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SUB-SURFACE DRAINAGE OF PAVEMENTS
ONDERGRONDSE DREINERING VAN PLAVEISELS

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THE EFFECT OF POOR DRAINAGE ON PAVEMENT STRUCTURES STUDIED UNDER ACCELERATED TESTING

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Abstract
Most of the structural failures in road pavements are in one way or another associated with excess water trapped within the pavement structure owing to poor drainage. The combined effect of traffic loading and trapped water within the pavement is very destructive, particularly in the upper layers. The effect of excess porewater pressure (EPWP) was studied on several types of pavement structures with the aid of the South African Heavy Vehicle Simulator (HVS).

The following pavement structures were tested, viz of bituminous base, cemented base, granular base and concrete base pavement structures. During the EPWP state, moisture-accelerated distress (MAD) of the pavement occurs. It was shown that non-durable materials must be avoided, especially in the upper layers of the pavement structure. The measurement of permanent deformation on the surface of the pavement during HVS testing proved to be a relatively good indicator of behaviour during both dry and soaked conditions. In bituminous and concrete base structures durable subbases of adequate thickness are indispensable, whereas in cemented base and granular base structures it is essential to prevent surface water from entering through cracks in the relatively thin surfacing layers. This is accompanied by preventive maintenance and adequate drainage provision. Faulting and pumping on concrete pavement structures can also be limited by the use of durable subbase layers and concrete reinforcement to limit deflections.

EKSERP
Die meerderheid van strukturele swigtings in padplaveisels word op die een of ander wyse geassosieer met 'n oormaat water wat in die

plaveiselstruktuur vasgekeer is as gevolg van swak dreinering. Die gekombineerde effek van verkeersbelasting en vasgekeerde water in plaveisel vernietig hoofsaaklik die boonste lae in die struktuur. Die effek van 'n oormaat poriewaterdruk (OPWD) is bestudeer op verskeie tipes plaveiselstrukture met behulp van die Suid-Afrikaanse Swaarvoertuignabootser (SVN).

Die volgende tipes strukture is getoets, naamlik bitumenkroonlaag, gesementeerde kroonlaag, gruiskroonlaag asook betonkroonlaag-plaveisels. Gedurende die OPWD-toestand vind vogversnelde vervorming (VVV) van die plaveisel plaas. Daar word aangetoon dat die gebruik van nie-duursame materiale vermy moet word, veral in die boonste lae van die plaveiselstruktuur. Die meting van permanente deformasie op die padoppervlak gedurende SVN-toetswerk is 'n relatief goeie aanduider van plaveiselgedrag sowel in die droë as die versadigde toestande. Die studie het verder aangetoon dat duursame stutlae met voldoende dikte onontbeerlik is vir veral bitumen- en betonkroonlaagplaveisels. Vir gesementeerde en gruis-kroonlaagplaveisels is dit egter noodsaaklik om te verhoed dat oppervlakwater deur die krake in relatiewe dun oppervlakseëllae penetreer. Dit kan gedoen word deur voorkomende onderhoud en effektiewe dreineringsvoorsiening. Trapvorming en pomping in betonkroonlaagplaveiselstrukture kan beperk word deur die gebruik van duursame stutlae asook deur betonbewapening om defleksie te beperk.

1 INTRODUCTION

Most of the structural failures in road pavements are in one way or another associated with excess water trapped within the pavement structure owing to poor drainage. The combination of traffic loading and captured water in a pavement structure is the primary cause of distress in most road pavements. The aim of this paper is to summarise several case studies on the effects of poor drainage on several types of pavement structure studied under accelerated testing with the South African Heavy Vehicle Simulator (HVS) (Freeme et al, 1986). Per se free water within a pavement structure does not have detrimental effects, but, when this free water is exposed to traffic loading and trapped within the pavement structure, excess porewater pressure (EPWP) develops, even in the unsaturated state. This is often called the EPWP state, in which severe structural damage is done to almost any type of pavement structure: moisture-accelerated distress (MAD) occurs, which leads to rapid failure of pavements.

Experience has indicated that the failure mechanisms of pavements in the EPWP state differ from pavement type to pavement type. Both artificial water and rainwater have been allowed on some of the structures tested with the HVS. During HVS testing, the EPWP state can be initiated by rainwater or by artificial water sprayed upon or one of the several techniques induced into the pavement structure using techniques that are discussed in the next section.

The case studies under consideration include bituminous base structures, cemented base structures, granular base structures and concrete base structures.

2 WATER INGRESS

Water infiltrates into a pavement structure from below, the top or the sides. In the programme of accelerated tests with the fleet of HVSs, water entered the pavement structures accidentally on several occasions and in various ways. The behaviour of the various pavement structures was so interesting that it stimulated the need to induce water into the pavement structures artificially.

Water ingress from the top is accomplished by means of a perforated pipe spraying water onto the surfacing of the trafficked section. The water infiltrates the pavement through cracks, but in some cases slots or holes are ground or drilled through the surfacing layer when cracks are not visible yet (see Figure 1).

Water ingress from the side is induced by flooding side channels. Normally, water is introduced into the pavement structure by a system of perforated pipes installed into the pavement right next to the test section in order to ensure that the water flow across the section will follow the cross and longitudinal gradients at the selected level. The water is usually fed into the perforated pipes with a system of calibrated water bottles. Pressure heads of up to 1,5 m can also be applied to water induced into the pavement structures in this way (Figure 1).

For functional purposes, in this paper the moisture condition of a pavement or pavement layer is described as dry, wet and soaked. Dry by definition means the normal in situ state (equilibrium) in which the moisture content is below the optimum moisture content (OMC) and less than 50% saturation. Wet by definition means that the moisture content approximates the OMC or is between 50% and 80% saturation. Soaked by definition means that the moisture content is above the OMC or above 85%

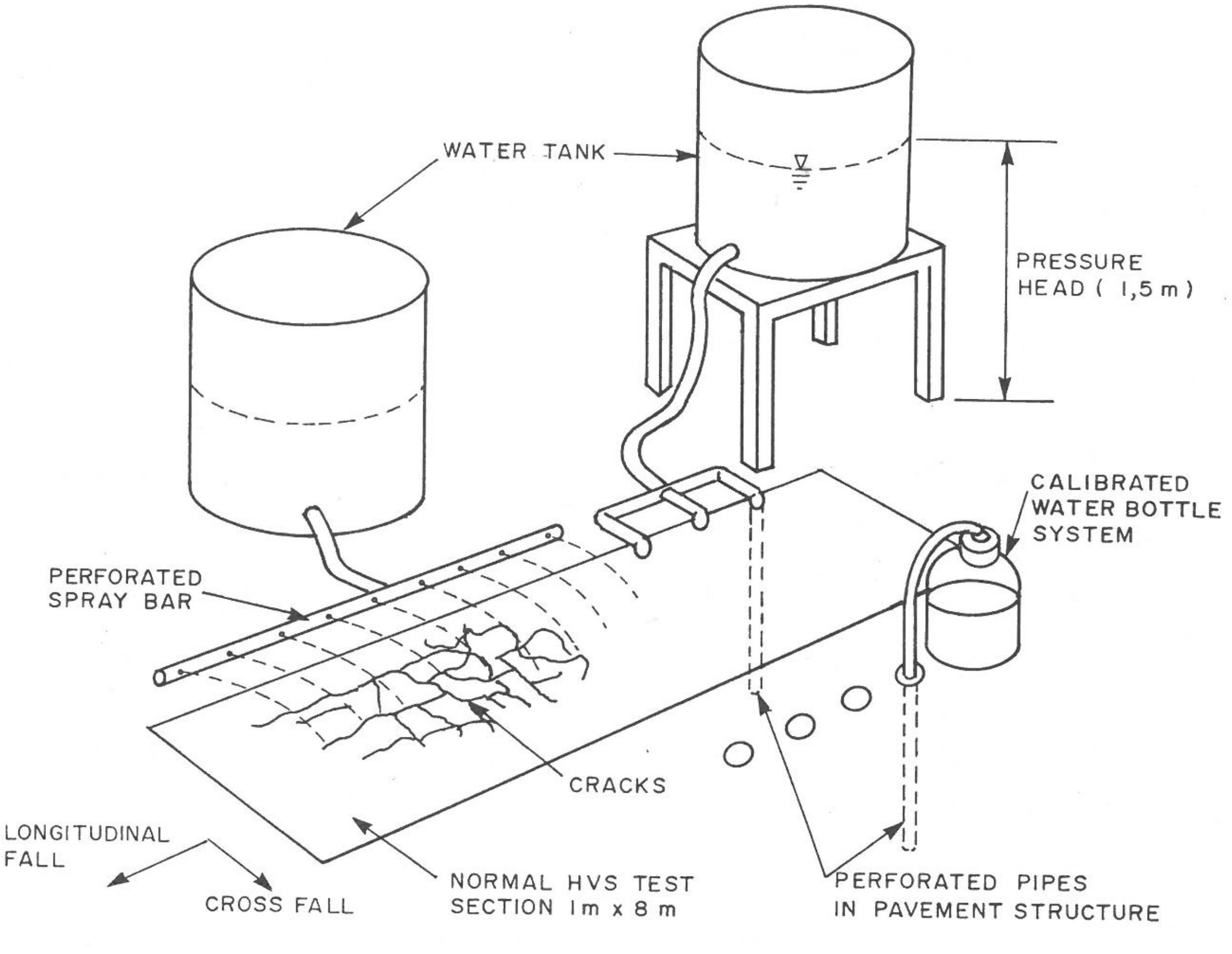

FIGURE 1

ILLUSTRATION OF WATER-INDUCEMENT SYSTEMS ON AN HVS TEST SECTION saturation. The condition of real interest in the soaked state is the state of EPWP. This state is mostly associated with the MAD condition, as mentioned in the introduction.

3 PAVEMENT BEHAVIOUR

In the following section the behaviour of several types of pavement structures during the wet state in particular is discussed.

3.1 Bituminous Base Structures

In the wetter regions of South Africa it is current practice to construct bituminous base pavement structures. Such a bituminous base protects the sublayers against water ingress from the surface and provides a durable and stable base layer in wet conditions. Freeme et al (1982) describe how the cemented subbases are used to construct more economical bituminous base designs. These designs were extensively tested and the results verified with the fleet of HVSs. The typical behaviour of such a pavement structure is portrayed in Figure 2 in which various indicators of behaviour (such as radius of curvature, road-surface deflection, effective elastic modulus of the stabilized subbase, change in permanent deformation, Dynamic Cone Penetrometer (DCP) results and change in dry density of the stabilized subbase) are shown versus the increase in trafficking.

This discussion will focus on the wet phase of such tested pavement structures. In this particular case, water was induced into the pavement under a pressure head of about 1,5 m (De Beer,

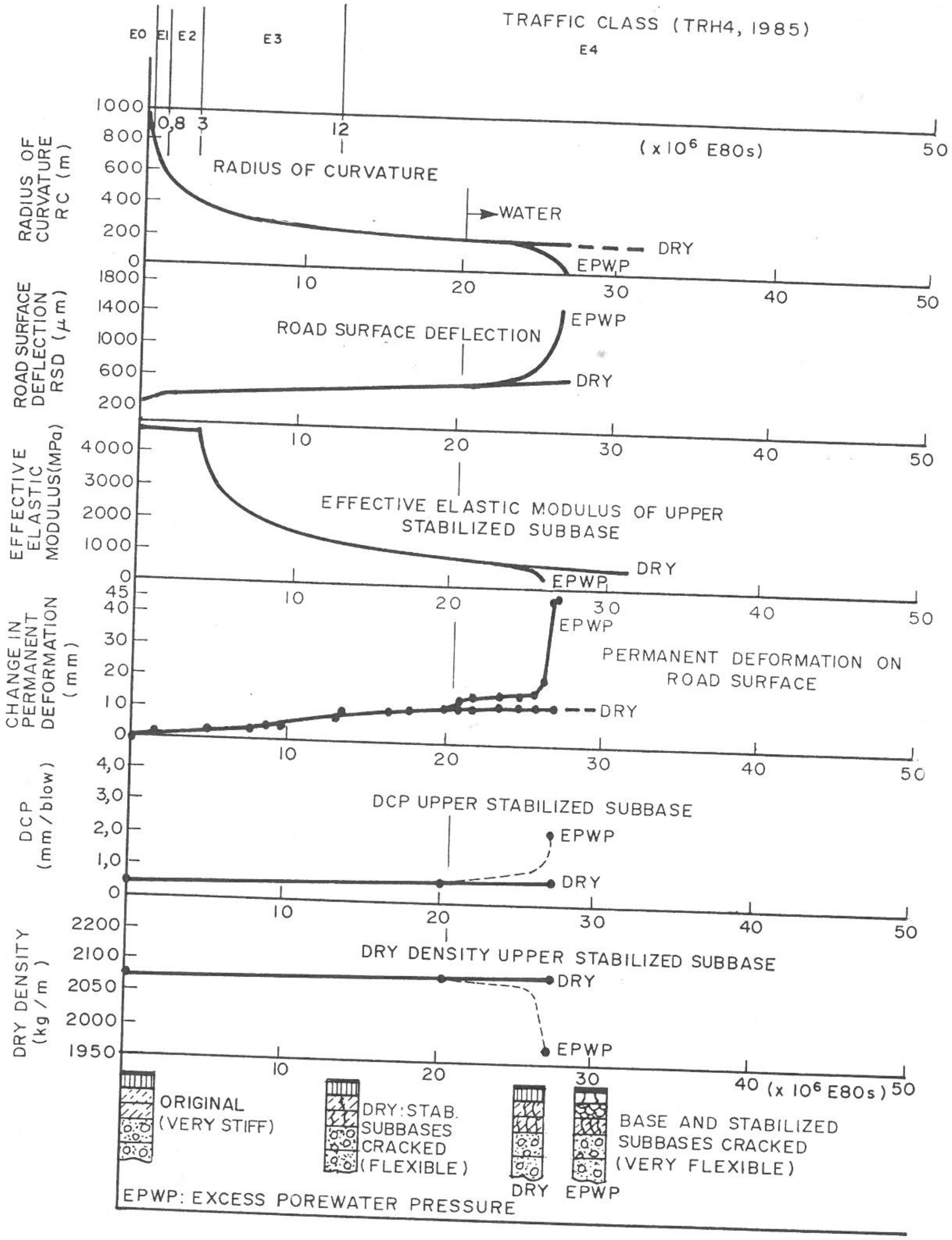

FIGURE 2

INDICATORS OF THE STATE OF THE PAVEMENT STRUCTURE AT VARIOUS STAGES OF TRAFFICKING AND MOISTURE CONDITIONS, N3/1 (MARIANNHILL)

1985). Effective permeabilities using the Marvil instrument* (Viljoen and Van Zyl, 1983) were measured on the lime-stabilized (cemented) subbases after various stages of trafficking in the dry state (De Beer, 1985). In Figure 3 the typical Marvil permeabilities on the stabilized layers are shown. The subbase

layers were constructed of weathered granite treated with 3% lime, and were of C3- quality. The upper subbase showed higher permeability values than the lower subbase which was indicative of a possible advanced state of fatigue cracking. The rate of inflow as measured with the Marvil also increased with the increase in HVS trafficking.

When the water was induced, the EPWP state was created and led to the typical MAD condition. The MAD-related deformation originated mainly within the upper subbase layer. At the end of the test the upper subbase was granulated and loss of fine material from this layer caused the excessive deformation of the road surface as shown in Figure 2. In this particular case the MAD state could only be initiated after the cemented subbase was fatigue-cracked and crushed into relatively small blocks.

Other mechanisms of failure in the MAD state were also observed. During the HVS test on a bituminous base pavement with fine-grained lime-stabilized subbases (Berea red sand), lack of durability or erosion resistance caused the mechanism of failure. During the wet state of the HVS test (De Beer,

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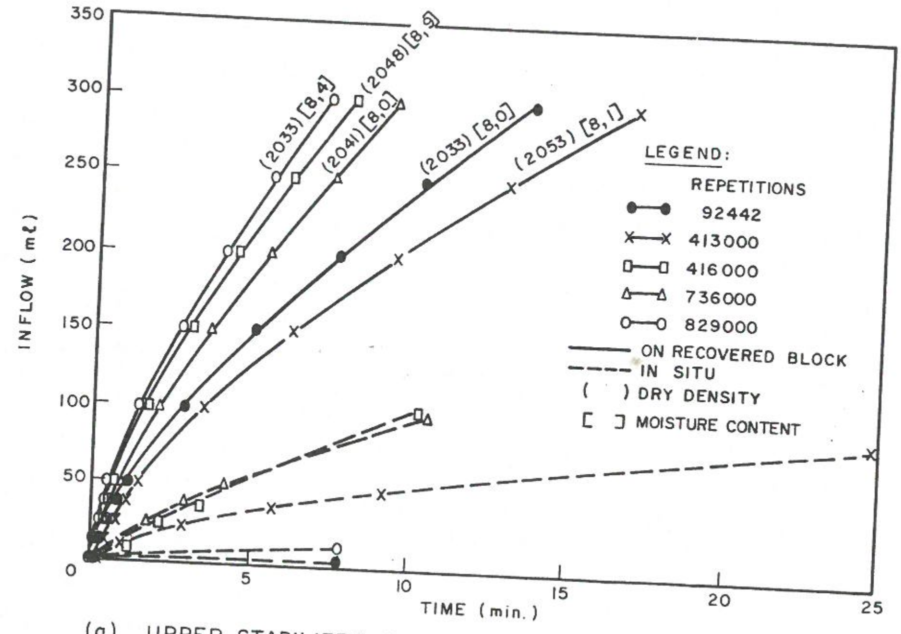
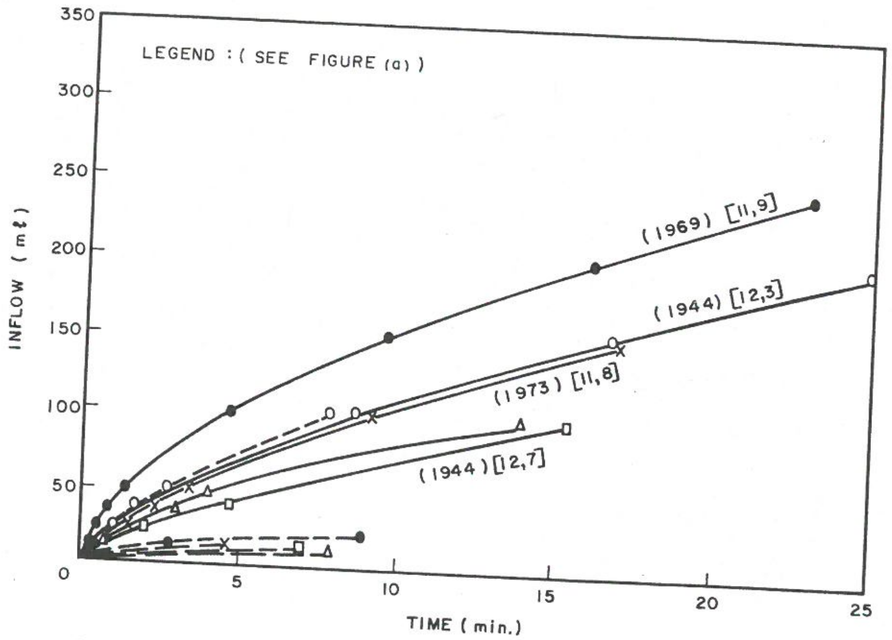
* Effective permeability measured with the Marvil apparatus is only a measurement of the inflow of water under gravity into the pavement from a constant area.



(a) UPPER STABILIZED SUBBASE



(b) LOWER STABILIZED SUBBASE

FIGURE 3
MARVIL PERMEABILITIES MEASURED ON THE STABILIZED SUBBASES ON SECTION 2 AT VARIOUS STAGES OF HVS TRAFFICKING ON N3/1 (MARIANNHILL)

1985), MAD occurred very rapidly and resulted in excessive deformation on the road surface. At this stage of the HVS test an excessive amount of fine material from the upper subbase was pumped to the road surface through fatigue cracks in the bituminous base layer. The water was induced under pressure, as mentioned earlier. In other cases on the same pavement structure, material from the upper subbase eroded and was pumped horizontally from the wheel path towards the sides, upheaving the bituminous base layer. In Figure 4 a cross-section of the completed test section is shown, indicating the origin of the permanent deformation owing to the loss of fines from the upper subbase. Following from this work, a durability test was developed, viz the Erosion test (De Beer, 1986a), to evaluate the durability of cemented layers.

When the cemented subbase layers in bituminous base structures are in an unhomogeneously cemented state or even granular as at Van Reenen's Pass (N3/6), the poor support leads to early fatigue cracking of the bituminous base (De Beer, 1985). This may be due to various factors such as poor construction or carbonation-forming lenses or zones of unstabilized material in the subbase. In the wet state the EPWP state is quickly reached and leads to the MAD condition. Pumping of fines and failure due to the excessive deformation are typical of this type of pavement. It is therefore important to invest in adequate support for relatively stiff bituminous base pavements. This is accomplished by selecting durable material with adequate cementing characteristics and by providing adequate surface and subsurface drainage to prevent the pavement from reaching the EPWP state.

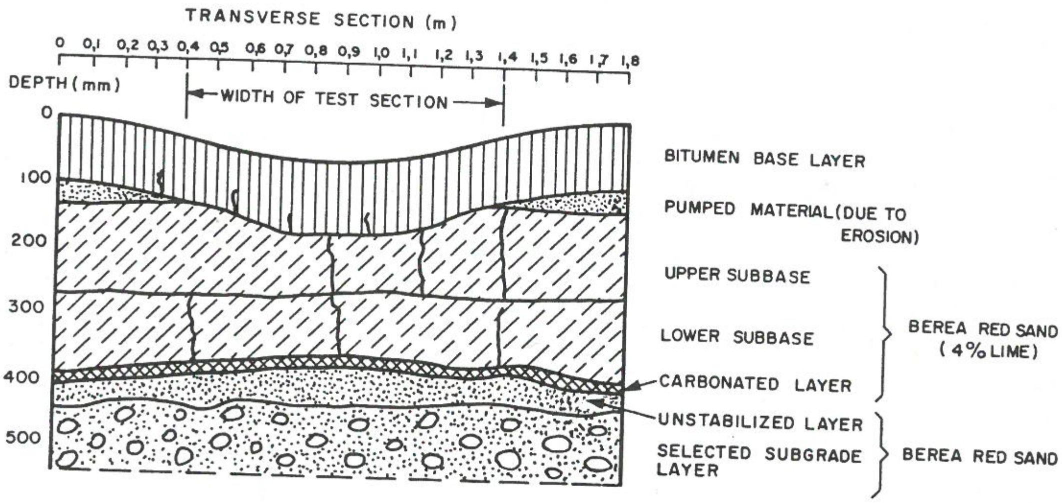


FIGURE 4

TYPICAL PROFILE AFTER HVS TESTING ON N2/24 (UMGABABA)

NOTE EROSION OF UPPER SUBBASE LAYER.

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DRAINAGE DURING ACCELERATED TESTING

3.2 Cemented base structures

Cemented base pavements are commonly found in the rural areas of the Transvaal. Lightly cemented base pavements are normally used for the lower class of traffic conditions. Such a typical pavement structure is found at Rooiwal (De Beer, 1986b). This pavement structure (shown in Figure 5) consists of a cemented base and subbase layers with a double-seal surface treatment. According to the DCP classification system (De Beer, 1986c), the structure is a relatively good to well-balanced deep pavement structure. During the HVS tests it was observed that the failure mechanism was such that the top 50-75 mm of the cemented base layer was crushed during trafficking, resulting in cracking of the surfacing layer with subsequent permanent deformation measured on the surface of the road. During the HVS tests water was sprayed onto the section and also induced in depth (De Beer, 1986b). The rate of depth water infiltration in litres per day is illustrated in Figure 6. No evidence could be found that this depth water influenced the rate of deformation. This is mainly owing to the relatively strong and impermeable nature of these cemented layers. This guards against the development of the EPWP state in the cemented layers. These HVS tests indicated that the surface deformation is mainly dependent on the rate of degradation of the top 50-75 mm of the base layer and its moisture content. During this degradation there is early fatigue cracking of the thin surfacing which becomes highly permeable to surface (rain) water.

This leads to the EPWP state and MAD behaviour in the top of the base layer of this type of pavement. In this process the surfacing layer is totally destroyed which accelerates the forming of potholes. It is therefore important to reseal this

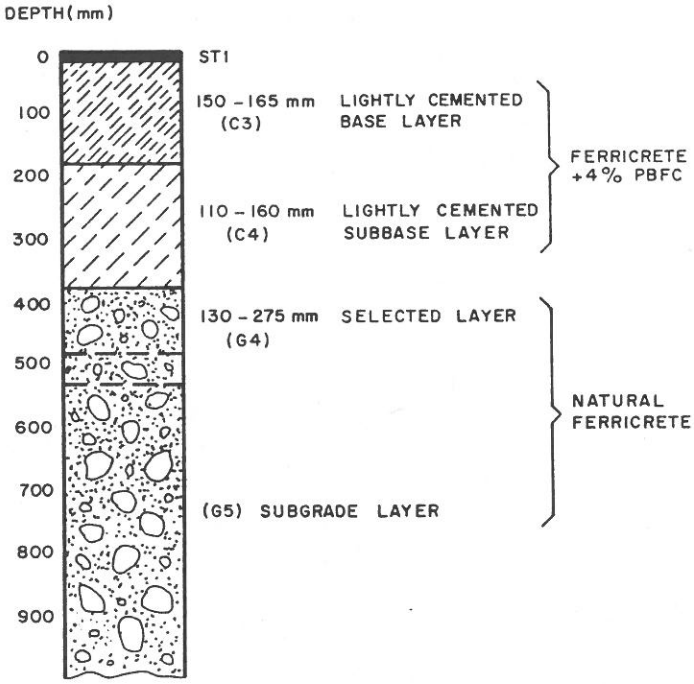

FIGURE 5

PAVEMENT STRUCTURE OF ROAD 1932 NEAR ROOIWAL (TVL) type of pavement structure before surface cracking and marked degradation occurs.

When this pavement type has stronger cemented bases and is relatively shallow in terms of the DCP classification (De Beer, 1986c), base failure owing to cracking and pumping can occur as in the case of Road 30 at Hornsnek (Kleyn et al, 1985). In this case though, the fatigue cracking of the base layer was mainly owing to lenses of unstabilized material in the base and subbase layers, see Figure 7(a). This relatively weak support led to early fatigue cracking of the upper stabilized layers. When water was induced the fines of the unstabilized lenses were pumped out owing to the development of the EPWP state. This caused the MAD condition to occur and led to failure due to excessive deformation. In Figure 7(b) the cross profile of this pavement section is shown after the completion of the test. The mechanism of failure and its effects are illustrated in this figure. In the dry state this pavement is very strong and this fact reinforces the principle of preventive maintenance in the form of crack sealing and overlays to prevent water infiltration. Most important however, is to avoid relatively soft lenses and interlayers between cemented layers in the pavement. The authors are of the opinion that by increasing the quality of construction of cemented layers, impermeable pavement layers and hence longevity of this type of pavement structure in general, will be ensured.

3.3 Granular base structures

The basic behaviour of granular bases described by various indicators is illustrated in Figure 8. It is described by Freeme et al, (1986) in detail in terms of the change with

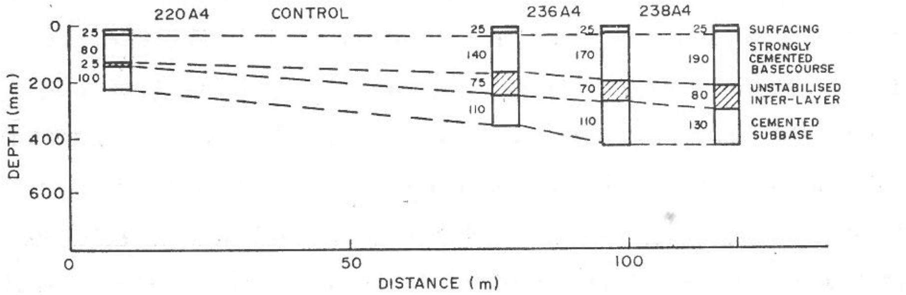

FIGURE 7(a)

VARIATION OF LAYER THICKNESSES AT HORNSNEK

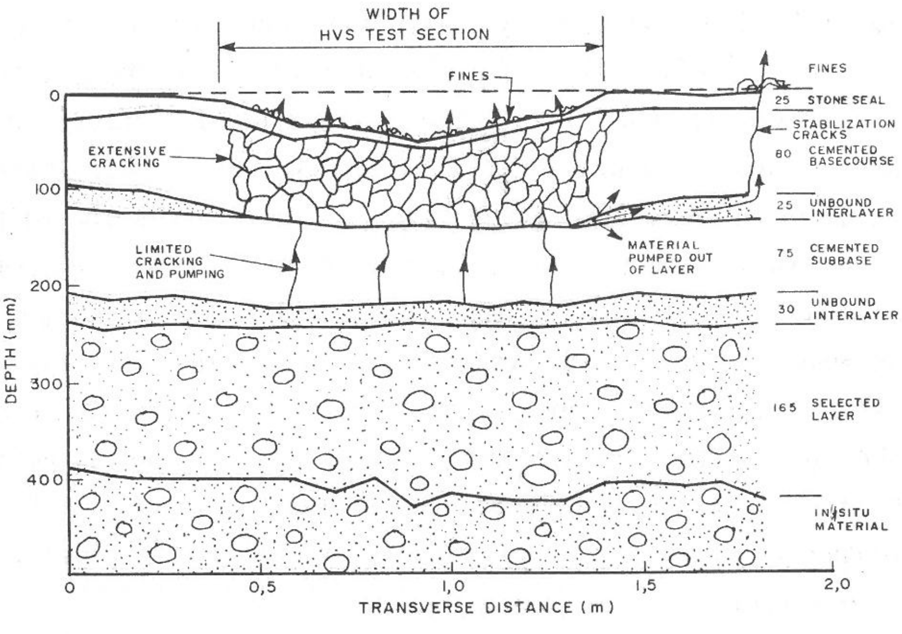

FIGURE 7(b)

ILLUSTRATION OF THE PUMPING MECHANISM OF THE PAVEMENT AFTER TESTING WITH THE HVS (ROAD 30 AT HORNSNEK)

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DRAINAGE DURING ACCELERATED TESTING

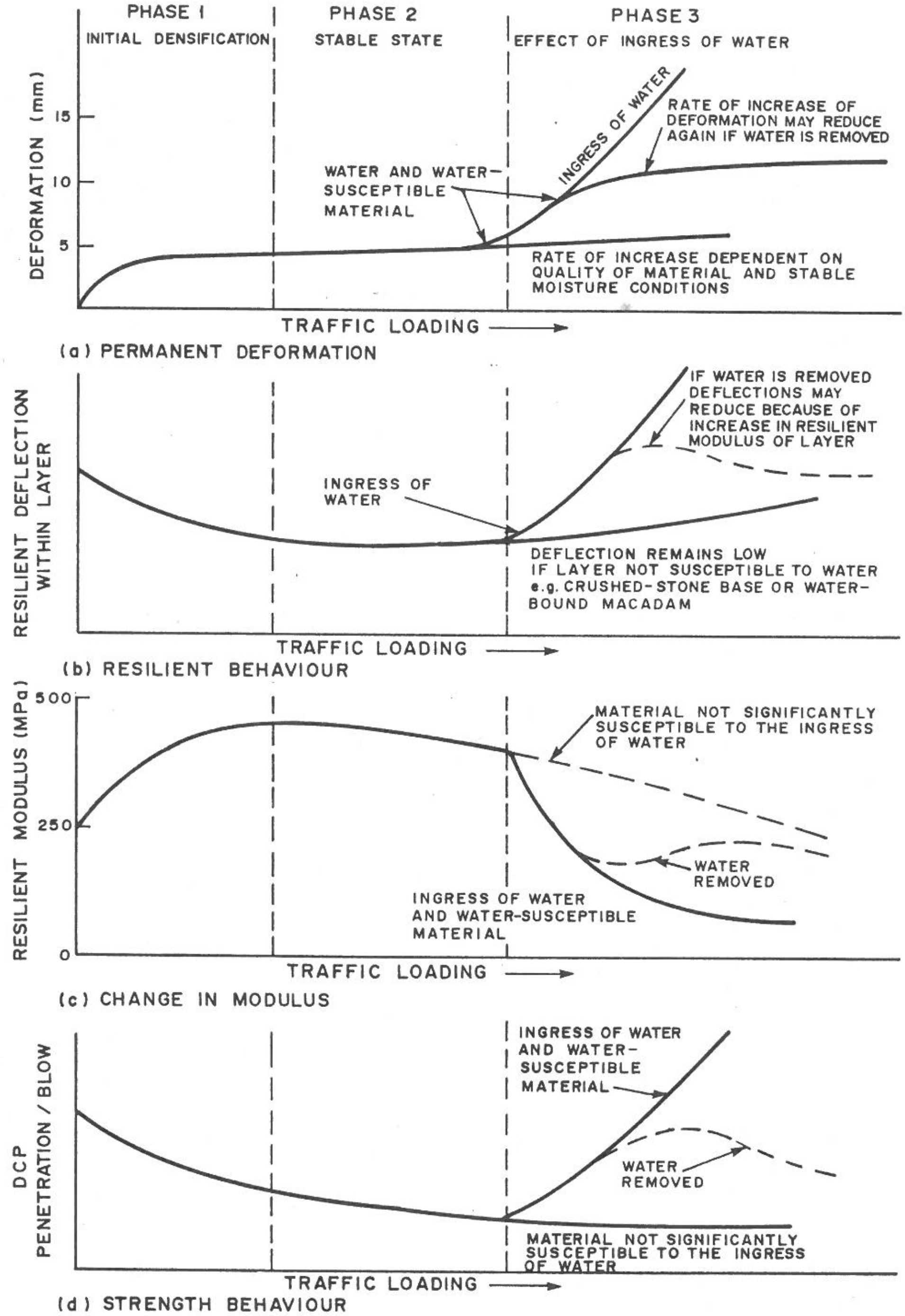

FIGURE 8

INDICATORS OF THE BEHAVIOUR OF GRANULAR LAYERS

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time or traffic in deformation, deflection, resilient modulus and strength. The discussion in this paper is focused on phase 3.

In this phase the ingress of water has the effect of an increase in deformation, an increase in resilient deflection within the base layer, decrease in resilient modulus and in increase in Dynamic Cone Penetrometer (DCP) penetration per blow with traffic loading.

In most of the HVS tests done on granular-base pavements the Marvil apparatus (Viljoen and Van Zyl, 1983) was used to get an indication of effective permeability. In Table 2 the average permeability ratings (inflow) for some HVS tests are shown with indications of the quality of the materials concerned. In general, the higher quality granular bases, such as G1 and WM1 bases, have higher densities and lower permeabilities. The lower quality granular bases, such as G2 and G3 bases, have higher indications of permeability.

TABLE 2 FIELD RESULTS OF PERMEABILITY RATINGS

Location	Base quality	Average permeability rating (ℓ/hour)
Erasmia P39/1	Slag (G2)	40,4
Jan Smuts P157/2	G1	0,15
Koeberg TR 77/1	G3	118,7
Mariannhill MR85	WM2	1,3
Umhlatuzana N3	WM1	0,3

The permanent deformation as measured under HVS trafficking is one of the best indicators of the behaviour of granular-base structures when water ingresses the pavement (Maree et al, 1982). For that reason the rest of the discussion will focus on this aspect. In Figure 9 the permanent deformation behaviour of

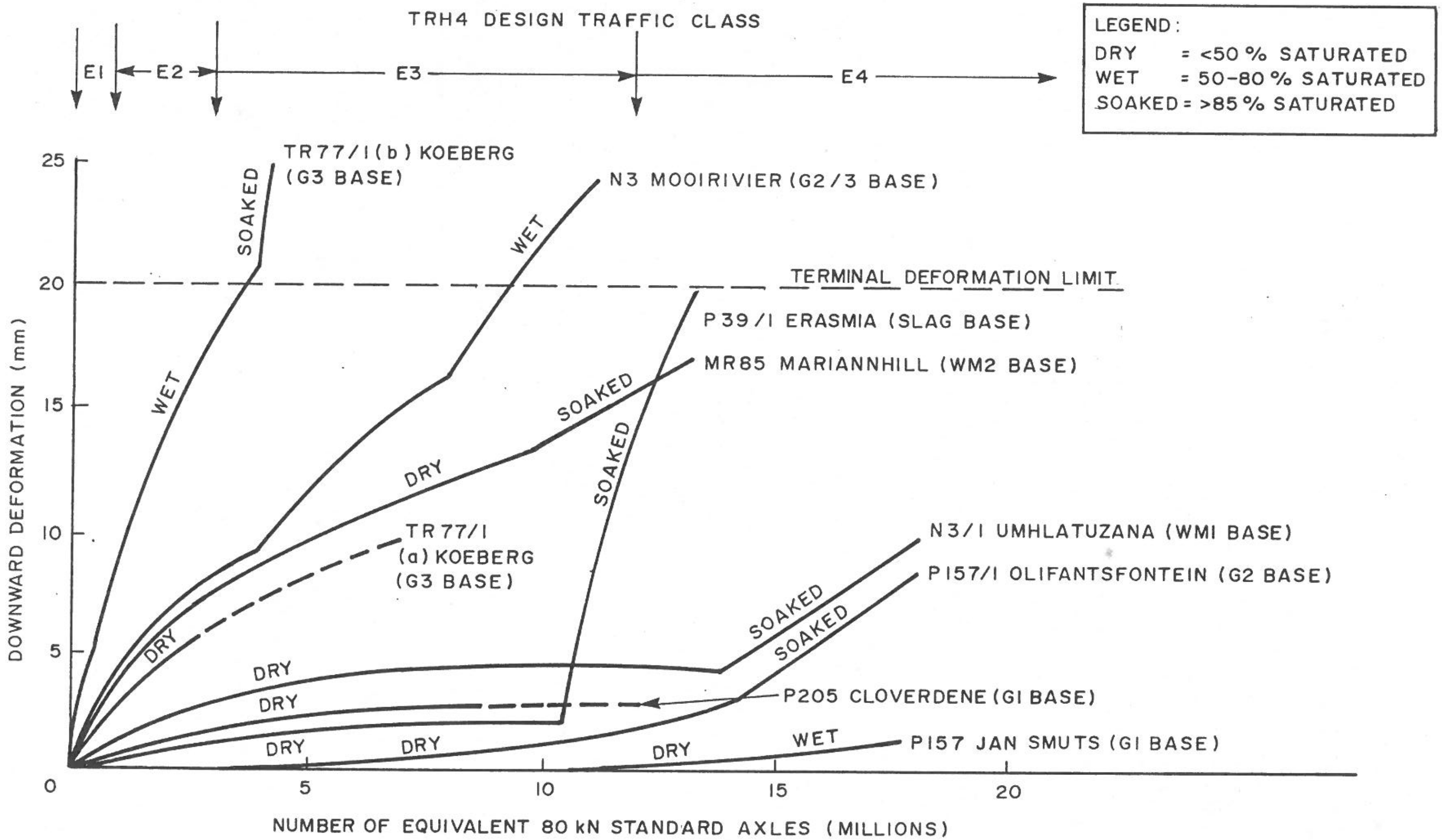

FIGURE 9

COMPARISON OF THE DEFORMATION INDUCED IN VARIOUS GRANULAR-BASE PAVEMENTS BY HVS TRAFFICKING BOTH IN THE DRY AND SOAKED CONDITIONS various granular-base structures as tested with the HVS is shown versus the number of equivalent 80 kN standard axles (E80s). The highest quality of granular base, the G1 such as P157/2 at Jan Smuts (Van Zyl and Maree, 1983), is relatively impermeable and it is difficult to get this base layer wet with the system of calibrated water bottles.

The result is that there is only a slight increase in the rate of deformation versus E80s. No EPWP state could develop either. On the other extreme of the spectrum, a lower quality granular base with a relatively high permeability shows a marked increase in the rate of deformation versus E80s only when wet. TR77/1 (b) at Koeberg (Maree et al, 1982) is typical of such a base material. In the final soaked state, the EPWP state which leads to the MAD behaviour state, was observed. The rate of increase in deformation versus E80s is lower when a better quality base like the G2/3 base at Mooi River (Shackel, 1979) becomes wet. In this case the soaked condition was not reached as the water ingress was not artificially induced. As a result the EPWP state was not reached.

The effect of proper drainage out of the granular base layers is clearly illustrated by the difference in permanent deformation behaviour in the soaked condition. The soaked WM2 base tested at Mariannhill (Horak and Triebel, 1986) had adequate drainage out of the base layer. As a result the EPWP state did not develop and the rate of permanent deformation versus E80s showed only a slight increase. When the highly permeable slag base at Erasmia (Horak and Maree, 1982) was soaked, it showed the classic EPWP behaviour with the extreme MAD state developing. No provision was made for drainage out of this pavement layer.

In the EPWP state pumping of fines through the fatigue cracks of the surfacing was observed. When the surface was still intact subbase interlayer during the EPWP state which led to the MAD condition and hence to fatigue cracking of the concrete layer above (Viljoen, 1987).

In another HVS test on the relatively new concrete pavement near Pietermaritzburg in Natal, pumping occurred from underneath a durable C2 subbase layer. This is an indication that it is not only important that the subbases of concrete structures must be durable or erosion-resistant, but they must also be of adequate thickness. According to the design of economical bituminous base structures (Freeme, et al 1982) a minimum thickness of 300 mm cemented subbase is specified for these structures and this must serve as a guide for subbases for concrete pavements.

Furthermore, concrete structures do need drainage protection, mainly in the vicinity of the joints. In order to minimize the relative deflections at the joints the use of continuous concrete reinforcement has definite advantages.

4 SUMMARY AND CONCLUSIONS

In this paper several case studies were discussed, highlighting the effects of trapped water within the pavement structure. The following types of pavement structure were discussed: bituminous base, cemented base, granular base and concrete base pavement structures. Most of these structures were tested with the Heavy Vehicle Simulator (HVS). Water was induced into most of the pavements tested using one of several techniques, viz surface spraying, introduction of water by means of a set of calibrated water bottles and perforated pipes and introducing subsurface water under pressure. During the HVS tests in the wet states, excess porewater pressure (EPWP) develops, initiating moisture-accelerated distress (MAD) of the pavement structure. These tests firstly indicated that durable or erosion-resistant subbase layers are

Relatively weakly cemented materials (C3 and C4) of fine grading tend to erode rather than to crack during the EPWP state. The coarser grained materials tend to undergo advanced cracking and in some cases crushing, especially if the parent rock is highly weathered. In the crushed state of this material, there is a risk of shear failure, similar to that of granular materials.

(iv) Concrete layers

Concrete is normally insensitive to water under pressure. However, it is important that concrete base pavements should be well supported. Experience with the HVS indicated that thin (<150 mm) slabs have relatively short fatigue lives (D-cracking) and that step faulting occurs for thick slabs if they are not adequately supported. The life of concrete pavements can be greatly prolonged through the use of durable cemented subbase layers of adequate thickness (300 mm).

It is impossible to assign structural capacities to the abovementioned material types, but it is believed that if one understands the various mechanisms of failure involved, one will be able to make more effective use of these materials in future.

From this study it can be concluded that since the major types of distress in pavements occur as a result of excessive porewater pressures, there are several alternatives possible for reducing the distress level. These include:

(i) reducing deflections;
(ii) excluding water from the pavement;
(iii) providing for rapid surface and subsurface drainage and
(iv) using durable subbase materials.

The authors are of the opinion that by incorporating the abovementioned alternatives into pavement design and construction that we will be moving closer to the optimum cost-effective design and construction of roads in South Africa.

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