A study of the end effects in specimen cores under compression tests, with a view to the elimination of these effects*

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SYNOPSIS

It is well known that a cylindrical rock specimen tested under uniaxial compression in conventional fashion is subject to end effects; that is, towards the end of the core, the stress and strain distribution becomes non-uniform. The experiment described illustrates such end effects with an aluminium core between steel platens. An attempt was then made to nullify these effects by compressing the core between pads of mercury. The resulting stress and strain distribution was significantly more uniform, but a slight over-correction was introduced.

SAMEVATTING

Dit is welbekend dat 'n silindriese rotstoetsstuk wat op die konvensionele manier onder uniaksiale kompressie getoets word, aan enteffekte onderhewig is, met ander woorde dat die spannings- en vervormingsverdeling na die ente van die kern toe, nie eenvormig is. Die eksperiment wat beskryf word, illustreer sodanige enteffekte met 'n aluminiumkern tussen staaldrukplate. Daar is vervolgens 'n poging aangewend om hierdie effekte uit te skakel deur die kern tussen kwikkussings saam te druk. Die gevolglike spannings- en vervormingsverdeling was opvallend meer eenvormig, maar daar was 'n effense oorkorreksie.

INTRODUCTION

Uniaxial compression tests on rock cores, or cores of other materials, are made so that the ultimate compressive strength (*UCS*) Young's modulus (*E*), and Poisson's ratio (v) for the material in question can be determined, and the failure mechanisms examined. The majority of these tests are done with the specimen between steel platens (this being simple and easy), and the end effects under these conditions are fairly well understood[1, 2].

When a core is compressed between steel platens, the ends of the core in contact with the steel are not free to move or spread laterally compared with the middle section of the core, owing to the inward-directed frictional forces exerted by the steel platens on the core. The core becomes barrel-shaped as a result of these compressive shearing stresses on the ends. Since these end effects restrict lateral expansion, they are likely to give false values for *UCS* and *E*. These apparent values will probably be higher than the true values. Hence, if these end effects could be eliminated, a more significant value of *UCS* and *E* of specimen rock samples could be determined. In addition, the fracture and failure mechanisms would be represented more accurately under a uniform compression test with no end effects.

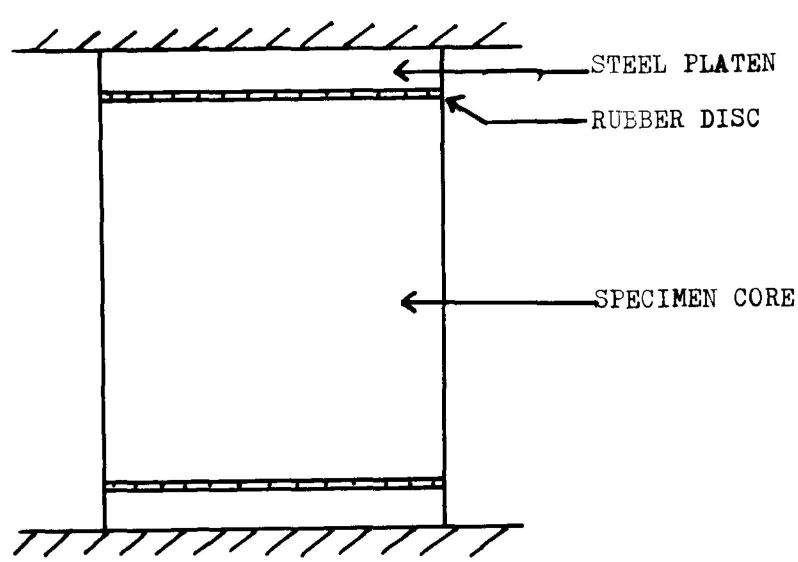

Fig. 1—Section showing rubber disc between the platens and the specimen

The first step towards obtaining a completely uniform compression seemed therefore to be a reduction or elimination of the frictional forces due to the compressing media on the ends of the specimen core.

It was thought that a thin disc of rubber placed between the steel platens and the specimen might eliminate these shearing forces (Fig. 1). However, Brady[1, 2], using a three-dimensional finite element investigation, showed that the rubber would extrude under load, i.e., it would undergo an excessive lateral spread causing substantial tensile shearing forces capable of splitting a rock specimen core.

The use of some sort of fluid to compress the specimen would eliminate shearing forces.

THE FLUID-PAD ASSEMBLY

The prototype design is shown in Fig. 2 and was based on the following considerations in addition to that of strength.

(1) The fluid pad has a narrower diameter in the upper part of the containing ring to aid in sealing the apparatus from fluid leaks when under high pressure (Fig. 3). The hydrostatic fluid pressure acting upwards on the

*This paper was awarded the Institute's student prize for 1971-72.

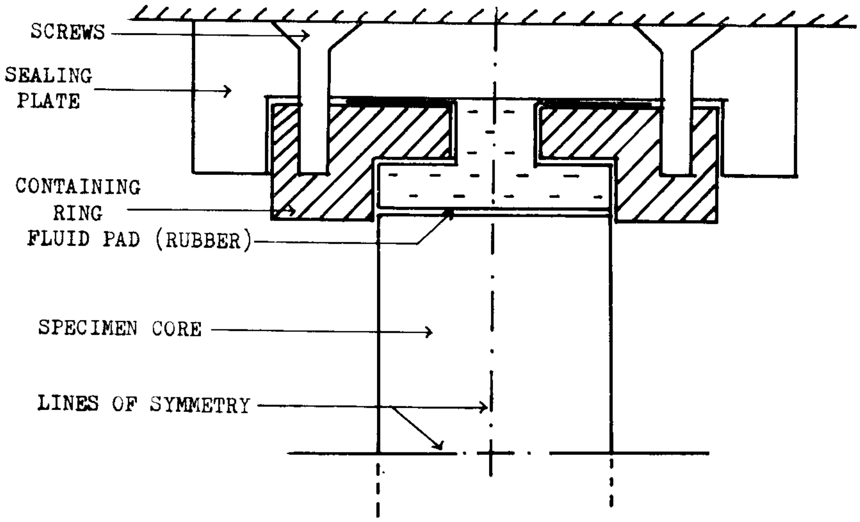

Fig. 2—Section showing prototype fluid-pad assembly

projected plan area provides the force for sealing the rim of the rubber pad between the containing ring and the sealing plate.

(2) The three screws serve the purpose of providing initial sealing pressure, prior to the building up of the hydrostatic fluid pressure that provides the sealing pressure proper.

This prototype pad-assembly was tested with an Amsler compression machine, and a series of modifications was made to the design.

(a) A small hole was drilled through the centre of the sealing plate so that the fluid could be poured in. Since oil attacks latex rubber and is troublesome, mercury was chosen as the fluid.

(b) It was found impossible to rid the rubber pads (filled with mercury) of large air bubbles, even with careful pouring, tilting, and tapping. Hence, the rubber mould and the containing ring were re-designed to have a sloping 'upper roof' to free trapped air bubbles (Fig. 4). This alteration did not affect the projected plan area, and therefore the sealing force. Rubber pads of this shape were then dipped.

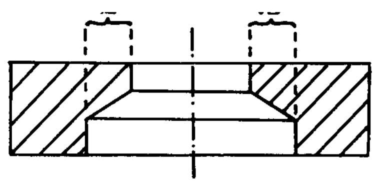

Fig. 4—Section showing sloping 'upper roof' with the same projected plan area as in Fig. 3

(c) A compression test was attempted on a sandstone specimen core. However, mercury started leaking from the seal under very small loads.

It was decided that the pre-load sealing pressure would have to be increased considerably. Consequently, six high-strength steel screws (Allen key type) were fitted to tighten the containing ring against the sealing plate.

As an additional measure, a small 'seal bump' at the inner diameter on the top of the containing ring served to increase the sealing pressure and to ensure sealing on the innermost diameter (Fig. 5).

(d) A test was carried out, and the sealing was successful. However, at a pressure of some 1000 lb/in^2, the rubber pad burst through the small gap between the specimen core and the inside of the containing ring. This gap is necessary to allow for lateral expansion of the core under load:

say $p = 40\,000$ lb/in^2
$E = 10^6$ lb/in^2, and
$v = 0{,}26$.

Then lateral expansion

$$= \Delta x = d \frac{V}{E} p$$

$= 15/1000$ in.

Hence, inner diameter of containing ring

$= 1{,}655 + 0{,}015$
$= 1{,}670$ in (4,24 cm).

To prevent the rubber from bursting out of this 15/1000 in gap, a thin bronze ring was designed to just fit into the containing ring. This ring, it was thought, would not appreciably affect uniform loading, i.e., it would not produce any end effects. The ring was very thin (about 0,1 in by 0,05 in) and had an L-shaped cross-section (Fig. 6).

(e) A successful test was carried out on a sandstone core, which broke at a load of 112 kN, which is equivalent to 12 000 lb/in^2 (pressure in lb/in^2=load in kN × 104,6).

The final design of the fluid-pad assembly is shown in Fig. 7. Two fluid-pad assemblies were made, one for each end of the specimen core.

EXPERIMENTS AND RESULTS

Since the object of the experiment was to measure the strain distri-

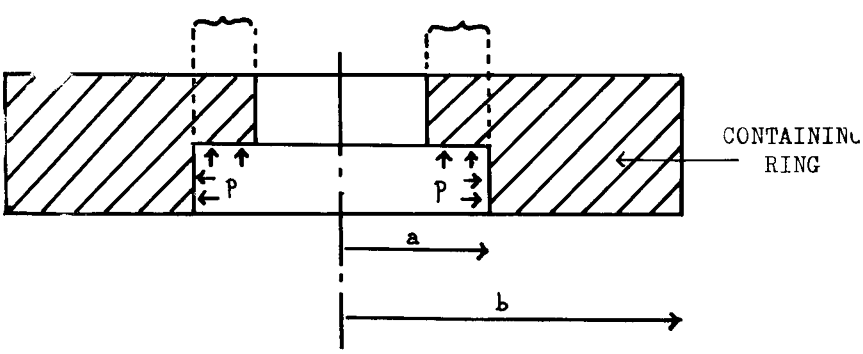

Fig. 3—Section showing hydrostatic fluid pressure acting on the projected plan area

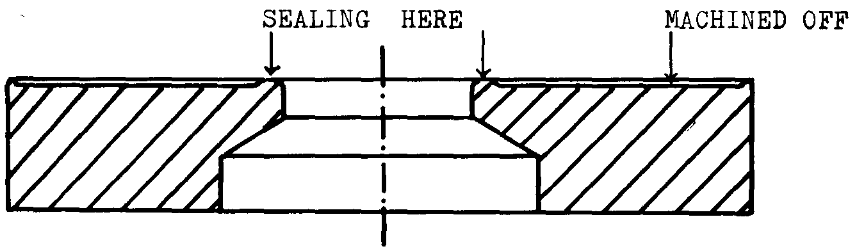

Fig. 5—Section showing how pre-load sealing pressure was increased

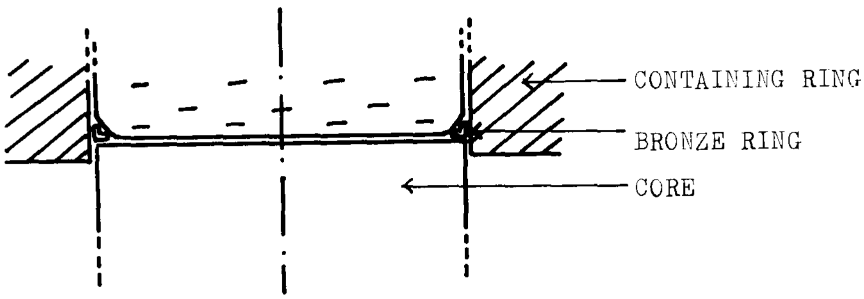

Fig. 6—Section showing bronze ring to hold the rubber pad

bution of a core under various loading conditions, two aluminium cores were machined, instead of rock specimens. The aluminium was selected for its good isotropic properties. Five strain gauges were cemented along each of four equally spaced generators on each core. On core No. 1 they were cemented parallel to the axis of the core (i.e., longitudinally); core No. 2 had the gauges cemented perpendicular to the axis (i.e., laterally). See Fig. 8.

The strain gauges were a Japanese Kyowa make, of the following specification:

Length	10 mm
Resistance	$120 \pm 0{,}3\ \Omega$
Gauge factor	$2{,}00 \pm 1\,\%$.

Schnellklebstoff X60 (HBM) cement was used.

One lead from each of the 20 gauges on each core was commoned, and the other 20 leads on each core were connected to the Huggenburger switchbox and Wheatstone bridge. All connections were soldered to ensure good electrical contact. When one core was being experimented on, the other core (the 'dummy') was connected to com-

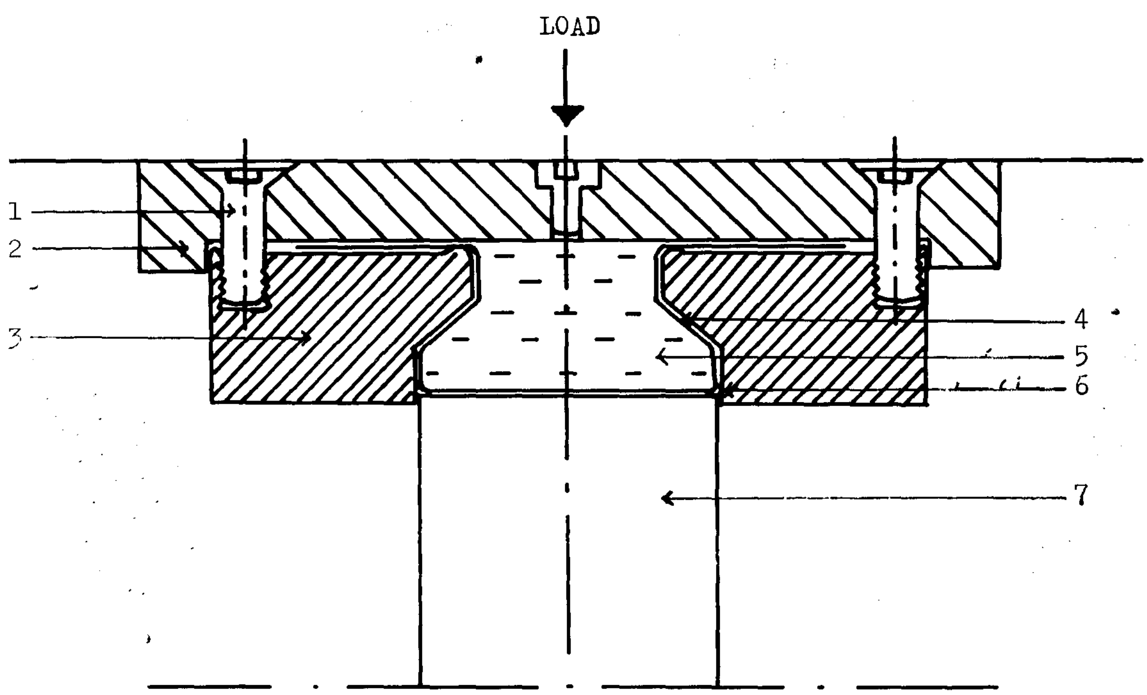

Fig. 7—Section (to scale) of the final fluid-pad assembly
1 = high-tensile screw
2 = sealing plate
3 = containing ring
4 = rubber pad
5 = fluid
6 = bronze ring
7 = specimen core

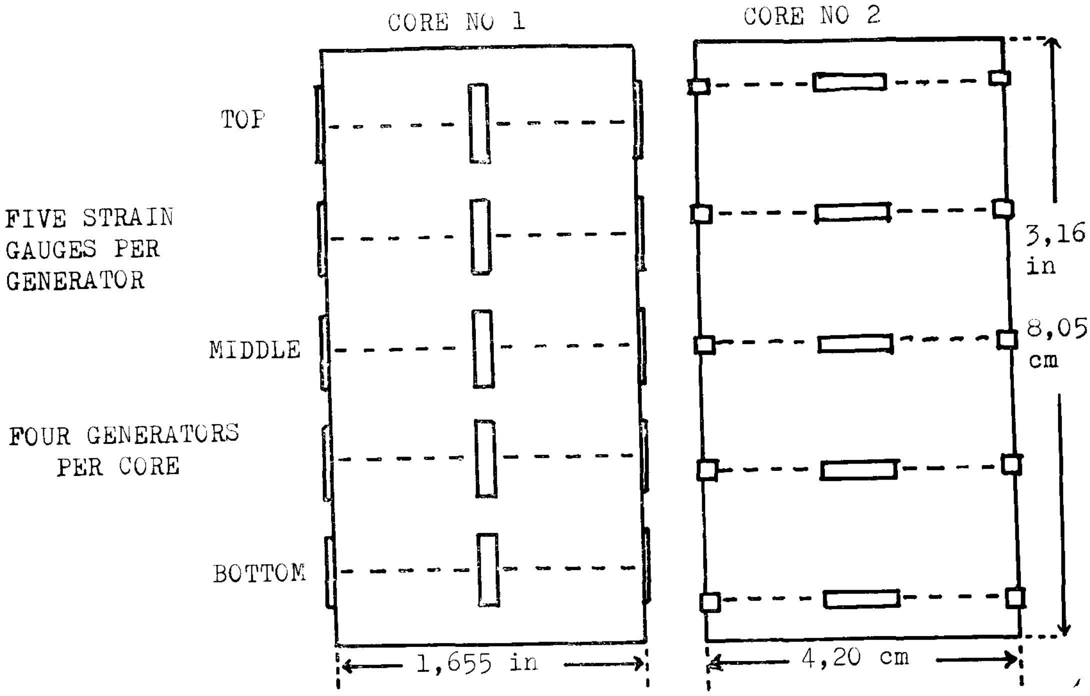

Fig. 8—Experimental set-up (to scale)

pensate for temperature rises in the gauges being read.

The first experiment was to determine the approximate elastic limit of aluminium so that the tests could all be conducted within the elastic limit for comparison purposes. Between steel platens, core No. 1 was loaded in increments of up to 150 kN (about 15 000 lb/in^2), the load-strain curve being plotted as loading progressed. Up to 150 kN, no bend in the linear relationship was evident, so that loads up to 150 kN were assumed within the elastic limit. All the following tests were done under a load of 100 kN (about 10 000 lb/in^2) as this was thought to be of sufficient magnitude to display any differences in the strain distribution between the steel platens and the fluid pads.

In each test, the core was aligned under no load on the Amsler machine, zero readings for each gauge were taken, the core was loaded to 100 kN (10 000 lb/in^2 or 7,2 kN/cm^2), and the final readings on the Huggenburger bridge were taken. The strains for each gauge on the core were then calculated by subtraction of the final reading from the zero reading (in compression positive convention).

Three independent tests were attempted for each loading condition. For example, for core No. 1 and steel platens, three tests were made (Tests No. 1 to No. 3), and, for each test, the core was removed from between the platens and then realigned.

Most of the tests were done on core No. 1, because the strains on this core were larger than those on core No. 2 by the factor $\frac{1}{v}$ (which is about 3,0) and correspondingly more accurate. Hence the comparisons were concentrated on core No. 1.

Because the test results are lengthy, they are not given in this paper. They are summarized diagrammatically in the graphs (Figs. 9 and 10). However, for the purposes of illustration and discussion, one test (Test 4) is shown (Table I).

The strain distributions along the cores in each test, given by the figures in the 'average' column, are shown in the graphs. The figures quoted for strains must be multiplied by a factor of 10^{-2}.

DISCUSSION

As expected, tests 1 to 12 and 13 to 18 on cores 1 and 2 respectively illustrated the significant difference between steel platens and fluid

TABLE I
RESULTS OF TEST 4

Core No. 1—Thick pads with mercury.

	Generator 1	Generator 2	Generator 3	Generator 4	Average (1+2+3+4)/4	Diff. 1 (1−3)/2	Diff. 2 (2−4)/2
Top	1,039 0,981	1,097 0,998	1,050 0,958	0,936 0,943	1,030 0,970	−0,005 +0,011	+0,031 +0,027
Middle	0,956 0,953	0,974 0,961	0,923 0,969	0,960 0,984	0,954 0,967	+0,017 −0,008	+0,003 −0,012
Bottom	1,024	0,978	1,010	1,065	1,019	+0,006	−0,043

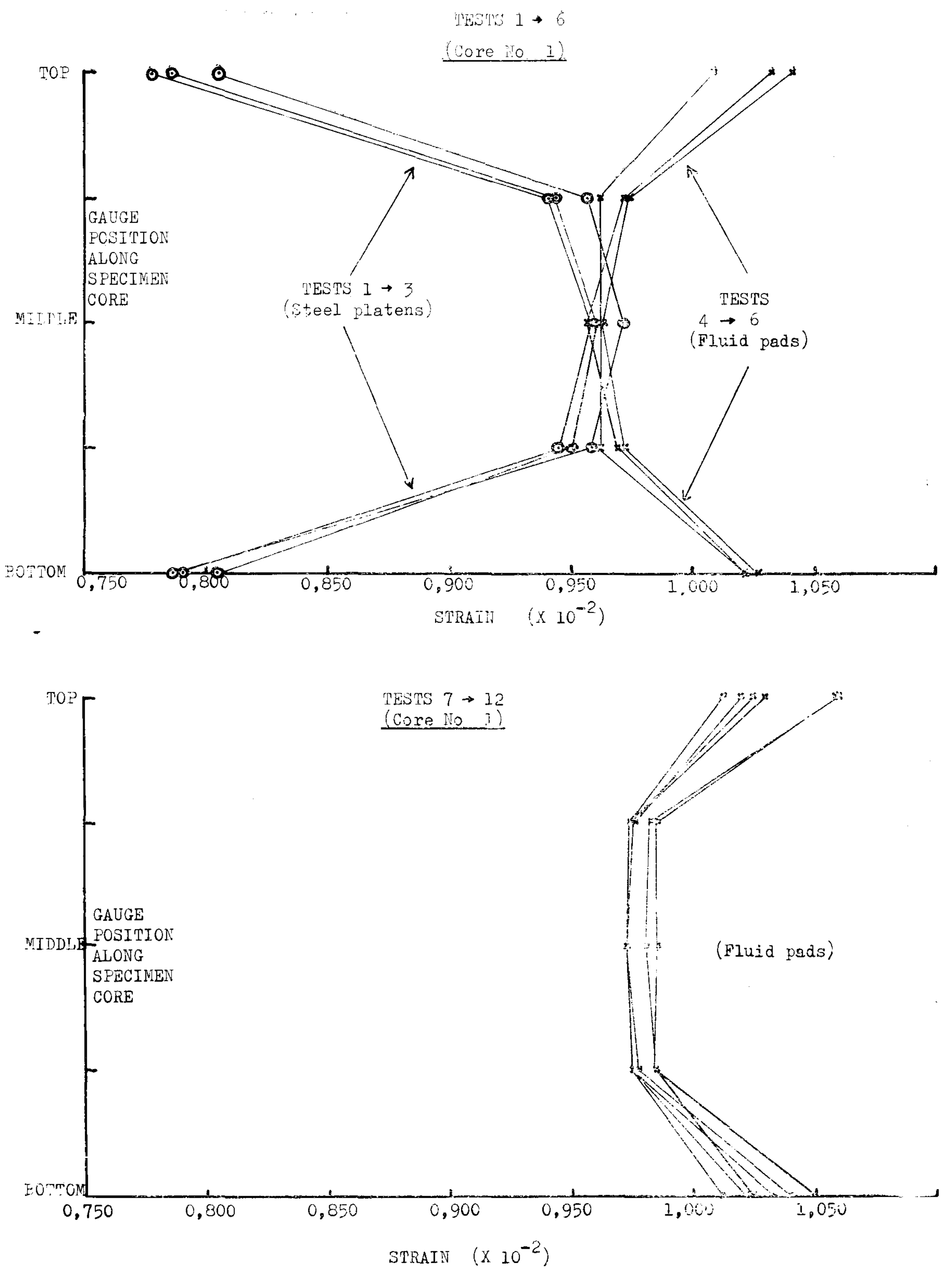

Fig. 9—Results of tests 1 to 12

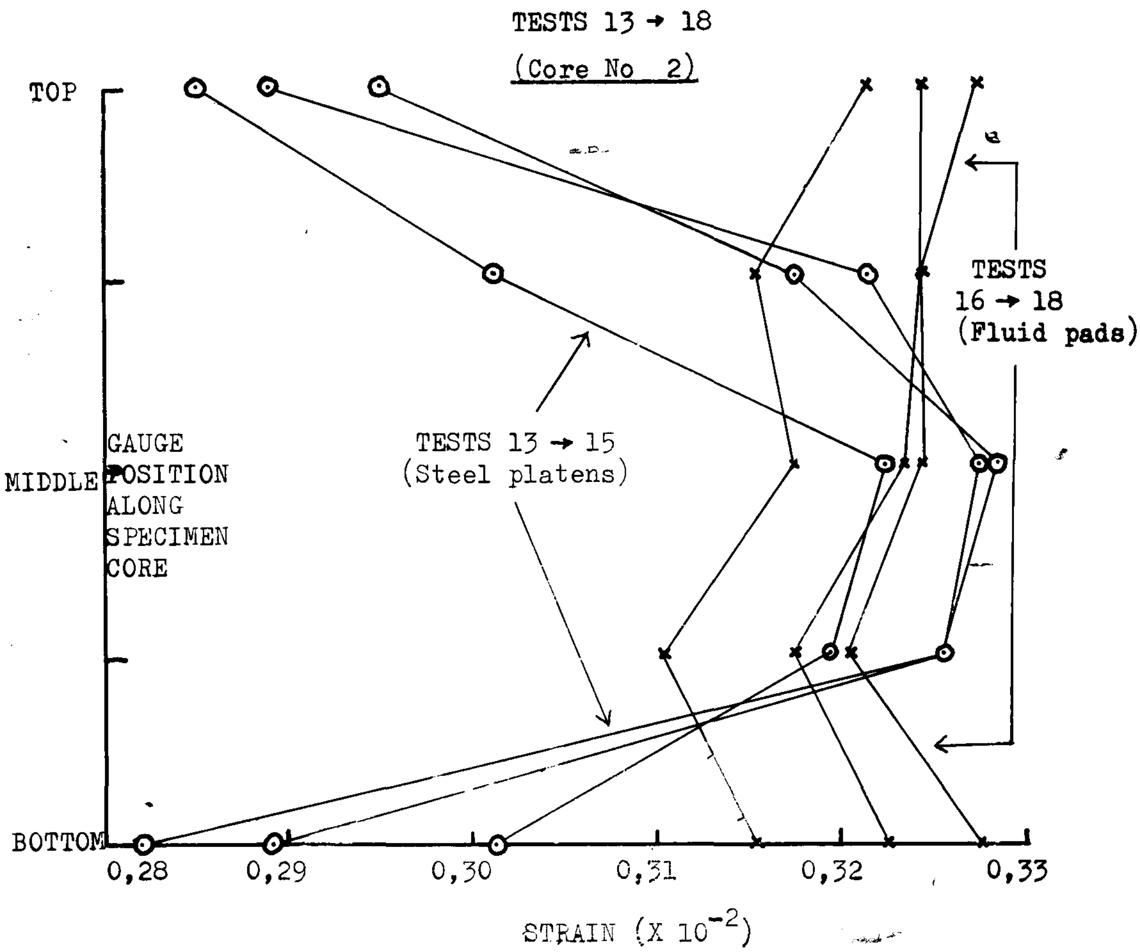

Fig. 10—Results of tests 13 to 18

pads for uniform loading.

Between steel platens, the cores, as predicted, displayed the barrel end effect, i.e., the ends were confined by frictional shearing stresses and were therefore subjected to smaller lateral expansions (see tests 1 to 3, Fig. 9).

However, the strain distributions along the cores between fluid pads, although being significantly more uniform, were subject to an 'over-correction' from the barrel end effect; that is, the ends expanded laterally slightly more than did the middle regions of the specimen core. (Tests 4 to 6, Fig. 9). Not only were the cores between fluid pads more uniformly loaded, but they were also subjected to less bending. This is evident in tests 1 to 6, because the 'diff. 1' and 'diff. 2' for steel platens are much larger than those for fluid pads.

Tests 7 to 12 were aimed at finding the cause for this over-correction in the strain distribution under fluid pads. As mentioned previously, all these subsequent tests were conducted on core No. 1, the strain readings on this core being more accurate.

It was initially suspected that the cause of the correction was the extrusion of the rubber fluid-pad under load, causing substantial tensile shearing forces on the end surfaces and hence larger strains towards the ends. The mechanism of this extrusion process might be as illustrated in Fig. 11.

If this explanation is correct, then the use of a thinner rubber pad will reduce the extrusion of the pad considerably. This was tried out in tests 7 and 8, when pads 0,05 cm in thickness were used, instead of the usual 0,15 cm thick pads. However, the results showed no significant

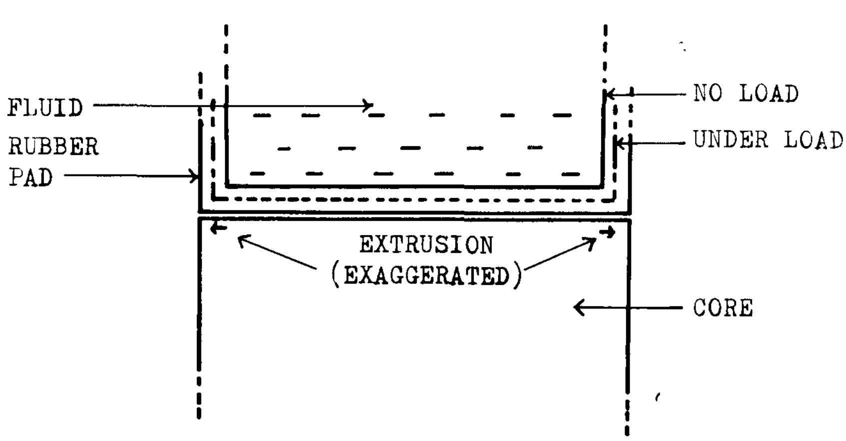

Fig. 11—Section illustrating possible mechanism of the extrusion process

differences. Obviously a more detailed analysis of the extrusion effect is needed.

The bronze ring was also suspected of having caused this extrusion, since, under pressure, the ring would have been pushed outwards by the radial fluid pressure. As the ring was also pushed down onto the core by the pressure, a tensile shearing stress might have resulted from the outwards drag. To test this, the bronze ring in test 6 was carefully cut into four segments; at the outset, these segments would be against the containing ring and no lateral movement would therefore be possible. However, no difference was found, and an over-correction was still evident in the strain distribution. It was therefore concluded that the bronze ring was not the causal factor, probably because it fitted fairly tightly into the containing ring, allowing very little lateral movement.

Oil was tried out as the fluid in tests 9 to 11, and again no variance from the over-correction was found.

Test 12, which had no grease on the pads (unlike the other tests), also failed to show any difference.

The cause of the over-correction then seems to be obscure, but it is possibly due to extrusion of the rubber pad from zero to full load conditions. Obviously, more detailed research and analysis are required before any conclusion can be drawn with some degree of confidence.

SUGGESTIONS FOR FURTHER EXPERIMENTS

Any follow-up tests should aim at an improvement in the design of the fluid-pad assembly (or its equivalent), so that it gives completely uniform loading conditions under load.

Then a series of tests on various rock samples could be carried out in which steel platens are compared with the fluid pads. For example, the ultimate compressive strength of several specimen rock cores might be tested under the two conditions; also, the Young's modulus and Poisson's ratio values might be compared. Correction factors could then be calculated to convert the values for the steel platens to values for uniform loading (fluid-pad). The mining industry, if advised of these factors, would not need to develop the fluid-pad assembly. It is obviously easier to apply correction factors to the values for steel platens (which are already available) than to re-test under uniform loading conditions. Even if the present design of fluid pad is used, these correction factors could still be obtained by interpolation from the graphs presented in this paper.

Other parameters could be tested for differences under the two loading systems. Ratios of length to diameter may show no relationship with stress distribution under fluid pads, and *vice versa* with steel platens. If this is so, then cores with smaller ratios of length to diameter may be tested.

The advantages of testing under uniform loading conditions are obviously numerous.

ACKNOWLEDGEMENTS

Thanks are due to Mr H. A. D. Kirsten and Mr J. P. G. Pretorius (Senior Lecturers at the University of the Witwatersrand), without whom this experiment would not have been possible. Thanks are also due to the Staff in the Research Laboratory in the Mining Department of the University for their assistance and for permitting the use of their equipment.

REFERENCES

1. Brady, B. T. *Int. J. Rock Mech. Min. Sci.*, Mar. 1971.
2. Brady, B. T. *Ibid.*, Jul. 1971.

Notices

FOURTH EUROPEAN CONFERENCE ON PLASTICS AND RUBBERS

The above conference is to be held in Paris from 4th to 7th June, 1974. There will be simultaneous French-English-German translation. Enquiries should be directed to Mr Jean Le Bras, AFICEP, 42 rue Scheffer, Paris 16e, France.

EIGHTH INTERNATIONAL CONFERENCE ON THE PROPERTIES OF WATER AND STEAM

The above conference is to be held in Giens (France) from 23rd to 27th September, 1974. The conference will deal with all the properties of light and heavy water or their mixtures in all their physical states (from gaseous to solid), the experimental determination of these properties, their correlations, and their formulation. Further information is obtainable from The Secretariat, c/o S.F.T., 28 rue de la Source, 75016, Paris.

CONFERENCE ON RE-SHAPING CITIES USING UNDERGROUND CONSTRUCTION

The Australian Tunnelling Committee is organizing a conference on the use and potential of underground construction in urban areas, the aim of the conference being to encourage contact and co-operation between specialists in underground construction and specialists in urban development. The Committee is a technical unit of the Australian Geomechanics Society, jointly sponsored by the Institution of Engineers, Australia, and the Australian Institute of Mining and Metallurgy.

All enquiries relating to the conference, which is to be held in Melbourne on 21st and 22nd October, 1974, should be addressed to: The Secretary, 'Re-shaping Cities Using Underground Construction', Institution of Engineers, Australia, 157 Gloucester Street, Sydney, N.S.W., 2000, Australia.