

THE PERFORMANCE OF JOINTED CONCRETE PAVEMENTS AS AFFECTED
BY FACTORS OTHER THAN TRAFFIC INDUCED STRESS

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Design and construction techniques as developed overseas have been used in Southern Africa on Portland cement concrete pavements with little variation based on local experience. This paper describes methodology by which Portland cement jointed unreinforced pavements are being evaluated with the aim of improving local design and construction techniques. Indications are that failures found on the pavements can primarily be attributed to inadequate construction techniques and control. Although the pavements are performing very well (only 11 % of the road system have cracked outside the joints) it is felt that an improvement in performance is possible if subgrades are compacted properly to reduce settlement, non erodible subbases are constructed, load transfer at joints are enhanced by using low shrinking concrete, joints are kept properly sealed and Portland cement paved shoulders are used.

In the past Portland cement concrete pavements have not been used extensively on highways in Southern Africa. This situation however changed in the early seventies when traffic volumes on the planned freeway system increased to such an extent as to warrant the use of sophisticated construction equipment in obtaining high quality Portland cement concrete pavements, both in terms of riding quality and noise levels. The increase in traffic loading associated with the higher volume of traffic has also increased maintenance problems on flexible pavements and the need developed for relatively maintenance free pavements. Several sections of jointed unreinforced concrete pavements were therefore built in the Cape Town, Johannesburg, Natal and Eastern Transvaal areas from 1968 onwards.

Excluding the section between Cape Town and Somerset West, which was overlaid two years ago because of alkali aggregate reaction and premature failures (1), all Portland cement concrete pavement sections are performing satisfactory and are in a relatively good condition. Some sections, however, have performed better than others for no apparent reason and it was felt that after about 20 years of service the time had come to re-evaluate the design and construction procedures that were and are presently being used. The benefit of past experience as well as new design and evaluation techniques can be to the advantage of future application of Portland cement concrete pavements and an investigation was launched to analyse design and construction aspects of the pavements.

Investigations

The prime objective of the study was to further refine the guidelines in design and construction presently in use, through the following steps:

- field evaluation of the performance of pavements presently in use, taking into account as built data
- a study of developments elsewhere in the world (2, 3)
- a simulation of pavement behaviour through analytical modelling
- modelling of pavement behaviour in the laboratory by varying typical parameters in the extreme.

Performance of the pavements in the field was monitored in order to identify manifestations of distress. These surveys were compared with experience elsewhere by a study of the literature as well as communication with the relevant engineers. Typical pavements were then modelled using computer simulation in order to

isolate and quantify the relevant parameters. Factors that could not be quantified properly were then simulated in laboratory models where design and construction parameters were varied to the extreme and behaviour was monitored and compared to theoretical predictions. Figure 1 shows a flow diagram of the relevant actions and its interaction with different activities.

Priority was given to the evaluation of existing pavements, design methods and construction practice since they provide an input into the selection and characterization of parameters that may influence performance. These inputs were then used to compile theoretical and laboratory models. Laboratory models were used to study grey areas found in field studies as well as to calibrate the theoretical computer models. The output of the system was planned to provide the capabilities to extrapolate beyond present experience and to incorporate new technology, materials and techniques.

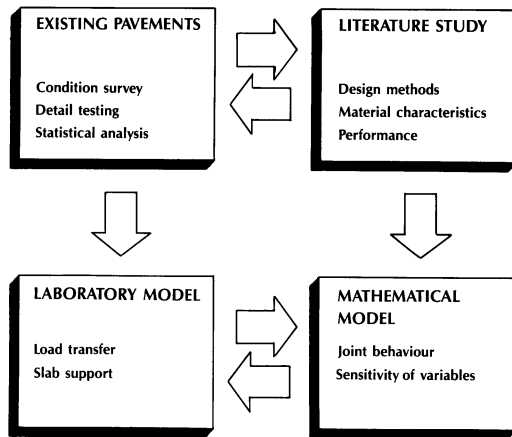


Fig 1. Flow diagram of study

Pavement evaluation

In the evaluation of the existing pavement, an attempt was made to relate existing behaviour to variables such as concrete stiffness, thickness, type of joint and the quality of supporting layers. The actual load applications from traffic as well as the climate under which the pavement is performing was quantified through measurements and the pavement itself was physically investigated to try to determine reasons for failures.

The investigation was conducted in three phases as shown in figure 2. First a visual condition survey was to determine the extent of distress. Secondly detail testing was done on

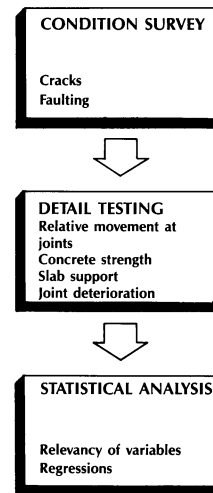


Fig 2. Flow diagram of field evaluation

sections with and without failure particularly where such sections were found next to each other. Testing was aimed at determining the characteristics and condition of the different layers, the joints and the cracks. Methods such as crushing and tensile strength, cement content, resistance against penetration (using the dynamic cone penetrometer), relative vertical movement at a joint under a moving truck and deflection measurements were used. Joints were filled with epoxy and cores drilled in order to determine voids, extent of weathered joints and secondary cracking (see figure 3).

All data was analysed statistically in order to determine the significance of parameters whereupon the correlation between performance and the relevant parameters was determined. Laboratory simulation

In order to further investigate the interaction between load transfer at a joint, characteristics of the slab itself and the influence of subgrade support, a laboratory model was built upon which cyclic loading of different magnitudes could be applied. Figure 4 shows the layout of the half scale model where different subgrade materials can be experimented with in the 500 mm deep test pit. The facility was also provided with a mechanism to introduce a horizontal force in order to simulate shrinkage and temperature stress as well as different joint openings.

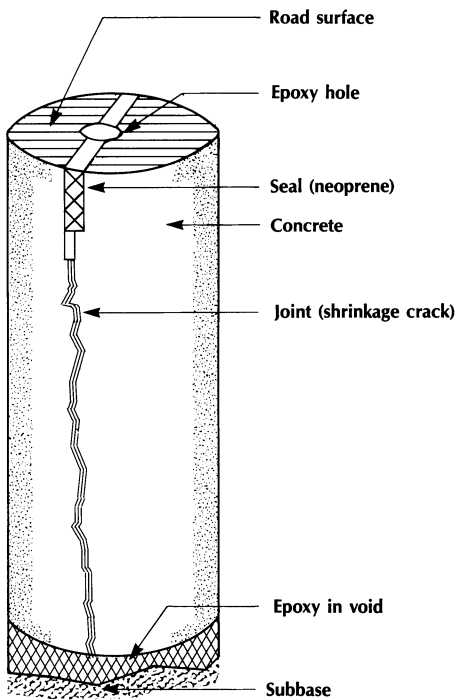


Fig 3. Typical core after injection of epoxy

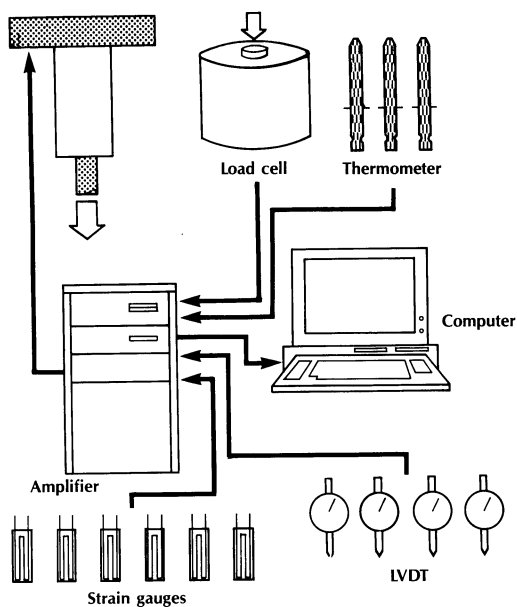


Fig 4. Layout of instrumentation

Wheel loading was simulated through a computer controlled hydraulic cylinder whereby the dynamic application of loading was possible. Both the frequency and the shape of the load curve could be varied whilst movement and strains were monitored digitally.

Mathematical model

Field evaluation of pavement behaviour together with laboratory monitoring of the relative effect of different parameters was able to provide only a limited insight into the influence of the different design and construction variables. In order to extrapolate beyond the experience of laboratory and field data and to quantify the effect of design and construction variables, a mathematical model was compiled.

Traditionally Westergaard theory has been used to evaluate Portland cement concrete pavements but the field studies have indicated that load transfer at and the condition of the joint might have a significant influence on pavement performance as a whole. Finite element modelling was selected since variable materials properties, non linear elastic joint behaviour, secondary cracking as well as non uniform slab support could be handled when using this method of modelling (4). A two phase approach to the analyses was used where a simplified three dimensional model was initially employed, see figure 5, followed by a sophisticated main frame model which could handle non linear elastic materials properties, specifically in the support system and in the joints and cracks (5).

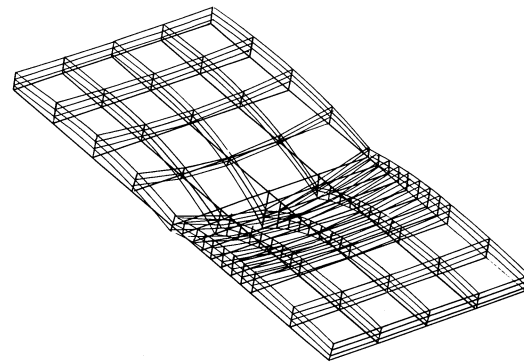


Fig 5. Finite element model

The success of the mathematical modelling depended to a great extent on the accuracy of the input. Previous experience was used for initial input and the final model was calibrated by comparing field and laboratory behaviour with predicted values of deflection and relative movements using the theoretical models.

Results

The field study indicated that all the jointed unreinforced Portland cement concrete pavements that were investigated were performing very well. Where failures occurred they did not fail according to the mechanism assumed in design. No section indicated cracking that could be attributed to fatigue of the slabs where homogeneous support was encountered. Almost all slab cracking that occurred could be related to construction problems, a loss in slab support and/or a loss in load transfer at joints or cracks.

Construction problems

Effective quality control is of critical importance if adequate performance of a Portland cement concrete pavement is to be expected. Of the 110 km of road section investigated, only 11 % of the 4,5 m long slabs of the jointed unreinforced pavement showed one or more cracks, of which 85 % could be attributed to construction problems. The primary reasons for these cracks were uncontrolled transverse cracking due to late or shallow initial saw cuts or plastic cracking due to inadequate curing.

A histogram of the frequency of types of cracks is shown in figure 6. It has been established that the thickness of slabs varied in the extreme between 175 mm and 265 mm and crushing strengths of cores varied between 13,5 and 50,9 MPa. No significant correlation could be found between these individual measurements and cracking but these variations may be indicative of the control that was exercised on the few sections where cracking did occur.

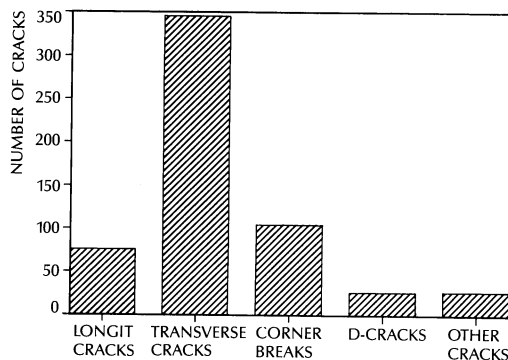


Fig 6. Frequency histogram of type of cracks

The cores drilled from cracked sections indicated segregation as well as a variation in strength at different levels of the slab. Higher strengths as well as cement content were generally found in the top layer and this could be due to segregation since signs of a concentration of water was found at the top third of the slab.

Loss of slab support

The durability of supporting layers for Portland cement concrete slabs plays a significant role in the performance of this type of pavement. This has been illustrated by the performance of a section with a lime treated subbase which shows severe pumping in places. Where a high quality cement stabilised crushed stone was used as a subbase, almost no erosion was evident.

Many of the transverse cracks not associated with construction problems could be related to a loss in slab support. This loss in support was the result of pumping, curl of the slab or plastic deformation or settlement in the sublayers. Although the subbase layer was stabilised in most of the sections that were investigated, a certain amount of erosion could always be detected. Fines that were generated by erosion, was displaced towards the approach end of the joint with subsequent faulting. In one particular case the loss of fines under the leave slabs caused voids to form which subsequently lead to localised structural failures in the form of punch outs.

It was quite evident from the investigations of materials quality in the subbase that erosion could be associated with material strength. Figure 7 shows a plot of the gap between subbase and slab as a function of stiffness, as determined by dynamic cone penetrometer.

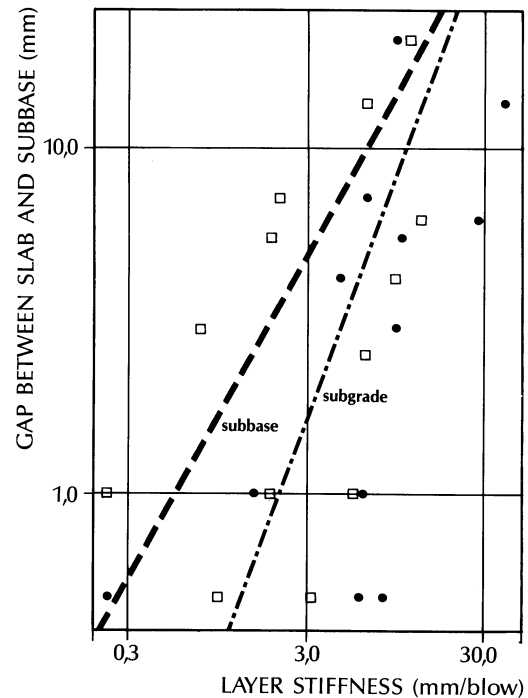


Fig 7. Void between slab and subbase as a function of support stiffness

Two relationships are shown namely the stiffness of subbase and stiffness of the subgrade. This figure is based on limited data but it illustrates that poor material for example with a penetration of 20 mm/blow used as support to a Portland cement concrete slab will tend to form voids between the slab and the support. Detailed investigations of failed sections where the gaps were in excess of 5 mm, indicated that subgrade movements also may have contributed significantly to the size of gaps, a loss of slab support and subsequent structural failures.

Load transfer at joints

It is a known fact that the stress in a slab depends to a great extent on the position of the load in relation to joints and the free edge. Not only is stress in the slab influenced by this but also the deflection of the slab and thus stress on the sublayers.

Table 1 shows some typical average deflections on typical road slabs loaded at the corner, free edge the interior and at a joint with excellent load transfer characteristics.

Table 1 Deflections of slab under a 40 kN load

Position	Deflection (mm)
Interior	0,03
Edge	0,12
Corner	0,20
Joint	0,07

The values in table 1 indicate that construction of a proper joint instead of having edge loading conditions can contribute significantly towards the lowering of deflection and thus stress on the subgrade.

In order to determine the efficiency of load transfer at a joint, relative movements as well as deflections at transverse shrinkage joints were measured at different crack widths. Figure 8 shows an example of the values measured at new shrinkage joints without any dowels. It is clear from this figure that almost perfect load transfer occurs when the crack width is less than 0,5 mm since relative vertical movements are almost zero.

This implies that the loaded and unloaded slabs deflect by the same amount. As crack width increases, it is found that deflection of the unloaded slab gradually reduces from a maximum of about 0,1 mm but that relative movement at the joint increases. At a crack width of more than 3 mm, the contribution of the unloaded slab in taking up some of the stress is beginning to decrease. This seems to imply that load transfer is enhanced by a narrower crack and that a crack width of more than 3 mm should be avoided.

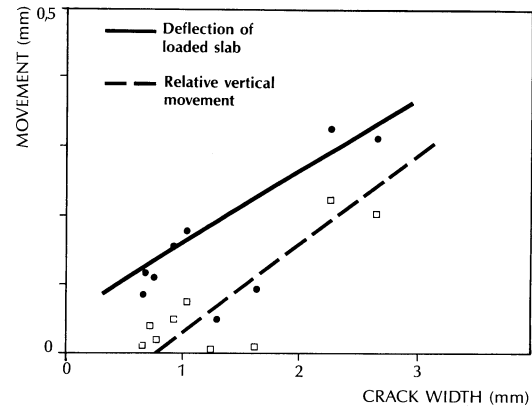


Fig 8. Vertical movement under traffic loads at shrinkage joints as a function of crack width

In a separate phase of this study (6) it was found that crack width and crack spacing was very much influenced by the maximum temperature during the first 24 hours after construction, especially if high temperature was associated with wind. As far as construction control is concerned, cracking was induced whenever quick drying out of slabs occurred.

Discussion and conclusions

Although the study is still in progress, the results so far have indicated that the performance of jointed unreinforced concrete pavement in Southern Africa has been good. The majority of distress manifestations that occurred can be associated with factors outside the control of the designer. Where problems have occurred they have been mainly the result of inadequate construction technique and controls. The more important aspects can be summarised as:

1. Variation in slab characteristics, both in thickness and consistency of mix may lead to unwanted cracks. Non-uniform concrete was more prone to cracking, especially where segregation or bad compaction occurred.
2. Slab support is crucial to good performance and in this regard erosion free subbases under the slab greatly enhanced performance. Not only is it important to prevent erosion (pumping) of the subbase but water should be kept out of the system by proper maintenance of joint seals. However, in the majority of cases where cracks occurred and it could be associated with poor slab support, big voids were found

between slab and subbase and these voids could be associated with subgrade movements. Settlements of the subgrade as well as non uniform clay movement were the biggest contributors to poor slab support.

3. Edge or corner loading of slabs should be avoided by using Portland cement paved shoulders and proper load transfer at joints was found to be crucial. Crack widths of more than 3 mm at joints resulted in a loss in load transfer. For this reason high shrinking concrete should be avoided.
4. The timely sawing of shrinkage joints is important if unplanned transverse cracking is to be avoided. Furthermore, special care is required when slabs are being constructed when high temperatures and a dry wind is to be expected 24 hours after construction of the slabs. Proper curing membranes can be highly advantageous in avoiding this type of cracking.

The obvious lesson to be learnt at this stage of this investigation is that construction control requires improvement in order to reduce deviations from good practice. Should this be possible, jointed concrete pavements are likely to provide a high standard of performance even if slab thickness is reduced resulting in a lower initial cost.

References

1. Strauss, PJ, du Plessis, J, Francis, V and Viljoen, AW, "The application and validation of an analytical method in the structural rehabilitation of a cracked rigid pavement", Third Internat. Conf. on Concrete Pavement Design and Rehabilitation, Purdue, 1985.
2. Roman, RJ, Shahin, MY and Freeman, TJ, "Analysis of concrete pavement performance and development of design procedures", Transportation Research Record No. 1099, Washington DC, 1986.
3. Marais, LR, "The design and construction of concrete pavements". Portland Cement Institute, Johannesburg, 1973.
4. Macleod, DR and Monismith, CL, "Comparisons of solutions for stresses in plain jointed Portland cement concrete pavements", Transportation Research Record No 888 Washington DC, 1982.
5. Lourens, JP and Strauss, PJ, "Mechanistic design of continuously reinforced concrete pavements : Phase I" Eighth Quinquennial Convention of SAICE, Pretoria, 1988.
6. Brink, AC, "Cracking of long slabs due to shrinkage of the Portland cement concrete", Dissertation for Masters Degree, Stellenbosch, 1988.

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