A NOVEL RESEARCH FACILITY TO STUDY THE PERMANENT DEFORMATION CHARACTERISTICS OF ASPHALT

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ABSTRACT

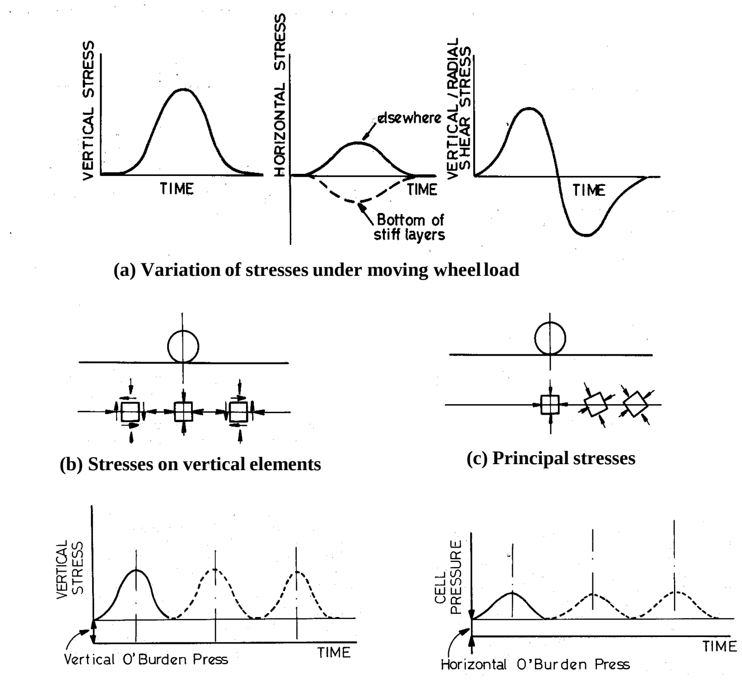
The design and testing of asphalt to minimise wheel track rutting and the prediction of its development with time remain areas requiring improved technology. Simple tests such as wheel tracking and repeated load compression are, at best, approximate and rely on empirical calibration against field performance. In the US, the Superpave Shear Test (SST) was developed during the Strategic Highway Research Program (SHRP) but, while this has proved useful, question marks remain about its reliability for fundamental research.
A major new research apparatus has been developed at the University of Nottingham which uses a hollow cylinder as the test specimen and applies repeated torsion and axial stress together with a confining stress, if required, to a large test specimen suitable for mixtures with a 10mm maximum particle size. The test philosophy is that an element of the cylinder wall can be subjected to the combination of shear and normal stresses that arise in the pavement under a moving wheel load.
By use of displacement transducers attached to the outer and inner surfaces of the specimen, the precise strain conditions on a centrally located element can be determined, while the applied stress components are easily computed from load cell and pressure transducer outputs.
The 350mm diameter test specimens were prepared by accurate concentric coring from a 450mm thick slab compacted by roller in four layers. Some typical results are presented from the initial test programme involving a limited range of stress conditions at 30^{o}C.

Keywords: Mechanical Properties, Permanent Deformation, Testing

1. INTRODUCTION

This paper describes the recent development of a novel piece of research apparatus for the study of permanent deformation in asphalt under conditions that more closely simulate those under a moving wheel than is the case with compression testing such as the uniaxial or triaxial configurations used in current practice.

In a paper published in 1972, Pell and Brown (1) discussed the need to design laboratory materials testing apparatus that could reproduce the stress conditions experienced in a pavement structure under traffic loading. Their ideas were stimulated by the need to understand and to quantify the key mechanical properties required for developing an analytically-based pavement design method. Figure 1(a), reproduced from their paper, has appeared in many publications since and illustrates the variations in normal and shear stresses on a pavement element beneath the centre line of a moving wheel load. Of particular note is the reversal of shear stress on the element which is further illustrated in Figure 1(b) from the same paper.



(a) Variation of stresses under moving wheel load

(b) Stresses on vertical elements

(c) Principal stresses

(d) Stresses in the repeated load triaxial compression test

Figure 1. Stress regimes under a moving wheel and in a triaxial test (after Pell and Brown, 1)

This discussion coincided with the first serious experimental research aimed at studying the permanent deformation characteristics of asphalt in order to develop improved methods for designing against wheel track rutting (2, 3, 4), earlier research having focussed on stiffness and fatigue cracking. These permanent deformation experiments used the repeated load triaxial test, as this apparatus had been effectively applied to soils and granular materials since the early 1960's (5, 6). Pell and Brown (1) pointed out that this equipment could only reproduce the insitu normal stress regime [see Figure 1(d)] and that the associated variations in shear stress could be very significant, particularly in the asphalt layer. Later Brown and Bell (7) quantified such errors for a particular case, based on a combination of theory and experiment, showing them to be significant and illustrating that data from triaxial testing would tend to overestimate rut depth. This is because the triaxial configuration generates data on the axial permanent strain, which is only equal to the vertical value insitu when the wheel load is immediately above the element [see Figure 1(c)]. Hence, the principal stresses applied by the triaxial equipment relate to an insitu element that rotates as the wheel passes, a phenomenon known as "principal stress rotation" or "shear reversal".

Pell and Brown (1) concluded their discussion by stating that the time had come to develop apparatus that could directly apply shear stresses to test specimens as well as normal stresses. The Nottingham team pursued this philosophy over subsequent years in their research on unbound materials. From this they concluded that the torsional hollow cylinder apparatus (HCA) provided an accurate means of testing that represented insitu stress conditions under a moving wheel (8). In the recent research described here, the same configuration has been used to develop a larger HCA for the testing of asphalt. This type of apparatus was first introduced for this material by Sousa (9) at the University of California at Berkeley in the 1980's and, subsequently used by Alavi and Monismith (10) to study the dynamic properties of asphalt. Neither of these projects studied permanent deformation characteristics in any detail.

During their SHRP research, the team at UCB concluded that it was necessary to design and build a direct shear apparatus to study the permanent deformation characteristics of asphalt. In order to develop a test that was not unduly complex but which captured the importance of shear stress application under repeated loading, they developed the Superpave Shear Test (SST) rather than going back to their HCA configuration (Sousa et al, 11). The SST was simplified for more general use to what is now known as the Simple Shear Test at Constant Height (RSST-CH) (12). In this test, the vertical stress on the specimen is adjusted to ensure that the height and, therefore, the volume remain constant so that all the strain is solely derived from shearing action. The results from this test yield relationships between permanent shear strain and number of load applications for a particular combination of temperature and applied shear stress.

The shortcomings of this test configuration are similar to those identified for granular materials testing but its use for asphalt over the past decade has demonstrated that it is effective as a research tool, as part of a design method for rutting and for the design of asphalt mixtures intended for heavily trafficked situations (12, 13, 14).

The new HCA, with which this paper is concerned, was developed to provide a more accurate apparatus for quantifying the permanent deformation characteristics of asphalt with respect both to shear and volume change characteristics. This allows the simpler, more practical test methods, such as the RSST-CH and uniaxial or triaxial tests to be assessed and calibrated. It also provides a means of studying permanent deformation in asphalt in greater detail so as to generated high quality data that can be used to improve computational modelling of pavement rutting.

1. A NEW TORSIONAL HOLLOW CYLINDER APPARATUS

2.1 Loading system

Figure 2 shows a schematic of the HCA indicating how a combination of normal and shear stresses can be applied to an element of material in the wall of the cylinder through the application of vertical and torsional loads to the end platens. This can be combined with the application of a confining stress which, in more advanced forms of the equipment, can be of different magnitude on the inside and outside of the wall. Figure 2 shows that the major principal stress acts at an angle to the vertical when torsion is applied. As the shear and normal stresses are cycled, the general stress regime experienced under a moving wheel load, as shown in Figure 1, may be applied to the test element.

The general approach to design of this new facility was to base it broadly on the HCA developed at Nottingham for testing granular materials (8) but to increase the dimensions so that the specimen wall thickness would be large enough to accommodate realistic maximum sized aggregate, without resulting in an apparatus that was too large. Taking 10mm maximum size as reasonable, indicated a minimum wall thickness requirement of 50mm to give a ratio of five, which was similar to that used earlier. The outside diameter of the specimen was fixed at 350mm, as was the height, based on the concept that instrumentation would be arranged around a 150mm long section at mid-height to minimise end effects from the loading platens. These sizes compared with a wall thickness of 12.5mm and an external diameter of 114mm used by Sousa (9) and by Alavi and Monismith (10), so this new facility is significantly larger than anything used hitherto for asphalt testing of this type.

The maximum levels of shear and normal stress, which would need to be applied by the servo-hydraulic loading system, were estimated from computations carried out using linear elastic analysis of a range of typical asphalt pavement structures. Using this information and the need to compromise somewhat on the size of the facility, a decision was made to select 100kN and 50kN actuators for the vertical and shear loads respectively. In addition to the geometric and load parameters defined above, the following additional factors were defined for the design: applied stress frequencies up to 5Hz, test temperatures from 20 to 40^{o}C and confining stresses from zero to 200kPa, applied statically with equal values internally and externally to the cylinder.

A servo hydraulic system was selected as this had the accuracy of control to meet the above specification over the range of loading. The general arrangement of the apparatus is shown in Figure 3 and a photograph in Figure 4. A large stiff frame was designed to provide an adequate reaction to the applied loads from the hydraulic actuators and to accommodate the heavy specimen on a low solid steel base provided to facilitate installation.

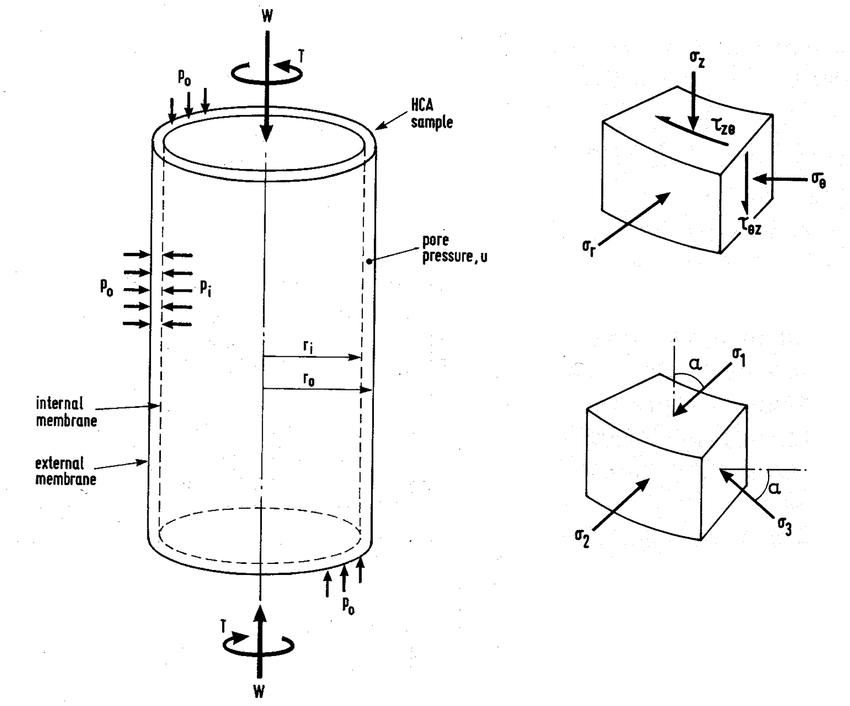


Figure 2. Schematic of a torsional hollow cylinder specimen

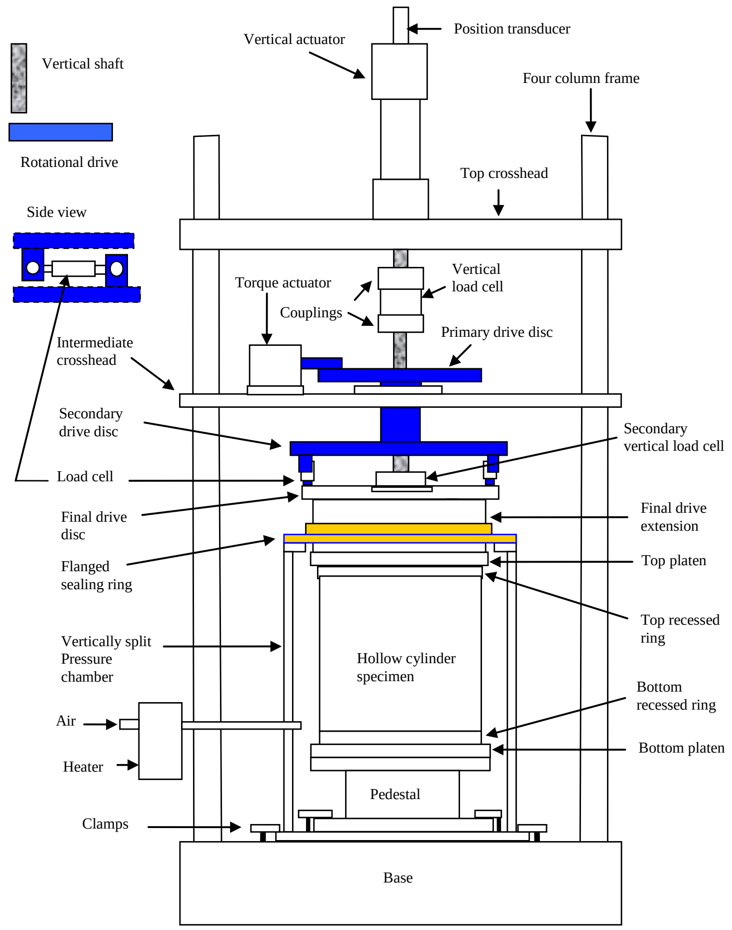


Figure 3. Cross section of Hollow Cylinder Apparatus showing principal component

Figure 4. HCA with test specimen in position and pressure chamber open

An intermediate steel crosshead with adjustable height was provided to support the two cylinder torque actuator that was used and an upper solid steel crosshead for location of the vertical actuator. Four round guide columns were used to align the base and crossheads and these provided stability and strength to resist the vertical and horizontal forces from the two actuators. Two long stroke pistons with extensions were fitted to raise or lower the crossheads prior to clamping them in their correct positions after final assembly of the test specimen.

The vertical and torque loading components are incorporated in the frame as shown in Figure 3. This diagram also shows the location of the specimen in a pressure chamber, the front of which has been removed in the photograph of Figure 4. Full details of the mechanical design used for the complex independent application of vertical and shear loads are given elsewhere (15).

1.2 Instrumentation

The instrumentation used to monitor specimen deformations is shown in Figure 5. It consists of a set of eight LVDT displacement transducers arranged to measure vertical, radial and 45^{o} components with two instruments for each parameter to generate replicate readings. The radial measurements are taken both internally and externally to define the change in wall thickness. Pot marked metal studs were glued to the specimen at the required locations to define the measuring points at either end of the gauge lengths. The instruments are arranged around the central 150mm of the specimen height to minimise end effects as the test specimens are glued into the end platens and are, therefore, unable to deform radially at each end. The two strain collars are located on studs at diametrically opposite points. These serve to determine both the axial and the external radial deformations.

Combining the output from these instruments provides a set of mean values from the sets of replicate data as follows:

ε_z = Vertical strain.

ε_{45} = Strain at 45^o.

ε_θ = Tangential strain.

These are then used to compute the principal strains (ε_1, ε_2, ε_3) and, hence, the volumetric (ε_v) and shear (γ) strains from these linear components using the following equations:

$$\gamma = 2\varepsilon_{45} - \varepsilon_z - \varepsilon_\theta \quad (1)$$

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \quad (2)$$

The shear strain is that on the z – θ plane as defined in Figure 2 and is comparable with the parameter measured in the SST.

Figure 5. LVDT displacement transducers

1.3 System control and data acquisition

A digital control system is used to operate the HCA. For the initial programme of work, the applied load regime was the same as used for the SST, namely 0.1s haversine waves with 0.6s rest periods between each. The control system was designed to apply a wide variety of input signals and the control can be either through deformation or load, initial work using the latter. The digital data acquisition system has sufficient channels to allow all the load cells and deformation instrumentation to be monitored through frequent sampling to define the wave forms. The data are then transferred to a spreadsheet for subsequent analysis and presentation.

The specimen temperature is controlled by a heated air system forming part of the confining stress application arrangements as shown in Figure 4.

2. SPECIMEN PREPARATION

The asphalt mixture selected for initial experiments was a standard AC 10, 10mm maximum sized continuously graded aggregate containing 5.2% of 125 Pen bitumen. It was considered very important to use a method of specimen preparation that would reproduce the insitu compacted state of the asphalt, since permanent deformation characteristics depend crucially on aggregate packing arrangements. Hence, roller compaction was required and the large size of the specimens dictated that a slab of asphalt 400mm thick would be needed. This was constructed in four, 100mm lifts on a prepared base with plan dimensions of 6 x 2.4m. This gave sufficient area for 18 specimens to be cut using large core barrels. This involved initially cutting a core with a hole of 250mm diameter and then, concentrically, making another cut having an internal diameter of 350mm, thus leaving a specimen with a 50mm wall thickness and of sufficient length for trimming of the ends. This procedure produced quite accurately dimensioned specimens. They were transferred carefully to the laboratory in a refrigerated van during warm weather, to avoid any distortion, and stored in a temperature controlled room at 5^{o}C. Site coring is shown in Figure 6. In order to accurately trim the specimen ends so that they were flat and at right angles to the vertical axis, a rotating jig was manufactured to clamp the specimen while cutting took place.

Figure 6. Cutting of test specimens from slab

The profile of air void contents through each specimen was determined on 50mm slices taken from 150mm diameter cores that were cut from the internal 250mm cores taken on site. These 150mm diameter x 50mm specimens were cut for SST and axial load tests in order that these should be conducted on the same material as was used for the HCA experiments. Figure 8 shows how the mean and standard deviation of void content varied through the test specimens. The data were derived as averages from 17 specimens. The approximate positions of the interfaces between the 100mm lifts that were used for construction of the slabs are shown. There is no obvious influence of these on the void content profiles. The overall mean void content of all the samples from the 17 test specimens was 6.7% with a standard deviation of 1.3%. Figure 7 also identifies the zone at the centre of the specimens over which the instrumentation for deformation measurement was located. The mean and standard deviation for this zone was 6.4 % and 1.2% respectively, showing marginally less variability than for the overall figures. Figure 8 focuses just on the central instrumented zones as these are the most important parts of the test specimens. It presents the mean and standard deviations for all 17 specimens. The overall conclusion from this exercise was that the void content of that volume of each specimen that has most influence on the data was between about 5 and 8%. While this is not ideal, it was considered adequate for experiments to proceed.

3. EXPERIMENTAL RESULTS

The initial experiments were designed to allow direct comparisons to be made with a companion set of tests carried out in California with the SST. At the time of writing these data are still being analysed. The same applied stress regime as in the SST of 0.1s pulses with 0.6s rest periods was used for both the shear and normal stresses as shown in Figure 9. All initial experiments were conducted at 30^{o}C.

In order to illustrate the type of results which are being generated by the HCA, some typical data are presented in Figures 10 and 11. These show how the permanent shear and volumetric strains change as the number of load cycles increases. The effects of shear stress level and stress ratio, defined as shear stress ($\tau_{z\theta}$) divided by vertical normal stress (σ_z) (see Figure 2) are illustrated. All data are taken from the mean of two replicate tests, typical variability being illustrated in Figure 12 for the shear strain data in Figure 10.

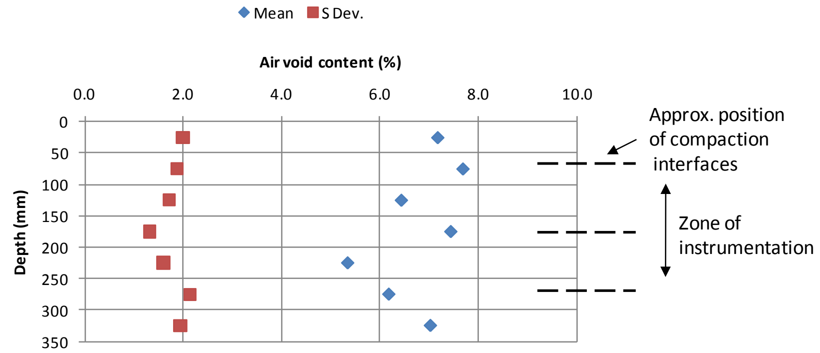


Figure 7. Mean and Standard Deviation of air void content profiles through test specimens

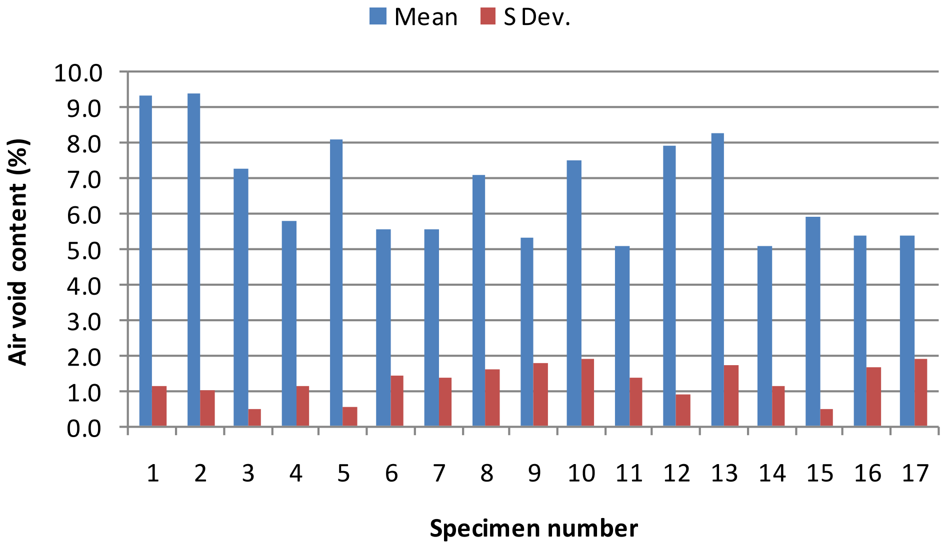


Figure 8. Mean and Standard Deviation of air void content over the instrumented sections of 17 test specimens

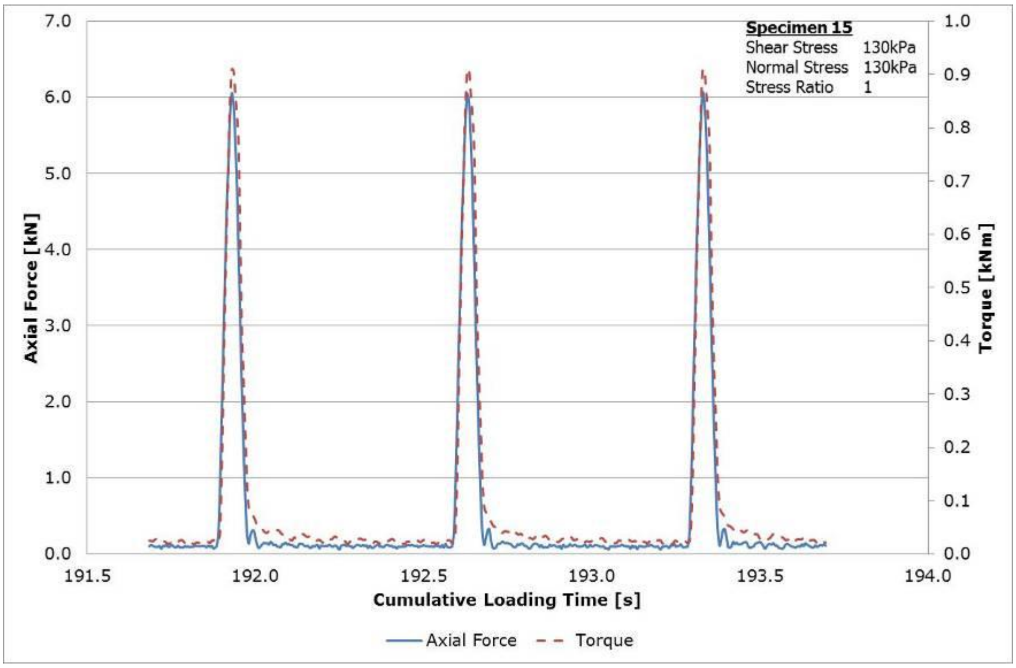
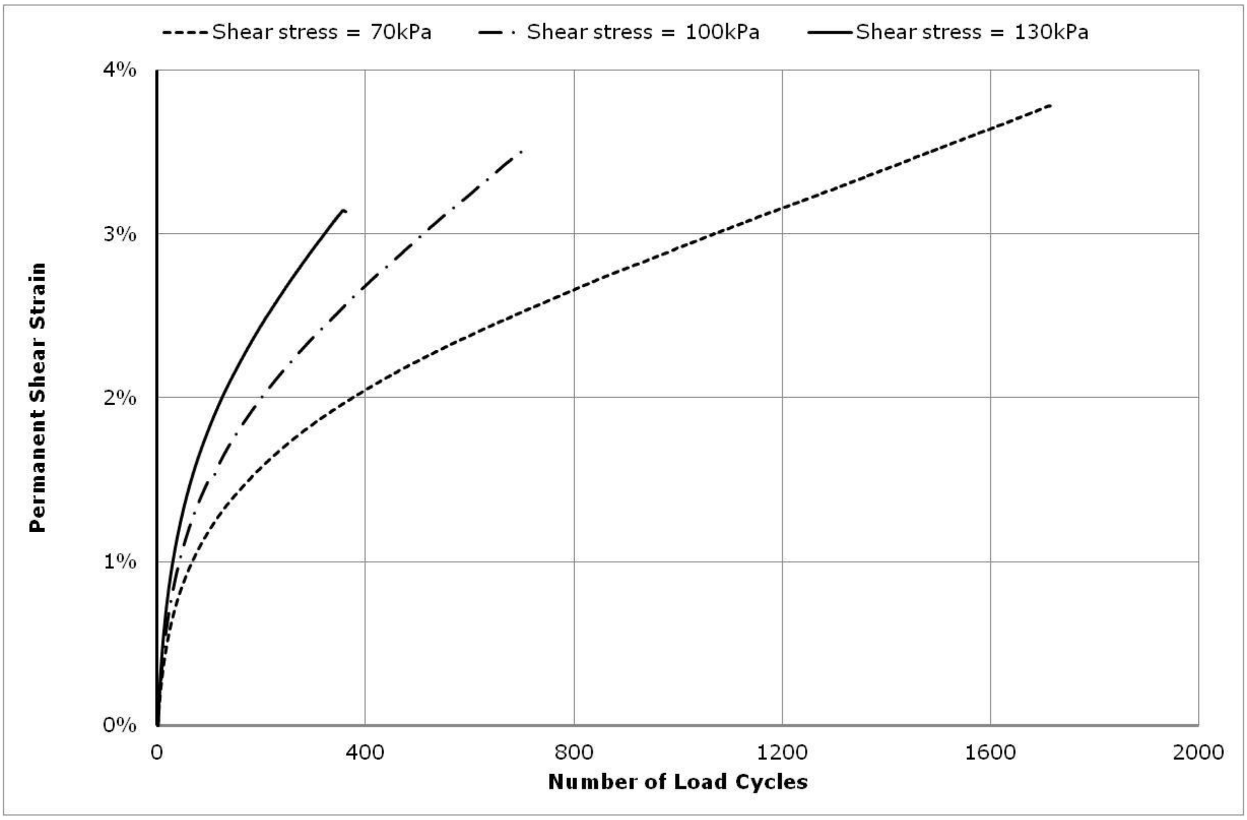


Figure 9. Typical wave form applied in HCA



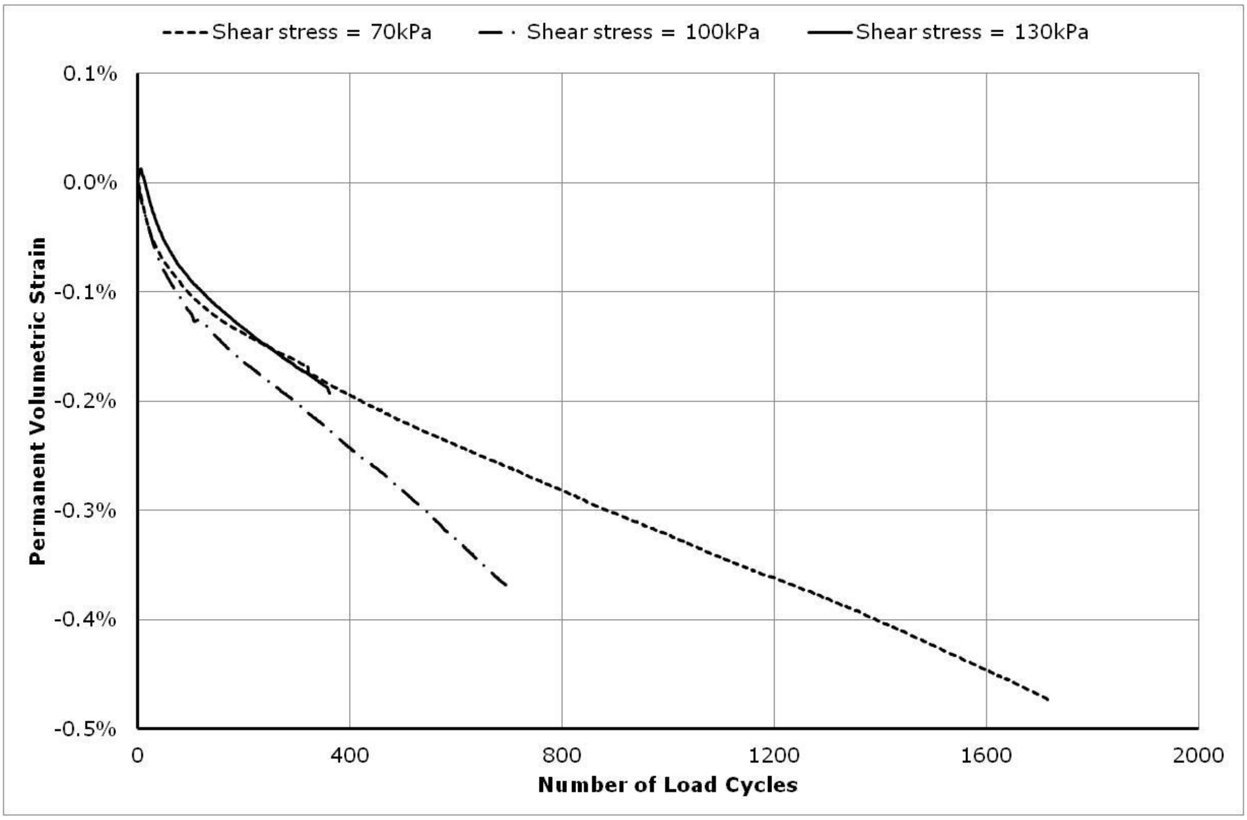
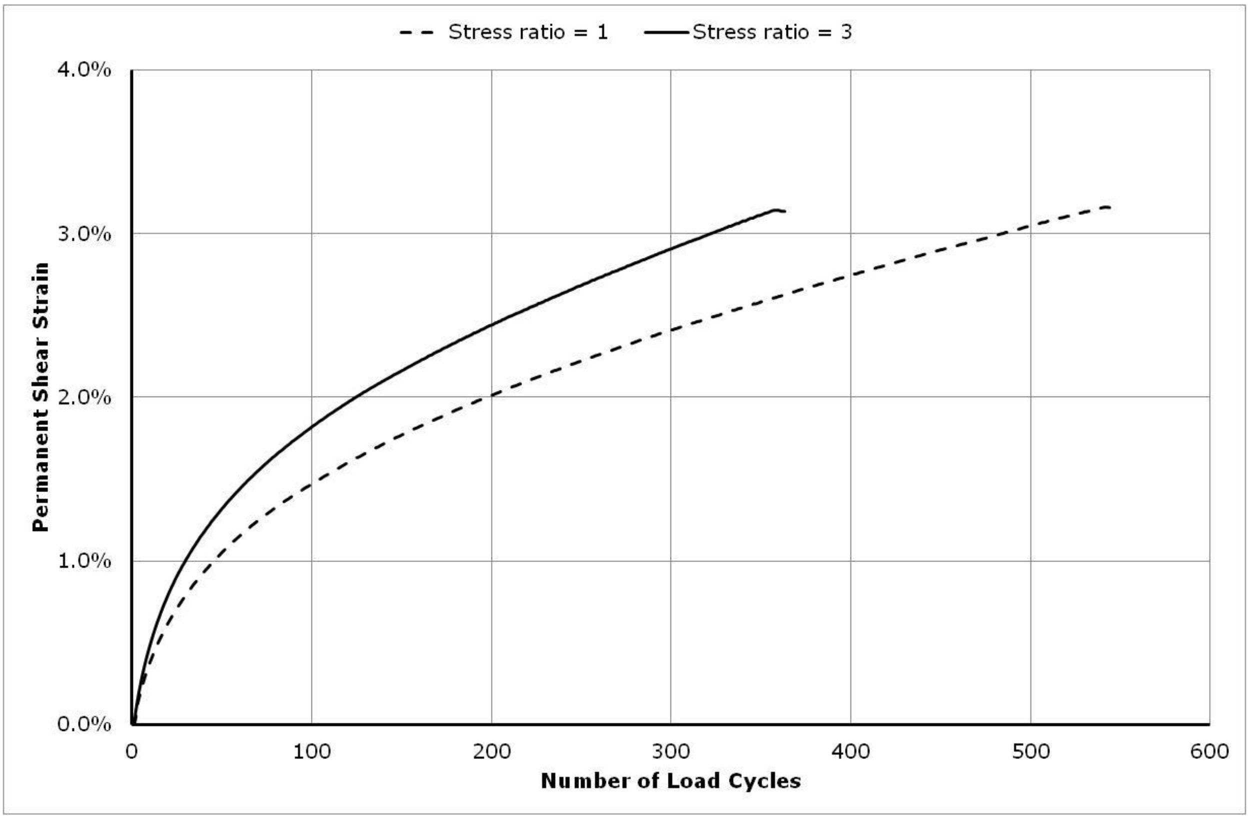


Figure 10. Permanent shear and volumetric strain against number of load cycles at three shear stress levels and a stress ratio of 3



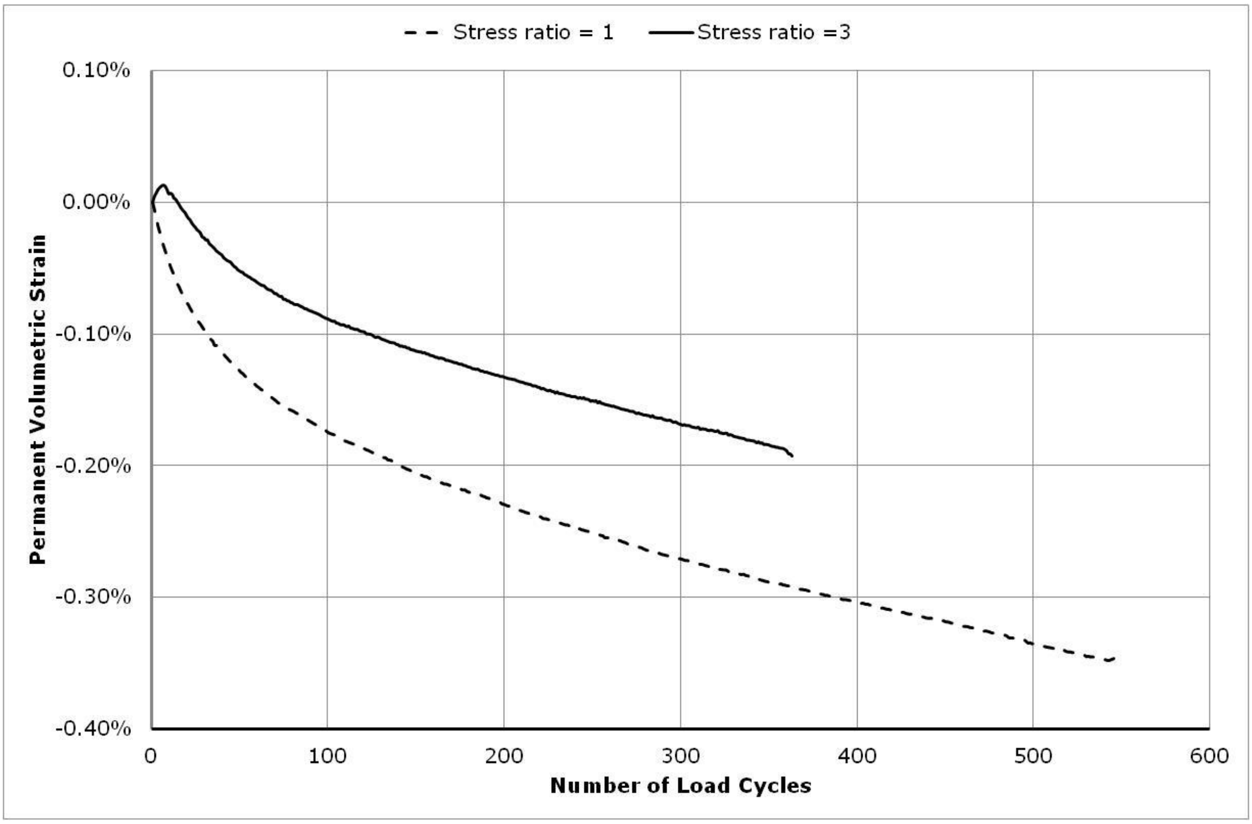


Figure 11. Permanent shear and volumetric strain against number of load cycles at two stress ratios and a shear stress of 130kPa

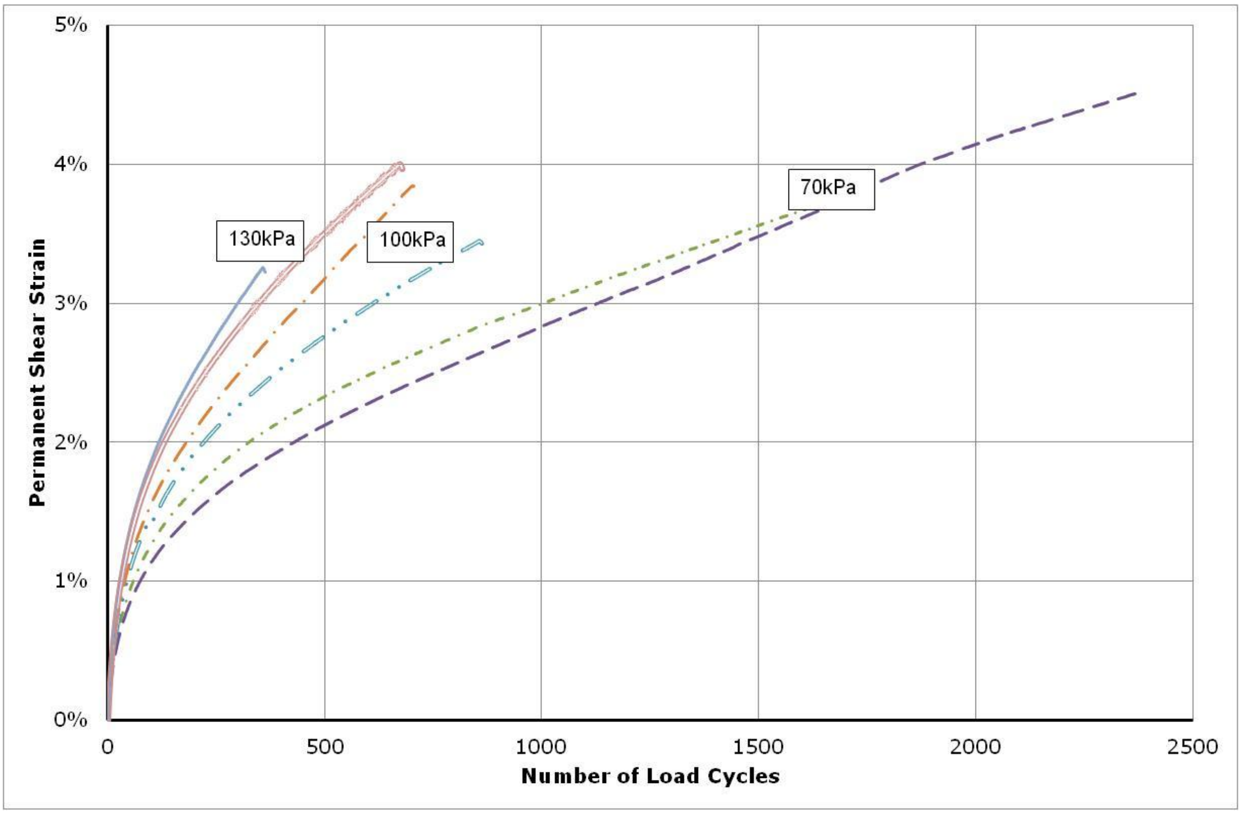


Figure 12. Data for the individual tests illustrated in Figure 11 for shear strain

Two points arise from this preliminary data. The volumetric strains are negative, following slight compression in some tests during the first few load cycles, indicating that the specimens generally dilated during testing rather than compacting. The dependence of the strains on both shear stress level and stress ratio is apparent, particularly for shear strain. These matters will be the subject of further study as the research progresses.

4. CONCLUDING DISCUSSION

This paper describes a novel piece of test equipment for research studies into the permanent strain characteristics of asphalt and presents some initial data which is part of an investigation aimed at studying the accuracy and reliability of existing facilities in the form of the SST and axial loading tests. The development has been based on earlier experience in soil and granular materials research, which identified the shortcomings of simple shear testing and the advantages of the torsional hollow cylinder format for the accurate application of the complex stress conditions that arise under a moving wheel load in a pavement. The flexibility of the HCA in terms of the stress regimes which it can apply is such that a wide range of possibilities arise for future research. The overall objective will be to use the apparatus as a generator of high quality data on the relationships between applied stress and permanent strain for asphalts of various types, constituents and mixture proportions. These data will be used both as a reference standard for the simpler tests used in engineering practice and to assist in the development of improved theoretical models for the prediction of rutting.

It is expected that future work will result in some improvements both to the HCA, in the light of early experience of its use, and to the specimen preparation procedure in order to minimise the variability in air void content.

5. ACKNOWLEDGEMENTS

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