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SIGNIFICANCE OF PRINCIPAL STRESS ROTATION IN PAVEMENTS

IMPORTANCE DE ROTATION DE CONTRAINTE PRINCIPALE DANS LES ROUTES

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SYNOPSIS: A study was conducted on crushed dolomitic limestone to investigate the effect of principal stress rotation on the accumulation of plastic strains under repeated moving wheel loading. These strains in a granular pavement layer will contribute to surface rutting.

A repeated load Hollow Cylinder Apparatus (HCA) capable of cycling both the axial and torsional stresses was developed and used. The results demonstrated clear differences between the plastic strain accumulation for tests involving the direct application of repeated shear stresses and those under axi-symmetric (triaxial) conditions.

To validate the HCA test results, two full scale and well instrumented pavement sections involving the same granular material were constructed and subjected to repeated wheel loading. Points within the granular layer were identified from the insitu measurement, where transient stress and strain conditions were similar to those in the HCA. Comparison of the insitu plastic strains with those measured in the HCA were favourable. This demonstrated that the HCA has the potential to simulate the stress condition under moving wheel loads.

INTRODUCTION

The idea of using a mechanistic, rather than an empirical, approach to flexible pavement design has resulted in the need for better knowledge of the behaviour of all materials used in pavement construction. When a thin or low-stiffness bituminous layer is subjected to heavy wheel loads, the behaviour of the granular base and its role in providing structural support and contributing to the long-term serviceability of the pavement becomes particularly important.

The variation of stress in a vertically orientated pavement element as a result of a passing wheel load is complex, as shown in Figure 1. It indicates a reversal in the direction of the shear stress on the vertical and horizontal planes, resulting in a corresponding rotation of the principal stresses. Previous research (Youd, 1972, Ansell et al, 1978, Thom, 1988) has shown that principal stress rotation has a considerable effect on the accumulation of plastic strains in granular materials. These strains will contribute to surface rutting which is one of the main mechanisms of failure in flexible pavement construction.

One of the most promising methods of studying the effect of principal stress rotation is believed to be the Hollow Cylinder Apparatus (HCA). It facilitates application of repeated torsion to a hollow thin-walled cylindrical test specimen. If the hollow cylinder is at the same time subjected to an axial stress and a lateral stress over both the inner and outer cylinder faces, then the stress conditions imposed on an element of material along the wall of the cylinder will be similar to those shown in Figure 1.

A repeated load HCA has recently been built at the University of Nottingham. The device was used to study the effect of reversed shear stresses on the permanent deformation behaviour of crushed dolomitic limestone. The emphasis of the tests was on the difference between simple triaxial conditions and those involving principal stress rotation. In order to provide validation for the findings from the HCA tests, a pilot scale experiment, involving two fully-instrumented flexible pavement sections was performed in the Nottingham Pavement Test Facility (PTF) (Brown et al, 1981).

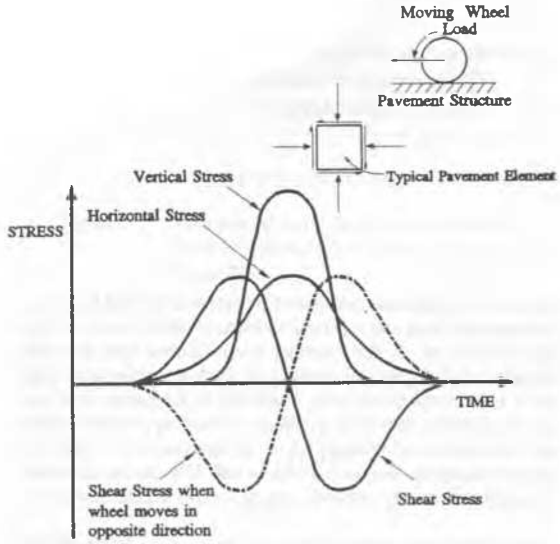

Figure 1. Stresses induced by a Moving Wheel Load on a Vertically Orientated Element of Granular Material

THE NOTTINGHAM REPEATED LOAD HOLLOW CYLINDER APPARATUS

A flow diagram showing the interconnections between the various components of the Nottingham repeated load HCA is shown in Figure 2. The specimen is in the form of a hollow cylinder with an external diameter of 280mm, wall thickness of 28mm and height of 500mm.

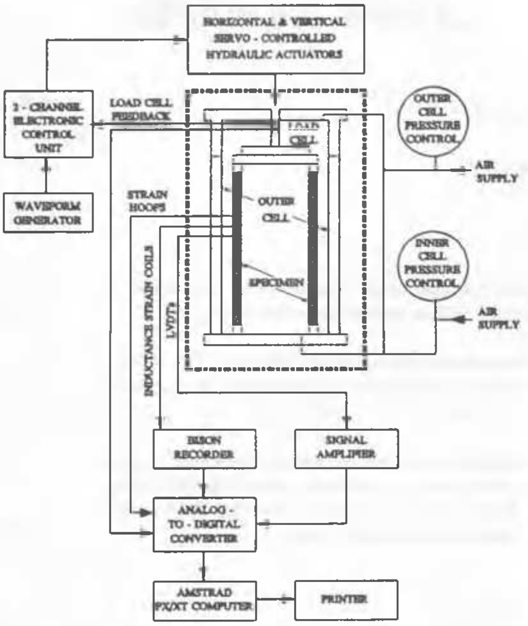

Figure 2. Inter-Relationship Between Different Components of the repeated load Hollow Cylinder Apparatus

Both the vertical and torsional loads are applied by servo-controlled hydraulic actuators. Maximum axial load and torsional moment of 20 kN and 4.6 kNm respectively can be achieved. A slip coupling device allows both the axial load and torque to be applied down the same shaft. It also enables both loads to be measured by a simple purpose-made, combined strain-gauged load cell which is located immediately above the specimen. Confining pressure can be applied through the medium of silicone oil or compressed air in both the inner and outer cell chambers. Pressure of up to 400 kPa can be achieved. These pressures are monitored by pressure gauges located outside the HCA.

Four independent deformation measurements are required to determine the complete strain pattern. To measure the change in specimen wall thickness or the radial deformation, two pairs of 25mm inductance coils attached to opposite sides of the specimen wall are used. Changes in specimen diameter are measured using two strain-gauged epoxy hoops attached to the inner chamber of the hollow cylinder specimen by embedded studs. Details of these devices were discussed elsewhere (Boyce et al, 1976). Axial deformation is measured by two Linear Variable Differential Transformers (LVDTs) mounted vertically on the specimen by means of embedded studs. Deformation in a direction at 45 degrees to the vertical is also measured by means of LVDTs. This latter measurement, together with those from the axial and circumferential directions is used to calculate the torsional deformation.

All the instrumentation is located over the middle third of the specimen to minimize end effects. The signals are captured by a data acquisition system consisting of an analogue-to-digital convertor and a microcomputer.

REPEATED LOAD HOLLOW CYLINDER TESTS

Test Material

The material used for the repeated load hollow cylinder tests was a continuously graded crushed dolomitic limestone. Because of the small thickness of the specimen wall (28mm), the maximum particle size was limited to about 5mm. The specific gravity of the slightly flaky aggregate particles was 2.7. The material was tested dry, hence ensuring that all stresses were effective stresses. A series of static triaxial compression tests was performed on the material and the shear stress ratio (q/p) at failure, was found to be around 2.25. q is defined as the deviator stress and p as the mean normal effective stress.

Permanent Strain Tests - Long Programme

The long permanent strain tests consisted of applying at least 10,000 cycles of the same stress condition and monitoring permanent deformation at regular time intervals. Because of the stress and strain history effects, only one particular set of stress conditions could be used for each specimen.

Six tests were carried out. The tests were divided into three pairs as detailed in Table 1. In each pair, the specimens were subjected to the same repeated vertical stress. However, an additional reversed shear stress was imposed on one of the specimens but with the same peak stress ratio (q/p). Both stresses varied sinusoidally at a frequency of 0.5 Hz but the shear stress was 90 degrees out of phase with the repeated vertical stress. A constant pressure was used in both the inner and outer cells. On average, seven working days were required to complete one test.

Permanent Strain Test - Short Programme

In the short programme, a series of permanent strain tests involving several stress paths, each of increasing severity from the previous one, were carried out on a single specimen. The use of increasingly damaging stress conditions was intended to reduce the strain history effect. Each test was divided into two parts, each consisting of 25 cycles at the same stress condition. In one part, only the vertical stress was cycled while, in the other, an additional reversed shear stress was applied. The main objective of the test was to make use of a less time-consuming method to examine the effect of the reversed shear stresses on the rate of development of permanent strain. Six tests were carried out and details of the stress conditions are shown in Table 1.

Table 1. Details of Permanent Strain Tests

Test Type	Test Number	Vertical Stress (kPa)	Torsional Shear Stress (kPa)	Cell Pressure (kPa)	Maximum (q/p) Ratio
Long	1	0-150	0	100	1.00
	2	0-150	-20 to +20	100	1.00
	3	0-200	0	100	1.20
	4	0-200	-20 to +20	100	1.20
	5	0-200	0	100	1.20
	6	0-200	-30 to +30	100	1.20
Short	1	0-200	-30-+30	100	1.20
	2	0-200	-30-+30	70	1.46
	3	0-250	-30-+30	50	1.88
	4	0-300	-30-+30	50	2.00
	5	0-250	-30-+30	38	2.06
	6	0-200	-30-+30	23	2.23

HOLLOW CYLINDER TEST RESULTS

Long Programme

Plots of the relationships between the permanent axial $(\epsilon_a)_p$ and horizontal $(\epsilon_h)_p$ strains and the number of cycles of stress are shown in Figures 3 and 4 respectively. The horizontal strain is defined here as the sum of the radial and circumferential strains.

Figure 3 does not indicate any consistent trend regarding the influence of the reversed shear stresses on the accumulation of $(\epsilon_a)_p$. This could be due to the relatively small magnitude of the shear stress, compared with the vertical stress. Figure 4 consistently indicates that under triaxial conditions, $(\epsilon_h)_p$ was dilatant and tended to stabilize rather rapidly to a terminal value. However, when reversed shear stresses were applied, the initial permanent strain was dilatant but after 100 to 300 cycles of stress, it tended towards compressive. This may lead to an increase of the permanent volumetric strain, as reported by Ansell et al (1978) from simple shear tests.

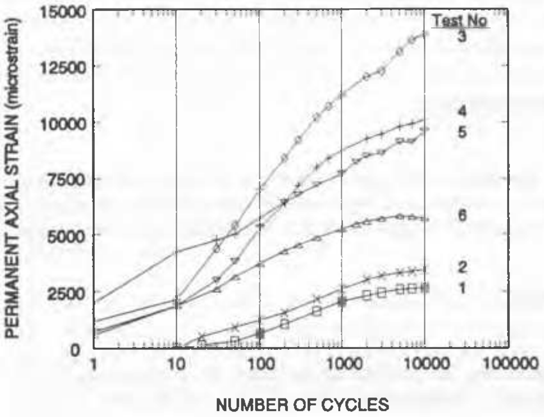

Figure 3. Variation of Permanent Axial Strain with Number of Stress Cycles for the Long Permanent Strain Tests

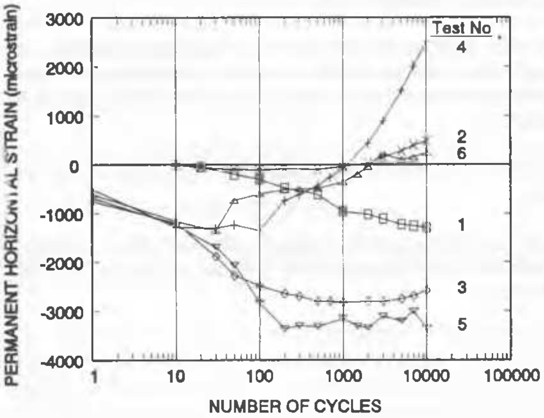

Figure 4. Variation of Permanent Horizontal Strain with Number of Stress Cycles for the Long Permanent Strain Tests

Short Programme

A typical plot of the variation of axial strain, including both the recoverable and non-recoverable components, with the logarithm of the number of cycles for the two parts of the test is shown in Figure 5. The permanent axial strain varies approximately linearly with the logarithm of the number of cycles within both parts of the test but, clearly, at different rates. This behaviour was also observed for the permanent horizontal strain although the strains were generally dilatant. A summary of the slopes of the lines shown in Figure 5, which represent the corresponding rates of permanent strain development is given in Table 2. With one exception, the results indicate that a much higher permanent strain rate can be expected under the application of reversed shear stress. It should be noted that the peak stress ratios in these tests were almost all larger than in the long programme experiments (see Table 1).

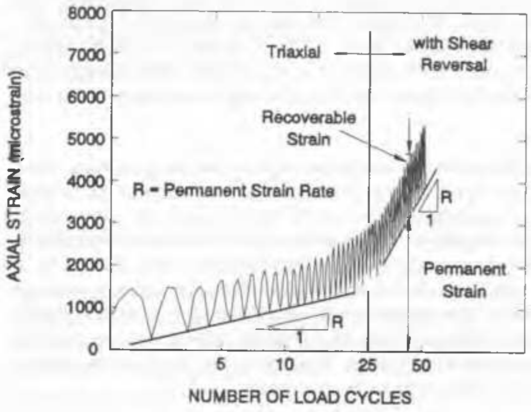

Figure 5. Variation of Axial Strain with Number of Stress Cycles during a Short Permanent Strain Test

Table 2. Summary of Permanent Strain Rates in Short Permanent Strain Test

Test Number	Strain Rate[1]			
	Axial		Horizontal[2]	
	Shear	No Shear	Shear	No Shear
1	2600	2352	-300	-600
2	264	220	-76	-50
3	2530	334	-2616	-630
4	5964	1832	-3737	-1532
5	10740	1471	-15226	-4712
6	7291	3388	-14176	-9956

Note: 1. See Figure 5 for the definition of strain rate. All strains were measured in microstrain.
2. Horizontal strain is defined as the sum of circumferential and radial strain.

VALIDATION OF REPEATED-LOAD HOLLOW CYLINDER TESTS

Approach to the Validation Experiment

Validation of the HCA test results was carried out by means of wheel tracking experiments in the Nottingham Pavement Test Facility. Two flexible pavement sections consisting of a granular base layer of the same crushed limestone used in the HCA, were designed and constructed. Forty inductance strain coils and 10 strain-gauged pressure cells were used to identify points within the granular layer where the stress and strain conditions were similar to those in the HCA. Comparison of permanent strain at these points was then made with values obtained from the HCA tests.

Results of the Validation Experiment

The designed pavement sections consisted of 60mm of bituminous material overlying 225mm of granular base at 2% moisture content. The moisture was added to facilitate handling of the material which was rather dusty. It was recognised that this will have generated some suction which was not quantified but is unlikely to have influenced the overall conclusions from the experiments. The average compacted dry density of the granular base was 97% of that used in the HCA tests. The subgrade consisted of a stiff silty clay with a California Bearing Ratio (CBR) of around 5%. Both sections were subjected to over 10,000 passes of a 10 kN wheel load moving along a single track. The wheel speed was 3.6 km/hr and the test temperature was 20 to 25°C.

The vertical resilient strain was used as the primary matching criterion. This parameter was considered appropriate since it is a function of the overall stress condition at a particular point. On this basis, a zone some 30mm thick in the top half of the granular layer was identified for comparison with the HCA. The detailed stress conditions in this sub-layer were checked by a combination of measured vertical stresses and finite element computations (Brunton et al, 1991). Comparisons of the permanent vertical strain obtained from the HCA tests with those from the sub-layers of the granular base in the pavement tests are shown in Figure 6. Both the rate of development and the magnitude of strain were found to be very similar.

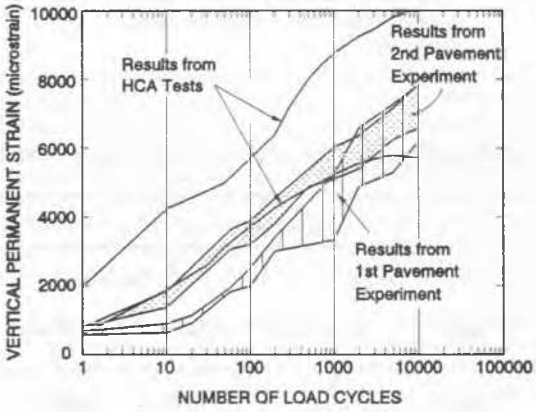

Figure 6. Variation of Permanent Vertical Strain with Number of Load Cycles for the HCA and Pavement Tests

CONCLUSIONS

Experiments in a new Hollow Cylinder Apparatus on specimens of a crushed dolomitic limestone, simulative of unbound road base material, lead to the following conclusions:

1. The effect of reversed shear stresses superimposed on triaxial stress conditions was to significantly change the pattern of plastic strain development under repeated loading. Vertical strains showed inconsistent effects but horizontal strains showed a tendency to compress after initial dilation in tests up to 10,000 cycles at relatively low stress ratios.

2. A series of tests with higher stress ratios, including 25 cycles of triaxial stress followed by 25 cycles with reversed shear stress added, clearly demonstrated an increase in the rate of plastic strain development under reversed shear stress.

3. Insitu measurements of stress and strain in the granular layer of a pavement section subjected to moving wheel loads demonstrated that the plastic strains which developed were similar to those measured in the HCA under comparable stress conditions.

ACKNOWLEDGEMENTS

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