A 100-MN jacking system for testing coal pillars underground

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ABSTRACT

Already about one-third of South Africa's coal is mined at depths exceeding 100 metres. Almost all this mining is done by the bord and pillar method. Conventional design procedures call for ever larger pillars as depths of workings increase, resulting in the loss of large amounts of coal and reductions in productivity. Barrier pillars are in general use to ensure against large collapses. The presence of these strong pillars would allow a more efficient design of the bord and pillar layout to yield improved extraction ratios by using smaller, yielding, pillars between the bords. Knowledge of the complete load-displacement curves for such pillars is a prerequisite for the design of such a system. A 100-MN, stiff jacking system for measuring the complete load-displacement curves of pillars with cross-sections of up to 2 m X 2 m is described.

The jacks are installed in a slot cut across the central plane of symmetry of a pillar, thereby ensuring that the stress distribution in the pillar during a test, especially at its contacts with the roof and floor, is identical to that caused in a similar pillar by convergence across the seam.

Preliminary results in the form of complete load-displacement curves for test pillars of about 1.5 metre square section are given.

INTRODUCTION

In the bord and pillar system of mining coal, parts of the seam are left unmined to form pillars for the purposes of support. The unmined pillars usually form a regular pattern of square (or rectangular) blocks. In an extensive area which has been mined according to some regular pattern, the maximum load which the pillars may be required to carry is equal to the entire load carried by the seam across the plane of the excavation prior to mining. If the virgin rock stress across the plane of the excavation is σ_v, then the average stress on the pillars, σ_{av}, is given by

$$\sigma_{av}=(A_m+A_p)\ \sigma_v/Ap, \quad \ldots\ldots \quad (1)$$

where A_m = area mined

A_p = area of pillars.

The virgin stress usually results from the weight of the overburden so that (1) may be expressed as

$$\sigma_{av}=H/4(1-e), \quad \ldots\ldots \quad (2)$$

where σ_{av} is in bars

H = depth below surface in metres

e = extraction ratio.

Conventional design procedures require that the load on the pillar given by (2) be less than the strength of the pillar C, which can be expressed (Salamon, 1967)[1] in terms of the height, h, and width, w, of the pillar as

$$C=C_p\ w^{\alpha}/h^{\beta}, \quad \ldots\ldots \quad (3)$$

where α = 0.46,

β = 0.66,

C_p = 71.8 "bars" when w and h are in metres.

The ratio C/σ_{av} can be regarded as the safety factor, S, of the pillar and Salamon, 1967[1] has shown that in most of the S table layouts the value of S lies between 1.3 and 1.9. Furthermore, it has become common to isolate different parts of a mine from one another with extensive barrier pillars of virtually unlimited strength. As a result of this approach, extraction ratios become progressively lower as the depth of mining increases.

Though this approach combines a very high degree of safety with a cheap system of mining the resulting loss of coal reserves and reductions in productivity are becoming less acceptable. The presence of strong barrier pillars allows the possibility of designing a more efficient bord and pillar layout using smaller, yielding pillars to provide roof support between the barrier pillars. This could allow extraction ratios and productivity to be improved without departing from the economic bord and pillar system of mining.

Such a system depends upon using the barrier pillars to carry the bulk of the weight of the overburden while the yielding pillars between the bords provide support to the immediate roof. To appreciate how such a system may work with safety consider what happens as mining proceeds.

Initially that part of the seam which is to be left as a pillar is subject to a stress determined by the weight of the overburden. As mining progresses, the pillar is compressed by convergence between the roof and floor and the stress on it increases. However, if the roof strata are competent, as they must be if they are to bridge the spaces between pillars as is assumed in the derivation of (1), then some of the weight of the overburden must be transferred to neighbouring abutments or barrier pillars in the process of convergence. Where considerable load transfer can take place from the pillars between the bords to abutments or barrier pillars in their vicinity, such pillars can be made so small that they offer much less resistance to convergence between the roof and the floor than those presently designed. Even though they may become crushed as a result of this convergence, these pillars could still provide stable roof support,[2] and apply stresses to the roof sufficient to keep it in place

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yet low enough not to damage the roof by causing excessive cracking. To do this, a knowledge of the complete load-compression curves for the pillars between the bords is essential.

In this paper a method of making the necessary measurements with the required degree of accuracy, and apparatus which has been designed and built for this purpose are described. The results of preliminary tests on pillars of about 1 m square section are also presented.

METHOD AND APPARATUS

The strength of coal pillars is largely dependent upon their shape, particularly their width-to-height ratio as indicated by (3). This arises from the complicated stress distribution in the vicinity of the contacts between the ends of the pillar and the roof and floor of the excavation. The same factor must be expected to have an equally important effect on the deformation of the pillar, especially beyond the elastic limit of the pillar.

Any method of testing the strength or complete load-deformation behaviour of pillars must reproduce these end-effects accurately, if the measurements are to be meaningful for pillars actually used in mining. The best way of reproducing these end-effects in a test pillar is to leave the contacts between the ends of the pillar and the roof and the floor unaltered by the test procedure.

Consider a pillar compressed by a uniform, normal convergence between the roof and floor. If the pillar is of uniform composition and properties and those of the roof and floor are identical to one another, any deformations of the system, elastic or inelastic, are symmetrical about a plane passing through the centre of the pillar and parallel to the roof and floor.

This plane is, therefore, one on which only principal, normal stresses act and remains plane during deformation as a result of convergence between the roof and floor.

The compression of a pillar such as this can be reproduced artificially by forcing the upper and lower halves of the pillar, separated by this plane of symmetry, apart by a uniform amount equal to the convergence, Fig. 1 (Cook, 1967).[3]

Previous methods for testing pillars employed a battery of flat-jacks or hydraulic rams connected in parallel to a pump. (Bieniawski, 1968[4]). In such a system each individual jack generates the same load as every other jack, whatever its position in the pillar, but is able to extend separately according to the reaction of its contact with the test pillar. The result is a uniform distribution of stress normal to the particular cross-section of the pillar across which the load is applied; the displacements being determined by the reaction of the pillar.

The use of strong cappings, such as layers of concrete or steel, between the pillar and the jacks in an attempt to enforce uniform displacement, introduces a high lateral constraint with foreign, poorly-defined, end-effects, and defeats the aim of reproducing the stress distribution of an actual pillar.

For a test on a pillar to be valid, the contacts between the roof and floor must not be altered and a loading technique must be adopted which achieves a uniform separation between the two halves of the pillar across its plane of symmetry with stresses which need not necessarily be uniform and which also allows free lateral expansion of the pillar to occur. Furthermore, if the complete load-displacement curve is to be measured the loading system must be stiff in comparison with the elastic stiffness of the pillar. The elastic stiffness of a coal pillar measuring 2 m cube with a Young's modulus of 35 kbars is 7 MN/m.

These considerations led to the development of a 100 MN, stiff jacking system for measuring the complete load-displacement curves of pillars with cross-sections up to 2 m$\times$2 m, in which 25 hydraulic jacks are separately and individually supplied with equal amounts of hydraulic fluid. A diagram showing the pumps, connections, pressure and displacement gauges, and alternative jack layouts is given in Fig. 2. Fig. 2 (a) shows

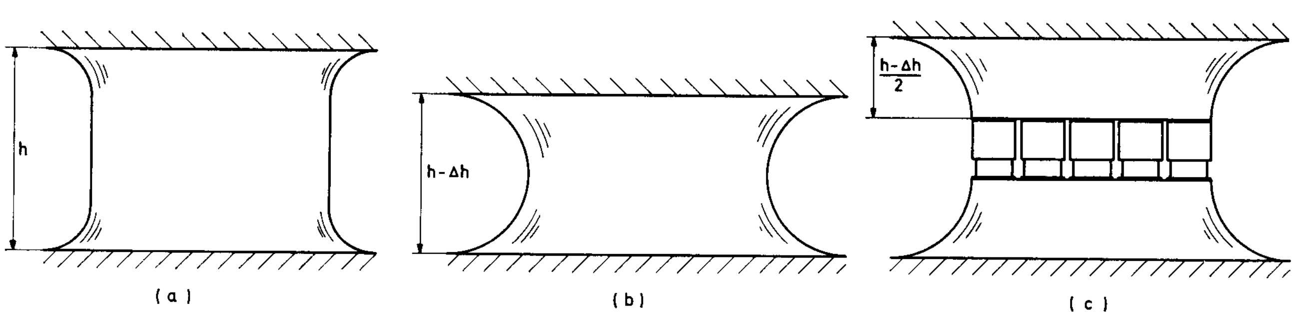

Fig. 1 (a)—A pillar before compression.

Fig. 1 (b)—A pillar which has been compressed by an amount Δh by convergence across an excavation.

Fig. 1 (c)—A pillar each half of which has been compressed by an amount $\Delta h/2$ by jacks installed across its midplane.

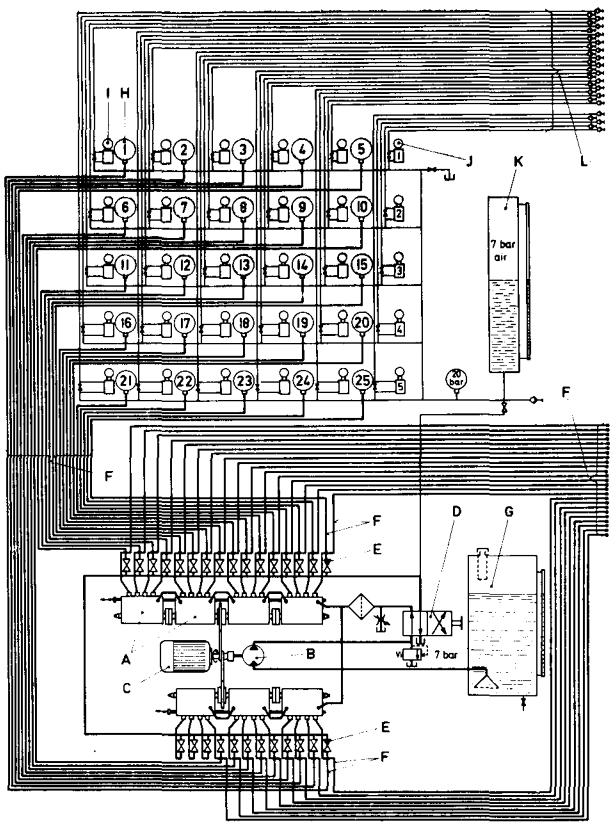

Fig. 2 (a)—Power and control unit

A Diesel injection pumps
B Low-pressure pump
C Electric motor
D Low-pressure control valve
E High-pressure by-pass valves
F Metal tube connections to jacks and gauges
G Oil reservoir
H 1..25 Gauges on control panel (800 bars outer jacks 1 000 bars inner jacks)
I 1..25 Displacement indicators and slave cylinders
J 1..25 Additional slave cylinders for coal displacements. (to be used in future tests)
K Pressure accumulator
L Nylon tube connectors with self-sealing quick couplers

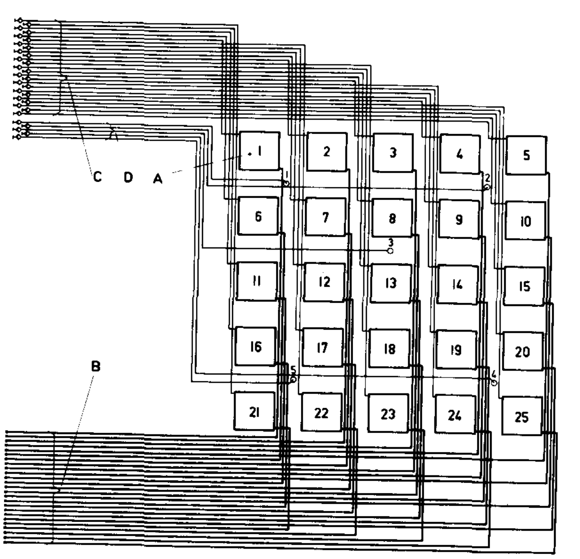

Fig. 2 (b)—Jack connections to 5 X 5 jacks

A 1..25 Loading jacks
B High-pressure metal tubes to jacks
C Low-pressure Nylon tubes to displacement indicators
D 1..5 Additional master rams when required

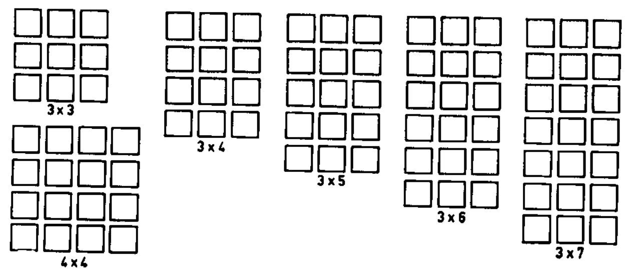

Fig. 2 (c)—Alternative jack arrangements to test the effects of pillar geometry.

the power, control and instrumentation for the jacking system provided by the unit. Seven, four-element, Bosch diesel fuel-injection pumps, (A), are used to provide a separate, accurately-metered, high-pressure supply of oil to each jack. A gear-type pump, (B) supplies low-pressure oil for priming the system, injection pump feed, and for the jack and pillar-displacement monitoring systems. The injection pumps are driven at 600 r.p.m. through a roller chain drive by a 7.5 kW, 1 450 r.p.m. flameproof electric motor which is connected to the pump by a coupling.

The hydraulic jacking system was designed to minimize, as far as possible, losses in stiffness normally found in hydraulic systems. The most serious sources of compliance were traceable to fluid compressibility, vessel dilation, seal deformation, and deflection of jack components carrying load.

The effects of fluid compressibility can be reduced by minimizing the volume of fluid in the system, and by using low working pressures with pistons of large cross-sections. Dilation of containing vessels, including pipes, can be reduced by ensuring that the smallest possible area of the vessel wall relative to its thickness is subjected to fluid pressure. Vessels should be constructed from materials having a high elastic modulus and the use of flexible hoses and other resilient components must be avoided. Compliance due to seal movement and compressibility can be minimized by using seals of small cross-section. Deflection of jack components can be reduced by keeping stresses low and struts as short as is practicable. Because of these considerations all high-pressure connections in the control unit and from the control unit to the jacks are by either 2 mm I.D. × 6 mm O.D. steel or 1.6 mm I.D. ×4.8 mm O.D. copper tubing, and all fittings are of the most compact type obtainable: no flexible hoses are used.

The design of the loading jack, as can be seen from Fig. 3, is simple. The piston, which is of cast iron, is sealed by a rubber 'O' ring of 3.2 mm section diameter, backed up by a leather anti-extrusion ring. Locating the seal near the crown of the piston ensures that only a small area of cylinder wall is subjected to fluid pressure, so that support by the end plate and by the unstressed cylinder beyond the seal contribute to the strength and stiffness of the jack. When the jack is at its minimum height, the volume of the oil contained in the clearance spaces is negligible.

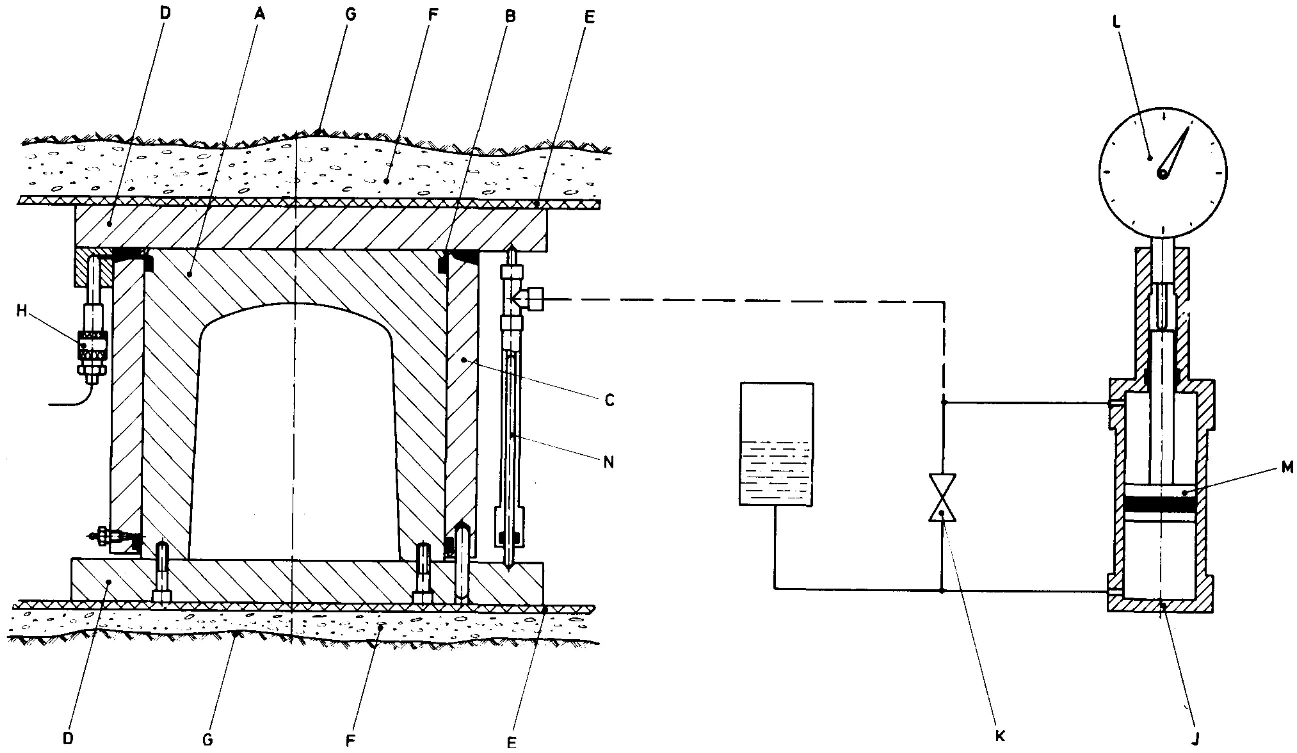

Fig. 3—Jack with master ram in position and showing connection to slave cylinder
A Piston
B Piston seal
C Cylinder
D Top and bottom plates
E Masonite
F Sand
G Coal
H High-pressure quick connector
J Slave cylinder
K Transfer valve for zero setting
L Dial test indicator
M Double-acting piston

Tests on the jacks indicated that at pressures of up to 450 bar the 'O' ring seal without an anti-extrusion ring was satisfactory, but at higher pressures extrusion of the 'O' ring into the clearance spaces occurred, causing damage to the seals and difficulty in closing the jacks. With leather anti-extrusion rings, 'O' rings have behaved perfectly at pressures up to the maximum of 1 000 bars at a jack extension of 100 mm, with no sign of extrusion or other damage. This performance is in part due to good cylinder finish and in part due to the small radial clearance of 0.025 mm between piston and cylinder.

Jack cylinders are fabricated from 0.35 per cent carbon steel mechanical tube welded to a 38-mm thick end-plate of mild steel. The cylinder bores are machined and ground to 254 mm diameter. An inverted lip-seal is used at the outer end of the cylinder to exclude dirt. Eccentric loading of the jacks at the boundaries of the pillar was anticipated and allowed for by using a comparatively long steel cylinder to act as a guide for the cast iron piston.

The weight of the jack is about 180 kg, and to facilitate placing them in a deep slot in the pillar a roller trestle which supports a long inserting beam is used. The beam is fitted at one end with pegs which engage sockets in the edge of the jack end-plate while at the other end there is a large hand grip onto which several men can hold at the same time.

Each jack is connected to its individual pressure gauge mounted on the panel of the control unit. Initially the needles of these gauges suffered from large amplitude oscillations caused by pressure pulsations resulting from the use of a plunger type pump feeding a small-volume, high-stiffness system and could not be cured by fitting restriction orifices to the gauges. Glycerine,filled gauges fitted with restrictors had to be used before needle oscillation was reduced to within acceptable limits.

The expansion of each jack is indicated by a dial test indicator mounted on the control panel adjacent to the pressure gauge for each jack. Movement of the jack piston causes movement of the ram in an hydraulic master cylinder placed between the top and bottom plates of the jacks, Fig. 3. The master cylinder is connected by thin-bore, Nylon tubing to the annulus side of the double-acting piston in the slave cylinder on the control panel. The constant volume of oil between the master ram and slave pistons is kept at a constant pressure by an air accumulator pressurized to 10 bars which is connected to the crown side of the slave piston. This accumulator acts as a spring, keeping the master ram in firm contact with the jack plates at all times, whether the jack is expanding or contracting. Movement of the slave piston rod is transmitted to the dial indicator and is exactly proportional to the extent of jack movement.

EXPERIMENTS AND RESULTS

Preliminary tests have been made on pillars with cross-sectional areas from 0.36 m^2 to 2.32 m^2 at the South Mine, No. 1 Shaft of Usutu Coal Mines, Limited.

The test pillars were cut with a universal boom cutter, from the corners of existing pillars situated near the edge of a panel.

Experience has now shown that the best procedure is to cut off the corner of an existing pillar as far in as is conveniently possible, to create the outside faces of the test pillar, removing at least a metre of the weathered and highly-strained coal from the edge of the pillar. A vertical cut of the appropriate height and distance from the one edge of the test pillar is then made to delineate the other side face. A similar vertical cut is also made behind, and parallel to, the other of the first cuts to form an isolated pillar. It has been found preferable to make the horizontal cut through the middle of the test pillar, which has to be a double cut so as to provide 0.3 m to 0.35 m of space for the installation of the jacks, before making the final cut behind the pillar.

After a test pillar has been cut, it is cleaned and carefully inspected for structures and damage which may influence the test result. The distance between the top and bottom surfaces of the horizontal slot in which the jacks will be installed is measured, and these surfaces are dressed by hand to remove all irregularities exceeding 1 cm in height and to provide just sufficient space for the jacking system. The cross-sectional and vertical dimensions of the test pillar are measured to $\pm$ 1cm. Two holes about 1 cm in diameter are drilled at the centre of the cross-section to a depth of 3 cm to 5 cm into the top and bottom halves of the pillar and expanding bolts, to which levelling scales are attached by springs, are installed between these.

The lower surface of the horizontal slot is carefully smoothed and flattened with a thin layer of fine river sand, nowhere more than 1 cm thick. This entire surface is then covered with a sheet of 'Masonite' 3 mm thick, in which a hole for the levelling bolt is left. With the aid of an adjustable trestle and lever, the jacks are installed, according to a pre-planned pattern. When all the jacks are in place and have been connected to their hydraulic pumps, another 'Masonite' sheet covered by a layer of fine sand about 1 cm thick is slid into the space between the top of the jacks and the upper half of the test pillar. A preload of about 30 bars hydraulic pressure is then applied to all the jacks to take up any irregularity in the thickness of the horizontal slot and to compact the smoothing sand. The hydraulic master rams for recording jack expansion during the test are then inserted between the top and bottom plates of each jack, and the dial gauges, connected to the expansion slave cylinders on the control panel, are set to zero.

At the beginning of the test the control on the injection pumps is set to deliver identical quantities of oil at the desired rate to each jack, and the zero positions of the levelling scales are measured with a precise level situated about 10 m from the test pillar. As the jacks expand, the expansion of each jack and the pressure in it are recorded at regular intervals by photographing the dial and pressure gauges on the control panel with a 'Polaroid' camera. Jack pressures can be read from these photographs to an accuracy of ± 2 bars and expansion to within ± 0.01 mm. At the same time, the displace-

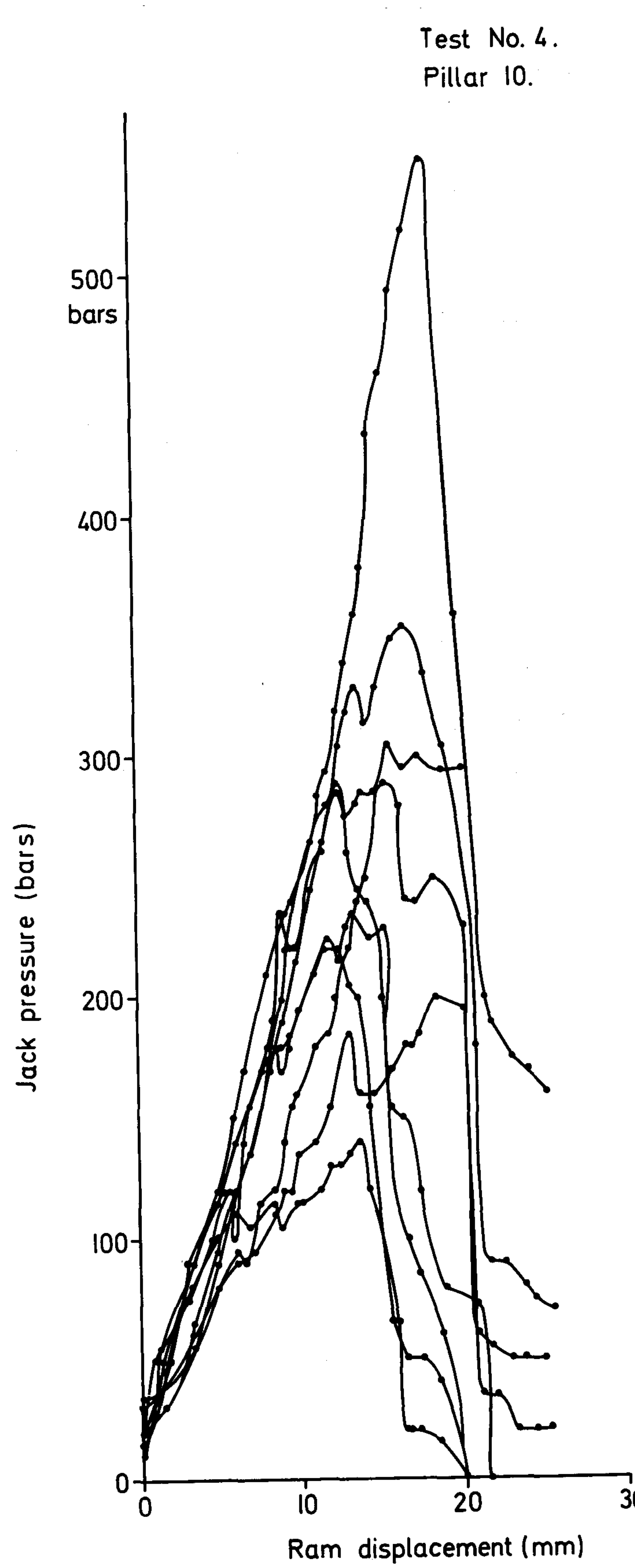

Fig. 4 (a)—Curves of jack pressure against jack expansion for individual jacks.

ment of the top and bottom surfaces of the horizontal slot are read with the precision level to an accuracy of ± 0.003 mm.

From the photographs, the expansion of, and pressure in, each jack can be read and plotted at intervals of about 1 mm to 1.5 mm of expansion. The absolute displacements of the top and bottom surfaces of the two halves of the test pillar are obtained from the levelling measurements. The latter measurements have proved to be meaningful only while the pillar is undergoing elastic compression; becoming erratic near and beyond the peak load. However, these measurements provide the only data on pillar compression until near peak load, because the measurements of jack expansion include the non-linear compression of the sand fill under and above the jacks. However, when the load is near maximum the measurements of jack expansion provide an accurate measurement of the compression of the pillar as happens when the load is falling, because the unloading modulus of the sand is at least an order of magnitude greater than its loading modulus (Jaeger and Cook, 1969)[5].

A plot of jack pressure against jack expansion, as read off the photographs, is shown in Fig. 4 (a). From this plot the stresses on the portions of the pillar above and below each jack are determined at regular intervals of expansion and an average pillar stress against jack expansion curve for that pillar, Fig. 4 (b), is obtained. Also plotted on this Figure are the actual expansion between the upper and lower halves of the pillar, as given by the difference between the two level readings, and the amount by which the two halves of the pillar indent the floor and roof, calculated from the usual equations for the elastic indentation of a semi-infinite body (Timoshenko and Goodier, 1951)[6]. The nett compression of the pillar, shown in Fig. 4 (c), as the average stress on the pillar against nett pillar compression, is determined as follows:

(i) *Elastic compression.* In this range the nett pillar compression is given by the difference in level readings, minus the combined elastic indentation of the floor and the roof.

(ii) *Brittle compression.* Once the pillar begins to yield the nett compression is given by the measured jack expansion plus the elastic rebound of the roof and floor due to the diminishing pillar load; the elastic rebound of the filling sand being negligibly small.

The first tests in January,1970, in which only four jacks were used, were done mainly to test the system, because so few jacks could hardly be expected to approximate the variable normal stress across the pillar and allow free lateral expansion with any degree of accuracy. Furthermore, even arrangements of jacks, such as 2×2 jacks and 4×4 jacks, are not preferred because the lateral expansion of the pillar tends to be concentrated into the two straight gaps between the jacks which run through the centre of the cross-section, dividing the pillar into four quadrants.

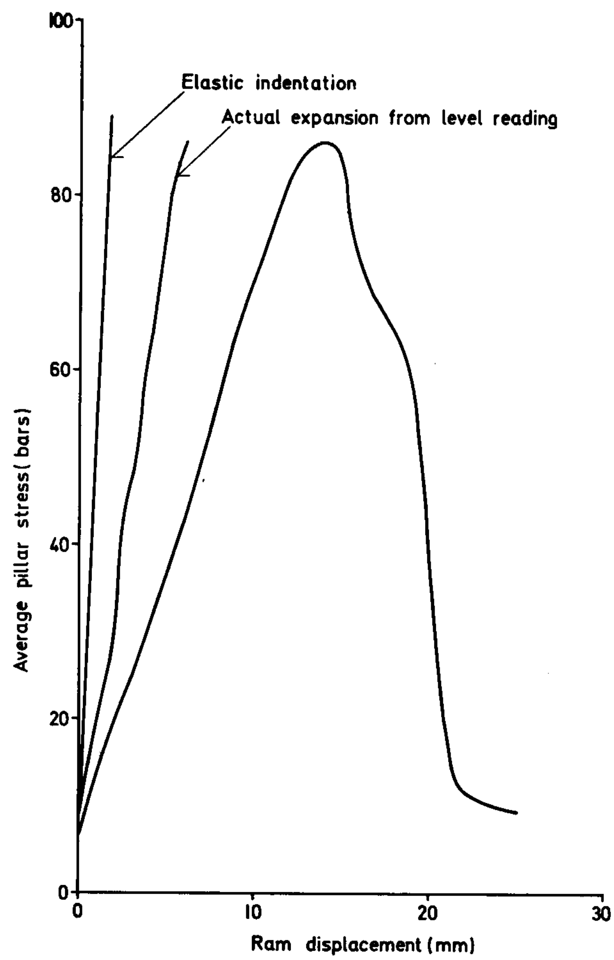

Fig. 4 (b)—Plot of average pillar stress against jack expansion, as determined from 4 (a).

At first it was also feared that one or other half of a pillar sliced symmetrically in two might prove to be sufficiently weaker than the other half to cause only the weaker half to fail. Accordingly, the lower halves of the first five pillars were made twice as high as their upper halves to ensure that the lower half would fail. This asymmetry is not desirable because it partially defeats the main purpose of this method of testing, namely to reproduce as accurately as possible the stress and displacement conditions obtaining when a pillar is compressed by convergence between the roof and floor. Nevertheless, in the first tests it enabled attention to be concentrated on the failure of one half of the pillar. Subsequently, it was found that both halves of a symmetrically sliced pillar fail and the next eight pillars were all bisected equally.

Average stress-compression curves for only two of the first six pillars tested with 4 jacks are given, Figs. 5 and 6, though the measured strengths of all the pillars tested are plotted as a function of their width to height ratio in Fig. 7, where they are compared with strength values, calculated from (3), for pillars of 1 m and 2 m height covering the range of the test pillars. Of the second series of tests using up to ten jacks, average stress-compression curves for two of the seven pillars are given.

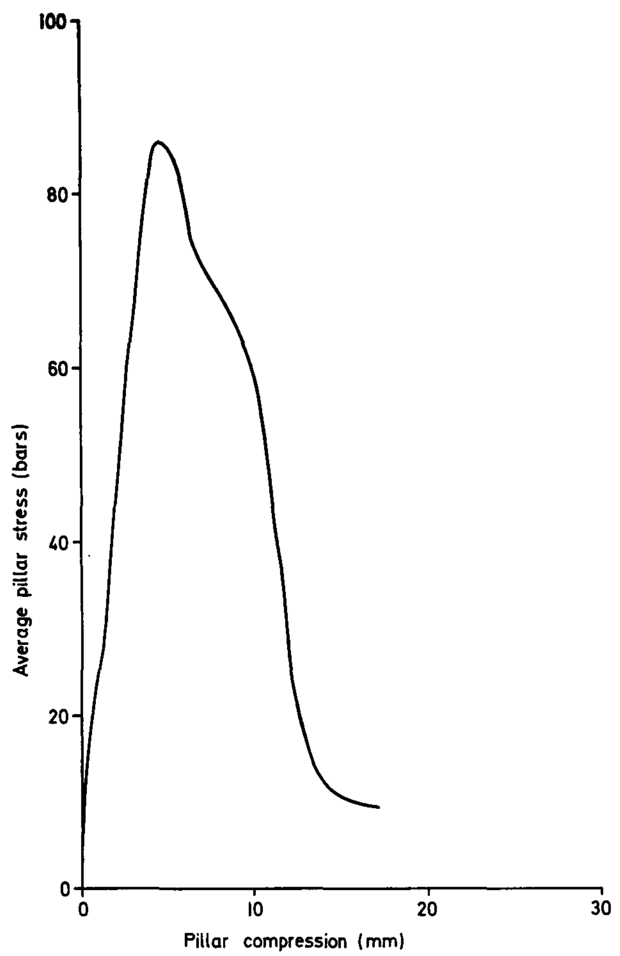

Fig. 4 (c)—Average stress against nett pillar compression as determined from 4 (b).

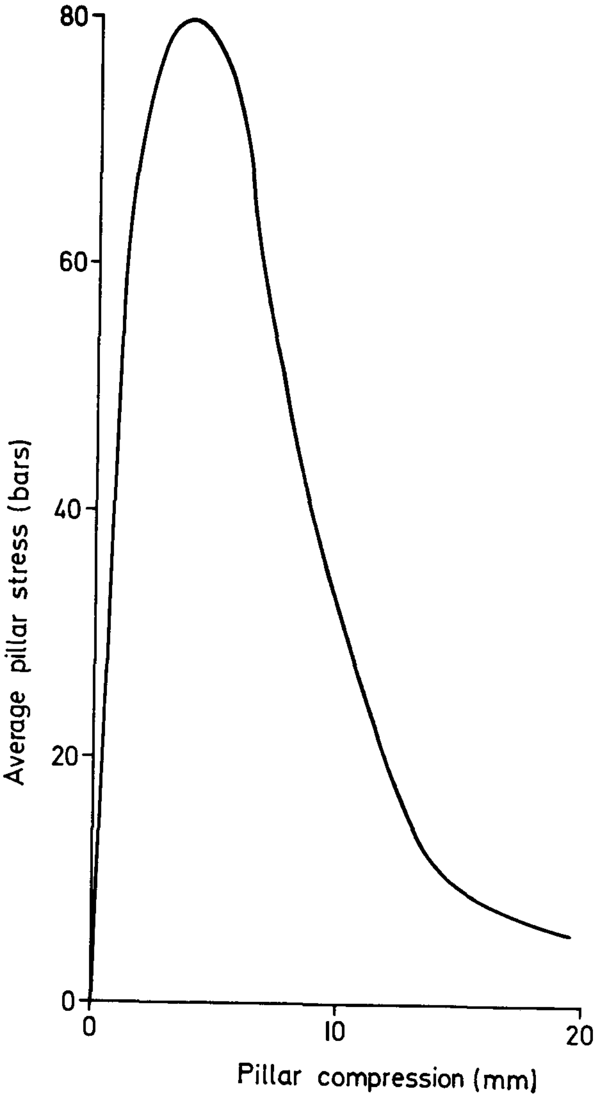

Fig. 6—Average pillar stress against nett pillar compression for a pillar 104 cm X 79 cm X 86 cm high using 2 X 2 jacks.

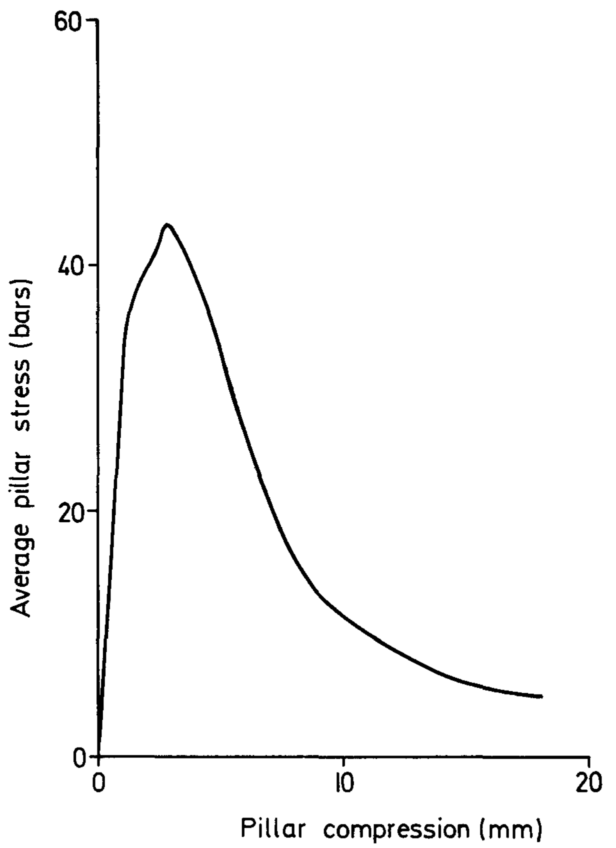

Fig. 5—Average pillar stress against nett pillar compression for a pillar 94 cm X 79 cm X 178 cm high using 2 X 2 jacks.

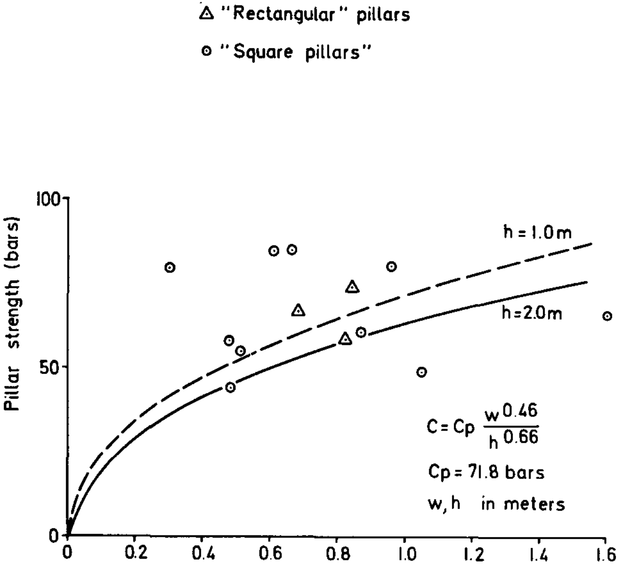

Fig. 7—Measured strengths of all pillars tested, as a function of their width to height ratio.

("rectangular" pillars, m x n jacks; "square" pillars, m x m jacks)

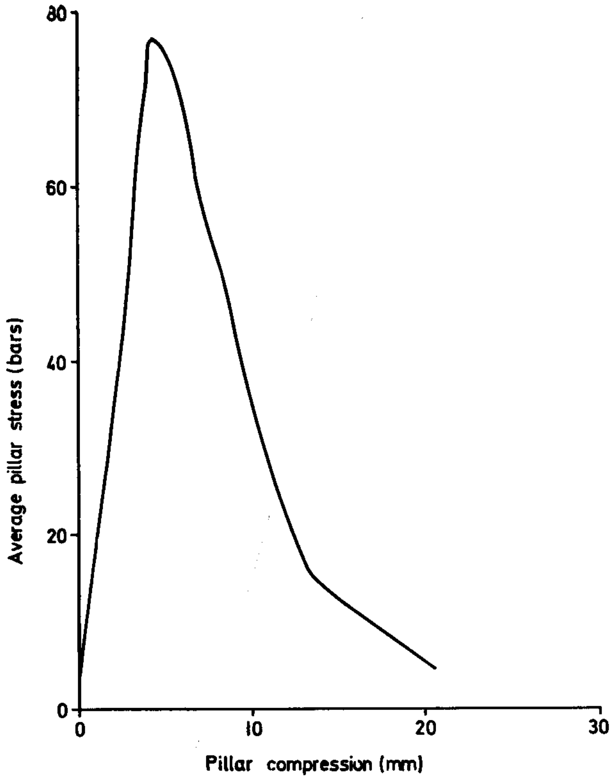

Fig. 8 (a)—Average pillar stress against pillar compression for a pillar 145 cm X 85 cm X 135 cm high using 2 X 4 jacks.

Fig. 8 (a) shows the average stress-compression curve for a rectangular pillar 145 cm × 85 cm × 135 cm high, with 2 × 4 jacks, and Fig. 8 (b) the stress-compression curves for the two pairs of four symmetrical corner and inside jacks. The dimensions of this pillar normal to its length are similar to those of the pillar from which the results of Fig. 5 were obtained. Notice that the stress-compression curves of the corner jacks of the rectangular pillar are similar to those of the square pillar, especially beyond the peak stress, and that the central portion of the rectangular pillar is almost twice as strong as its corners or the square pillar, indicating that the use of (3) to estimate the strength of rectangular pillars (Salamon, 1967)[1] is most conservative.

Figs. 9 (a), (b), show the stress-compression curves for the two sets of four symmetrically-placed jacks and the central jack when using 3 × 3 jacks, and the average stress-compression curves for the pillar. The pillar had dimensions of 125 cm × 104 cm × 170 cm high.

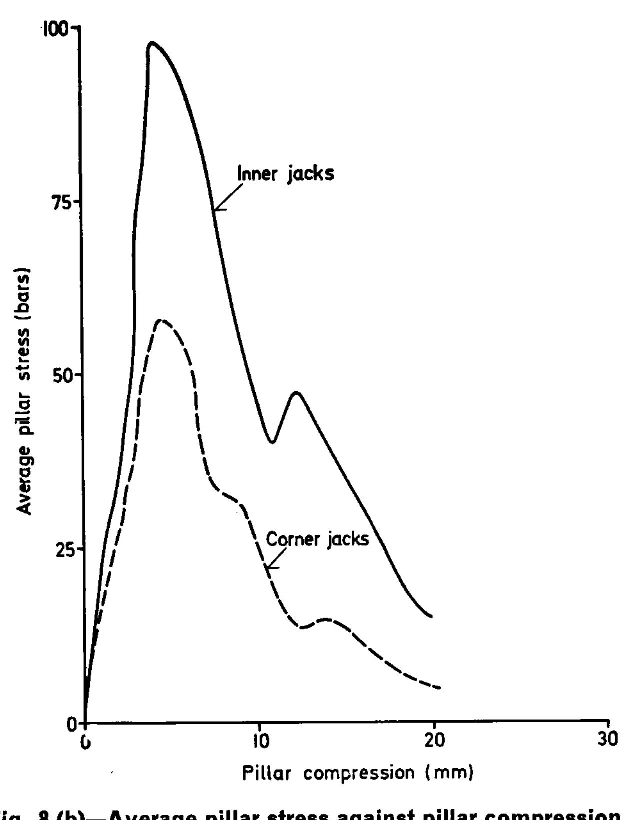

Fig. 8 (b)—Average pillar stress against pillar compression for the two pairs of four symmetrical corner and inside jacks for pillar referred to in Fig. 8 (a).

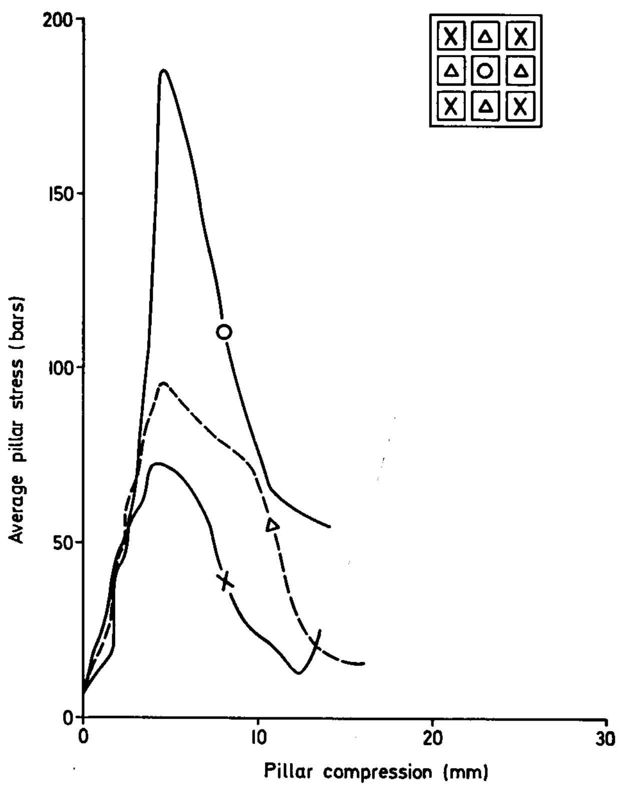

Fig. 9 (a)—Stress-compression curves for two sets of four symmetrically placed jacks and central jack for pillar referred to in Fig. 9 (b).

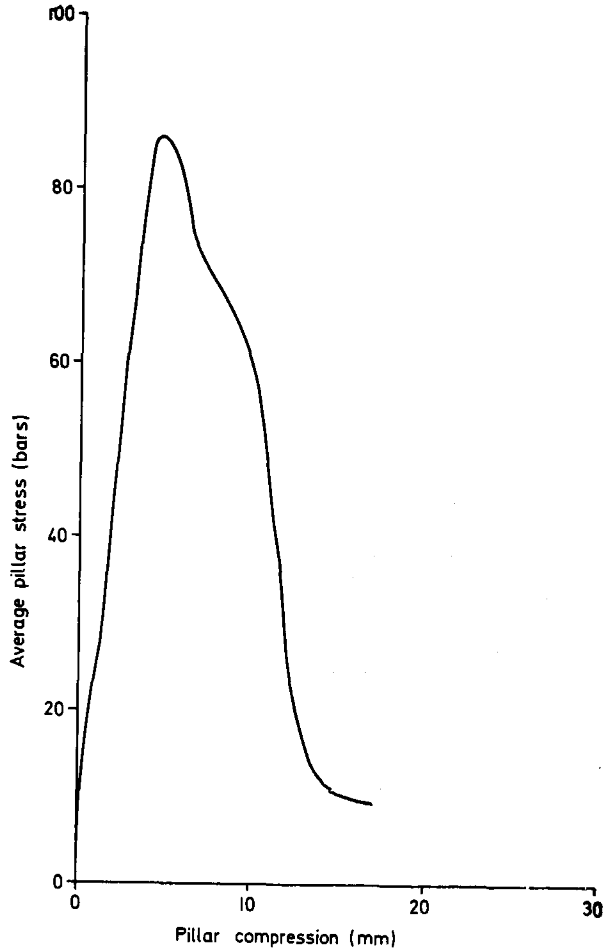

Fig. 9 (b)—Stress-compression curve for pillar 125 cm X 104 cm X 170 cm high using 3 X 3 jacks.

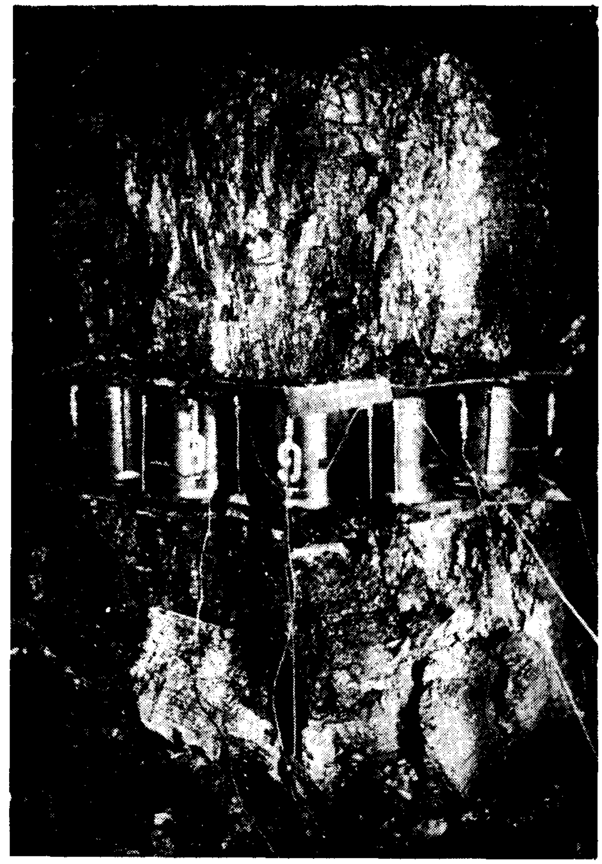

Fig. 10—Test completed. Pillar severely crushed but kep intact by residual pillar strength of the order of a few bars

CONCLUSION

Initial tests using only nine of the eventual 25 jacks of a stiff system for testing coal pillars underground have shown that it is possible to measure the complete average stress-compression curves of test pillars and to obtain a picture of the stress distribution-compression curves by combining the measurements from symmetrically situated jacks. The average strength of the pillars has been found to be of the same order as that given by equation (3) but the scatter in the values is such as to mask any effect due to width-to-height ratio or size in the range covered by the tests to date. However, the strength of the central portions of rectangular pillars was observed to be about twice as great as that of their corners or of square pillars of similar dimensions.

Earlier fears that one of the two halves of an equally sliced pillar might fail first and absorb all the deformation seem to be unfounded. In the testing of symmetrical pillars it was usually found that the top half started 'talking' and cracking from about two-thirds of the maximum load. Near maximum load the bottom half began to fail and compression past the point of maximum load was accompanied by heavy bumping and slabbing of the pillar. These seismic noises seem to be sufficiently characteristic to be indicative of the state of stress and deformation of a pillar and will be recorded in future tests.

The elastic moduli in loading the pillars were found to be of the order of 20 to 50 kbars and the brittle moduli during yielding of the order of 5 kbars.

In the course of each test the pillars were deformed by about 20 mm and retained a residual strength of the order of a few bars, Fig. 10. The pieces of a crushed pillar could only be separated forcibly and left behind a core with sufficient cohesion to hang under its own weight, Fig. 11. A residual strength of only 1 bar for a crushed pillar is sufficient to provide roof support of 0.1 MN/m^2 of pillar cross-section. If a stable bord and pillar system can be designed using yielding pillars not only will the extraction ratio be improved, but the possibility of damaging the roof as a result of high stresses from strong pillars will also be avoided.

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Fig. 11—Core of pillar after testing and barring, retaining sufficient residual strength to hang under its own weight.

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REFERENCES

1. Salamon, M. D. G. 'A method of designing bord and pillar workings'. *Jl. S. Afr. Inst. Min. Metall., 68,* (2), 1967, 68-78.

2. Salamon, M. D. G. 'Stability, instability and design of pillar workings'. *Int. J. Rock Mech. Min. Sci., 7,* 1970, 613-631.

3. Cook, N. G. W. Contribution to: 'A study of the strength of coal pillars', by M. D. G. Salamon and A. H. Munro — and 'A method of designing bord and pillar workings', by M. D. G. Salamon. *Jl. S. Afr. Inst. Min. Metall., 68,* (2), 1967, 55, 68.

4. Bieniawski, Z. T. 'Note on the *in situ* testing of the strength of coal pillars'. *Jl. S. Afr. Inst. Min. Metall., 68,* (10), 1968, 455-465.

5. Jaeger, J. C., and Cook, N. G. W. 'Fundamentals of Rock Mechanics', Methuen, 1969, 385-386.

6. Timoshenko, S. P., and Goodier, J. N. 'Theory of Elasticity'. McGraw-Hill Book Company, 1951, 366-372.