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REHABILITATION ANALYSIS OF A ROAD PAVEMENT CRACKED BY ALKALI-AGGREGATE REACTION

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SYNOPSIS

This paper concerns itself with the rehabilitation procedures for a concrete road that has cracked as a result of the alkali-aggregate reaction. Maintenance and light rehabilitation procedures may be applied to prolong the life of the pavement, or the existing pavement may be considered as still having some portion of remaining life which can be incorporated as an input in a structural analysis for the design of a suitable overlay.

SAMEVATTING

Hierdie referaat behels die rehabilitasieprosedures vir 'n betonpad wat as gevolg van alkali-aggregaatreaksie gekraak het. Onderhouds- en ligte rehabilitasieprosedures kan aangewend word om die leeftyd van die pad te verleng of daar kan besluit word dat die pad nog 'n deel oorblywende leeftyd inhou wat in die strukturele ontleding vir die ontwerp van 'n geskikte deklaag opgeneem kan word.

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1. INTRODUCTION

Pavement management involves the proper design of a pavement, the monitoring of its performance and the use of maintenance strategies to ensure that it fulfills its intended function. Occasionally unexpected malfunctioning does occur such as was the case with the jointed unreinforced concrete pavement on National Route 2 Section 1 in the Western Cape.

The pavement under discussion was the first Portland cement concrete pavement, designed and constructed by modern techniques in South Africa. Alkali-aggregate reaction was at that time not considered a problem. Little damage had been reported up to that time in structural concrete and no serious consideration was given to possible damage to concrete pavements. However, initial hairline cracking at the surface of this pavement initiated structural cracking at areas of critical stress such as pavement edges and joints. This caused rapid loss of stiffness in the pavement structure and consequent structural failure. Although the serviceability index is presently acceptable, structural failure initiated by alkali-aggregate reaction causes a rapid deterioration in structural serviceability and therefore requires timely maintenance and rehabilitation measures.

2. ALKALI-AGGREGATE REACTION AND DISTRESS

A variety of reactions are known to occur between cement and aggregate[1]. Some of these are deleterious causing disruptive expansion whilst others are beneficial, eg the pozzolanic effect which is responsible for strengthening the interfacial bonds between some siliceous aggregates and the surrounding matrix of cement paste.

The reaction between high alkali cement and siliceous aggregate, is a complex chemical reaction which under conditions such as continuous dampness at the bottom of the slab, as well as cyclic moisture and thermal variations, will result in map or alligator crack patterns.

These map cracks at the surface of the critically loaded edges, corners and joints of the slab effectively reduce the slab thickness and stiffness which induces structural cracking in the slab after fewer load applications. A further consequence is that any other cemented layers in the pavement structure, which are also subjected to the same chemical reaction, may also experience a loss of structural stiffness and reduction of subgrade support.

Monitoring of distress forms part of pavement management and in this particular case, is aimed at the structural serviceability. In order to systematically monitor the structural capacity of the pavement the development of distress can be hypothesised along the following lines. (See Figure 1.)

(a) Alkali-aggregate reaction initiates cracks all over the pavement. These cracks are defined as map cracking.

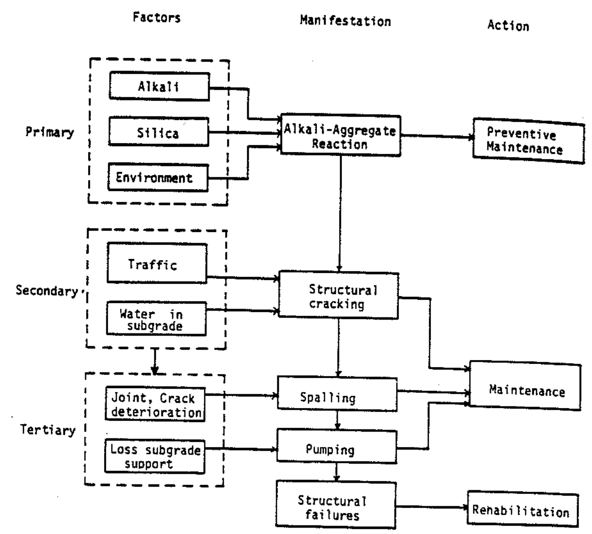


FIGURE 1: Factors leading to structural failure and appropriate action.

(b) As a result of traffic loading structural cracks develop from the map cracking and a pattern of wider cracks becomes obvious close to edges and joints. At this stage a decrease in slab stiffness can be expected.

(c) Water enters the subgrade and the slab through joints, cracks and the joint between the asphalt shoulder and the concrete pavement resulting in the reduction of subgrade support as well as weathering of aggregate interlock at the joints, thus further decreasing slab stiffness. Higher deflections then cause a certain amount of displacement of fines.

(d) An increase in relative movement at joints and cracks, because of higher deflections, causes failure of joint filler material as well as a certain amount of spalling which facilitates the entry of moisture, abrasion of the concrete and weathering of the sublayers.

(e) Deterioration of the subgrade causes a loss in subgrade support and since both slab stiffness and subgrade support have been reduced substantially, structural failures in the form of punch-outs appear in the concrete pavement.

3. MAINTENANCE CONSIDERATIONS

The systematic monitoring of distress is an important prerequisite to proper and effective maintenance planning. Having identified distress manifestation, maintenance can be planned to suit particular circumstances. The structural condition of the pavement in question is such that structural failures have already occurred over about 10 per cent of the road length whilst about 10 per cent is in perfect condition. The condition of the remainder varies between these two extremes with the major portion showing only map cracking due to alkali-aggregate reaction. Maintenance/rehabilitation therefore should be looked upon as a wide spectrum of possibilities. Four options seem to exist as possible maintenance alternatives:

(a) 'Do nothing' approach and allow complete failure of the pavement before major rehabilitation or even reconstruction is considered.

(b) Allow structural failures to occur in the weaker areas and rehabilitate before the benefit of a higher standard of subgrade support is completely lost.

(c) Do regular maintenance, even as preventive maintenance to discourage the development of structural cracking (definitely before pumping and punch-outs appear).

(d) Control the initial map cracking due to alkali-aggregate reaction.

The important question to answer is whether the development of map cracking can be avoided since map cracking invariably initiates a loss in slab stiffness and thus structural cracking. Although there are indications that the alkali-aggregate reaction terminates at some stage[2], reliable ways to end it by external means are unknown. Thus the fourth alternative above should be considered as a short term and probably futile approach.

The first approach of complete structural failure before rehabilitation or reconstruction may be unacceptable both from a road user's and an engineering point of view. The same effect can be achieved by artificial destruction, followed by rehabilitation which is more acceptable to the road user.

With the second approach consideration must be given to the possible deterioration of the existing pavement even after the construction of a rehabilitating measure and this must be taken into account in the design of the overlay.

The third approach would involve such actions as joint sealing, crack sealing, joint repair, restoration of load transfer, undersealing and improvement of drainage.

4. PAVEMENT CHARACTERISATION

The condition of the pavement at a certain point in time, will influence the decision as to which rehabilitation measure will be employed. (See Figure 2, page 3.)

Analysis 1 applies to sections of the pavement with adequate structural capacity in which the alkali-aggregate reaction has terminated. In such a case repair of defects, sealing of joints and cracks and possibly even a thin bituminous seal, such as a Cape Seal would be sufficient.

In the case where it is uncertain whether or not the alkali-aggregate reaction has terminated, this should be taken into account in the maintenance/rehabilitation strategy, possibly by assigning a reduced stiffness to the pavement and cement stabilised layers.

For pavement sections with inadequate structural capacity the remaining life of the existing pavement should be considered in designing rehabilitation measures.

A pavement with remaining life and with good subgrade support can be upgraded structurally by unbonded or bonded concrete or asphalt overlays as indicated by analyses 2 to 5. Concrete overlays can be jointed or continuously reinforced. Analysis 6 indicates the possiblity of increasing the structural capacity of such a pavement by measures such as joint repair and crack repair, using polymers, joint sealing and the improvement of load transfer by the installation of dowels.

For existing pavement sections with poor subgrade support, but still having useful life remaining, the same overlays can be considered. In addition, as indicated by analysis 11, other measures such as undersealing, joint sealing, chemical modification of subbase and the improvement of drainage systems can be considered to improve the pavement's capacity to carry traffic.

For pavements which do not have any remaining useful life, the structural capacity can be improved by thick concrete or asphalt overlays, or by recycling or reconstruction of the existing pavement. In the recycling process care should be taken not to repeat the alkali-aggregate reaction problem.

With reference to the different management strategies previously discussed analyses 12 to 16 represent approach 'a', analyses 2 to 5 and 7 to 10 imply approach 'b' and analyses 1, 6 and 11 would be approach 'c'.

In order to evaluate the structural condition of the pavement methodically, a theoretical analysis based on load transfer characteristics at a joint should be correlated with condition survey information.

Theoretical background. An investigation of the pavement condition leads immediately to the observation that although cracking may occur all over the pavement, structural failure starts at the transverse joints. This observation then automatically leads to further investigation of this part of the pavement, particularly since relative movements at joints greatly affect the performance of an overlay.

Using the basic equation[3] for deflections at (i) a free edge (ii) a corner and (iii) the interior of a stiff slab, a general equation for deflection can be written:

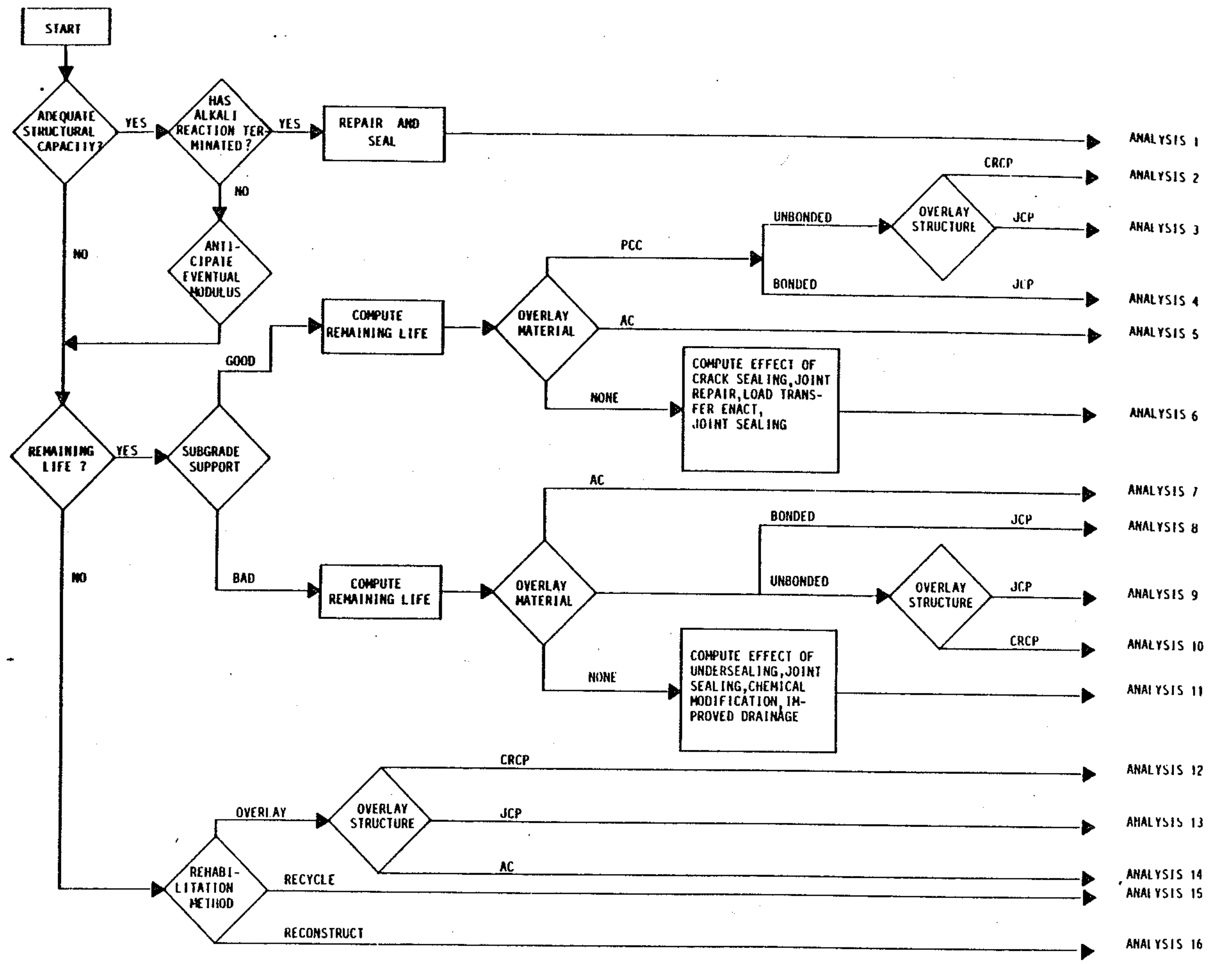


FIGURE 2 : Analysis system used in designing experimental sections

Deflection $y = C \dfrac{P}{\sqrt{Dk}}$

Where
C = load transfer constant
P = load
D = slab stiffness
k = subgrade stiffness

Theoretically determined values for C are as follows:

Loading condition	C
Interior (full load transfer)	0,25
Edge	0,43
Corner (no load transfer)	0,70

Conditions survey. A system of visually surveying the condition of the joints has been developed by rating them on a scale of 0,25 and bigger to coincide with the above-mentioned C values. A perfect joint is rated at 0,25, a joint with fine cracks visible but with no distinct cracks at 0,32 (as indicated on Plate 1, page 4) and a joint with clearly visible cracks parallel to the joint at 0,50 (see Plate 2, page 4). Joints where punch-outs have occurred are rated at 0,70 as indicated on Plate 3, page 4. This system is, as can be expected, somewhat subjective but nevertheless gives an indication of the joint condition which can be used together with stochastic principles, to assess the probability of failure.

In order to calibrate the structural capacity of joints as surveyed in terms of C, the actual structural capacity of a limited number of transverse joints is measured as described in the following section and then correlated with the subjective ratings (or determination of C) above.

Structural evaluation. Two basic methods of evaluation are employed. The first involves the use of a modified Benkelman beam (see Figure 3) whereby the relative movement of two adjacent slabs at a transverse joint under a moving 40 kN wheel load can be monitored electronically. The second method of evaluation involves measuring the relative movement at the transverse joint by increasing

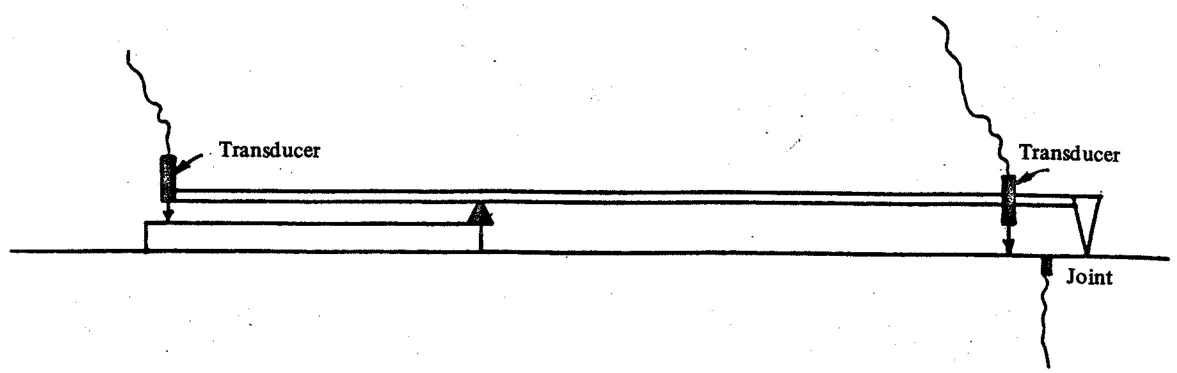


FIGURE 3 : Schematic view of modified Benkelman beam

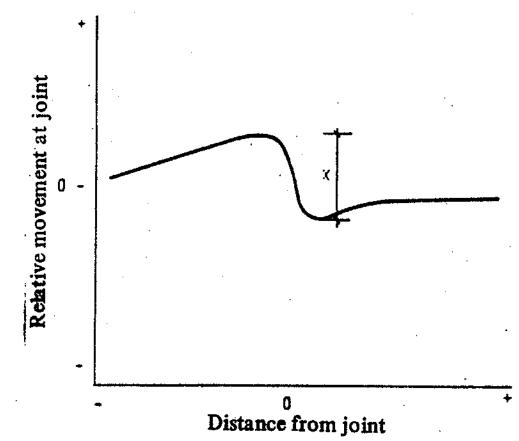


FIGURE 4: Relative movement at a transverse joint caused by a load of 40 kN

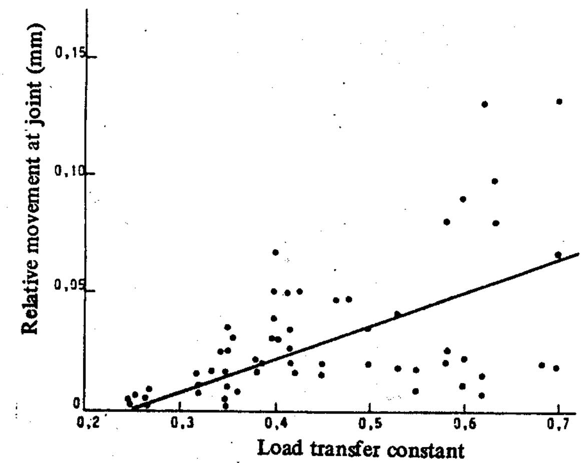


FIGURE 6: Relative movement at joint under 40 kN load versus load transfer constant C

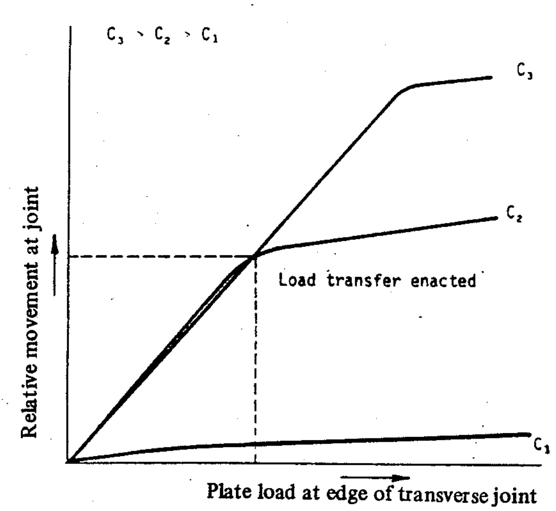


FIGURE 5: Relative movement at a joint as the load is increased

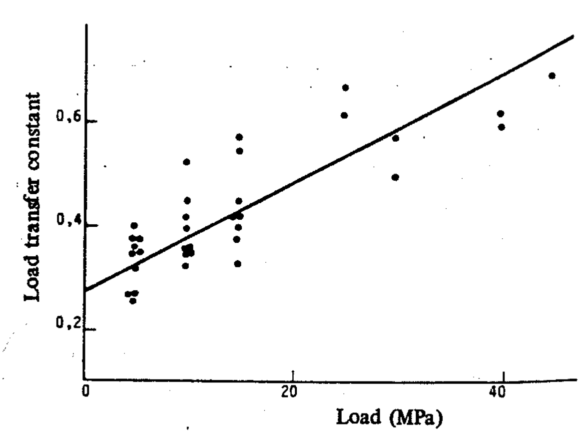


FIGURE 7: Load at which load transfer is enacted versus load transfer constant C.

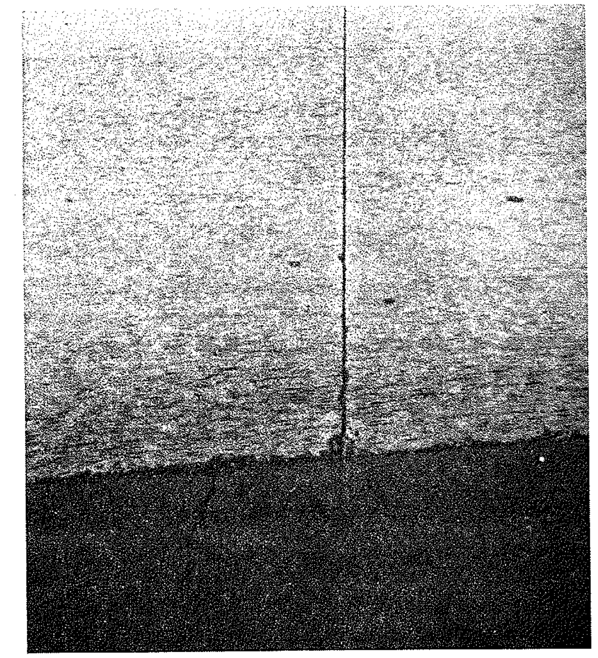


PLATE 1: Pavement section with fine but not distinct cracks (C = 0,32)

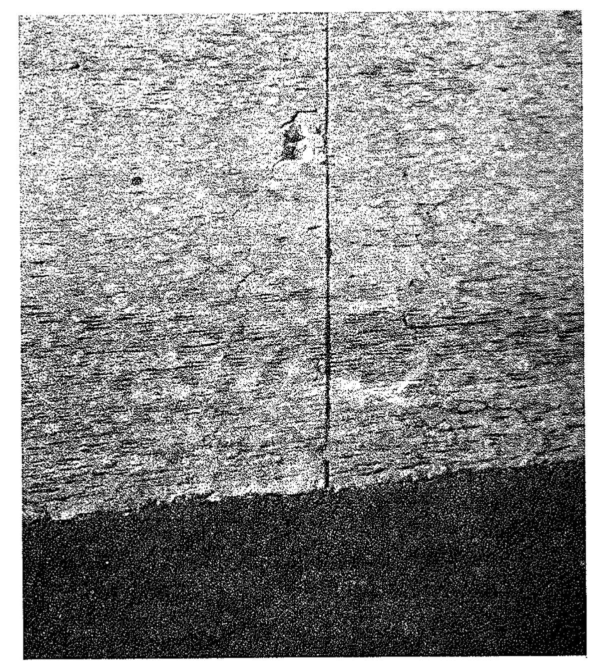


PLATE 2: Pavement section with clearly visible cracks parallel to the joint (C = 0,50)

the load from 5 to 55 kN on a 300 mm diameter bearing plate. Typical results of these measurements are shown in Figures 4 and 5.

In Figure 4 the relative movement as measured with the modified Benkelman beam is given by 'x' which is shown as a function of the subjectively determined C values in Figure 6. From Figure 6 it can be seen that a joint with no relative movement between adjacent blocks, ie full load transfer, has a C of 0,25. Figure 5 shows typical results of the plate

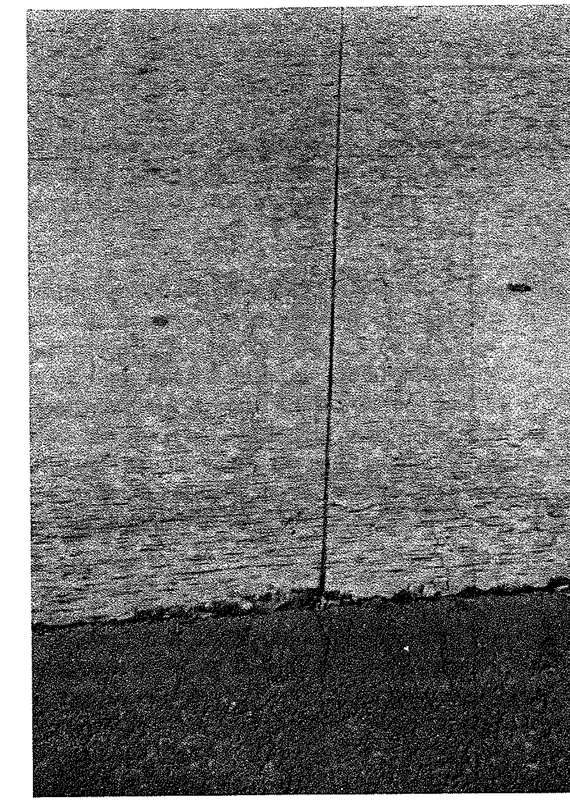


PLATE 3: Pavement section with punch-outs (C = 0,70)

load test, where for a joint with perfect load transfer there is very little relative movement between adjacent slabs regardless of load. For a joint with an average load transfer constant, say 0,4 the relative movement increases with load until load transfer is enacted after which further increases in load cause very little additional relative movement. For a joint with a C = 0,7 no load transfer exists and relative movement increases with increase in load.

Figure 7 indicates a correlation between relative movement at the joint and the load necessary to enact load transfer. Again for C = 0,25 it is clear that full load transfer exists.

Subsurface investigation. In order to investigate the subsurface condition of the pavement a method has been developed to 'freeze' the concrete slab/subbase system and to extract a core so that cracks in the slab and subbase as well as some voids between the slab and subbase can be visually examined.

Typical results of these cores are indicated on Plates 4 and 5, page 6. Plate 4 shows clearly that voids exist between the concrete pavement and the subbase and that this can be of the order of 1 mm. Plate 5 shows that in some cases the subbase can deteriorate to such an extent as to make it impossible to extract a core.

At the same time the slab stiffness is measured by ultrasonic means. Figure 8, page 7, shows a correlation between slab stiffness and the load transfer constant C. It can be seen that slab stiffness at joints that have deteriorated to

TABLE 1 : Typical pavement characterization results summarised from figures 6, 7 and 8

C	Condition of joints	Relative movement in mm under 40 kN load	Load (kN) at which load transfer is enacted	Slab stiffness % of undamaged
0,25	Perfect joint no signs of cracks	0	0	100
0,30	Fine cracks visible both sides of joint	0,01	2	95
0,40	Slight signs of secondary cracking parallel to joint	0,02	12	19
0,50	Secondary cracking clearly visible. Longitudinal cracks start showing across joint	0,04	21	81
0,60	Distinct cracks with signs of fine material pumping out of cracks	0,05	30	76
0,70	Punch-outs start occuring. Joints have been patched.	0,06	40	66

Typical values for subgrade stiffness in relation to C are:

C	Subgrade stiffness (MPa)
0,25	40
0,4	30
0,7	22

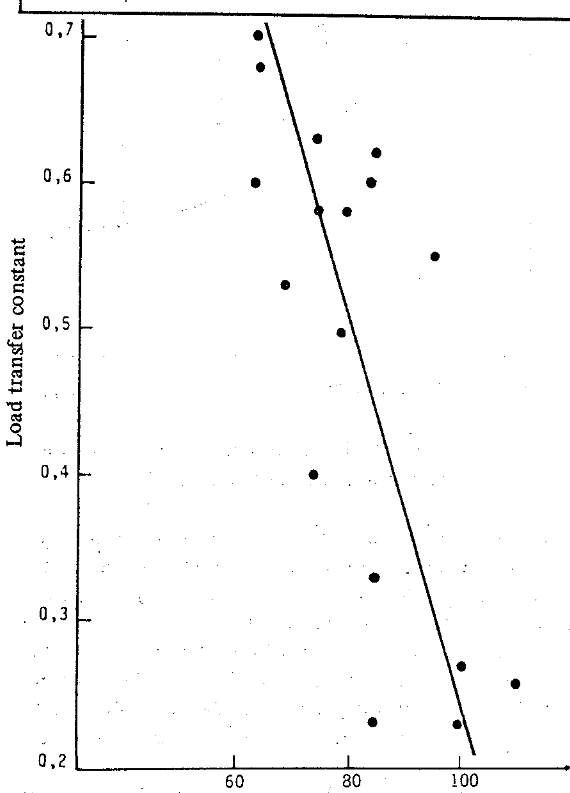


FIGURE 8: Relationship between slab stiffness and load transfer constant C

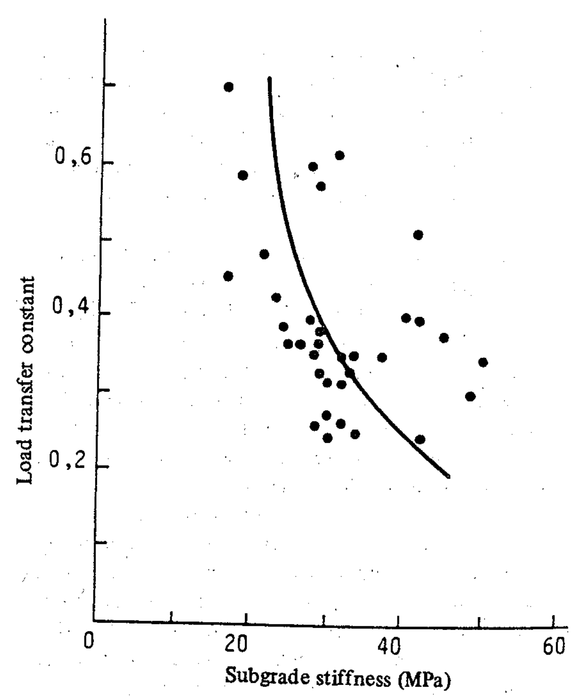


FIGURE 9: Relationship between subgrade stiffness and load transfer constant C.

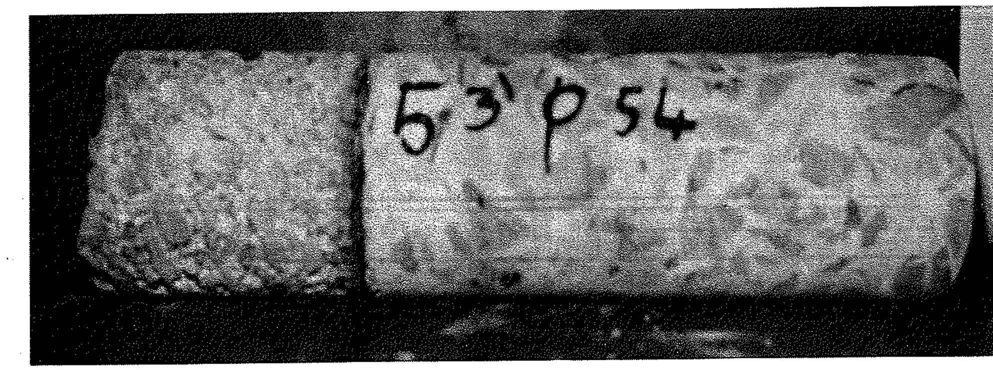


PLATE 4 : Core of 'frozen' slab/subbase system showing void between slab and subbase

PLATE 5 : Core showing deteriorated subbase

the stage where punch-outs occur is only approximately 66 per cent of the stiffness at a perfect joint.

Using plate load tests on the subgrade a relationship is found between subgrade stiffness and C as indicated in Figure 9. It can be seen that C can also to a limited extent be related to changes in subgrade modulus.

Summary of pavement characterisation results. The plate load and Benkelman beam tests indicate relationships between joint condition in terms of C and the relative movement at the joint. In addition the plate load test also relates the load at which load transfer is enacted to the condition of the joint. Table 1 summarizes typical values for:

(i) load transfer constant;
(ii) relative movement at the joint under a 40 kN load;
(iii) load at which load transfer is enacted, and
(iv) slab stiffness,

for the various joint conditions present in the pavement.

5. MATHEMATICAL SIMULATION

The mechanically measured and resulting calculated pavement properties are used to construct a mathematical model using finite element techniques as indicated in Figure 10. E_{C1} represents the concrete stiffness, whereas the concrete in the deteriorated joint is assigned a stiffness E_{C2} in Figure 10. E_{SB1} is the stiffness of the subbase and E_{SB2} is the reduced stiffness used in the model for a void or deteriorated subbase. Hooks that allow a certain amount of free movement before load transfer is enacted are used in the joints. This model is calibrated to field measurements and HVS tests[4] by adjusting the stiffness values of the various elements until field behaviour is adequately simulated.

This model is useful in determining the sensitivity of specific variables in the pavement an example of which is given in Figure 11. From this figure it is, for example, evident that a reduction in concrete stiffness from 23,3 GPa to 15,5 GPa has the same effect on deflection as lowering

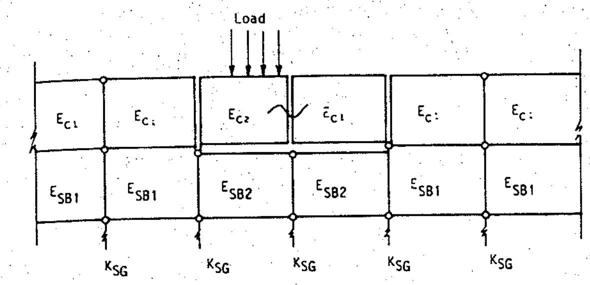


FIGURE 10: Mathematical model

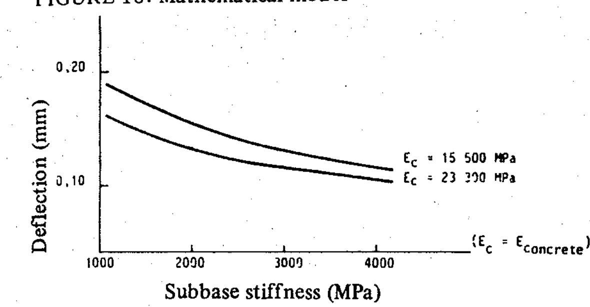


FIGURE 11: Deflections related to concrete and subbase stiffness

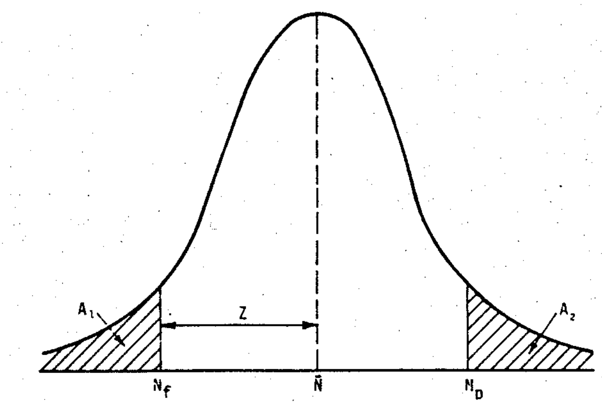
the subbase stiffness from 3,0 to 2,0 GPa. The measured relative deflection difference in this case is 0,015 mm.

This mathematical model is an extremely powerful tool in assessing the effect of certain rehabilitation measures such as undersealing, restoration of load transfer etc. It can also be used in designing overlays by superimposing layers on top.

Application of mathematical model. The variation in structural capacity from point to point in the pavement is of paramount importance and techniques to evaluate subgrade support need to take this into account. Thus stochastic principles are employed in the pavement evaluation with a view to designing rehabilitation techniques.

Figure 12 shows conceptually the normal distribution curve for the structural adequacy of the pavement. The area under the curve marked A_1 represents the probability of failure, or the percentage of the pavement expected to show failures due to structural inadequacy. A_2 indicates the area of pavement where no problems are experienced. The structural adequacy can be measured in terms of structural life, eg equivalent 80 kN single axle loads (E80's). Looking at Figure 12 again for those sections of pavement with a structural adequacy below N_f, overlays, reconstruction or recycling are the rehabilitation measures to consider. On the other hand for the pavement sections with a structural adequacy greater than N_p no structural rehabilitation is required. In between the abovementioned limits (N_f - N_p) preventative maintenance/rehabilitation is to be considered depending on the life expectancy of the pavement.

The structural capacity of the existing pavement finally influences the selection of the maintenance/rehabilitation



N_f = Structural adequacy below which failure occurs
$\bar{N}$ = Mean structural adequacy of pavement
N_p = Structural adequacy above which no problems are experienced

FIGURE 12: Normal distribution curve for structural adequacy of the pavement

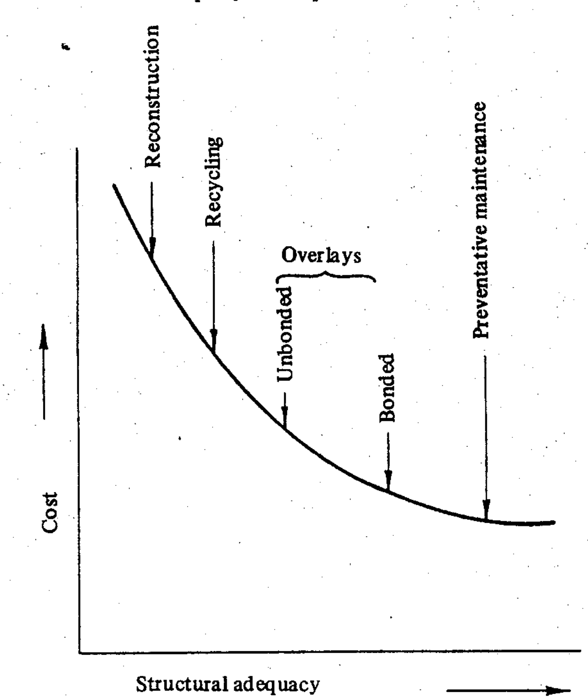


FIGURE 13: Conceptual relationship between structural adequacy and cost of rehabilitation

approach to be taken. This concept is indicated in Figure 13. The structural adequacy is a function of the allowable probability of failure or risk. Figure 13 is only illustrative, eg under certain circumstances preventative maintenance can be more costly than some form of rehabilitation, for instance if road user cost is very high or if the structural capacity of the existing pavement is allowed to deteriorate too far before structural rehabilitation is carried out.

Work by Shackel[4] has shown that where the structural capacity of certain sections of pavement is inadequate some form of overlay, recycling or reconstruction may be necessary. The principles discussed above can be employed to

locate areas of inadequate structural capacity through (i) correlation of condition survey information and mechanical measurements, (ii) mathematical simulation, and (iii) stochastic principles. On the other hand, as indicated in Figure 12, certain sections of the road are structurally still adequate and strategies to maintain them should be planned. The cost of the different approaches can then be superimposed on Figure 12 whereby the cost effectiveness of each approach can be evaluated.

Since the existing pavement has some residual value reconstruction or even recycling does not seem to be a practical approach. For structurally inadequate sections the following overlay types seem to be the most likely:

Unbonded jointed concrete overlay.
Unbonded continuously reinforced concrete overlay.
Thick asphalt overlay.
Crushed stone base with thin asphalt overlay.

The following other maintenance/rehabilitation measures are also to be considered:

Undersealing where voids exist beneath the slab.
Joint and crack repair.
Joint and crack sealing.
Improvement of drainage.
Improvement of load transfer.

6. CONCLUSIONS AND RECOMMENDATIONS

Fruitful and practical conclusions from the work done to date, are limited by the fact that the complete analysis of all information is dependent on the results of testing by the heavy vehicle simulator[4]. The following, however, are interim recommendations.

(a) Alkali-aggregate reaction apparently reduces both slab and subbase stiffness leading to higher stresses under traffic loading.

(b) Cracks initiated by the alkali-aggregate reaction as well as an increase in stress under load, enhances structural cracking of the slab which generally manifests itself as secondary cracking close to the transverse joints.

(c) Increased slab permeability following this cracking allows water to penetrate the slab, subbase and subgrade resulting in increased weathering via the action of water. Voids are formed between the slab and the subbase because of the migration of fines. In some cases the horizontal movement of fines causes faulting.

(d) Loss of subgrade support for the slab causes higher deflection. This leads to a deterioration in load transfer capability at the transverse joints which cause large relative movements followed by structural failure at the joint.

(e) The mechanism of distress as monitored by a condition survey, can be simulated on a computer which makes the design of rehabilitation techniques feasible. Thus overlays of different materials can be superimposed on the model and resulting stresses and strains can be calculated and compared to the fatigue characteristics of overlay materials.

Furthermore, the relative success of maintenance procedures such as undersealing or mud jacking, restoration of load transfer capabilities and the repair of deteriorated concrete can be theoretically analysed.

Based on the preliminary results, certain recommendations may be appropriate at this time:

(i) A detailed assessment of National Route 2, Section 1 should be launched in order to isolate poorly performing sections for a study of appropriate maintenance measures.

(ii) Sections with a C of greater than 0,5 are seemingly beyond inexpensive maintenance. However, an economic study based on the occurrence of poor sections on the road and different rehabilitation measures will have to be performed before any final recommendations can be made.

(iii) There are a considerable number of sections of the road that still have a C value below 0,4 and serious consideration should be given to investigating ways and means of prolonging their structural life.

(iv) From the above it is clear that the construction of an experimental section, employing a predetermined number of various rehabilitation alternatives, will be essential in order to arrive at the ultimate solution. This is especially necessary since a mathematical model cannot simulate all possible complications and distress mechanisms that can occur in a hostile environment such as has been experienced in this case. In order to get a quick evaluation of the effect of dynamic load on these experimental sections, the use of the heavy vehicle simulator is indispensible.

Discussion

Mr G H van Alphen (Hawkins, Hawkins and Osborn, Roggebaai, South Africa) said that the authors had suggested a concrete overlay as one rehabilitation measure and asked whether this meant that the reaction had stopped or was about to stop. Surely, he asked, would not such an overlay crack if this was not the case? The authors were also asked to suggest how an improvement in load transfer might be achieved at the joints when horizontal cracks in the concrete would cause failure of grouted dowel bars or concrete plugs.

Mr N van der Walt replied that the mathematical model allowed a fair amount of freedom for a bonded or an unbonded overlay and thought that where it was uncertain as to whether the reaction was complete an unbonded overlay should be considered. With regard to the question about load transfer it was essential to understand that he was not talking about a thin overlay such as that found on an asphalt road, which could be 20 to 40 mm thick, but one that was 125 - 150 mm thick and was a substantial structure in its own right.

Mr J F Pienaar, (Mackintosh, Bergh and Sturgess) asked Mr P Myburgh of the Department of Roads of the Cape Provincial Administration about the effectiveness of the bituminous overlay which his Department had laid about a year ago on a part of the N2 concrete pavement which had cracked.

Mr Myburgh replied that the surfacing on the concrete road was not done to retard cracking but to remove the effects of wheels and air and water from the abraded material in the cracked zones at the intersection of the wheel tracks and the transverse joints, thereby attempting to retard the development of spalls. It might well be that a spin-off could be that the pavement would now be less susceptible to moisture variations which might have an influence on the expansion and contraction of gels and consequent cracking of the pavement. Because it was a black surface this might also have an effect on temperature variations within the pavement. It was really an experimental section he said.

Prof S Diamond, (Purdue University, USA) said that it seemed to him that the distress being experienced was out of proportion with the severity of the attack factors. In America they were used to seeing concrete pavements deteriorate, mostly as a result of a combination of factors, sometimes involving alkali-aggregate reaction but very much aggravated by freezing and the effect of calcium chloride and sodium chloride which were used to keep the roads ice-free in winter. Even though South Africa had neither of these problems the pavement was showing unusual and relatively severe distress. In particular he did not understand the geographic distribution of the cracking at the sides of the highway and further the distress in the CTB was something wholly unexpected. He thought somebody ought to look into that situation petrographically to figure out exactly what was happening 'down there'. He suggested that an unbonded overlay was certainly a serious possibility and added that a steel fibre reinforced unbonded overlay would give the maximum advantage under those circumstances.

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