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ASSESSMENT OF PAVEMENT DAMAGE DUE TO ABNORMALLY HEAVY VEHICLES: A CASE STUDY

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SUMMARY

Some important aspects relating to structural damage caused by abnormally loaded vehicles on a range of typical South African pavement types are described. A summary of a detailed case study is given as is the determination of pavement damage. Damage was quantified relative to the effects of standard 80 kN loading using the South African Mechanistic Design Method. Based on the possible structural damage identified. operating rules were determined for the vehicles.

OPSOMMING

Sommige aspekte van potensieële strukturele skade aan 'n reeks tipiese Suid Afrikaanse paaie word hierin ondersoek. 'n Opsomming van 'n gevalle studie word bespreek, en dit word aangetoon dat strukturele skade aan 'n plaveisel suksesvol bepaal kan word op 'n relatiewe basis deur die gebruik van die huidige Suid Afrikaanse Meganistiese Ontwerp Metode vir plaveiselanalise. Moontlike strukturele plaveiselskade is ge-identifiseer waarvan bedryfsreëls afgelei is vir die gebruik van hierdie tipe voertuie op padplaveisels.

INTRODUCTION.

Damage to road pavements caused by heavy vehicles is a topic that is becoming increasingly important as the volume of road traffic and mass per axle increase. The present somewhat simplistic approach of using a "damage factor"[1] that is taken as $(P/80)^n$ (where P equates to the axle load and n is an exponent usually varying between 2 and 6, depending on the type of pavement, etc) has many drawbacks. For instance, the equation does not explicitly take into account the effects of wheel and multiple axle configuration differences, vehicle speed, tyre pressure, pavement structure and temperature These deficiencies may lead to heavily laden vehicles, being illegal in terms of present legislation[2], actually doing less or even more structural damage to pavements according to the above simplistic approach.

The aim and purpose of this paper is to summarise some of the important aspects regarding a case study which was done for Armscor on the effect of abnormally heavy loaded vehicles on possible pavement damage[18], based on the current South African Mechanistic Method for pavement analysis.

BACKGROUND

Transportek were contracted to assess the effect of heavy military vehicles on certain routes and to give recommendations on how and when these vehicles could be used. To do this field extensive field measurements were made and the South African Mechanistic Design method[3] was used to calculate pavement damage. The pavement damage was based on six (6) different failure criteria, as described below. The combination of effects of 5 (five) pavement structures, 3 (three) wheel configurations, 4 (four) wheel loadings, 3 (three) speed categories and 3 (three) temperature categories were investigated.

The South African mechanistic design method[3] has been in existence for the past three or so decades and provides a rational and quantitative means of predicting pavement life from the interaction of wheel loads and pavement structures. Pavement response-life functions (termed "Transfer Functions" in this paper) converting calculated stresses and strains to the number of traffic passes have largely been derived from data obtained from results of Heavy Vehicle Simulator (HVS) tests[4], and therefore relate directly to South African field conditions.

PAVEMENT TYPES USED IN THIS STUDY

The field deflection measurements (using permanently installed Multi-depth Deflectometers (MDDs)[8]) were done on the range of pavements listed below:

- A heavy asphalt base pavement structure on the N1-22 north of Pretoria,
- A heavy granular base pavement structure on the P157-1 highway between Pretoria and Jan Smuts airport,
- A light, lightly cementitious base pavement structure on the R375 (D433) between Coligny and Biesiesvlei,
- A light granular base pavement structure on the R47 (P28-1) near Tarlton, and
- A heavy, strongly cemented base pavement structure on the N4/1 west of Pretoria.

A generic description for each of these pavements is given below:

N1-22: Heavy Asphalt Pavement

This pavement is representative of road category A, E4 design traffic, bitumen hot-mix based pavements in the TRH4 design catalogue[5], and according to IDM deflection basin parameters[6], the pavement is classified as being "Stiff". The average Impulse Deflectometer (IDM) deflection being measured as 0.198 mm and the Surface Curvature Index (SCI) 0.09 mm.

N4: Heavy strongly cemented pavement

According to the IDM deflection basin parameters the pavement is classified being in the "Initial fatigue" cracking state[6]. The maximum IDM deflection is 0.223 mm and the Surface Curvature Index is 0.071 mm.

P157-1 (R21) Heavy Granular Pavement

This road category is designed for E4 traffic[5] and is also representative of Class V and VI pavements in the TPA catalogue[7]. In terms of IDM classification[6] the pavement is "Stiff", the Surface Curvature Index being measured as 0.179 mm and the maximum deflection 0.403 mm.

P28-1(R47) Light Granular Pavement

This category B pavement structure[5] is designed for E1 traffic[5] and is also representative of class I and II light granular pavements of the TPA catalogue[7]. IDM deflection criteria class the pavement as

"Flexible" where the maximum IDM deflection was 0.746 mm and the Surface Curvature Index (SCI) 0.433 mm.

D433(R375) Light, lightly cemented pavement.

This pavement is a category B road carrying E2 traffic[5] and also falls into the Class III and IV light lightly cemented base pavements in the TPA[7] catalogue. IDM deflection criteria class the pavement as "Flexible" the maximum deflection for this pavement being 0.547 mm and the Surface Curvature Index 0.270 mm.

TEST VEHICLES AND LOAD CONFIGURATIONS

Three test vehicles were involved in the study: the ALJABA and the WITHINGS and Deflectograph truck which was used for RSD measurements. The ALJABA and the WITHINGS are recovery vehicles that are 6 wheeled (three axles) and 16 wheeled (6 axles) respectively. Wheel configurations for the two vehicles are given in Figure 1. Note that the WITHINGS was tested whilst towing a RATEL armoured vehicle.

FIELD MEASUREMENT PROCEDURE

Test sections on each pavement were identified using IDM deflection data and visual inspection. Multi-Depth Deflectometers (MDDs)[8] were then installed and calibrated, and testing commenced.

The test program for each of the 5 pavement structures was similar and simply involved repeated passes of each test vehicle over the in-situ MDD instrumentation at three target speeds: 10, 20 and 60 km/h.

EXAMPLES OF MEASURED DEFLECTIONS

An example of data obtained with the MDD apparatus is given in Figure 2, clearly showing the effects of the different wheel configurations.

DATA PROCESSING PROCEDURE

- In-situ, in-depth deflections induced by the different vehicles were measured using Multi-Depth Deflectometers (MDD[8]), and a high speed data-logging PC card. Deflections were measured at different speeds (nominally 10, 20 and 60 km/h) and at a range of temperatures (typically between 12 and 26°C).
- Maximum (peak) values were taken from deflection data (see Figures 3 and 4 for examples) and analysed using linear regression techniques.

- Using peak deflections, wheel load and configuration data and layer thicknesses, one of the programmes CHEVRON MODFIT or TOPFIT were used to backcalculate elastic moduli. Note that where MDD modules were not suitably placed to derive surfacing moduli, values were assigned to the surfacing using guidelines given in Reference 3, and other documentation.
- Moduli calculated in the previous step were used to calculate stresses and strains at selected points in the pavement structures under the different wheel loads using linear elastic theory. The depths required are defined by the failure mode and material type.
- The stresses and strains calculated were then applied to transfer functions linking these properties to pavement life. This was carried out for each vehicle at all speeds and temperatures.
- The effect of the total vehicle on the different roads (i.e. all axles for each vehicle) was calculated by taking the "medium speed-medium temperature" case for the vehicles, and comparing the lives thus obtained with that of the standard 80 kN rear axle truck (in this case the Deflectograph). The same relationship was then used for other combinations of speed and temperature.
- To obtain quantitative values of damage due to the various vehicles, traffic spectrums for the various pavements (taken from previous traffic counts) were used.
- The investigation of "thin surfacing life" (for the R47, N4 and R21 pavements) was carried out using assigned values of asphalt stiffness.

An example of the calculations used to quantify the relative damage of the different vehicles is now given.

Data: Present traffic spectrum per annum = 500000 (E80 axles).
Number of ALJABA journeys per annum = 20.
1 ALJABA is equivalent to 20 E80s (see below for details).

Calculation: The future traffic spectrum would be 500000+400 E80s, thus giving a reduction in the pavement life of 100*(20*20)/(500400)=0.08%

Values used for the normal traffic spectrum of each pavement were as follows:

P157 (R28):	597500 E80s per annum,
N1-22:	413500 E80s per annum,
N4:	254400 E80s per annum,
D433 (R375):	1830 E80s per annum, and for
P28-1 (R47):	28840 E80s per annum.

CALCULATION OF DAMAGE DONE BY THE TOTAL VEHICLE LOADING (ALJABA and WITHINGS)

Note that calculations were carried out to quantify vehicle effects for the "medium speed-medium temperature case only. It was then assumed that the same relationship held for the other speed and temperature cases.

Step 1: Calculation of residual lives for axle 1 and 2 of the Aljaba,

Step 2: Calculation of residual lives for axle 3 and 4 of the Aljaba,

Step 3: Calculation of residual lives for axle 5 and 6 of the Aljaba,

Step 4: Calculation of residual lives for the E80 loading of the deflectograph,

Step 5: Calculation of a "damage" factor for each case:-

$$\frac{RESIDUAL\ LIFE\ (Deflectograph)}{RESIDUAL\ LIFE(Axle)} = DamageFactor$$

Step 6: Calculation of a Damage Factor ratio for each set of axles using axles 5 and 6 as the basis for comparison:

$$\frac{DamageFactor(Axles1+2)}{DamageFactor(Axles5+6)} = DamageFactorRatio(1-2)$$

$$\frac{DamageFactor(Axles3+4)}{DamageFactor(Axles5+6)} = DamageFactorRatio(3-4)$$

Step 7: For each temperature and speed combination for each pavement the Damage Factor for the Deflectograph and axles 5 & 6 of the Aljaba is calculated.

Step 8: Calculation of Damage Factors for all temperature and speed combinations by multiplying the Damage Factor calculated for axles 5 & 6 (Step 7) by the Damage Factor ratios (calculated in Step 6).

Step 9 Sum all axle Damage Factors to obtain a single factor for the vehicle, (e.g. 1 Aljaba = 20 E80s).

FAILURE MODES

Thin Asphalt Surfacings (<75 mm layer thickness)

The failure mode for these materials has been identified as fatigue failure which is caused by excessive tensile strains in the material-usually at the bottom surface[9,10]. An important difference between thin surfacings and bituminous bases is that failure of thin surfacings is dependant on tyre pressure and not wheel load, hence the correlation between induced tensile strain and repetitions of the particular load under investigation and not standard 80kN axle loading[3].

Bituminous bases

Bituminous bases typically fail through flexural fatigue-induced cracking although permanent deformation can also be a problem in hot conditions. The possibility of deformation (rut) failure is normally minimised by mix design, and thus for purposes of structural analysis, only layer thicknesses, material stiffnesses and applied loads are used to calculate the maximum tensile strains developed. As the layers considered are relatively thick, some allowance has to be made for the propagation of cracks (usually initiated in the bottom of the layer) through the layer. Shift factors (depending on the road category) are therefore multiplied to the number of repetitions calculated for crack initiation.

Granular base materials

Granular materials normally show distress through permanent deformation or inadequate stability, both having been shown to be related to material shear strength[11]. The safety factor approach[11] has been developed for base layers of these materials to limit shear stresses, thus safeguarding the layer from excessive shear deformation failure. If stresses are kept within the elastic limit, (expressed by the Mohr-Coulomb strength parameters), then only "bedding-in" deformation occurs, but where stresses exceed the elastic limit however, deformation occurs at different rates according to the stress level and material type. Recommendations have been made regarding permissible values for the Factor of Safety for different road categories [3,11]

Granular or equivalent granular subbase

When cemented materials have successively cracked and become an equivalent granular material, the failure mode used is that of rutting, for which simple transfer functions describing 2, 10 and 20 mm ruts are available[12].

Cemented layers

Since the work of Otte[13] which gave expressions predicting crack initiation in cemented materials, de Beer has used field test data and observations to improve the existing relationships and developed new criteria[12]. For example, the concept of effective fatigue life (N_{ef})[12,14] is now used in preference to crack initiation. Failure is defined as being where deflections are between 0.5 and 0,75 mm with an associated permanent deformation of approximately 2 mm. Once this stage has been reached and cracks have propagated through the layer, the cemented material breaks into progressively smaller blocks with an associated increase in permanent deformation, elastic deflection leading to surfacing failure and potholing.

An additional failure criterion to fatigue failure has been recognised and defined by de Beer[15] as being that of crushing failure N_c. N_c is defined as the number of load repetitions required for 1% permanent deformation in the layer. For thinly surfaced pavements with cemented bases the permanent deformation occurring during crushing failure causes cracking in the seal almost immediately, leading to water ingress, pumping and disintegration of the pavement and potholes.

Subgrade

Vertical subgrade strain-traffic repetition relationships used in the South African Mechanistic Design Procedure are modifications of the correlations proposed by Dorman and Metcalf in 1962[14]. The present day curves correspond to ruts of 10, 15 and 20 mm for category A, B and C roads respectively.

TRANSFER FUNCTIONS

To predict pavement life from measures of stress and strain (as indicated in Table 1), functions linking life to these measures are required (which for this report are termed "Transfer Functions"), which were taken from References 3, 12, 14, 15 and 16.

SENSITIVITY OF RESULTS TO TRAFFIC SPECTRUM

It is quite obvious from the preceding section that the way in which damage is calculated depends very much on the traffic spectrum used. A range of traffic spectrums were therefore used to investigate the sensitivity of the calculations to traffic spectrum. Examples of results of the calculations are given in Figures 5 and 6, indicating the sensitivity of the different pavements to different traffic loads and assumptions of traffic spectrums.

IDENTIFIED FAILURE MODES

Table 1 Predicted Failure Modes

Pavement	WITHINGS	ALJABA & G6	ALJABA & TANK
N1*	(1) Asphalt (2) Rutting- lower subbase (3) Rutting- subgrade	(1) Asphalt (2) Rutting- lower subbase (3) Rutting- subgrade	(1) Asphalt (2) Rutting- lower subbase (3) Rutting- subgrade
N4*	(1) Rutting- selected layer (2) Shear-base (3) Asphalt	(1) Rutting- selected layer (2) Shear-base (3) Asphalt	(1) Rutting- selected layer (2) Asphalt (3) Shear-base
R21	(1) Rutting-selected layer (2) Crushing- subbase (3) Rutting- subbase	(1) and (2) Rutting- selected layer or crushing- subbase (3) Rutting- subbase	(1) Rutting - selected layer (2)Crushing - subbase (3) Rutting- subbase
R47	(1) Asphalt (2) Rutting- subbase (3) Rutting- subgrade	(1)&(2) Rutting- subbase or subgrade (3) Shear-base (4) Asphalt	(1) Rutting- subbase (2) Rutting- subgrade (3) Asphalt
R375	(1) Rutting-selected layer (2) Shear-base	(1) Rutting-selected layer (2) Shear-base	(1) Rutting-selected layer (2)Shear-base

*Combination of effective and equivalent pavement lives

DISCUSSION

When assessing results certain aspects should be borne in mind such as the fact that all calculations (and therefore moduli) are based on average values of deflection which do not give a "confidence envelope". Results could therefore be further refined by using (for example) the Rosenbleuth point estimate method[17], from which reliability can be built into calculations. Reliability of data should be assessed, especially with the scatter of points seen in Figures 3 and 4. Points were distributed in the manner seen due to wheels loading the MDD slightly differently each time. General trends are however identifiable and should be treated as such.

It should be noted that wheel load as such is not necessarily the most critical factor determining pavement life. This follows findings over the past twenty or more years indicating how single wheel loads can be disproportionately more destructive than multiple wheel configurations[19,20]

It is also apparent that even though there are some general principles relating to pavement damage it is difficult to generalize, even for pavements of a similar nature. This implies that for confidence in design each combination of pavement type, loading and tyre pressure should be taken into consideration, hence necessitating a detailed analysis.

Speed and temperature were seen to have a noticeable influence on deflection readings (see Figures 3 and 4) with asphalt base pavements being particularly susceptible to speed effects. The rate of change in deflection due to the effects of speed and temperature were measured as being quite similar for vehicles on any given pavement, although absolute values do differ.

Depending on the material and depth in the pavement, elastic moduli backcalculated from deflection measurements showed the effects of speed, load and temperature by either stiffening or softening, indicating the difficulty in determining moduli from limited data and implying that great care is required when calculating life for pavements.

Table 2 gives a summary of results obtained by considering the maximum and average damage calculated for the nine combinations of speed (x3) and temperature (x3).

Table 2 Summary of (calculated) Reductions in Pavement Lives (%)

Calculation and Pavement	WITHINGS	ALJABA & G6	ALJABA & TANK
Average Reduction-N1	0.02	0.07	0.09
Maximum reduction-N1	0.07	0.24	0.30
Average Reduction-N4	0.05	0.02	0.03
Maximum reduction-N4	0.07	0.03	0.05
Average Reduction-R21	0.06	0.02	0.17
Maximum reduction-R21	0.13	0.03	0.32
Average Reduction-R47	3.21	2.09	4.53
Maximum reduction-R47	5.43	3.26	7.02
Average Reduction-R375	18.07	38.04	44.66
Maximum reduction-R375	23.00	45.95	53.80

RECOMMENDATIONS AND OPERATING RULES

Detailed recommendations were made in Reference 18 suggesting operating rules for the vehicles on each of the pavements. These rules are based on potential damage to the pavements investigated, and depends greatly on pavement composition, temperature, condition and vehicle speed. For the purpose of this paper the following aspects are considered relevant and important:

- Where failure occurred in thin surfacings, the supporting structure should be stiff to limit the development of tensile strain in the asphalt. A maximum IDM deflection less than 0.4 mm and an SCI of less than 0.2 mm were thought appropriate criteria.

- For heavy asphalt pavements trafficking during relatively low temperatures (<15° C.) was not recommended but if unavoidable, a speed of 60km/h or more was suggested to be maintained to minimise damage.

- On heavy strongly cemented pavements few restrictions were deemed necessary if the maximum IDM deflection is less than 0.4 mm and the SCI less than 0.2 mm.

- The heavy granular base pavement tested performed well except for the heaviest loading condition for which excessive rutting in the selected layer was predicted. It was therefore recommended that the ALJABA-Tank combination is not to be used on this pavement. Use of the ALJABA-G6 combination on the other hand was considered acceptable if used under similar temperature and speed conditions to those experienced during the investigation (i.e. between 10 an 60km/h and 15 to 40° C.).

- Trafficking of either the WITHINGS or the ALJABA on either of the light pavement structures was not recommended as calculations indicate an excessive reduction in pavement life. There were indications that the thin seals would be severely damaged by the vehicles in hot weather, especially when negotiating sharp turns. However, it should be noted that the effects of the vehicles may be exaggerated due to the relatively low traffic spectrums used in calculation.

- In addition to the above points excessive braking and acceleration should be avoided, especially where new seals and fresh asphalt layers are encountered. When the vehicles are stationary the steering wheel should not be turned, thus avoiding damage to the surfacing due to horizontal shear forces.

CONCLUSIONS

The purpose of this study was to highlight and quantify some of the important aspects relative to possible damage caused to a range of typical South African pavement types under abnormally loaded heavy vehicles. The study was carried out for Arniscor, and incorporated detailed field deflection measurements at different speeds and temperatures using three different vehicle and load configurations. The study indicates that pavement damage and hence reduction in pavement life can be determined using the South African Mechanistic Design Method and associated principles. Using this method the most critical layers in a range of pavements were identified. From the mechanistic analysis potential pavement damage was quantified and practical operating rules determined to minimize pavement damage for the specific combination of pavement types and vehicles under investigation .

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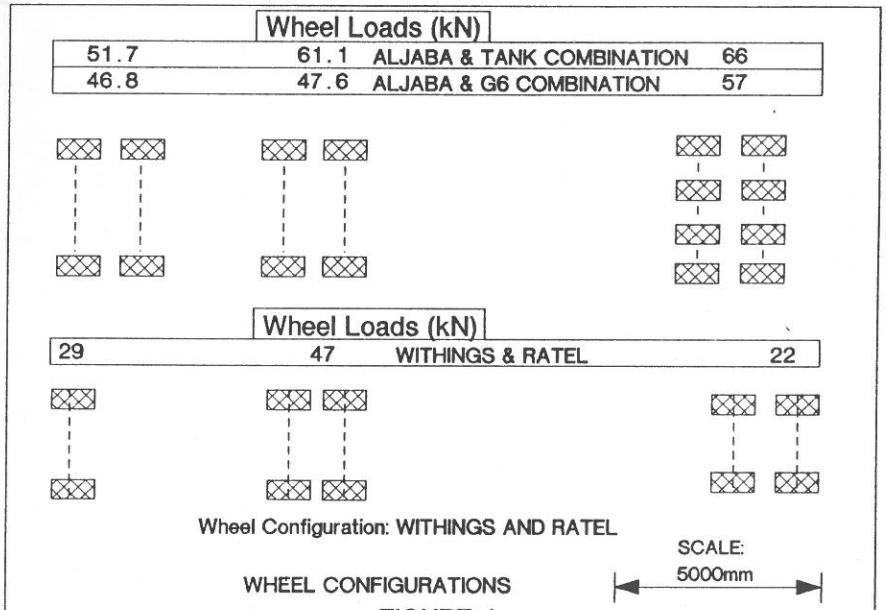


FIGURE 1

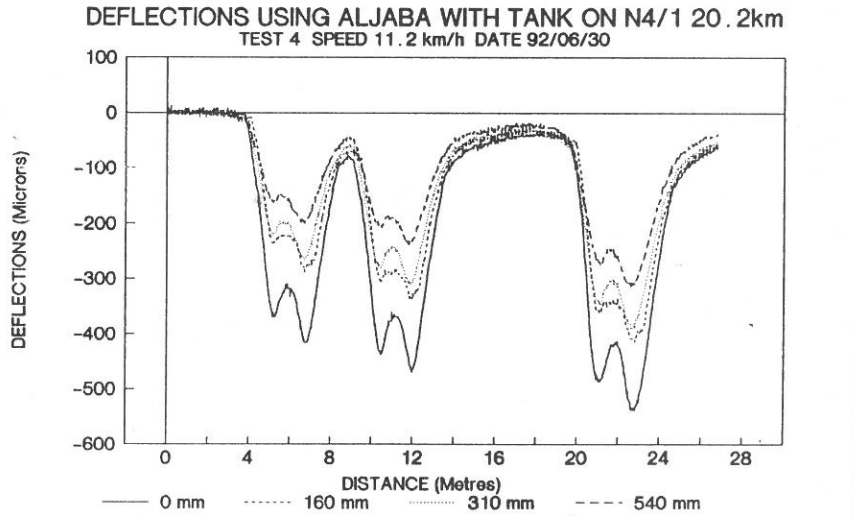
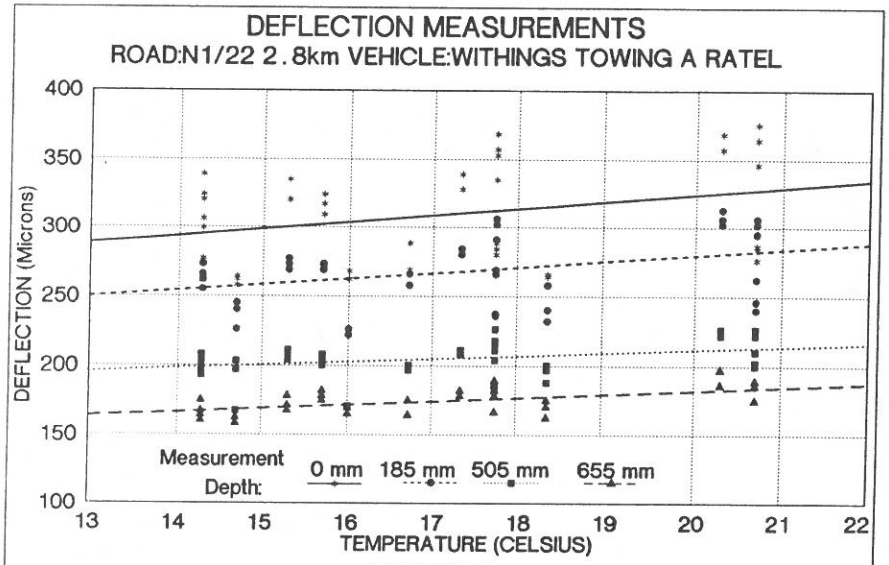


FIGURE 2



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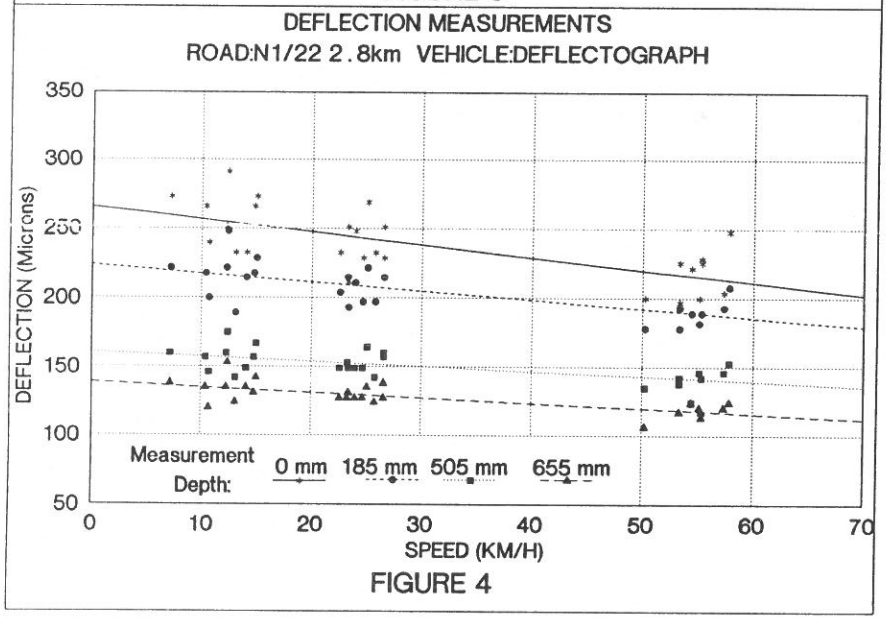

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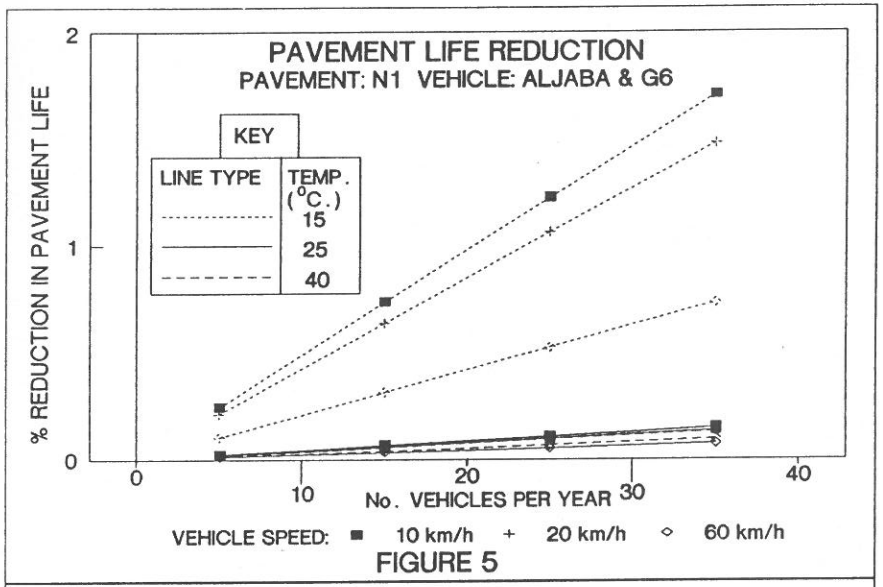

FIGURE 5

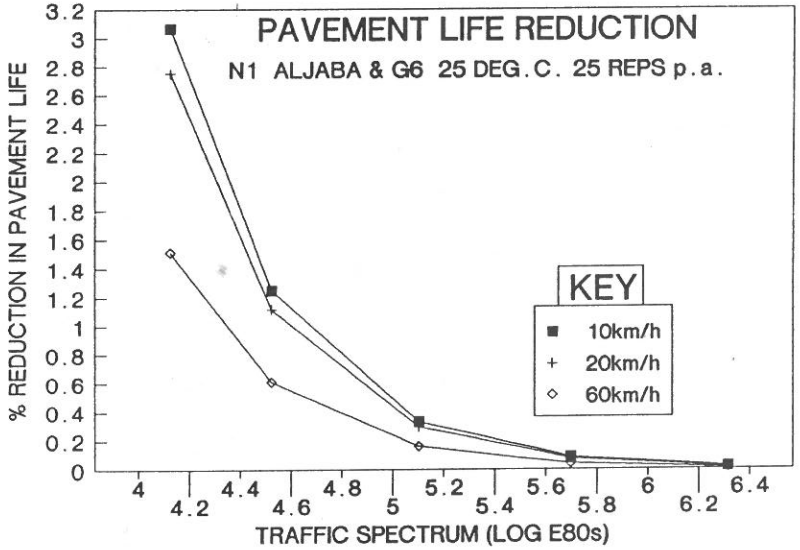

FIGURE 6