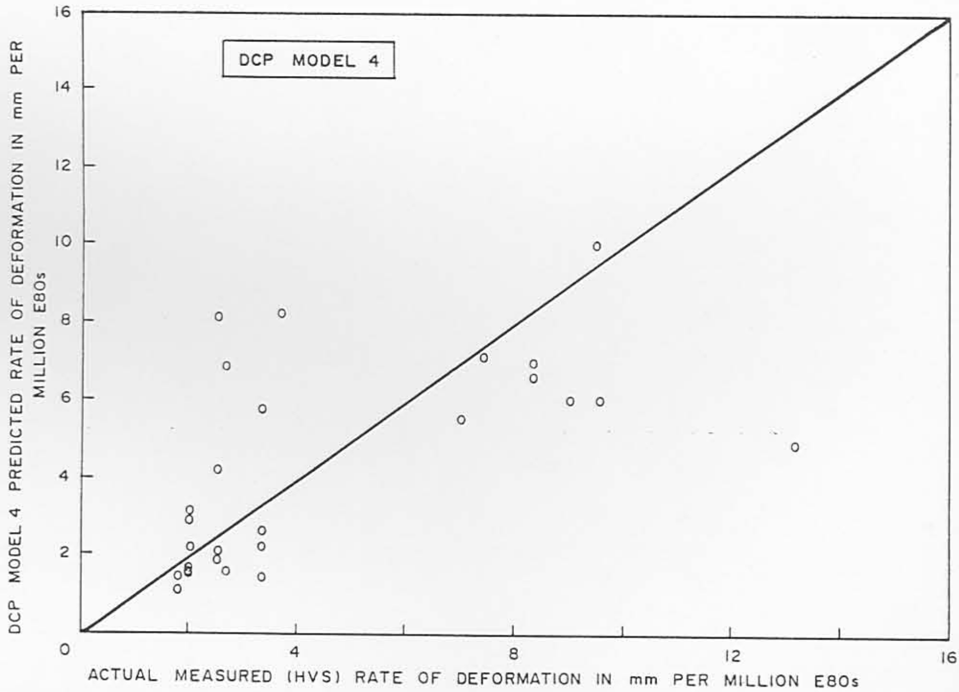


FIGURE 6.29

DCP MODEL 4 PREDICTION OF RATE OF DEFORMATION VERSUS ACTUAL MEASURED (HVS) RATE OF DEFORMATION

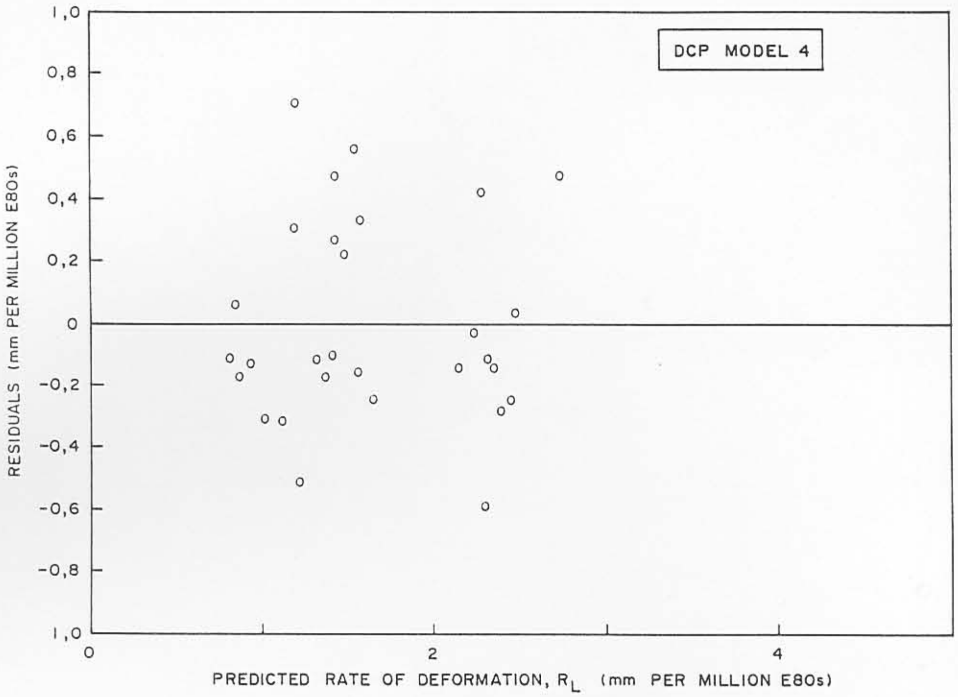


FIGURE 6.30

RANDOM SCATTER OF THE RESIDUALS OF DCP MODEL 4

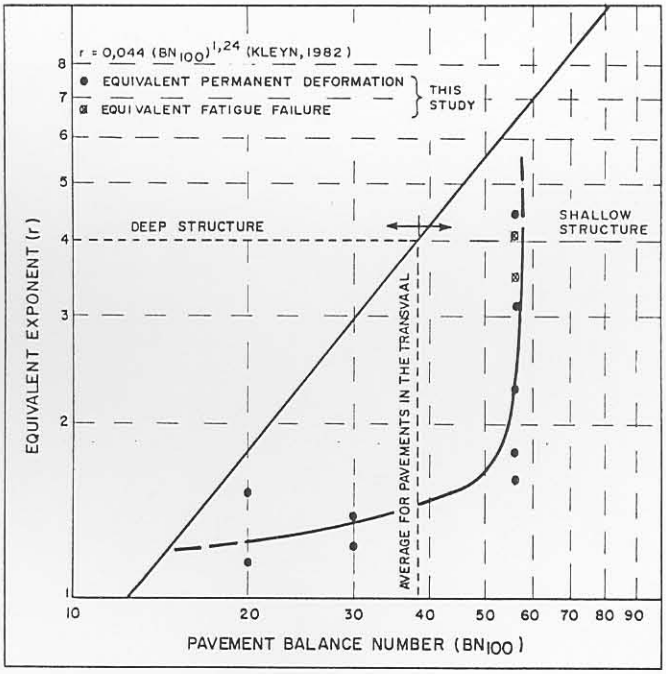


FIGURE 6.31

RELATIONSHIPS BETWEEN BN_{100} AND THE LOAD EQUIVALENT EXPONENT (r) FOR STRENGTH – BALANCED PAVEMENTS AND THE PAVEMENTS IN THIS STUDY

Various other models (Models 5, 6, 7 and 8, in Table 6.9) were evaluated using different DCP parameters, but with less success. Although it is accepted that many models other than those indicated in Table 6.9 are possible, it is my opinion that with the present available data, these models give an indication of some of the possibilities which may be investigated further on other types of pavements.

Research, however, should be continued in order to improve on these models in the future.

6.5 RELATIVE DAMAGE COEFFICIENTS

Kleyn (1984) published the first DCP-derived relative damage coefficients, in association with HVS research. In Chapter 4 (Paragraphs 4.2.4.4 and 4.3.4.4), discussions on the coefficients (r) determined for the two types of pavements discussed here, are given. The relationship proposed by Kleyn (1984) is illustrated in Figure 6.31, together with the results found in this study. Kleyn (1984) indicated that there appears to be a linear relationship between the log of the coefficient (r) and the pavement balance number, BN_{100}. The results of this study, however, indicate that this relationship is not linear, and that BN_{100} is not a good predictor of the relative damage coefficient, r, especially for the shallower pavements ($BN_{100} > 50$).

Further research, however, is necessary to define these relationships more accurately.

6.6 CONCLUSIONS AND RECOMMENDATIONS

6.6.1 Conclusions

The use of the Dynamic Cone Penetrometer (DCP) as a tool for predicting the behaviour of lightly cementitious base and subbase layers was studied. The concept of pavement strength - balance paths is introduced and appears to assist in describing pavement behaviour on a more quantitative basis than was done in the past. This is done by studying the changes caused by traffic loading in the two unique DCP parameters A and B. In general, parameter B, the balance number, appears to be more sensitive to change (owing to traffic) than parameter

A, the deviation from standard balance. Both parameters, however, are used to define the balance paths, introduced in this chapter.

The results from two basic types of pavements, deep and shallow, are discussed in detail and important differences are highlighted by the DCP. The main difference between these two pavements is reflected by the B parameter. For the deep pavement B showed an initial average of 19, and for the shallow pavement an average of 41. Both pavements were classified as averagely balanced, according to the classification system described in Chapter 3.

The DCP quantified the observed behaviour of these pavements adequately, in that higher penetration rates where measured where compression (crushing) failure occurred in the top of the base of the deep pavement, and compaction (densification) in the lower poorly cemented layers of the shallow pavement. As a result of traffic loading and prevailing moisture conditions, the balance paths of these pavements indicated that both pavements becomes deeper (decrease in B), but not necessarily better balanced. This was also found for pavement sections tested under excessively high single wheel load tests.

The structural capacity of these pavements was also evaluated and it was found that this capacity was overestimated by a factor of 2 to 29 by the original model (Model 1) developed by Kleyn (1984) and by a factor of 1 to 950 using Model 2 (Jordaan, 1988). Both these models are based on the structure number, DSN_{800}. The main reason for this overestimation is that most of the deformation originated in the upper layers of the pavements, tested in this study, and that DSN_{800}, which is a measure of all the layers in the pavement down to a depth of 800 mm, is not sensitive enough for this condition.

Alternative models were developed and evaluated, and it was found that the **rate of deformation** on the pavements studied here is adequately predicted by the number of blows needed to penetrate the upper 200 mm of the pavement, DSN_{200}, and the average penetration rate of the top 50 mm of the pavement, DN_{50}. These DCP parameters were selected because most of the deformation occurred in the upper 200 mm of these pavements.

Model 4 is only applicable for pavements with lightly cemented bases with the following DCP conditions:

$$200 \leq DSN_{800} \leq 750$$
$$B \geq 0 \text{ and}$$
$$A \leq 3000.$$

Use of Model 4 outside these limits may lead to inaccurate structural capacities, because it was empirically developed for pavements within the above limits.

6.6.2 Recommendations

It is recommended that the concept of strength - balance paths should be applied to other pavement types for further verification and refinement, as more data becomes available. It is also recommended that the effect of changes in the moisture content only on these paths be better studied as well as the natural variations in both the degree of balance, A and the balance number, B.

Further refinement of the models for the prediction of remaining structural capacity is necessary as more data becomes available. More experience with HVS will improve the data base of DCP/traffic loading, and may help to define the underlying fundamental relationship for these predictions properly. It is my opinion that a fundamental relationship exists between basic DCP parameters and the remaining structural capacity (shear strength, bearing capacity) for most normal pavements. Research should be guided to improve the understanding of and to quantify this relationship more accurately.

6.7 REFERENCES

Division of Roads and Transport Technology (DRTT), (1985). Guidelines for Road Construction Materials. Technical Recommendations for Highways, TRH14: 1985, CSIR, Pretoria, 1985.

Marais, G P, Maree, J H and Kleyn, E G (1982). The Impact of HVS testing on Transvaal Pavement Design. Paper delivered at the Annual Transportation Convention during 9-13 August 1982 (ATC 1982), Session H, S.313, Volume 3, CSIR, Pretoria, 1982.

Galpin, J S (1981). SWISK 25. Regression Package REGPAC (Version 3). Special Report, National Research Institute for Mathematical Science, CSIR, 1981.

Kleyn, E G (1984). Aspects of Pavement Evaluation and Design as determined with the Dynamic Cone Penetrometer (DCP). M Eng. thesis (In Afrikaans), Faculty of Engineering, University of Pretoria, Pretoria, 1984.

Jordaan, G J (1988). Analysis and Development of some Pavement Rehabilitation Design Methods. Ph.D Dissertation, Faculty of Engineering, Department of Civil Engineering, University of Pretoria, Pretoria, 1988.

Kennedy, C K and Lister, N W (1978). Prediction of Pavement Performance and the Design of Overlays. TRRL Laboratory Report 833, TRRL, Crowthorne, 1978.