

AGGREGATE INTERLOCK LOAD TRANSFER EFFICIENCY AT JOINTS IN CONCRETE PAVEMENTS DURING DYNAMIC LOADING

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ABSTRACT

This paper presents certain aspects of an investigation into methods for modeling aggregate interlock shear transfer in un-doweled jointed concrete pavements. In particular, the results of the investigation into deflection load transfer efficiency due to aggregate interlock across joints in 35 MPa concrete slabs constructed with 19 mm and 37.5 mm granite aggregate, respectively, subjected to simulated 20 kN dynamic loads, are presented. The test setup 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 modeling with finite element method (FEM) software. At small crack widths (<0.5 mm) the FEM results compared well with what was measured in the laboratory, but at larger crack widths the results differed substantially.

1 BACKGROUND AND INTRODUCTION

The South African concrete pavement fraternity recognized the need to upgrade the South African Concrete Pavement Design and Construction Manual (Manual M10, 1995), to a manual based on mechanistic design principles. During a re-evaluation of factors affecting riding quality, structural service life, maintenance and rehabilitation needs, the prominent influence of joint performance was re-confirmed. It was identified that the analytical equation used in the manual to predict load transfer efficiency at joints was only applicable to a small range of aggregate sizes. Further research was therefore needed, which resulted in the study of which preliminary results are presented in this paper.

A main objective was to evaluate the significant difference in pavement response in terms of deflections, to static and moving impulse or dynamic loads (equivalent to traffic loads). A secondary objective of the study was to investigate the applicability of existing methods for modeling aggregate interlock shear transfer efficiency. This was done to determine a fundamental model with which variations in joint load transfer efficiency with joint opening, load magnitude, subbase characteristics, and concrete properties could be simulated.

The aim of the paper is to present certain aspects of an overall study. These aspects are restricted to evaluation of the results of the investigation into deflection load transfer efficiency due to aggregate interlock across joints in two 35 MPa concrete slabs constructed with 19 mm and 37.5 mm granite aggregate, respectively. The slabs were subjected to simulated 20 kN dynamic wheel loads across joints formed at mid-length in the slabs. The specific test setup and methodology used to obtain relevant load, deflection and temperature data are described.

After analysis of the data, the results were compared with values obtained from theoretical modeling with finite element method (FEM) software (Davids et al, 1998), as well as compared with relationships plotted from an equation derived from a study by the South African Roads Board (SARB, 1991).

2 PREVIOUS RESEARCH

The primary purpose of transverse contraction joints, formed by saw-cutting $\frac{1}{4}$ to $\frac{1}{3}$ of the pavement thickness, is to relieve tensile stresses caused by shrinkage during curing of the concrete, and due to temperature and moisture changes in service. The saw-cut facilitates a stress-relieving crack to occur at the sawed joint through the pavement thickness. Aggregate interlock is the main load transfer mechanism at transverse joints in un-doweled pavements.

Deflection load transfer efficiency (LTE_{δ}) due to aggregate interlock 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:

$$LTE_{\delta} = \Delta_U / \Delta_L \quad (1)$$

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 localized 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. Modeling 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 modeled 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 a 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 the mostly theoretical models were still required. Further research was therefore required into the particular 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 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 “one-sided”, but a dynamic load is transferred from one slab to the next. During mobilization of the experiments it therefore became clear that the response of the pavement had to be captured under dynamic loading as well as under static loading 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 formulated as follows:

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

Where:

- $\{F\}$ = Vector of nodal point forces;
- $[K]$ = Stiffness matrix;
- $\{u\}$ = Vector of nodal point displacements;
- $[C]$ = Damping matrix;
- $\{\dot{u}\}$ = Vector of nodal point velocities;
- $[M]$ = Mass matrix; and
- $\{\ddot{u}\}$ = 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 $\{\ddot{u}\}$ 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 reported 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 RESULTS ON TWO SLABS

4.1 Test Set-up

The test set-up, as well as the practical aspects that needed sorting out, prior to conducting the experiments are described in a paper presented at the 20th Annual South African Transport Conference (Hanekom et al, 2001). An important aspect that need to be mentioned once again, is that the crack/joint in the concrete across which static and dynamic load testing was carried out had to be formed within 24 hours after casting the concrete. A 40 mm deep incision was cut into the concrete surface with a grinder (vertically above the angle iron), where after the desired crack was formed. The combined depth effect of the cut joint and the angle iron was still less than $\frac{1}{4}$ of the slab thickness. A schematic layout of the test set-up is given in Figure 2.

4.2 Material Tests

Apart from the slabs, a number of cubes, beams and cylinders were also cast for testing purposes, as summarized in Table 1. The two slabs were cast, using 19 mm and 37.5 mm granite aggregate, respectively. For both slabs Ordinary Portland Cement (CEM I 42.5), and a water/cement ratio of 0.56 was used. The average compressive strength values obtained for the concrete at 7 days, 28 days, and after the application of 2 million dynamic load cycles, are summarized in Table 2.

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 slab, 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 slab, 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

Table 2: Compressive strength test results on concrete cubes

Experiment number	Maximum aggregate size (mm)	Compressive strength (MPa) at:		
		7 days	28 days	2 million load cycles*
Water-cured cubes				
1	19.0	24.5	38.7	50.0
2	37.5	27.2	45.0	57.5
Air-cured cubes				
1	19.0	20.0	30.0	36.7
2	37.5	29.0	41.7	50.0

* Experiment 1: 2 million load cycles 66 days after casting
Experiment 2: 2 million load cycles 138 days after casting

For both slabs the 28-day design compressive strength of 35 MPa was achieved for the water-cured cubes. The compressive strength of the air-cured cubes of the 19 mm aggregate slab was below 35 MPa at 28 days, but reached 36.7 MPa by the time the dynamic load cycles were completed.

The properties of the granite aggregate used in the concrete mix are summarized in Table 3.

Table 3: Properties of granite aggregate

Description of test	Result
Aggregate crushing value (ACV) (%)	25
10% Fines aggregate crushing value (FACT) (kN)	150(dry)
Relative density (kg/m^3)	2.65
Water absorption (%)	0.33
Modulus of elasticity (GPa)	27

The maximum ACV for concrete stone is 29%, and the minimum 10% FACT value for stone for use in concrete subject to surface abrasion is 110 kN. The stone therefore met the relevant specifications. The modulus of elasticity for crushed rocks produced in South Africa vary between 27 GPa for granite, and 40 GPa for dolomite. The granite used in the concrete mixes for the experiments discussed in this paper, therefore lies at the lower side of the spectrum of modulus of elasticity values.

4.3 Test Procedure

For the first slab (19 mm aggregate), a total of 15 data channels were recorded continuously on a computer, using HBM KWS and HBM Spider-8 amplifiers, namely:

- 2 Load cells
- 2 Actuators
- 1 Actuator deflection
- 5 Linear Variable Displacement Transducers (LVDT's)
- 2 Strain Displacement Transducers
- 3 Thermocouples

The strain displacement transducers for the first slab measured the horizontal displacement at the top of the crack. However, the need arose to measure the horizontal displacement at the bottom of the crack as well. The total number of data channels recorded was therefore increased to 17 to include a further two horizontal displacement transducers when testing the second (37.5 mm aggregate) slab.

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 sampled and saved to file for analysis purposes.

The slabs were subjected to 2 million dynamic load applications. After every 0.5 million load applications, static loading tests were carried out, and the data analyzed to determine general trends. The equipment was also calibrated at the time of static load testing.

After completion of the dynamic loading the two sections of the beams were pulled apart horizontally in a controlled fashion, 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 cracks increased, the actual crack width stayed at 0.1 mm, even after completion of the 2 million dynamic load applications. Therefore, before pulling the two sections of the slabs apart at the crack, the ends of the slabs were pressed down by inserting jacks beneath the steel frame holding the actuators. This was done in order to ensure that the aggregate interlock bond that still existed across the joint was broken, to be able to pull the two sections apart.

4.4 Analysis Of Data

There was no significant deterioration of the cracks up to 2 million load cycles, which indicated that fatigue of the aggregate 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. The implication of this is that it will not be necessary to allow so much time 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 slabs were not subjected to normal day-night temperature variations, nor exposed to rain, and other environmental effects detrimental to a joint in a concrete pavement.

The increase in deflection with increasing crack width for both dynamic and static loading, obtained during the study, is shown in Figure 3. From this figure it is obvious that at small crack widths, the repeated dynamic loads caused the slabs to be in a deflected state with deflections higher than under static loading. The dynamic loading lines crossed the static loading lines 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 under dynamic loading.

The deflection load transfer efficiency at different crack widths was calculated directly from the deflection measurements for both dynamic and static loading, using equation (1). The results are plotted on Figure 4. As expected, the load transfer efficiency for the 37.5 mm aggregate was higher than for the 19 mm aggregate. Moment and inertia in the slab contributed to the greater load transfer efficiency under dynamic loading, than under static loading.

4.5 Comparison With Published Results

EverFE (Davids et al, 1998) was used to perform theoretical analyses, as described earlier. A maximum crack width of 2.5 mm was considered, as most of the 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 3 and 4. EverFE predicted an initial deflection value very similar to that measured under dynamic loading, but the EverFE deflection values dramatically decreased at a crack width greater than 0.5 mm, to a constant value far less than what was measured in the laboratory. The theoretical load transfer efficiency was initially close to a 100%, but at a crack width greater than 0.5 mm, it decreased to values considerably lower than what was calculated from the laboratory results.

It is suspected that the difference with the EverFE results in particular 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 stabilized subbase beneath the concrete would also be cracked, contributing to a decrease in load transfer efficiency.

During a field investigation by the South African Roads Board (SARB, 1991) into the role that the type of aggregate in a concrete mix and crack width play in load transfer, the following equation was derived:

$$y = 114000 \frac{x^3}{agg^{4.5}} \quad (3)$$

Where:

y = Relative vertical movement (mm);
 x = Crack width (mm); and
 agg = Maximum aggregate size in concrete mix (mm).

The resultant lines calculated at different crack widths for maximum aggregate sizes of 19 mm and 37.5 mm are plotted on Figure 5. For comparison purposes, the relative vertical movement for both experiments, as well as for EverFE is also plotted on the same graph. In this instance, the experimental results compared well with the EverFE results, and also with the line plotted for the 37.5 mm aggregate. However, the line plotted for the 19 mm aggregate, did not compare well with any of the other results. The main shortcoming of equation (3) is that it was developed assuming an average maximum aggregate size of 26.5 mm. It is obvious that it does not approximate the actual behavior at a joint for smaller aggregate sizes.

The results of the SARB (1991) study formed the basis for the load transfer model used in the prediction of load transfer efficiency at joints and cracks in the South African Concrete Pavement Design and Construction Manual (Manual M10, 1995). The shortcomings in the relationship were recognized, which necessitated the study reported in this paper.

5 CONCLUSIONS

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

1. There was no significant deterioration of the crack face 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;
2. At small crack widths, repeated dynamic loads caused the slabs to stay in a deflected state with deflections higher than under static loading. The dynamic loading lines crossed the static loading lines 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;
3. 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;
4. Comparison with a theoretical relationship developed during field studies when compiling the South African Concrete Pavement Design and Construction Manual (Manual M10, 1995), showed the shortcomings of the formula used to predict load transfer at joints and cracks; and
5. 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, confirmed intuition. The preliminary findings are promising, paving the way for further investigations.

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FIGURES

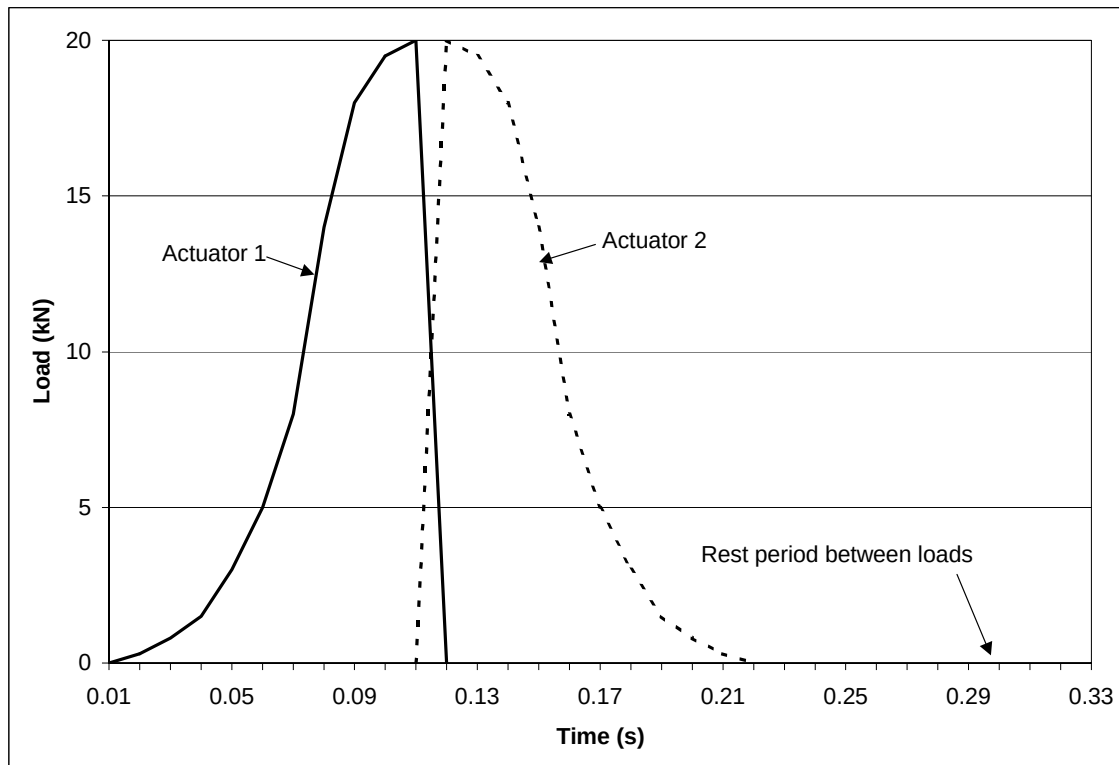


Figure 1: Typical load waveforms for dynamic loading

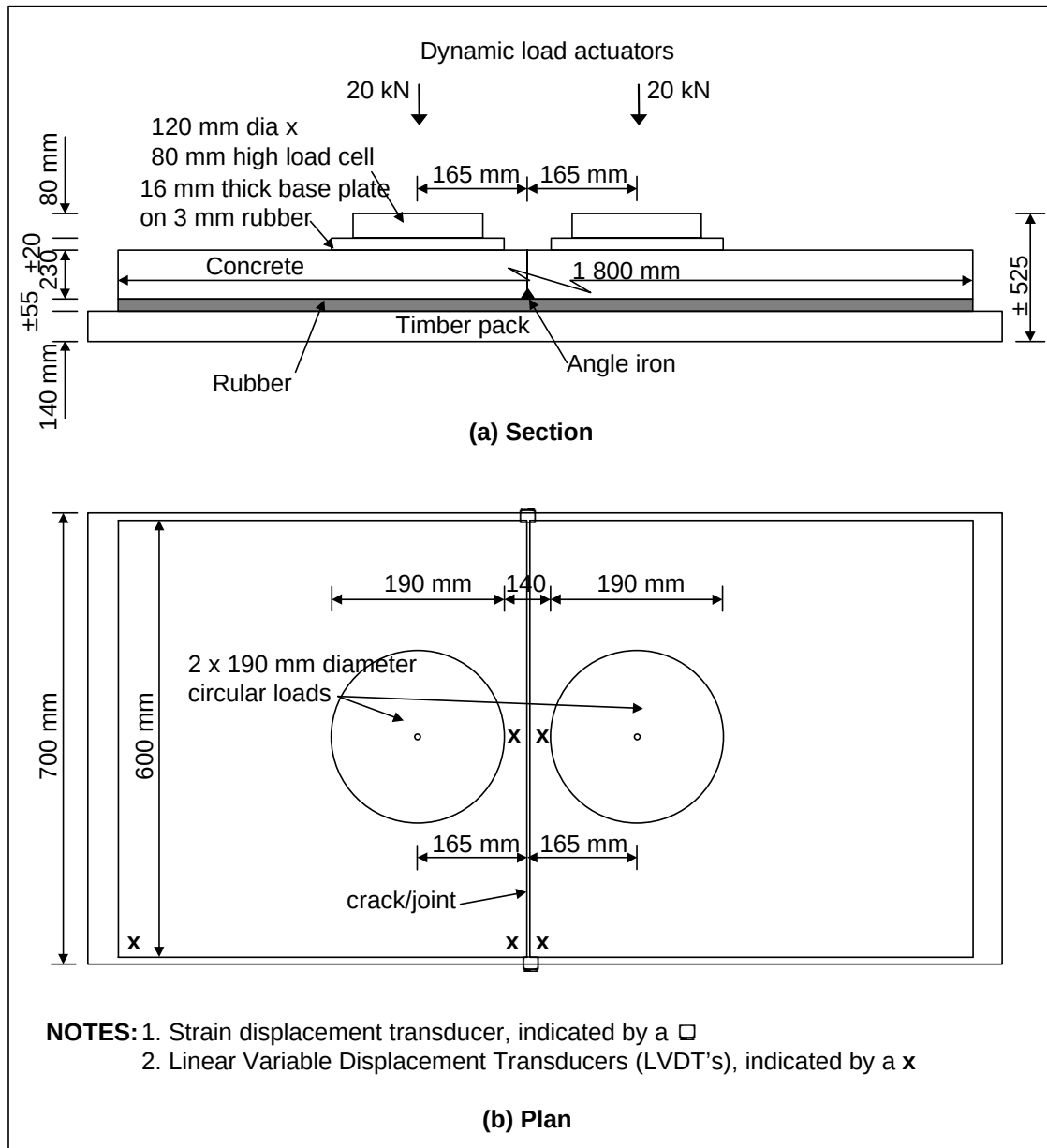


Figure 2: Schematic layout of test set-up for pilot study

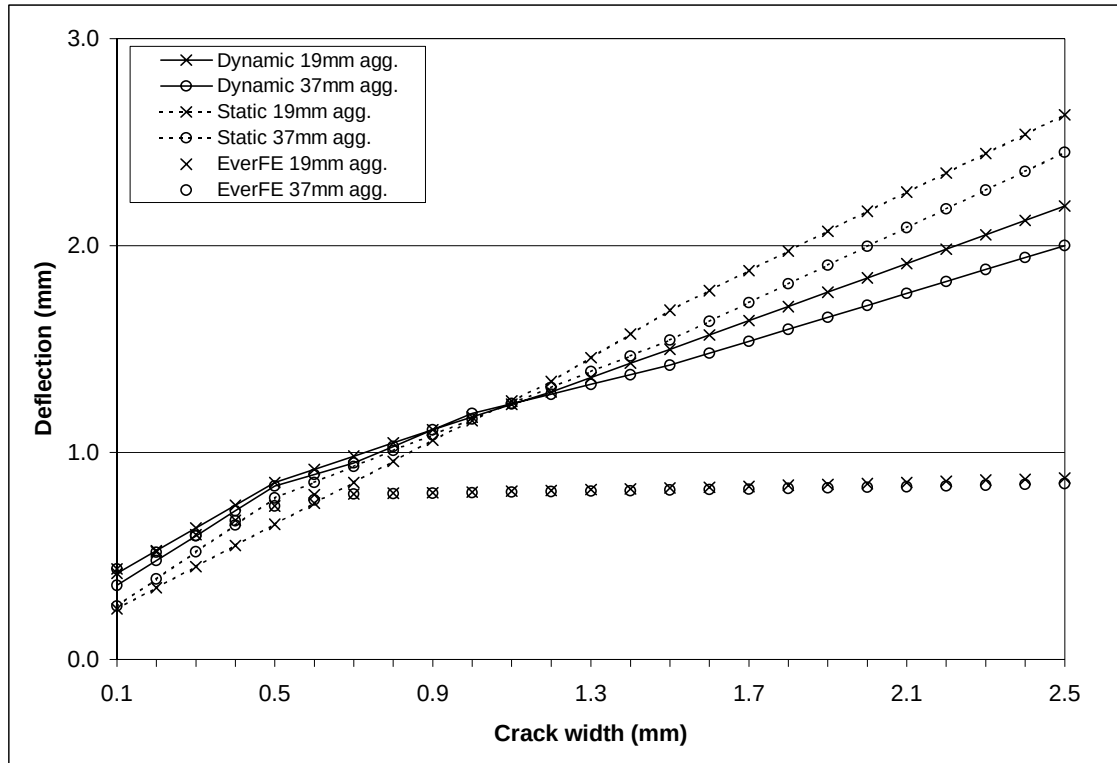


Figure 3: Deflection versus crack width

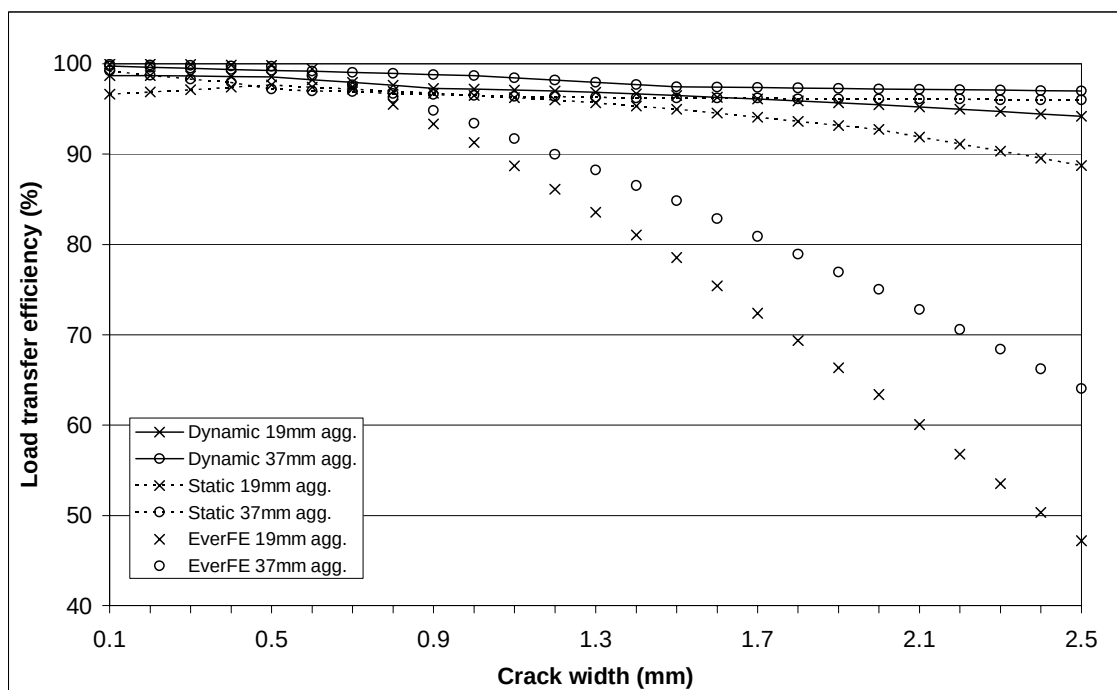


Figure 4: Deflection load transfer efficiency versus crack width

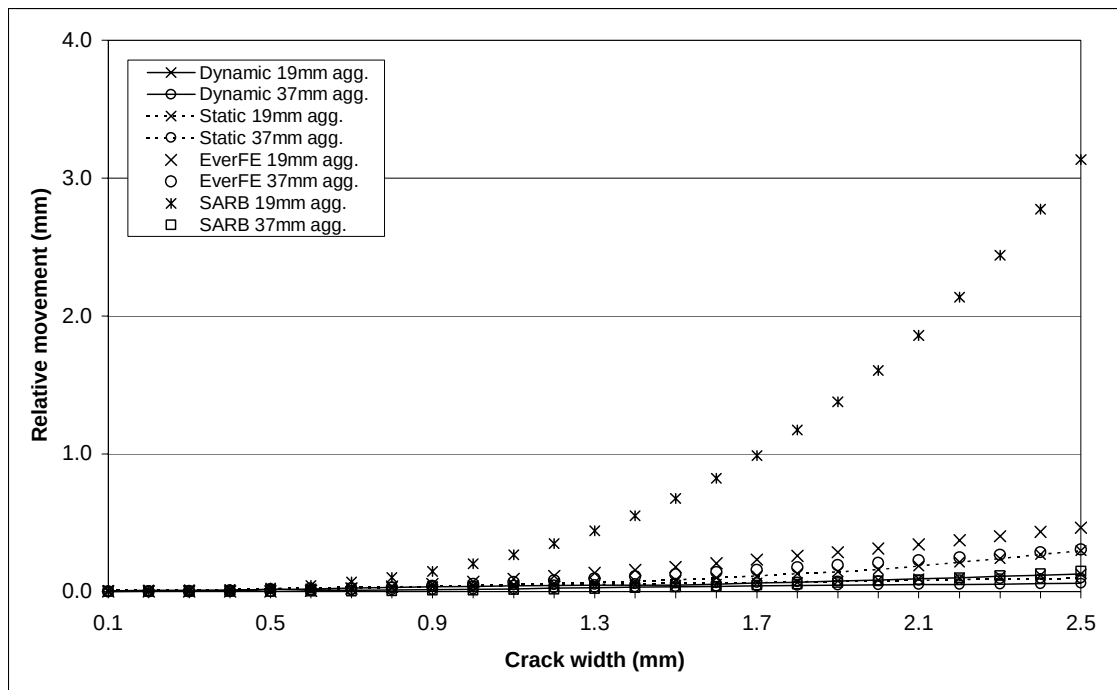


Figure 5: Relative movement versus crack width