RESULTS OF PILOT STUDY INVESTIGATION INTO AGGREGATE INTERLOCK LOAD TRANSFER EFFICIENCY AT JOINTS IN CONCRETE PAVEMENTS

A C HANEKOM, E HORAK* and A T VISSER*

Ph.D. Candidate (UP), BKS (Pty) Ltd., PO Box 3173, Pretoria, 0001
Tel.: (012) 421 3500, e-mail: annach@bks.co.za

*Department of Civil Engineering, Faculty of Engineering, Built Environment, and Information Technology, University of Pretoria, Pretoria, 0002
Tel.: (012) 420 2429/3168, e-mail: ehorak/avisser@postino.up.ac.za

ABSTRACT

This paper presents a limited aspect of an investigation into existing methods for modelling aggregate interlock shear transfer in jointed concrete pavements in order to determine a fundamental model reflecting variations in joint load transfer with joint opening, load magnitude, subbase characteristics, and concrete properties. It presents the evaluation of the results of the investigation into deflection load transfer efficiency due to aggregate interlock across a joint in a 35 MPa concrete slab with 19 mm granite aggregate, subjected to simulated 20 kN dynamic wheel loads. The test set-up and methodology used to obtain relevant load, deflection and temperature data are described, together with an analysis of data and comparison with results obtained from analytical formulae and/or modelling with existing finite element method (FEM) software.

1 BACKGROUND AND INTRODUCTION

The South African National Roads Agency Limited and the Cement and Concrete Institute organised a task force during 1998 and provided funding to upgrade the South African Concrete Pavement Design and Construction Manual M10, to a concrete pavement design manual based on mechanistic design principles. In the upgrading process a re-evaluation of factors affecting riding quality, structural service life, maintenance and rehabilitation needs re-confirmed the prominent effect of joint performance. It was identified that insufficient information was available to model the mechanism of concrete joints in shear (aggregate interlock), and to establish the life cycle from the “bonded” to “failed” state. Further research was needed, which resulted in the study whose preliminary results are presented in this paper.

A main objective of the study was to investigate the applicability of existing methods for modelling aggregate interlock shear transfer efficiency in order to determine a fundamental model simulating variations in joint load transfer efficiency with joint opening, load magnitude, subbase characteristics, and concrete properties. Furthermore, to show the significant difference in pavement response to static, and moving impulse or dynamic loads (equivalent to traffic loads) in terms of deflections in the pavement.

The aim of the paper is to present a limited aspect of an overall study, namely, the evaluation of the results of the investigation into deflection load transfer efficiency due to aggregate interlock across a joint in a 35 MPa concrete slab with 19 mm granite aggregate, subjected to simulated 20 kN dynamic wheel loads. The test set-up and methodology used to obtain relevant load, deflection and temperature data are described, together with analysis of data and comparison with results obtained from analytical formulae and modelling with finite element method (FEM) software already developed (Davids et al, 1998).

2 PREVIOUS RESEARCH

The primary purpose of transverse contraction joints, formed by saw-cutting $^1/_4$ to $^1/_3$ of the pavement thickness, is to relieve tensile stresses induced by shrinkage during curing of the concrete, and due to temperature and moisture changes in service. The saw-cut forces a crack to occur at the joint through the pavement thickness. In un-doweled pavements aggregate interlock is the main load transfer mechanism at transverse joints.

Deflection load transfer efficiency (LTE_δ) is defined as the ratio of the deflection of the unloaded slab (Δ_U) to the deflection of the loaded slab (Δ_L) as follows:

$$LTE_\delta = \Delta_U/\Delta_L \qquad (1)$$

Load transfer efficiency at the joint can vary with concrete pavement temperature, age, moisture content, construction quality, magnitude and repetition of load and type of joint (Hammons and Ioannides, 1996). As mentioned above, the main objective of the study is to model the aggregate interlock shear transfer efficiency at the different crack widths that would normally be induced by these factors.

Research by Walraven (1981) into the more general problem of shear transfer across discrete cracks in concrete has shown the mechanics of aggregate interlock shear transfer to be highly complex. In addition to contact between sharp edges of aggregates on joint surfaces, there may be localised crushing of both the cement paste and the aggregate, as well as entry of loose materials. The amount of crushing and the bearing area of the surfaces depends on the joint opening, normal restraint of the joint, the strength of the concrete (both the paste and the aggregate), and the size and distribution of the aggregate particles. Modelling aggregate interlock shear transfer in rigid pavements should take all these factors into account. Cumulative damage to the joint due to cyclic loading reduces the ability of the joint to transfer shear. Walraven (1994) used the principle that two distinct materials represent concrete: hardened cement paste and a collection of embedded aggregate particles. The cement paste is modelled in terms of a rigid-plastic stress-strain law, while the aggregate particles are treated as incompressible.

More recent research by Davids et al (1998) incorporated the aggregate interlock model developed by Walraven (1981) in the development of the three-dimensional computer program EverFE. He used a 16-noded isoparametric joint element to incorporate the crack constitutive relations in the finite element models, permitting the effects of joint opening and concrete properties to be captured.

Davids et al (1998) admitted that field validation of his mostly theoretical models were still required. Further research was therefore required into especially the aggregate types used in South Africa, before applying EverFE with confidence.

3 TEST METHODOLOGY

In order to make a contribution to the current state of knowledge a testing method had to be developed that simulates real life conditions. One of the most common methods used in practice to determine deflection load transfer efficiency at a joint in a concrete pavement, is by using a falling weight deflectometer (FWD). With the FWD a static impulse load is applied to the pavement, by dropping a load onto the pavement on the one side of a joint, and measuring the deflection at both sides. The deflection load transfer efficiency is then calculated using equation 1. In practice, however, the loads applied to a pavement are not static, but dynamic. During mobilisation of the experiments it therefore became clear that the response of the pavement had to be specifically captured under dynamic loading, but under static loading as well to be able to compare the results.

The dynamic response of a pavement is fundamentally a function of the inertia and damping characteristics of the structure (Huang, 1993). These characteristics generally invalidate attempts to approach the problem with static or quasi-static analyses and experiments. In a study by Lourens (1991) the equation for motion was implemented in a finite element method:

$$\{F\} = [K]\{u\} + [C]\{\dot{u}\} + [M]\{\ddot{u}\} \tag{2}$$

Where:

{F}	=	Vector of nodal point forces;
[K]	=	Stiffness matrix;
{u}	=	Vector of nodal point displacements;
[C]	=	Damping matrix;
{u̇}	=	Vector of nodal point velocities;
[M]	=	Mass matrix; and
{ü}	=	Vector of nodal point accelerations.

The last two quantities in equation 2 are exclusive to dynamic analyses and need some clarification. The term [C] is necessary to dampen the induced movement, as an un-dampened system will oscillate up to infinity in time after acceleration. Damping therefore defines the loss of energy due to friction and other effects. The mass term [M] and acceleration {ü} is Newton's Second Law of Motion, and can be viewed as the inertial effect or "resistance to movement" which is experienced when an attempt is made to accelerate an object.

Measurements on pavements and vehicles have shown that the frequency of dynamic loads at a discontinuity in a pavement stay more or less constant at about 3 Hz, and is not affected to a large extent by the speed of the vehicle (Papagiannakis et al, 1988; Sousa et al, 1988). The forces developed by the vehicles vary according to a host of factors, the most important being the road roughness and suspension type, although contradicting results have been reported on this aspect. The dynamic forces were nearly always substantially higher than the static forces (Papagiannakis et al, 1988; Sousa et al, 1988), and measured forces of up to 150% of the static values have been reported (Bergan and Papagiannakis, 1984).

An impulse force that simulates the impact of one wheel (20 kN) of a standard 80 kN dual wheel axle load, crossing a joint/crack at 80 km/h had to be developed. This was achieved by using two actuators. The first actuator had to apply a maximum load of 20 kN within 0,11 seconds, and revert back to zero in 0,01 seconds. In this same 0,01 second interval that the first actuator reverted back to zero, the second actuator had to move from zero load to 20 kN load. The two waveforms thus created had a total duration of 0,12 seconds each, with a rest period of 0,11 seconds (corresponding to approximately 3 Hz), as shown in Figure 1.

Measuring the applied loads, as well as the deflections induced during dynamic loading necessitated accurate measuring equipment. The deflection measuring devices, especially had to be accurate to at least 0,1 µm, as the difference in the deflections at different crack widths was expected to be approximately 0,1 µm.

4 PILOT STUDY

4.1 Background

Aspects of the experimental work that had to be sorted out in a pilot study involved the following:

a. Make up of the shutters/mould in order to obtain the most practical method of moving the concrete beam and rubber to the test floor, without damaging/moving the pre-formed joint;
b. The number of compressive strength cubes, flexural beams, shrinkage beams and E-modulus cylinders that would be required for each experiment, as well as the time of testing for each;
c. The most practical method of casting the thermocouples into the concrete, without damaging them, and obtaining relevant temperature data;
d. The type of crack inducer to be placed at the bottom of the concrete slab, as well as the method of forming the crack;
e. The optimum positions for placing deflection measuring devices, and the number required;
f. The optimum positions for reference points to monitor crack/joint width;
g. The testing frequency and period of testing; and
h. The number of data cycles to be saved to file for analysis and conclusions.

4.2 Test Set-up

The beam was cast on approximately 55 mm thick rubber to simulate a dense liquid Winkler foundation and provide a uniform subgrade with continuous support. When tested in a California Bearing Ratio (CBR) press to determine the equivalent bearing capacity of the rubber, it was measured as 24. This is equivalent to a selected gravel layer with a resilient modulus of approximately 150 MPa (Theyse et al, 1996) and a k-modulus of 80 MPa/m. The beam was 1 800 mm long, 600 mm wide, and 230 mm thick. The rubber and shuttering were placed on a timber pack (2 800 mm long, 700 mm wide, and 140 mm thick), where after the concrete beam was cast. The timber pack had to render a sound base for transporting the beam from the position where it was cast to where it was tested. A crack inducer in the form of an angle iron was put across the beam at mid-length on the rubber foundation. The crack/joint had to be formed within 24 hours after casting the concrete. A 50 mm deep incision was cut into the concrete surface with a grinder (vertically above the angle iron), where after the desired crack was formed. A schematic layout of the test set-up is given in Figure 2.

4.3 Material Tests

The beam was cast, using 19 mm granite aggregate, and CEM I 42,5 cement. To ensure that a 28-day compressive strength of 35 MPa would be obtained with the materials used, test cubes were made up beforehand, using water/cement ratios of 0,59 and 0,63. The test cubes were crushed after 7 days, and the 28-day strengths were calculated from the assumption that the 7-day compressive strength is approximately two-thirds that of the 28-day compressive strength (Fulton, 1994). The average 7-day compressive strength values obtained for water/cement ratios of 0,59 and 0,63 were 21,5 MPa and 20,5 MPa, respectively, which indicated that the corresponding 28-day compressive strength would be 32,5 MPa and 30,5 MPa. From these results it was determined that a water/cement ratio of 0,56 should be used to obtain a 28-day compressive strength of 35 MPa. The actual strengths obtained were 38,7 MPa and 30,0 MPa for the water-cured cubes and the air-cured cubes, respectively.

A total of 15 data channels were recorded continuously on a computer, using KWS, and HBM Spider-8, amplifiers, namely:

- 2 Load cells
- 2 Actuators
- 1 Actuator deflection
- 5 Linear Variable Displacement Transducers
- 2 Strain Displacement Transducers
- 3 Thermocouples

Apart from the beam, a number of cubes, beams and cylinders were also cast for testing purposes, as summarised in Table 1.

Table 1: Basic information on cubes, beams and cylinders cast for testing purposes

Test specimen	Dimensions (mm)	Number	Time of test
Compressive strength cubes (SABS test method 863: 1994)	150 x 150 x 150	18	At 7 and 28 days after casting beam, and at end of 2 million load cycles
Modulus of rupture beams (SABS test method 864: 1994)	750 x 150 x 150	6	At 28 days after casting beam, and at end of 2 million load cycles
Shrinkage beams (SABS test method 1085: 1994)	300 x 100 x 100	4	Measure gauge length L_0 before casting specimen, and L_1 after 7 days in curing bath. Place in drying oven with temperature 50°C, and relative humidity 25%, and measure L_2 at 48 hour intervals there after, until difference in length less than 2µm/100 mm.
Modulus of elasticity cylinders (BS1881: Part 121: 1993)	300 x 150 diameter	3	At 28 days after casting

4.4 Test Procedure

The thermocouples were read every 30 minutes. All other data channels were logged continuously during the dynamic loading process. This created a large data file. In order to save file space only data from 2 load cycles at 1-minute intervals were saved to file for analysis purposes.

The beam was subjected to 2 million dynamic load applications. After every 0,5 million load applications, static loading tests were also carried out, and the data analysed to determine general trends. The equipment was also calibrated at this time. After completion of the dynamic loading the crack was pulled apart horizontally to measure responses under static and dynamic loading at different crack widths.

While applying the dynamic loads, the crack width was continuously monitored. Although the relative horizontal movement at the crack increased, the actual crack width stayed at 0,1 mm, even after completion of the 2 million dynamic load applications. Therefore, before pulling the beam apart at the crack, the ends of the beam were pressed down by inserting jacks beneath the steel frame holding the actuators. This was done in order to break the aggregate interlock bond that still existed, to be able to pull the two slabs apart

4.5 Analysis Of Data

Although the primary aim of the pilot study was to test each aspect of the overall handling of the experiments, it was imperative that the data recorded was relevant.

Figure 3 presents a typical plot of the deflection data obtained for 1,5 to 2 million load cycles. There was no significant deterioration of the crack up to 2 million dynamic load cycles, which indicated that fatigue of the aggregates at the joint face did not play a role in this instance. This can be attributed to the high quality of the crushed stone used in South Africa. This conclusion will be tested in the follow-up study that will be conducted under similar conditions, but using 37,5 mm crushed granite aggregate, instead of 19 mm aggregate. The further implication of this, is that it will not be necessary to allow so much time (18 days in this instance) for dynamic load testing at the initial crack width, but that the testing at different crack widths could commence as soon as the test set-up is complete. Other factors that have to be borne in mind, are that testing was conducted inside a laboratory building, and that the beam was not subjected to normal day-night temperature variations, nor exposed to rain, and other environmental effects detrimental to a joint in a concrete pavement.

Although the horizontal displacement at the crack increased from 0,017 to 0,040 mm during dynamic loading, the actual crack width stayed the same, even after 2 million load cycles. The concrete compressive strength was 50,0 MPa and 36,7 MPa for the water-cured cubes, and air-cured cubes, respectively, by then 66 days after casting.

The increase in deflection with increasing crack width for both dynamic and static loading, obtained during the study, is shown in Figure 4. From this figure it is obvious that at small crack widths, the repeated dynamic loads caused the beam to stay in a deflected state with deflections higher than under static loading. The dynamic loading line crossed the static loading line at a crack width of between 1,0 and 1,1 mm. At this crack width the two slabs started to react independent of each other, resulting in higher deflections under static loading than dynamic loading.

The deflection load transfer efficiency at different crack widths was calculated directly from the deflection measurements for both dynamic and static loading, and is shown in Figure 5.

At 2,5 mm crack width the deflection load transfer efficiency was 94,2% and 88,8% for dynamic and static loading, respectively. This showed that shear forces across the crack were still active. Moment and inertia in the slab contributed to the greater load transfer efficiency under dynamic loading, than under static loading.

4.6 Comparison With Published Results

EverFE (Davids et al, 1998) was used to perform theoretical analyses. A maximum crack width of 2,5 mm was considered as most of the theoretical analyses showed no significant change in results after this point. For this reason, experimental results during the pilot study were only obtained up to a maximum crack width of 2,5 mm.

A model consisting of the same geometry, material properties, loading, and aggregate interlock parameters as the pilot study was tested with EverFE. The results are also plotted on Figures 4 and 5. As for deflection, EverFE predicted an initial deflection value very similar to that measured under dynamic loading, but the EverFE deflection values dramatically decreased after a crack width of 0,5 mm, to a constant value far less than what was measured in the laboratory. The load transfer efficiency was also considerably lower than what was calculated from the laboratory results. It is suspected that the main difference in results may be attributed to the fact that the crack in the concrete could not reflect into the rubber. The rubber therefore still provided a continuous support. In practice a stabilised subbase beneath the concrete would also be cracked, contributing to a decrease in load transfer efficiency.

In an attempt to establish a method of quantifying the decrease in load transfer efficiency with an increase in crack width, and to provide an estimate of the abrasion that has taken place since fracture, Vandenbossche (1999) developed a volumetric surface texture (VST) test at the University of Minnesota. The test apparatus consisted of a spring-loaded probe with a digital readout, mounted on a frame over a computer-controlled microscope of the type typically used to obtain linear traverse and other measurements of concrete air void systems.

The CSIR in Pretoria has developed a similar apparatus, using lasers. The volumetric surface texture ratio (VSTR) determined on the face of the crack formed during determination of the modulus of rupture of a test beam (referred to in Table 1) from the pilot study was 0,32 cm^3/cm^2. This value was higher than the results published by Vandenbossche (1999), and reproduced in Figure 6. The graph is based on VSTR measurements made with cores from 16 different doweled joints (the joints considered in this study are aggregate interlock joints). For comparison purposes, the VSTR of the "weathered" crack face on a section from the pilot study test beam will also be determined.

5 CONCLUSIONS

Results published in this paper are preliminary, and need to be confirmed with follow-up experiments. The following preliminary conclusions could however be made from the study:

a. There was no significant deterioration of the crack up to 2 million dynamic load cycles, which indicated that fatigue of the aggregates at the joint face does not play a role. This can be attributed to the high quality of the crushed stone used in South Africa;
b. At small crack widths, repeated dynamic loads caused the beam to stay in a deflected state with deflections higher than under static loading. The dynamic loading line crossed the static loading line at a crack width of between 1,0 and 1,1 mm. At this crack width the two slabs started to react independent of each other, resulting in higher deflections under static loading than dynamic loading;
c. EverFE predicted an initial deflection value very similar to that measured under dynamic loading, but the EverFE deflection values dramatically decreased after a crack width of 0,5 mm, to a constant value far less than what was measured in the laboratory. The load transfer efficiency was also considerably lower than what was calculated from the laboratory results; and
d. Moment and inertia in the slab contributed to the greater load transfer efficiency under dynamic loading, than under static loading.

Trends observed in the data, followed intuition, and considering all the different aspects that had to be sorted out during the pilot study, the end-result was a great success. Preliminary findings are promising, paving the way for further investigations.

6 REFERENCES

British Standard. Test Method for Determination of Static Modulus of Elasticity in Compression. BS1881: Part 121: 1993.

Bergan, A.T. and Papagiannakis, A.T. 1984. Axle and Suspension Systems of Heavy Trucks for Minimizing Pavement Distress. *Fourth Conference on Asphalt Pavements for Southern Africa*, Vol. 1, March, pp. 177-200.

Davids, W.G. Turkiyyah, G.M. and Mahoney, J.P. 1998. *Modeling of Rigid Pavements: Joint Shear Transfer Mechanisms and Finite Element Solution Strategies.* Washington State Department of Transportation. Washington State Transportation Commission Planning and Programming Service Center in Cooperation with the US Department of Transportation Federal Highway Administration. WA-RD 455.1.

Fulton, F.S. 1994. *Fulton's Concrete Technology*. 7th revised ed. Portland Cement Institute, Midrand, South Africa.

Hammons, M.I. and Ioannides, A.M. 1996. Developments in Rigid Pavement Response Modelling. US Army Corps of Engineers. Waterways Experiment Station. Technical Report GL-96-15. Washington D.C.

Huang, Y.H. 1993. *Pavement Analysis and Design*. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Lourens, J.P. 1991. *Nonlinear Dynamic Analysis and Design of Road Pavements.* South African Roads Board. Research and Development Advisory Committee. Project Report PR 90/030/2. Pretoria.

Papagiannakis, T. Haas, R.C.G. Woodroffe, J.H.F. and Leblanc, P.A. 1988. Effects of Dynamic Loads on Flexible Pavements. *Transportation Research Record*. No 1207, TRB National Research Council, National Academy Press, Washington D.C., pp. 187-196.

Sousa, J.B. Lysmer, J. Chen, S. and Monismith, C.L. 1988. Effects of Dynamic Loads on Performance of Asphalt Concrete Pavements. *Transportation Research Record*. No 1207, TRB National Research Council, National Academy Press, Washington D.C., pp. 145-168.

South African Bureau of Standards. Standard Test Method for Compressive Strength of Hardened Concrete. SABS 863 - 1994.

South African Bureau of Standards. Standard Test Method for Flexural Strength of Hardened Concrete. SABS 864 – 1994.

South African Bureau of Standards. Standard Test Method for Initial Drying Shrinkage and Wetting Expansion of Concrete. SABS 1085 – 1994.

Theyse, H.L. De Beer, M. Rust, F.C. 1996. *Overview of the South African Mechanistic Pavement Design Analysis Method.* CSIR, Divisional Publication DP-96/005, March.

Vandenbossche, J.M. 1999. Estimating Potential Aggregate Interlock Load Transfer Based on Measurements of Volumetric Surface Texture of Fracture Plane. *Transportation Research Record*. No 1673, TRB National Research Council, National Academy Press, Washington D.C., pp. 59-63.

Walraven, J.C. 1981. Fundamental Analysis of Aggregate Interlock. *Journal of the Structural Division*, ASCE, Vol. 107, No ST11, pp. 2245-2270.

Walraven, J.C. 1994. Rough Cracks Subjected to Earthquake Loading. *Journal of Structural Engineering,* Vol. 120, No 5, pp. 1510-1524.

FIGURES

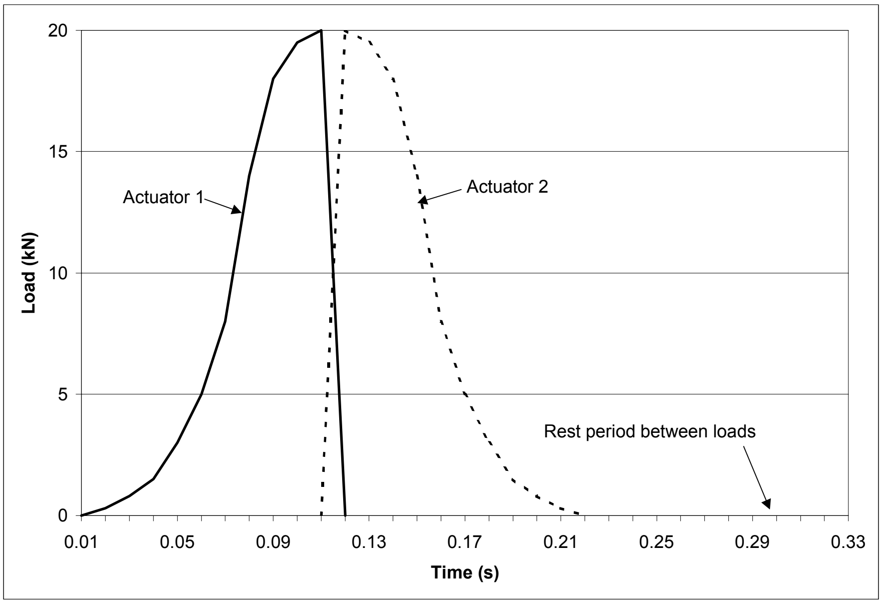

Figure 1: Typical load waveforms for dynamic loading

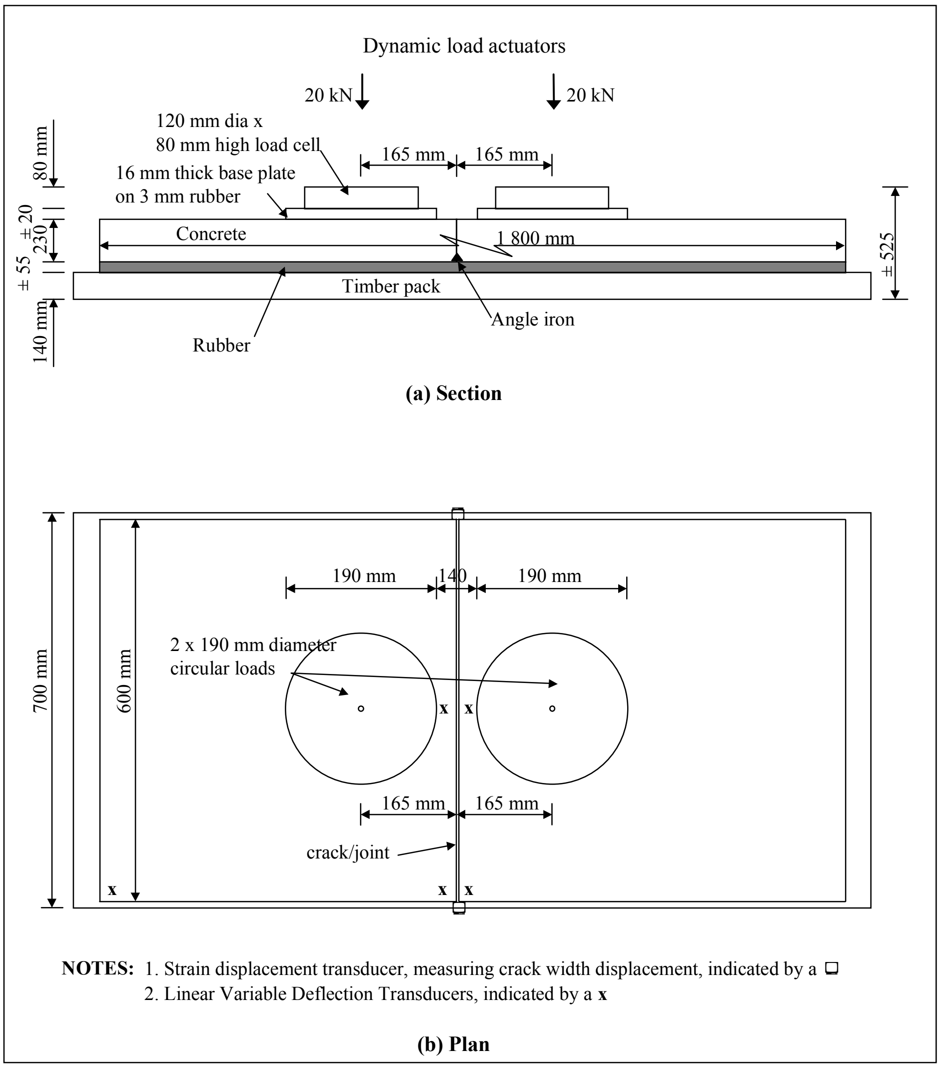

Figure 2: Schematic layout of test set-up for pilot study

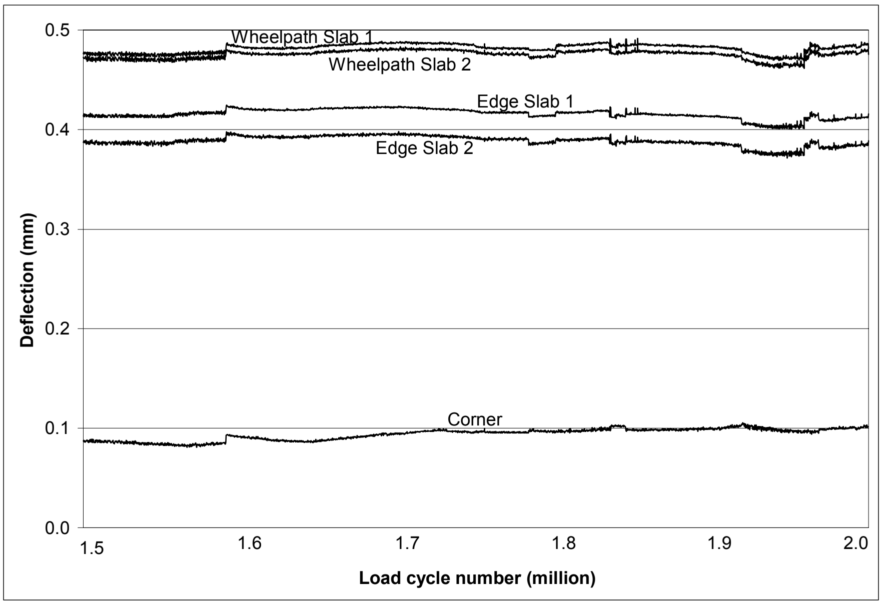

Figure 3: Deflection measurements – 1,5 to 2 million dynamic load cycles at 0,1 mm crack width

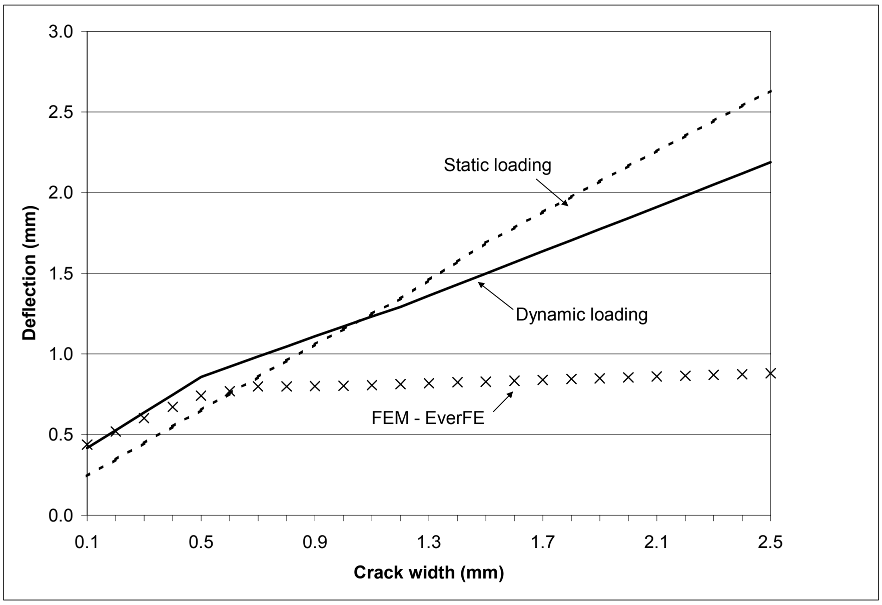

Figure 4: Deflection versus crack width

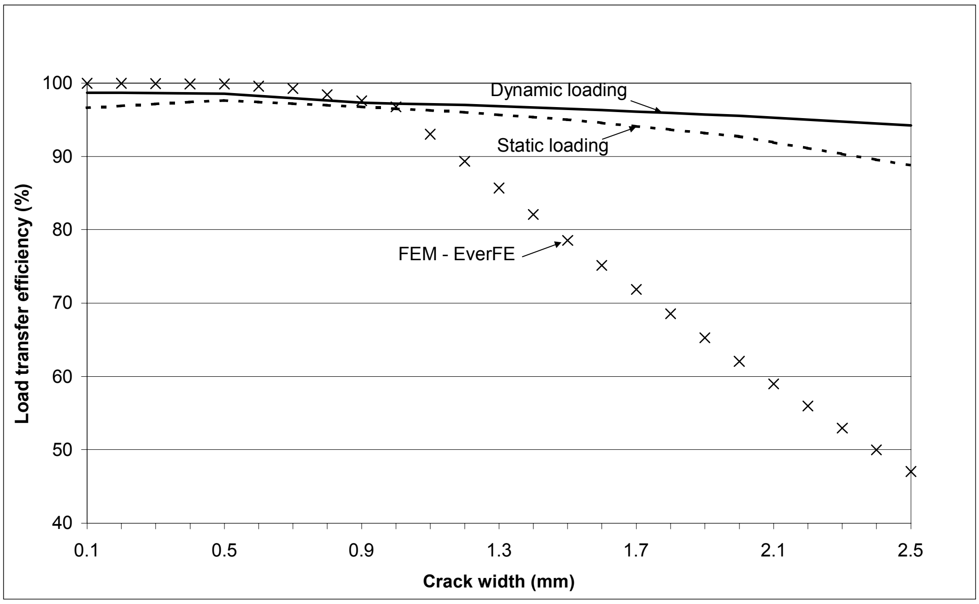

Figure 5: Deflection load transfer efficiency versus crack width

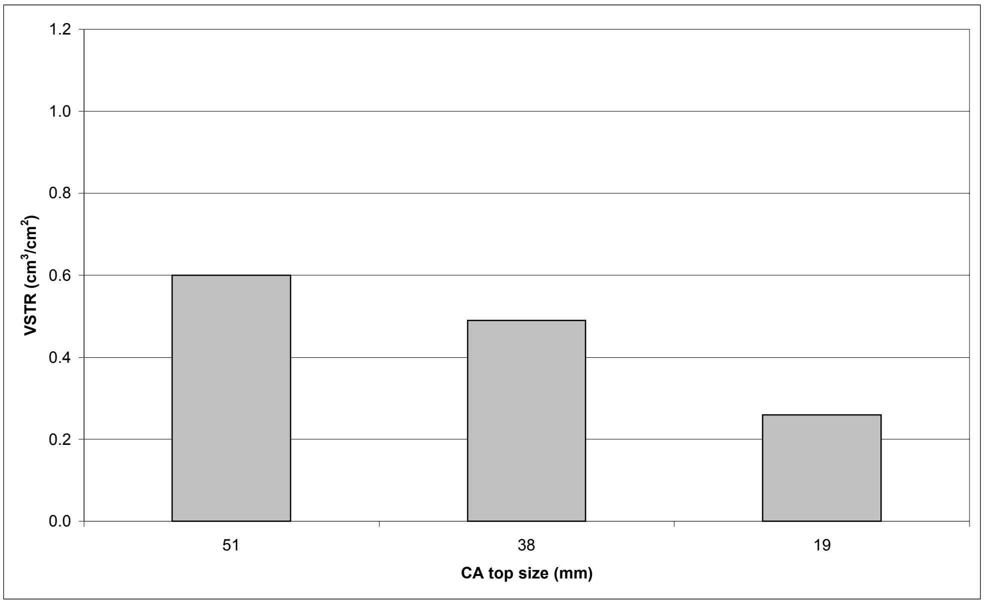

Figure 6: Effect of coarse aggregate (CA) top size on VSTR for cores retrieved from doweled joints (Vandenboschhe, 1999)

RESULTS OF PILOT STUDY INVESTIGATION INTO AGGREGATE INTERLOCK LOAD TRANSFER EFFICIENCY AT JOINTS IN CONCRETE PAVEMENTS

A C HANEKOM, E HORAK* and A T VISSER*

Ph.D. Candidate (UP), BKS (Pty) Ltd., PO Box 3173, Pretoria, 0001
Tel.: (012) 421 3500, e-mail: annach@bks.co.za

*Department of Civil Engineering, Faculty of Engineering, Built Environment, and Information Technology, University of Pretoria, Pretoria, 0002
Tel.: (012) 420 2429/3168, e-mail: ehorak/avisser@postino.up.ac.za

CURRICULUM VITAE

Name of firm	BKS (Pty) Ltd
Name	Anna Catharina Hanekom (Anna-Carin)
Profession	Civil Engineer
Nationality	South African
Membership in professional societies	Engineering Council of South Africa
	Society for Asphalt Technology

KEY QUALIFICATIONS

Pavement design engineer with 16 year's experience in the theoretical analysis of road pavements. Proficient in evaluating both asphalt and concrete pavements by implementing mechanistic design methods. Practical site experience in inter alia the rehabilitation of the N2 Cape concrete road - a jointed concrete pavement overlaid with a bitumen rubber single seal and bitumen rubber overlay, as well as in the construction of the N1 through Du Toitskloof – a dual carriageway freeway through an environmentally sensitive area. Obtained MIng at the University of Stellenbosch in 1988. Presently studying towards a PhD at the University of Pretoria.