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Accelerated Pavement Testing of Load Transfer through Aggregate Interlock and the influence of Crack Width and Aggregate Type - a case study

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Abstract

It is well known that performance of plain jointed concrete pavements depends on aggregate interlock to transfer load from the one slab to the next. In order to quantify the relative contribution of crack width and the strength of the aggregate to the long-term performance of a plain jointed pavement, experimental sections of road were built using different aggregates types. These sections were subsequently loaded to failure using the Heavy Vehicle Simulator (HVS). Some typical sections of interstate-type highways, which had been under traffic for between ten and twenty years were also investigated using FWD testing and determination of changes in crack width with changes in temperature. Detailed as-built information including concrete mix characteristics was available for all these sections.

This paper discusses the prediction of crack width using the RILEM model which predicts early age shrinkage. The model was modified to include the effects of aggregate type, environmental conditions and age. The change in load transfer at the joints and cracks, as indicated by relative vertical movement under dynamic loading as a result of temperature variation and humidity, is reported on. It was found that a change in load transfer occurred under increased loading and that this could be related to the crushing characteristics of the coarse aggregate.

This paper presents the final outcome of the study in terms of theoretically based equations that were adjusted using regression techniques to fit the field experience. These equations have now been incorporated into a mechanistically-based design method for concrete pavements, cncPave.

Keywords: *PCC Evaluation, Accelerated pavement Testing, Load Transfer Efficiency, Aggregate interlock*

Background

Concrete pavements have been designed and constructed in South Africa using “modern” technology since 1969. The performance of several of these sections has and is still being monitored and the information is being used in upgrading design and construction methods. Incorporated into some of the above sections were short test sections of thin concrete pavements that have been intensively tested, including testing with the Heavy Vehicle Simulator (HVS), and monitored with time.

As a result of the need to develop a mechanistically-based design method for concrete pavements, an overall plan was drawn up to address necessary aspects of the design process and included a motivation for the revision of the nomogram-based M10 Design Manual. Subsequently a new mechanistically- and computer-based design method, cncPave, was developed (Strauss et al. 2001 and 2004). Following more input from research, test sections and the performance of real road sections, the program has been further refined to predict the extent rather than the risk of failure.

The program now consists of modules that address the following aspects:

- External loading as defined by the distribution of typical vehicles
- The transfer of loads from one slab to the next through aggregate interlock or dowels
- Slab support stiffness and the loss of this support through erosion, pumping or settlement
- Slab characteristics including strength and stiffness
- Stress in the slab as a function of the above variables
- The structural performance of the slab as a result of stress within the slab
- Variability of the input parameters and the prediction of the extent of failures with time
- Cost implications of the final design.

Research Needs

The design program cncPave is presently used extensively by designers and road owners and has created an awareness of the sensitivity of the different input parameters. Furthermore, monitoring of the program’s reliability together with feedback from practitioners has indicated that the program could be further improved – particularly by refinement of the load transfer module.

A load transfer coefficient C was introduced into cncPave to distinguish between the load transfer capabilities of aggregate interlock and dowels in joints so that the differences in performance of Plain Jointed (PJP), Dowel Jointed (DJP) and Continuously Reinforced Concrete Pavements (CRCP) could be mechanistically explained. This approach, together with feedback on the performance of concrete pavements in South Africa, is being considered in the process of updating and improving design and construction procedures.

Based on the use of cncPave and monitoring the performance of existing concrete roads and test sections, it became clear that research was needed to establish the effect of the number of loads on a change in slab support, materials and the load transfer at joints and cracks.

Theoretical Background

For the purpose of this paper the structural performance of a concrete pavement is evaluated as a function of the maximum stress at a joint or crack in the pavement (Strauss et al 2001):

$$\text{Stress} = f\left(C, \frac{P}{h^2}, \sqrt[4]{\frac{D}{k}}\right) \tag{1}$$

where: stress = maximum tensile stress close to a joint or crack in the pavement

C = coefficient that depends on load transfer at a crack or joint

D = slab stiffness

k = slab support stiffness

P = magnitude of load

h = slab thickness.

The magnitude of the load transfer coefficient C is dependent on the aggregate interlock or the dowel action of longitudinal steel bars at the joint or crack. In both cases load transfer is a function of the relative vertical movement, Δy, at the joint or crack under a moving load. The slab support is dependent not only on the stiffness of the supporting layer but also on any void that may develop below the slab as a result of slab curling or erosion and pumping.

Based on work by Walraven (1981) as well as a laboratory study to develop the South African Concrete Pavement Design Manual (1990), it was confirmed that relative vertical movement, Δy, and thus aggregate interlock, is a function of crack width, aggregate shape and size, as well as the strength of the aggregate itself. Relative vertical movement at a joint/crack under the influence of aggregate interlock can be written as (Brink 2003):

$$\Delta y = 0.118(1 - e^{-((v + 11.4/agg)\Delta x)^{1.881}}) \tag{2}$$

where Δy = relative vertical movement at joint/crack
v = factor influenced by speed of loading
Δx = crack/joint width

agg = nominal size of the 20% biggest particles in the concrete mix

In the case of dowel action of steel bars in the pavement, the strength of concrete around the steel and the size of the steel bars are important to reduce or maintain a low level of relative vertical movement at a joint. Relative vertical movement at a joint or crack in which steel bars are installed can be written as (Yoder and Witczak 1975):

$$\Delta y = P\,(2 + \beta x) / (4\beta^3 EI) \qquad (3)$$

Where $\beta = [Kb / 4EI]^{0.25}$
K = Winkler stiffness of the concrete around the steel bar
b = steel bar diameter
E = modulus of elasticity of the steel bar
I = moment of inertia of the steel bar
P = load on the steel bar
x = crack width

It is clear from equations 2 and 3 above, that crack width is important in predicting relative vertical movement and thus the successful transfer of load at a crack or joint in the pavement.

Crack width in turn depends on the shrinkage and thermal characteristics of the concrete used in constructing the concrete pavement. Shrinkage can be measured at the time of construction or it can be calculated from other known variables.

The shrinkage strain in concrete can be calculated using the RILEM equation (RILEM 1995):

$$\text{Strain with time} = S(t)\, k_h\, \varepsilon \qquad (4)$$

$$\text{where: } S(t) = \tanh \{(t-t_0)/4.9D^2\}^{0.5} \qquad (5)$$

$$\varepsilon = \alpha_1 \alpha_2 [0.019\, w^{2.1}/f^{\,0.28} + 270] \qquad (6)$$

k_h = 1- h_u^3
t = age of the concrete
t_0 = age when drying starts
D = effective cross section thickness = 2 v/s
(v/s is the volume to surface ratio)
α_1 = cement type
α_2 = factor for curing
w = water content of the concrete
f = cylinder compressive strength of the concrete
h_u = factor for relative humidity

where 100% humidity = factor of 1)

Adding a factor α_3 to account for the influence of different types of aggregate on shrinkage, as suggested by Badenhorst (2003), as well as strain due to the change in the temperature from the temperature at the time of placing the concrete, results in the following equation:

$$\text{Strain} = C_1\,\alpha_1\,\alpha_2\,\alpha_3/h\,[0.019\,w^{2.1}/f^{\,0.28}+270]+(T_0 - T_t).\eta \qquad (7)$$

Where α_3 = aggregate type
C_1 = constant
h = slab thickness

T_0 and T_t = temperature at time of paving and present temperature respectively

η = thermal coefficient of the concrete

Heavy Vehicle Simulator Testing

In order to address some of the research needs listed above, a series of HVS tests were conducted on short sections of jointed concrete pavement (JCP) at Hilton on the N3 close to Pietermaritzburg in KwaZulu Natal, South Africa. To gain full value from these tests it was important that each test should be conducted in a systematic way so that the performance of the variable under investigation could be evaluated. In this way a substantial database of all possible variables that have an influence on pavement behaviour was created. However, since the main aim of the study was to improve the models in cncPave, the following were tested as part of this study and will be reported on in greater detail in this paper:

- *The change in load transfer with traffic loading and time.* Load transfer is a function of aggregate interlock and the dowel action of steel bars, when used. Aggregate interlock is a function of crack/joint width, aggregate shape and size as well as the strength of the aggregate itself. In the case of dowel action of steel bars in the pavement, the strength of concrete around the steel and the size of the steel bars are important. However, the wear or abrasion of aggregate as well as the concrete with loading and time had to be established. Dolerite and quartzite aggregate was used in the two sections at Hilton that were tested with the HVS to determine the influence of the hardness and type of aggregate and its performance under loading.

- *Prediction of thermal and shrinkage behaviour of concrete in a pavement.* Load transfer at a joint or crack is a function of the width of the crack or joint. This in turn is directly dependent on the shrinkage and thermal movement of the concrete used in the pavement. The test sections at

Hilton provided an excellent opportunity to investigate these factors and to supplement the data with actual performance of pavements on the N3 and N2 highways.

The scope of the accelerated pavement-testing programme was limited to the investigation of doweled and plain jointed 3.5m x 4.0m x 150mm thick slabs with both 19mm dolerite and quartzite stone. In order to evaluate the relative contribution of these variables to joint behaviour and thus to performance of the pavements, the test sections were constructed on top of three 150mm layers of natural gravel with in situ CBR of 15 (Brink 2004) The test site is shown in Figure 1.

Details of the as-built properties of the sections are contained in the construction report (Brink 2004).

Figure 1. General view of the HVS and the test site

Each test section was subjected to 40kN wheel loading using unidirectional load application. The HVS is capable of applying 10 000 unidirectional wheel loads per day. A relatively low strength slab support was selected and water was introduced with a drip irrigation system. Vertical and horizontal movements at the joint were monitored and environmental data as well as the variation in crack width were measured on a regular basis,

Figure 2 shows the typical crack pattern that had developed by the end of the HVS test. The transverse joint is indicated in a reddish colour while the cracks that developed later are indicated in yellow and blue, the blue being a crack that developed at the very beginning of the testing. The crack pattern indicates a bigger void under the leave slab than under the approach slab.

This void was as a result of pumping (as shown in Figure 3) where pumped material is more prominent at the side of the leave slab.

Figure 2. Crack pattern at the end of the test on the undowelled dolerite section

Figure 3. Pumping from under the leave slab, the right hand side of the crack

Figure 4. Spalling of a crack as a result of relative vertical movement and pumping

As a result of the void and thus larger relative vertical movements at the joint and the cracks, spalling as shown in Figure 4 occurred. For greater detail on the sequence of distress at each test, reference is made to the first-level-analysis report (Brink and du Plessis 2004).

Analyses of field measurements

The main purpose of this paper is to report in general on the refinement of the design methods for concrete pavements and on the cncPave program in particular. The analyses are focused on the effect of an increase in the number of loads on joint behaviour and performance. Data generated by HVS and other testing was used for this purpose and analysis of data was carried out using statistical principles. However, pure regression analyses may be misleading since the reliability of the resulting equations will depend on the reliability of the data. The study is based on limited testing and in order to extend the applicability of the equations generated to beyond the experimental data, equations needed, wherever possible, to be based on theoretically derived relationships.

Test sections were well instrumented on both the surface of the pavement at and between joints and cracks, and as well into the depth of the pavement. The analyses of data obtained from these measurements were based on theoretical models already developed and discussed earlier. Data generated by measurements of crack widths at different temperatures, FWD deflections, and pavement behaviour with increased HVS loading, were used for this purpose. Although a great number of data points were obtained (especially under HVS testing), the variation in readings was such that a wide spread of results was obtained. Forcing this data into a format obtained from theoretical models, generally resulted in low R^2 values, but the benefit of this approach is that the reliability of the resulting equations are high in terms of their applicability beyond the experimental data.

Crack width. The total shrinkage strain in a concrete pavement constitutes two phases – a first phase of shrinkage strain over the first few weeks, assuming controlled curing, and a second phase consisting of the long-term shrinkage that depends primarily on the age of the pavement and the environment under which the pavement is performing.

Shrinkage over the longer term can be calculated using the following equation that was derived using data generated by Troxell (1958):

$$\varepsilon_t = C_2 [900-t] [t-0.08]^{0.18} [1- h_u] \qquad (8)$$

where: h_u = relative humidity (value of 1 = 100% humidity)
t = time (years)
C_2 = constant

Crack width Δx can be calculated by combining equations 7 and 8:

$$\Delta x = [C_3/h\{\alpha_1 \alpha_2 \alpha_3 (0.019w^{2.1}/f^{0.28}+270) +(900-t) (t-0.08)^{0.18} \}(1-h_u)+(T_0–T_t) \eta].L \quad (9)$$

Crack widths on the surface of the pavement were measured daily at 8h00 and 14h00 using a microscope. Air and concrete surface temperatures as well as humidity were recorded at the same time. Crack widths were subsequently also measured inside cored holes for all joints and cracks on the Hilton sections as well as on some sections of road on the N3 and N2. It was found that the crack widths measured on the surface of the pavement using the microscope were between 0.20 and 0.32mm wider than the core measured values.

The data was subsequently used to compare measured crack widths with theoretically predicted values determined using equation 9. In the case of the data from the N2 and N3, the average daily values of humidity and the concrete characteristics at the time of construction were obtained from design mix data.

Despite the lower accuracy of the environmental and concrete mix data thus obtained, an R^2 of 0.61 was still arrived at for equation 9. It was interesting to note that air temperature rendered a better correlation to crack movement than did concrete surface temperatures. Since the air temperature can be predicted more easily in the design process, it was decided to use it rather than concrete surface temperature in the finally derived equation. Figure 5 shows a plot of measured versus calculated crack widths obtained from equation 9 and using core hole measured crack widths and air temperature as variables.

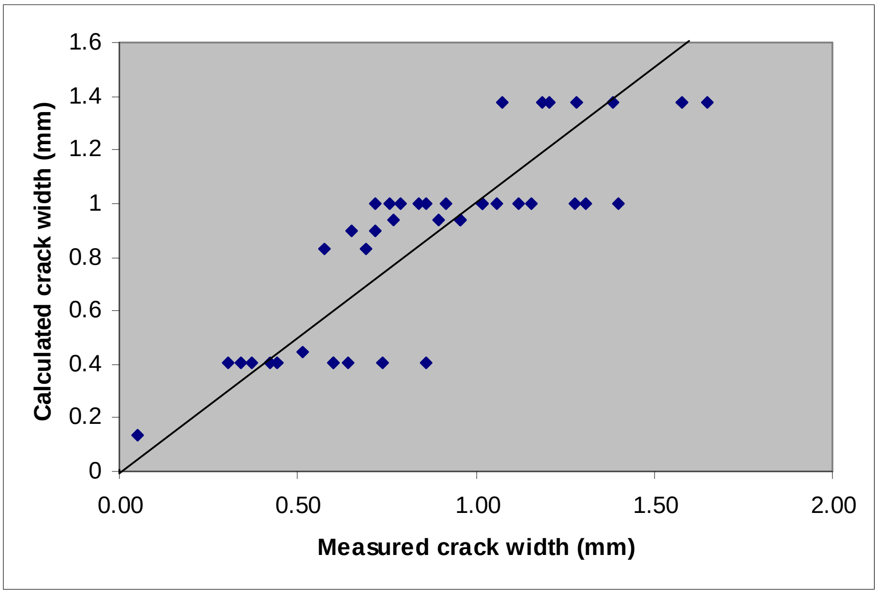

Figure 5. Measured versus Predicted Crack Widths

Relative vertical movement. Relative vertical movements (the movement of 2 slabs on either side of a joint) were measured under both HVS and FWD loading. The HVS testing was conducted using unidirectional travel and a 40-kN wheel load. Movement at cracks was measured by using multi-depth deflectometers (MDDs) as well as joint deflection measuring devices (JDMDs). MDDs are anchored about three meters below the surface thus measuring the absolute movement at different levels in the pavement structure while JDMDs are installed on the surface and measure only surface movements relative to the anchor placed at 3m depth. Both these instruments were found to be accurate in measuring relative vertical movement under the rolling wheel load and a high correlation was found between the two measuring instruments.

The following equations were generated from regression techniques using 1475 data sets obtained from HVS testing:

$$\Delta y = 8.37\ (\Delta x_m{}^{1.5} / \mathrm{Agg}) + 0.030.n.\ \mathrm{ACV} - 0.254 \qquad (10)$$

$$\Delta y = 2.22\ (\Delta x_c{}^{1.5} / \mathrm{Agg}) + 0.030.n.\ \mathrm{ACV} - 0.040 \qquad (11)$$

where:

Δy = relative vertical movement (mm)

Δx_m = crack width using actually measured values in equation 10 (mm)

Δx_c = calculated crack width using equation 9 to calculate crack width (mm)

Agg = nominal size of the 20% biggest particles in the concrete mix (mm)

n = number of load applications actually applied (million E 80's)

ACV = aggregate crushing value, an indication of the strength of the aggregate (larger numbers indicate weaker aggregate)

R^2 values were: 0.57 for equation 10 and 0.37 for equation 11 and Standard Error of the Estimate (SEE) of 0.12 and 0.14 respectively.

The calculated crack widths do not render the same reliable relative vertical movement at the crack under HVS loading (equation 11) as do the measured crack widths (equation 10). Note that the slab thickness, the humidity and the rainfall were not significant (did not contribute to an improved R^2) or the coefficients did not make engineering sense. Accepting that equation 10 depicts the best relationship between relative vertical movement and crack width, a plot of the measured relative vertical movement versus the predicted values can be compiled and is shown in Figure 6 below.

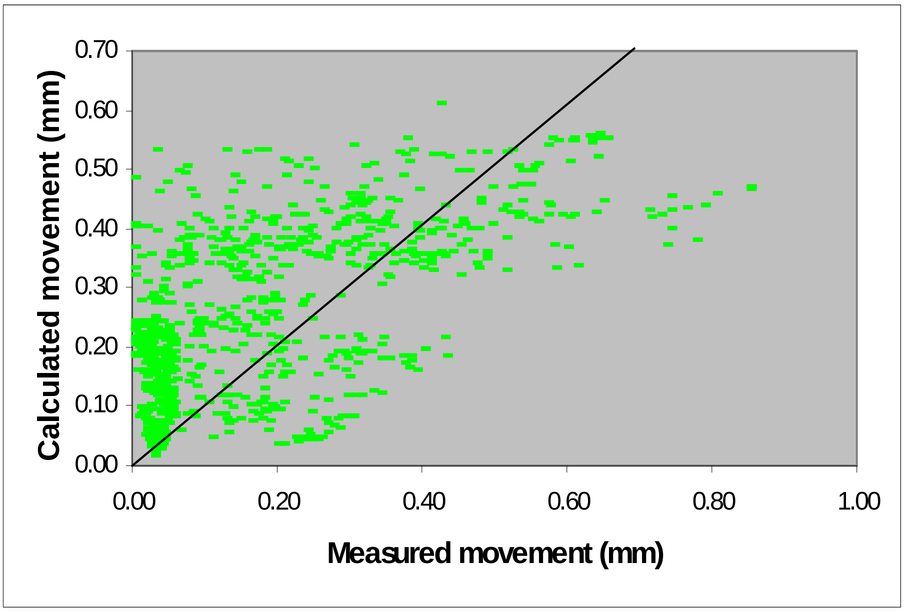

Figure 6. Calculated versus Measured Relative Vertical Movements under 40 kN HVS loading

Relative vertical movement was measured using the FWD equipment on the sections tested by the HVS as well as selected sections on N2 and N3. The loading plate of the FWD was placed on the leave side (down stream of the joint as traffic moves) of the joint and deflections were measured on either side of the joint. It was found that calculated crack widths, traffic loading, strength of the aggregate and bond between slab and subbase showed the following relationship:

$$\Delta y = 7.4\ [\Delta x_c^{1.5}\ /\ Agg\ ] + 0.0015\ .n\ (ACV - 2.5\ Bond) \qquad (12)$$

where: Δx_c = crack widths using equation 9 to calculate crack width

and Bond = bond between concrete and subbase.

Based on 50 data sets the R^2 = 0.67 and SEE = 0.076 for this equation

Using equation 12 to calculate relative vertical movements and comparing them to the measured relative vertical movements renders the plot as shown in Figure 7 below.

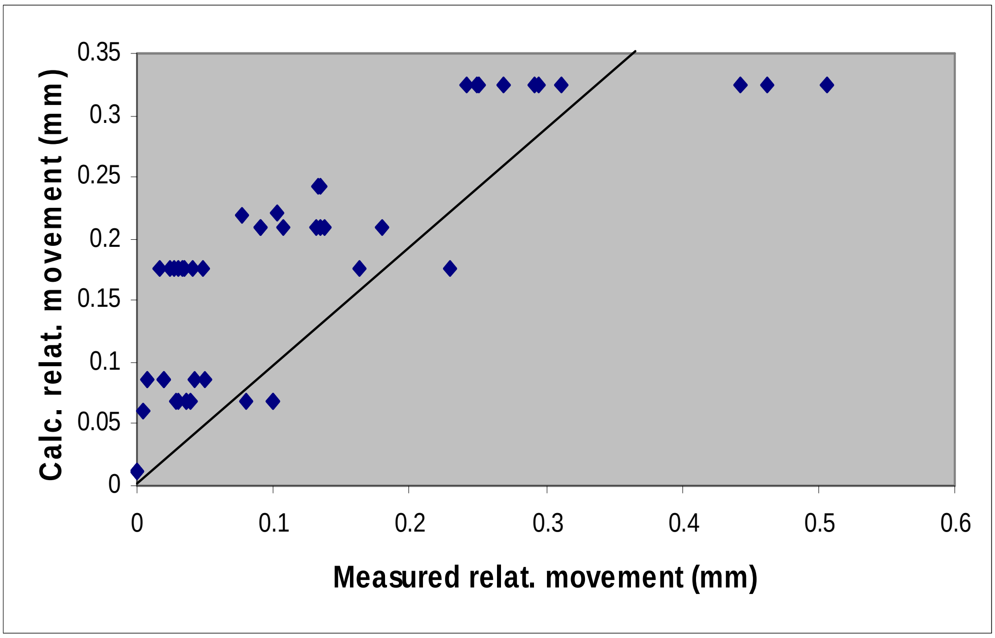

Figure 7. Calculated versus Measured Relative Vertical Movements under FWD loading

In equation 12, bond between slab and support is defined subjectively on a scale of 0 to 10 where 0 implies no bond at all and 10 a perfect bond. In this study it was found that, in cores drilled from N3 where the slab had been placed on asphalt, the concrete had bonded much better than on the cemented subbase used on N2. As a consequence, a value of 8 was assigned for bonding on the asphalt and a value of 2 for the cemented subbase. It is interesting to note that the stiffness of the subbase played a lesser role than the bond between subbase and slab based on the outcome of the regression analysis using the data in the database.

Aggregate interlock. Aggregate interlock is also a function of the roughness of the concrete surface inside a crack. In an attempt to quantify this roughness, the volumetric surface texture ratio (VSTR) was determined by measuring the cracked surface using laser technology and dividing it by the flat area of the sample (Brink 2003). The VSTR of the crack after being trafficked was compared to the sections that had not carried any traffic and was found to be less textured, but the difference was insignificant when different samples were compared.

Dowel action. Steel reinforcement in a CRC or dowels in a dowel-jointed pavement contribute significantly to load transfer at a joint or crack. The basic equation to quantify this phenomenon has been discussed previously and is reflected in equation 3.

Simplification of equation 3 together with regression analyses on data obtained from the HVS, both from the short trial sections at Hilton as well as the CRC inlay on N3-3, resulted in the following equation for the dowel action of steel:

$$\Delta y = 0.4 \text{ Spac } P^{2.0} n^{0.16} / (\text{dia}^{1.75} E^{0.75}) \qquad (13)$$

where: Spac = spacing of steel bars (m)

P = wheel load (kN)

n = number of wheel load applications (million)

dia = diameter of steel bar (mm)

E = stiffness modulus of the concrete surrounding the steel (MPa)

Based on 2223 data sets, the $R^2 = 0.48$ and the SEE = 0.023 for this equation

The basic format of equation 13 is similar to the theoretical equation 3 and the effect of the number of load cycles was statistically determined. Because of this approach, the value of R^2 is relatively low, but the resultant variable $n^{0.16}$ indicates that the number of load cycles needs to be considered when predicting a change in load transfer capability of dowels or steel in the pavement.

Implementation

The original aim of the study was to establish the effect of number of load applications on the deterioration of load transfer at a joint or crack and on the loss of slab support.

All the data from the Hilton experiment and the N3 and N2 was evaluated and used in statistical analyses to enhance the theoretical equations developed for load transfer at joints and cracks, erosion of the slab support system and prediction of the performance of concrete pavements. The more significant findings that can be derived from the study as well as their application in practice, particularly in strengthening the design package cncPave, are the following:

Shrinkage. Shrinkage can be measured under controlled conditions and on small samples in the laboratory using recognized standard methods. However the relevance of accelerated laboratory test results in predicting shrinkage in a pavement is questioned (Badenhorst 2003). An equation was developed to calculate the initial shrinkage using fundamental properties such as water content, cement type, aggregate type, 28-day compressive strength and type of curing. Further shrinkage depends primarily on the age of the concrete and the humidity of the environment in which the slab is performing. The width of the crack in a pavement can then be calculated by combining both shrinkage and thermal behaviour. The calculated crack width was compared with the measured crack width and a final equation was derived through regression analyses. In compiling the equation, it was found that air temperature was a marginally more reliable predictor of thermal movement than concrete surface temperature. Air temperature was therefore used in the rest of the analyses because of the relative ease of measurement.

Crack width. Measuring the crack width has proven to be a difficult operation with variation in results depending on the method of measurement and the position of measurement, whether on the surface or within the slab. Eventually feeler gauges were used to measure the crack width inside a core hole. Because of the difficulties in accurately measuring crack width, the reliability of the predictions (R^2) was not high. The resulting regression equation 9 is therefore based on measuring crack width using a feeler gauge, and the values obtained from using the equation should be interpreted as such.

Figure 8 shows a plot of calculated crack width with time as a function of the more important variables – temperature and humidity. Typical values of temperature and humidity for Upington, a very dry desert area, and Durban, with a sub tropical climate, were used to compile the figure. The joint spacing was assumed to be 4,5m and a mix normally used for concrete pavements was used. The effects of cement type, water content and compressive strength are less important when compared to temperature, age and humidity, and were therefore kept constant in this case.

Equation 9 has been implemented in the design program cncPave to calculate crack width. Instead of using shrinkage values of mixes determined in the laboratory, the accuracy of which is now being questioned, variables such as the water content and the amount of paste as well as the strength of the mix, which are better known to the designer, can be used to predict crack width. Furthermore the change in both temperature and humidity with time can now also be introduced to increase the reliability of the predictions of pavement behaviour.

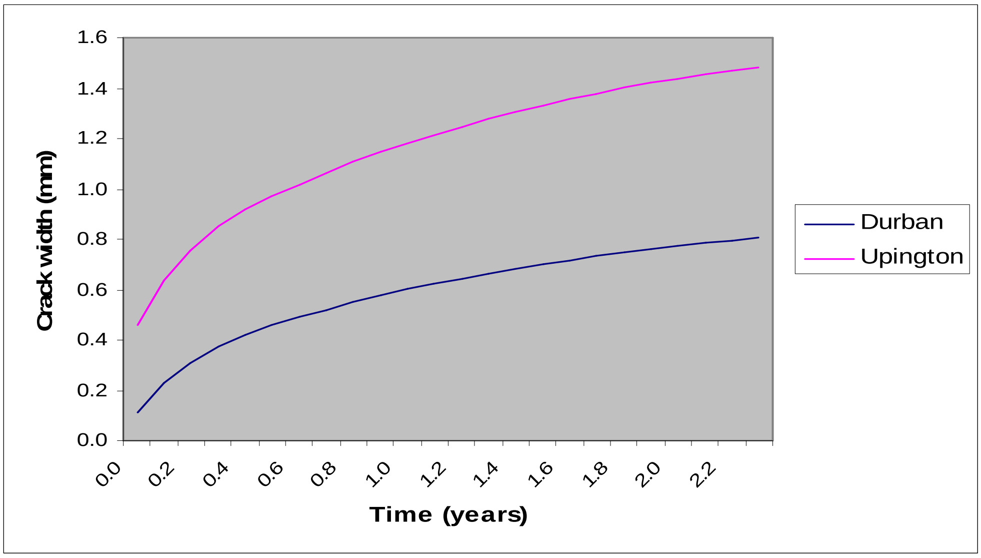

Figure 8. Crack width as a function of time for different climates

Aggregate Interlock. Load transfer is a function of aggregate interlock and the dowel action of steel bars where they are used in the pavement. Aggregate interlock is a function of crack/joint width, aggregate shape and size as well as the strength of the aggregate itself. In the case of dowel action of steel bars in the pavement, the strength of concrete around the steel and the size of the steel bars are important. The wear or abrasion with loading and time has been established in this study both for the aggregate as well as for the concrete around the steel.

Abrasion of the aggregate depends on its Aggregate Crushing Value (ACV) and the number of load applications. It is a linear relationship and the coefficient has been found to differ depending on whether relative vertical movement was measured under HVS loading or the FWD. In all the equations relating relative vertical movement to crack width, number of load applications, ACV and other variables, the R^2 values were found to be relatively low. The reasons for this include:

- The equations were forced into a format dictated by the theoretically derived equations discussed earlier
- Variables that are relatively easy to measure were given priority in the regression process. The reason for this being that the outcome of this study needed to be of use in practice and those variables that cannot be measured or estimated easily would only render equations of academic interest.

- Visual observations during the HVS testing raised some questions as to the effect of moisture on joint movement especially when it was observed that a reduction in movement occurred after “slush” from pumping of the subbase seemed to have “frozen up” the joint. This, however, could not be quantified adequately and it was found that in the regression analysis, rainfall did not play a significant role but that humidity was a more important variable. However, it was still not important enough to make a difference to the reliability of the equations. Humidity was however a significant contributor to predicting crack width and as such was included as a variable. Because of a high correlation between humidity and rainfall, and with humidity contributing more significantly to the reliability of the equations, rainfall was excluded.

- The measured and/or calculated crack width had a significant effect on the prediction of relative movement. However the accuracy with which the crack width could be measured was low. Surface measurements using a microscope resulted in wider crack widths than those determined deeper into the slab. The latter were measured using a feeler gauge, but again the success of these measurements depended on the roughness and shape at the point of measurement of the crack and thus the ability to insert the feeler gauge.

- Not only is aggregate size playing a role in load transfer, but the shape of the aggregate particles as well as the roughness inside the crack influence load transfer. The roughness of the concrete inside the crack was determined and expressed as the volumetric surface texture (VST). The VST of the crack after being trafficked was compared to the untrafficked sections and found less textured. However the difference was statistically insignificant and the measured values were not used.

The coefficient for the $\Delta x/Agg$ variable varies from 2.0 to 8.4 for FWD- and HVS-measured vertical movements respectively, with a realistic average value of 8 for calculated crack widths. However the coefficient for the variable *n.ACV* varies significantly for the different equations 10 to 12, from 0.0015 to 0.032. The coefficient was of the order of 0.0015 for the FWD-measured data and 0.032 for the HVS-measured data. The reason for this large variation can only be speculated on:

- The HVS load, which contributes to an increase in relative vertical movement with time, was applied systematically in one position. The loads under real traffic however, wander significantly across the width of the pavement and their contribution to damage is therefore smaller. If it is assumed that 30% of the weigh-in-motion (WIM) estimated E80’s on the N3 and N2 crossed the joint where FWD measurements were taken, the coefficient for *n.ACV* increases to 0.007 instead of the 0.0015 obtained in equation 12 indicating the merit of this approach.

- The HVS load applications applied could be determined much more accurately.

- The conversion of the number of loads to E80's using a damage coefficient of 4.2 is not realistic for *n.ACV*

- The number of load applications applied at the HVS test was limited to 0.75 million, but for the real-life traffic of the N3 and N2 it was as high as 12 million. If the latter traffic figure is used in the equations developed from the HVS data, unrealistic values of more than 10mm relative vertical movements are obtained. The use of a limited database, as was the case for HVS testing, to derive an equation from regression analyses can be misleading if the equation is used to predict movements beyond the limits of the database.

In view of the discussion above, it is recommended that equation 12, developed from FWD data, be used in design procedures. Although equation 11, developed from HVS data rendered a very similar equation, equation 12 is preferred because of a higher level of significance, a more realistic coefficient for the influence of traffic and the inclusion of bond between slab and subbase. Figure 9 shows the results of a plot of relative vertical movement as a function of time for a concrete pavement in a dry hot climate.

Equation 12 was used to calculate relative vertical movement at a joint as a function of time, taking into account traffic loading, the ACV of the stone and the bond between the subbase and the slab. The three cases that were considered and which are shown in Figure 9, are the following:

1. a traffic load of 20 million E80's using a stone with an ACV of 25 and with very little bond between subbase and slab,

2. a traffic load of 20 million E80's using a stone with an ACV of 25 and with high bond between subbase and slab.

3. a traffic load of 5 million E80's using a stone with an ACV of 15 and with very little bond between subbase and slab,

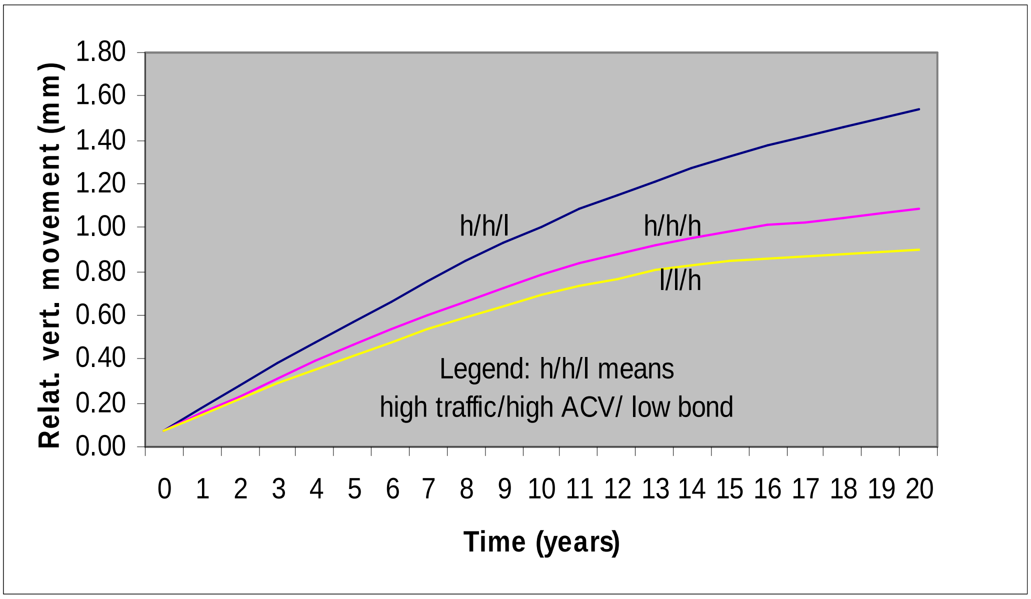

Figure 9. Calculated relative vertical movement as a function of time, traffic loading, ACV of the aggregate and bond between subbase and slab in a dry, hot climate

Important conclusions from this part of the study can be summarized as follows:

- Crack width is an important parameter in the success of load transfer at a crack or joint
- The bonding between subbase and slab was more important than the stiffness of the subbase. This finding should be seen in the context of the limited data available in this study. Theoretically the stiffness of the subbase will play a significant role if high bond exists between these two layers. However, in this study it was found that on the N2 the bond between the cement stabilized subbase and the jointed pavement, particularly in the vicinity of the joints, was limited.

Equation 13 presents the outcome of the change in relative vertical movement with increased loading for a dowelled jointed pavement. Unfortunately the stiffness of the concrete was virtually the same for all the sections and the coefficients for stiffness E in equation 13 came from the theoretical equation 3. Similarly the coefficient for number of loads n has a value of 0.16 instead of being a function of E as would be expected. Replacing 0.16 with a value of 7000/E where concrete stiffness E is in MPa, the equation 13 becomes:

$$\Delta y = 0.4 \text{ Spac } P^{2.0} n^{7000/E} / (\text{dia}^{1.75} E^{0.75}) \qquad (14)$$

Fig 10 shows a plot of equation 14 with some typical values for concrete stiffness and dowel diameter.

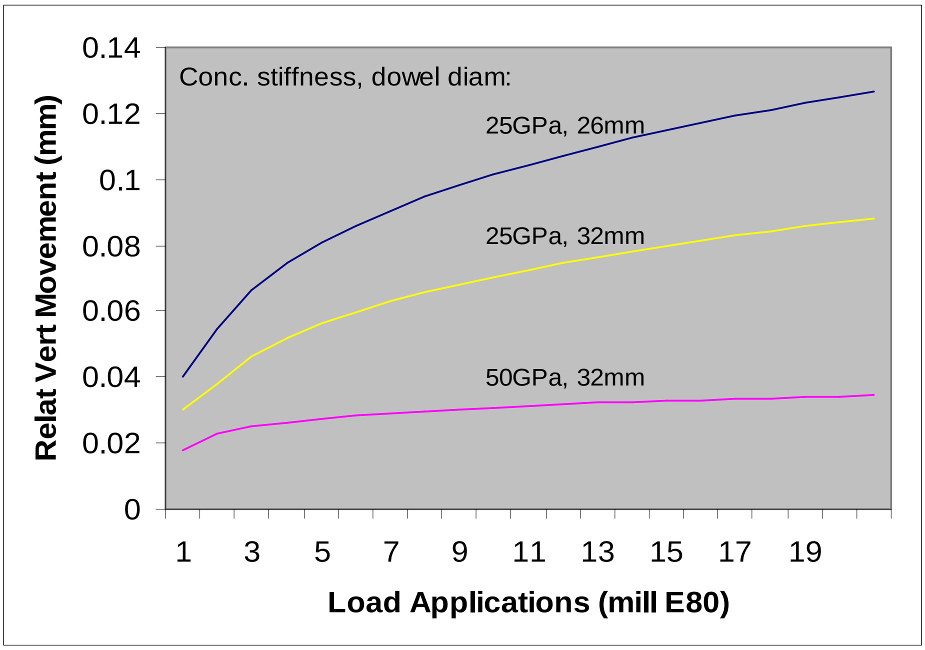

Figure 10. Relative movement at the joint of a dowelled pavement

Figure 10 shows that relative vertical movement (and thus load transfer at a dowelled joint) depends to a great extent on bar diameter, stiffness of the concrete and the number of load applications

Conclusions

Short sections of jointed unreinforced concrete pavement were constructed near Hilton, adjacent to the N3, to establish the effect of different aggregate types and dowels on the performance of joints under HVS loading. A section of the N3 was also tested using the HVS to establish the remaining life of a CRCP inlay. In order to expand these results to include other sections of road with a longer history of actual traffic loading, limited testing, including FWD, was also carried out on other sections of the N2 and N3. The test sections generally performed better than predicted and more load applications were necessary to arrive at the distress than was planned for. Because of financial restraints, this reduced the number of sections that could be tested and thus the data that could be collected. Other factors also had an influence on the final outcome of the study, the most important being:

- Pavement behaviour was monitored in great detail and an extensive database has been established. However due to environmental (predominantly rainfall and temperature) and other influences outside the control of operators, scatter of data was wide and influenced the reliability of the predictive equations derived from regression analyses

- In order to be able to use the resulting equations in environments outside those experienced on the selected sections, regression equations were forced to follow theoretical formats. This also added to the reduced reliability (using R^2).

Despite the above-mentioned constraints, very useful results were obtained – the most important being confirmation that structural failure is associated with poorly performing joints or cracks. The following specific conclusions, pertaining primarily to the load transfer efficiency of joints and cracks, have been arrived at:

- The hardness of aggregate plays an important role in the long term load transfer efficiency of a joint or crack; aggregate with a lower ACV is preferred for better long term performance

- Crack width is however the most important parameter in the load-transfer efficiency of a joint or crack. Crack width is in turn affected by the shrinkage characteristics of the concrete as well as by environmental factors such as the variation in temperature and relative humidity. High concrete shrinkage, substantial temperature variations, and a low relative humidity are detrimental to the performance of jointed concrete pavements

- The bond between the concrete slab and the subbase directly below the slab has a significant influence on the behaviour, and thus the structural performance, of the pavement. High bond was found wherever asphalt was used as the subbase. Where bond was lost because of erosion of the subbase, which was the case where the subbase consisted of gravel, the pavement showed distress.

Finally, the information gleaned from HVS testing, together with FWD testing of adjoining sections, has provided useful insight into the structural performance of concrete pavements. This information, together with the models developed, will be implemented in the design procedures and specifically in the upgrading of the cncPave design program.

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References

Badenhorst S, A Critical review of concrete drying shrinkage, test methods, factors influencing it and shrinkage prediction*, MSc project report*, University of the Witwatersrand, Johannesburg, July 2003

Brink, A.C. 2003. Modelling Aggregate Interlock Load Transfer at Concrete Pavement Joints. *PhD thesis*. University of Pretoria, 2003

Brink, A.C. Construction Report: HVS Testing of the Concrete Test Section on the N3 near Hilton, *Report CR-200/33*, CSIR-Transportek, July 2004

Brink, A.C. du Plessis, L First Level Analysis Report: HVS Testing of the Concrete Test Section on the N3 Section on the N3 near Hilton: Tests 424A5, *Report CR-200/70*, CSIR-Transportek, September 2004

Concrete Pavement Design Manual: Joint Behaviour, *Research Report 215/88*, National Transportation Commission, South Africa, 1990

RILEM Committee TC 107 GSC, Guidelines for the formulation of creep and shrinkage models, Vol 28, no 180, July 1995, pp 357-365

Strauss, P.J., Slavik, M. and Perrie, B.D. A Mechanistically and Risk Based Design Method for Concrete Pavements in Southern Africa, *Proceedings of the 7th International Conference on Concrete Pavements,* Orlando, Florida. September 2001.

Strauss, P.J., Slavik, M. and Perrie, B.D. Life cycle costing and reliability concepts in concrete pavement design: the South African approach, *Proceedings of the 9th International Symposium on Concrete Roads*, Istanbul, Turkey. April 2004.

Troxell G.E., Long time creep and shrinkage of plain and reinforced concrete, *Proceedings American Society for Testing Materials*, Vol. 58, 1958

Walraven J.C. Fundamental Analysis of Aggregate Interlock, *Journal Structural Division*. ASCE, Vol 107, No ST11, 1981.

Yoder E.J. and Witczak M.W., Principles of Pavement Design, *John Wiley,* New York, 1975