CONTROLLED DEFORMATION OF A CEMENTED SOIL AND SAND

UN GRES ET UNE TERRE AU CIMENT DONT LA DEFORMATION AXIALE EST REGLEE AVEC PRECISION
ДЕФОРМАЦИИ СЦЕМЕНТИРОВАННОГО ГРУНТА И ПЕСКА

I.K. LEE, B.C.E. M.Eng. Sc., Ph.D., M.I.E. Aust., Professor of Civil Engineering Materials, University of New South Wales, Sydney, N.S.W.
O.G. INGLES, B.A., M.Sc., C.Eng., F.R.I.C., Principal Research Scientist, Division of Applied Geomechanics, Commonwealth Scientific and Industrial Research Organization, Syndal, Victoria
R.C. NELL, B.E., M.Eng.Sc., M.I.E. Aust., Experimental Officer, Division of Applied Geomechanics, Commonwealth Scientific and Industrial Research Organization, Syndal, Victoria, Australia

SUMMARY. A study of the post-peak and unloading characteristics of brittle materials such as stabilized soils and rocks requires an extremely stiff, programmable testing machine. Only a limited amount of reliable data on these brittle materials is at present available due to the scarcity of suitable testing equipment.

In the present paper, the most significant results of an investigation of the stress-strain characteristics of replicate sets of a stabilized soil and sandstone are presented. Both unloading, reloading, and large strain ranges were investigated. The specimens were tested in uni-axial compression in an infinitely programmable stiff loading frame developed by Ingles and Neil (1971).

It was evident that the axial stress-axial strain, unloading-loading hysteresis loops were closely geometrically similar in the pre-peak and the post-peak stress ranges for all of the specimens tested. In contrast, the radial strain hysteresis loop expanded in the post-peak range. There was little recovery in the radial strain on unloading but a significant recovery of axial strain occurred.

The loading and recording system was sufficiently sensitive to detect fluctuations from the mean stress-strain curve. This 'noise' was barely detectable at low stress levels (say less than 20 per cent of peak stress) but increased to about 2 per cent of the peak stress when this state had been achieved. This level of noise was maintained in the post-peak range. From a knowledge of the machine characteristics, it was concluded that the noise was a true material characteristic brought about by the progressive rupture within the specimen.

INTRODUCTION

Recent advances in mechanical and sensor technology have led to the development of loading frames with very precise strain control. Using such equipment it is possible to examine the deformation characteristics of brittle materials in the post-peak range and during an unloading cycle.

The loading frame used in the present studies was the stiff infinitely programmable digital computerized machine, described by Ingles and Neil (1971), so that any stress or strain history could be imposed on the specimen. The present paper is, however, confined to a discussion of the characteristics of two brittle materials subjected to a uni-axial compressive state developed by applying a constant rate of axial strain.

EXPERIMENTAL PROCEDURE

The materials studied were a lightly bonded sandstone (Hawkesbury sandstone, Sydney region, with expected mean strengths of 300-350 kg/cm^2), and a 10 per cent cement-stabilized clay soil (Syndal, Victoria) with expected mean strengths of 35-70 kg/cm^2 after a 28-day moist curing.

The sandstone cores were turned to a true diameter on a lathe using a tungsten-carbide tipped tool, and the two ends, prepared similarly, were plane parallel within the accuracy of the grain size of the sandstone (to approximately 0.1 mm). The cement-stabilized soil was moulded at optimum moisture content and density, and required no further preparation. The sandstone specimens were finished to cylinders of approximately 10 cm height by 5 cm diameter and were 2.30 g/cc in density. The cement-stabilized soil specimens were cylinders of 15 cm height by 7.5 cm diameter, moisture content 12 per cent and dry density 1.95 g/cc.

These specimens were tested in unconfined compression. The control applied consisted of a constant rate of axial strain, with

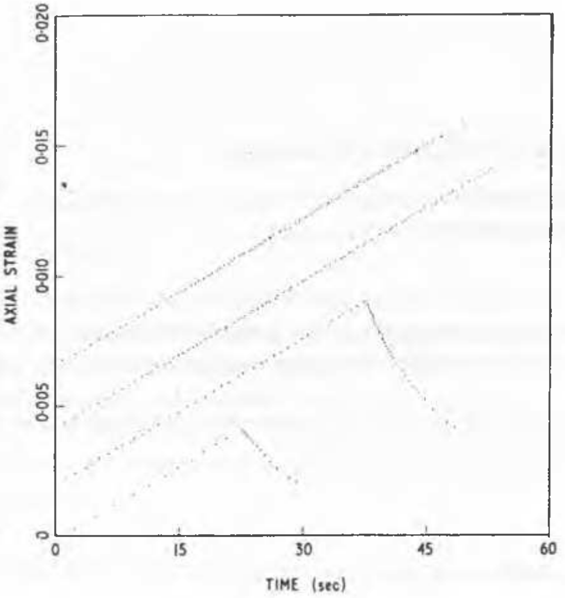

FIG. 1. RATE OF DEFORMATION IN LOADING (SANDSTONE, SPECIMEN No.4)

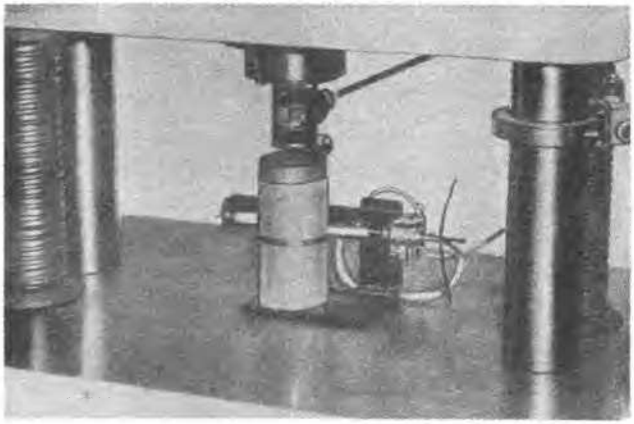

FIG. 2. CIRCUMFERENTIAL DISPLACEMENT DEVICE

precisely regulated unloading commands coupled to the total displacement, viz., a straining rate of approximately 0.01 min^{-1}, and a series of unload commands designed to intercept both pre- and post-peak regions, with a mean rate of 0.03 min^{-1} down to zero load, followed by immediate reloading at the original strain rate. Fig. 1 shows the perfection of loading control achieved. Upper and lower platens of highly polished hardened steel were used.

The sensors applied consisted of a load cell (Shinkō, 5-ton) directly bearing on the upper platen and previously bedded into it at an allowable cell overload, and two Schavitz LVDT transducers, one applied to direct measurement of the axial displacement, the other coupled to a circumferential displacement device, calibrated either by displacement slip gauges or dummy specimens as appropriate (Fig. 2). The sensitivity of these gauges was 0.1 per cent, and their output was taken via an SE strain bridge to the computer, which in turn commands the hydraulic system and stores the accumulated data. 'Noise' levels were estimated from dummy runs using a hard steel cylinder, and were found to be well below those observed for the soil and sandstone specimens.

RESULTS

Fig. 3 and 4 show the continuous trace of axial load displacement (and stress-strain) for two stabilized specimens, and the corresponding traces for the sandstone specimens are given in Fig. 5 and 6. Fig. 7 is a typical trace of the axial strain-radial strain (ε_1 *v.* ε_3) throughout the loading and unloading cycles for the sandstone (specimen No.4).

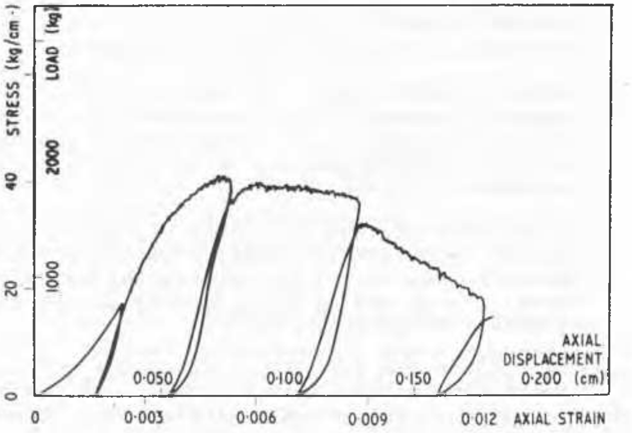

FIG. 3. CONTINUOUS TRACE OF AXIAL LOAD - DISPLACEMENT (STABILIZED SOIL, SPECIMEN No.1)

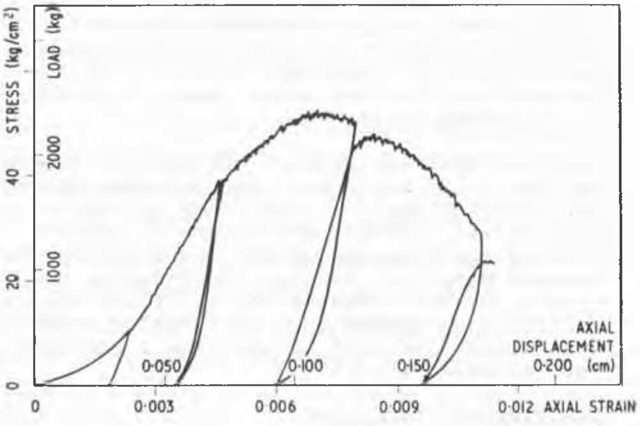

FIG. 4. CONTINUOUS TRACE OF AXIAL LOAD - DISPLACEMENT (STABILIZED SOIL, SPECIMEN No.2)

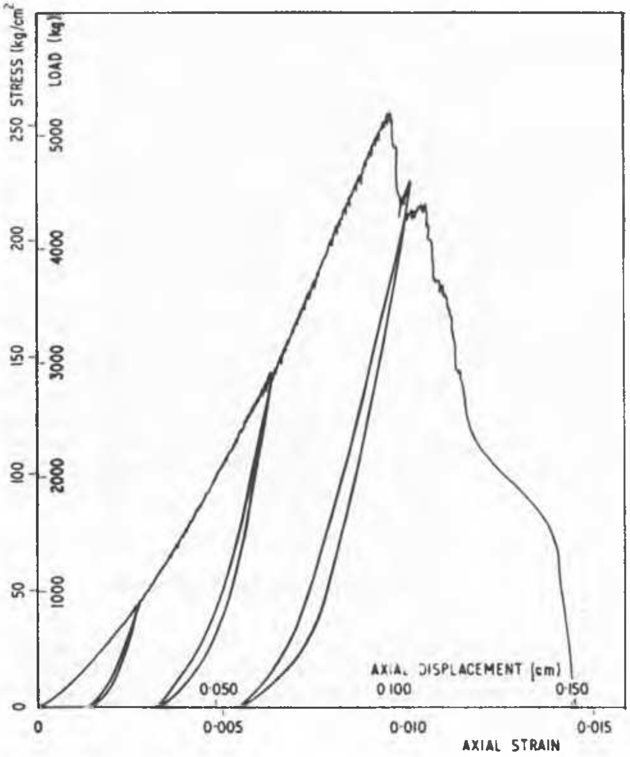

FIG. 5. CONTINUOUS TRACE OF AXIAL LOAD - DISPLACEMENT (SANDSTONE, SPECIMEN No.3)

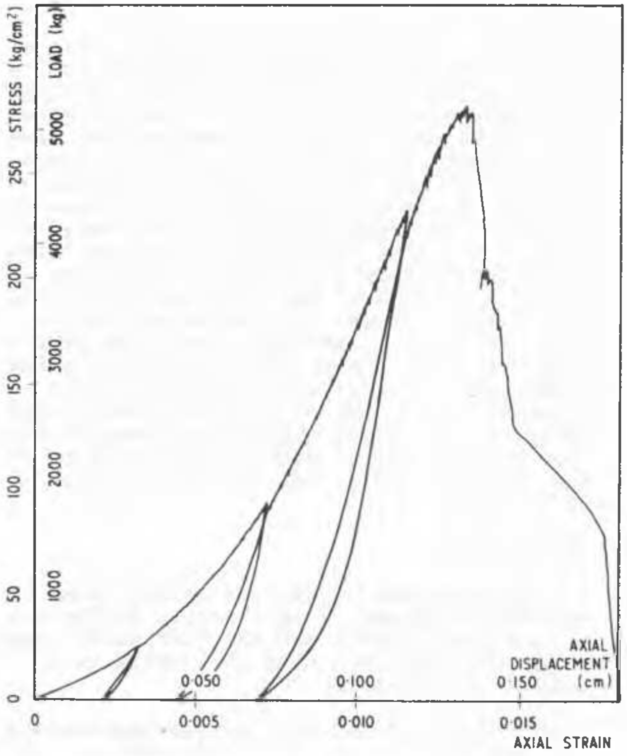

FIG. 6. CONTINUOUS TRACE OF AXIAL LOAD - DISPLACEMENT (SANDSTONE, SPECIMEN No. 4)

DISCUSSION

A. AXIAL STIFFNESS

When brittle materials can be tested in a stiff machine thus avoiding explosive rupture, their true post-peak behaviour is revealed. Their strength is not immediately lost, as has been commonly thought, and Fig. 3 to 6 show that the materials retain considerable strength in the post-peak region. The major difference between the behaviour of the sandstone compared with the stabilized soil is that the strain interval in the post-peak region in which there is a load capacity is considerably smaller.

It is evident in every case that the loading-unloading hysteresis loops are closely geometrically similar irrespective of the degree of strain, that is, in both the pre-peak and post-peak region of the load-displacement trace. The form of the hysteresis is also similar to that observed in triaxial compression tests on soils showing considerable irrecoverable axial strain.

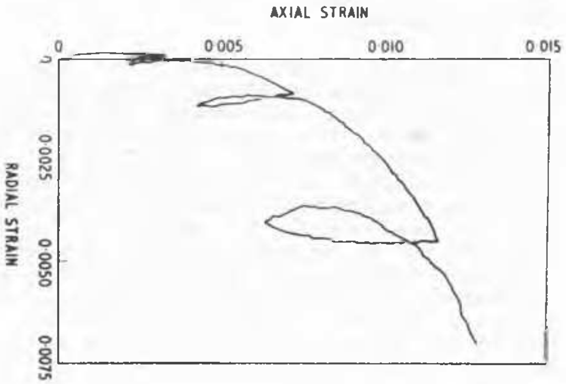

FIG. 7. CONTINUOUS TRACE OF AXIAL STRAIN - RADIAL STRAIN (SANDSTONE, SPECIMEN No.4)

More specifically, one can examine the overall slope of the unloading curve ('unloading modulus'). For the stabilized soils this slope was virtually independent of strain throughout the test (2.45 ± 0.1 x 10^4 kg.cm^{-1}) but the sandstone showed a somewhat more stress-dependent unloading modulus ranging from 2.5 to 4.0 x 10^4 kg.cm^{-1}, the latter value being typical of the unloading modulus near and beyond the strain corresponding to peak stress.

It is currently considered that irrecoverable deformations of brittle materials are due to the progressive propagation of micro-cracks.

The evidence obtained in the present test series clearly shows that the unloading-loading cycle causes a change in the crack pattern. Referring to Fig. 3 to 6, it is seen that there is a cross-over of the unloading-reloading curves just below the stress level from which the unloading commenced, that is, at a given load the strain has increased due solely to the cycling. As would be expected from a consideration of the mechanism of progressive rupture this effect increases with the stress level at which unloading is commenced.

All the experimental data contained in the tests confirm that irrecoverable strains are developed even at the earliest stress levels and this is compatible with progressive rupture.

B. 'NOISE' LEVEL

The continuous output from the load and displacement sensors showed an increasingly unsteady stress state as the strain was increased. There is a base noise level in the system which was found by calibration to be not more than 20 per cent of the amplitude of the noise recorded in the specimens at peak stress level. The balance is taken to manifest real material behaviour.

At or beyond the peak stress state the amplitude of the noise level was of the order of 2 per cent of the peak stress, and in the pre-peak region the noise level increased with increasing stress. It will be particularly noted from a study of these figures that the development of significant noise is a strain phenomenon. For example, if one compares the noise level registered during monotonic loading with the level during reloading at the same strain relative to the original origin it will be seen that the magnitude of the noise is much less on reloading. However, once an absolute strain relative to the reloading origin has been developed the noise level again becomes significant.

The phenomenon of noise (or stick-slip) has been observed in many materials, notably uniformly sized granular materials (Lafeber and Willoughby, 1970); and Rummell and Fairhurst (1970) have also reported measurement of the noise level in tests on a series of rocks. It is concluded that the crack propagation process is intermittent in the sense that sudden slips can occur, and that the peak stress is not a basic material constant or property but is conditioned by the statistical combination of the micro-fractures.

C. POISSON'S RATIO

As a typical example of the change in radial dimensions Fig. 7 shows a point trace of the relationship between the axial and radial displacements (or axial strain-radial strain drawn from the memory bank of the computer. It will be noted that there is only a small change in radial displacement during unloading and that this displacement can be outwards (at a small strain state, Fig. 7) or inwards (at a larger strain state, Fig. 7). This means that the axial micro-fractures which cause the radial strain of the specimen are substantially irrecoverable at any stage of the loading.

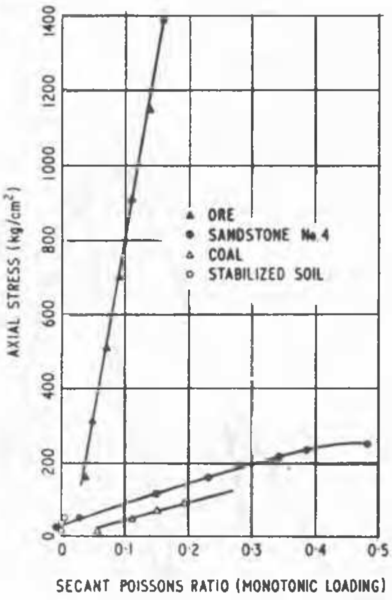

FIG. 8. DEPENDENT OF SECANT POISSON'S RATIO ON AXIAL STRESS (STABILIZED SOIL, SPECIMEN No.1; SANDSTONE, SPECIMEN No.4; △ COAL ▲ ORE)

The values of the secant Poisson's ratio relative to the initial strain state for the sandstone can be seen from Fig. 7. The progressive increase in this value is evident and in Fig. 8 the relationship between stress level and Poisson's ratio is shown for the sandstone (specimen No.4) and for a coal and a mineral specimen. The important characteristic shown by these results is that there is a virtually linear relationship between stress level and Poisson's ratio for the stress range, say, from 30 per cent to 80 per cent of the peak stress. At low stress levels the ratio is constant and near zero, but when the peak stress is approached the Poisson's ratio increases very rapidly and appears to be close to 0.5 at the peak stress state. The actual relationship depends not only on the type of rock but is critically dependent on the stress history (Ingles, Lee and Neil, 1972).

CONCLUSIONS

1) The mechanism of rupture is the same whether the material is strained to the pre- or post-peak state, and the fact that a peak does occur does not mean that there is a change in mechanism.

2) The axial stress-axial strain hysteresis loops defined by an unloading-loading cycle are closely geometrically similar, irrespective of the strain state imposed, but manifest a slight statistically detectable

decrease in the unloading modulus as the strain is increased.

3) The change in radial strain on unloading is relatively small. When the specimen is unloaded from a low stress level the hysteresis loops of axial stress-radial strain or axial strain-radial strain are very narrow. When unloading occurs from higher stress levels (or larger strains) the hysteresis loops become wider.

4) The secant Poisson's ratio, defined for mathematical convenience relative to the initial strain state, is closely proportional to the axial stress over a substantial range of stress, wherein the material approximates linear behaviour. However, as the peak stress is approached the secant Poisson's ratio tends to a value close to 0.5.

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