# In situ complete stress-strain characteristics of large coal specimens

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**SYNOPSIS**

The significance of *in situ* tests on large coal specimens is briefly reviewed. Tests aimed at obtaining complete stress-strain characteristics of large coal specimens with high width-to-height ratios are described. A formula for the relationship between strength and width-to-height ratios of coal pillars is proposed, and the influence of width-to-height ratios on the deformation characteristics of pillars is discussed.

**SAMEVATTING**

Die betekenis van *in situ* toetse wat op groot steenkoolmonsters uitgevoer word, word kortliks hersien. Toetse wat daarop gemik was om die volledige spannings-vervormingsgedrag van groot steenkoolmonsters, met groot wydte tot hoogte verhoudings, te bepaal word beskryf. 'n Formule vir die verband tussen sterkte en wydte tot hoogte verhoudings van steenkoolpilare word voorgestel en die invloed van wydte tot hoogte verhoudings op die vervormingsgedrag van pilare word bespreek.

## INTRODUCTION

Most of South Africa's coal is mined by the bord-and-pillar method, in which the pillars form a regular pattern of square or rectangular blocks. Different panels of a mine are separated from one another by large barrier pillars of great load-bearing capacity.

Conventional design procedures require that the strength of a coal pillar should be greater than the stress to which it will be subjected, so that, in this approach, the strength of the pillar is of major importance to the planning of a mine layout. *In situ* tests were carried out on large coal specimens, during which various sizes of coal specimens up to a maximum cross-section of 2 m by 2 m and width-to-height ratios of up to 3,1 were loaded to failure *in situ*[1-3] in order to obtain strength data.

The presence of barrier pillars between panels permits the design of a more efficient bord-and-pillar layout using smaller, yielding pillars to provide roof support between the barrier pillars. However, for this approach it is not only the strength that is of importance, but also the post-failure deformation characteristics of the coal pillars.

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Tests aimed at obtaining this information were carried out[4,5] and yielded data for specimens of various sizes and width-to-height ratios of up to 2,2. In South Africa, coal pillars with width-to-height ratios of up to 5,0 are used in some mines, and it is therefore important to determine empirical formulae for coal pillars having width-to-height ratios of greater than 2,2, the maximum width-to-height ratio for which data are available.

## STRESS-STRAIN CHARACTERISTICS OF COAL SPECIMENS

### 'Complete' Load-deformation Curve

If a rock or coal specimen is tested under uniaxial compression, as depicted in Fig. 1, a load-deformation curve of the type shown by the graph of Fig. 1 is obtained. The load recorded is a measure of the change in resistance of the specimen with increasing deformation, and a number of phases of this phenomenon can be discerned. First, the resistance increases almost linearly with the deformation (elastic phase). Then, the curve becomes concave (plastic and crack-propagation phase) until it attains a maximum, which can be termed *ultimate resistance* or *strength failure stress*, since at this stage the specimen fails in the sense that it is no longer a body with a compact appearance but an aggregate of pieces separated by cracks. This, however, does not mean that a failed or cracked specimen has no further resistance. The curve of Fig. 1 shows that the resistance decreases with increasing deformation but that it is still present, i.e. the specimen does not collapse or disintegrate. Whether one obtains information on the resistance of the specimen after strength failure depends upon the testing machine. In the course of the test, an ordinary testing machine, as a result of its elasticity, is also deformed, its deformation being in the opposite direction to that of the specimen. As soon as the resistance of the specimen drops a little at strength failure, the machine releases all its energy stored as a result of the machine deformation, onto the specimen, which consequently collapses so that the part of the curve between A and B in Fig. 1 cannot be obtained. If, however, the machine is made stiff, it cannot deform much, and consequently it cannot store a large amount of energy; thus the specimen does not collapse at strength failure but its resistance drops gradually with increasing deformation as shown in Fig. 1. In large-scale tests, the 'testing machine' is replaced by a 'testing arrangement', as will be discussed later.

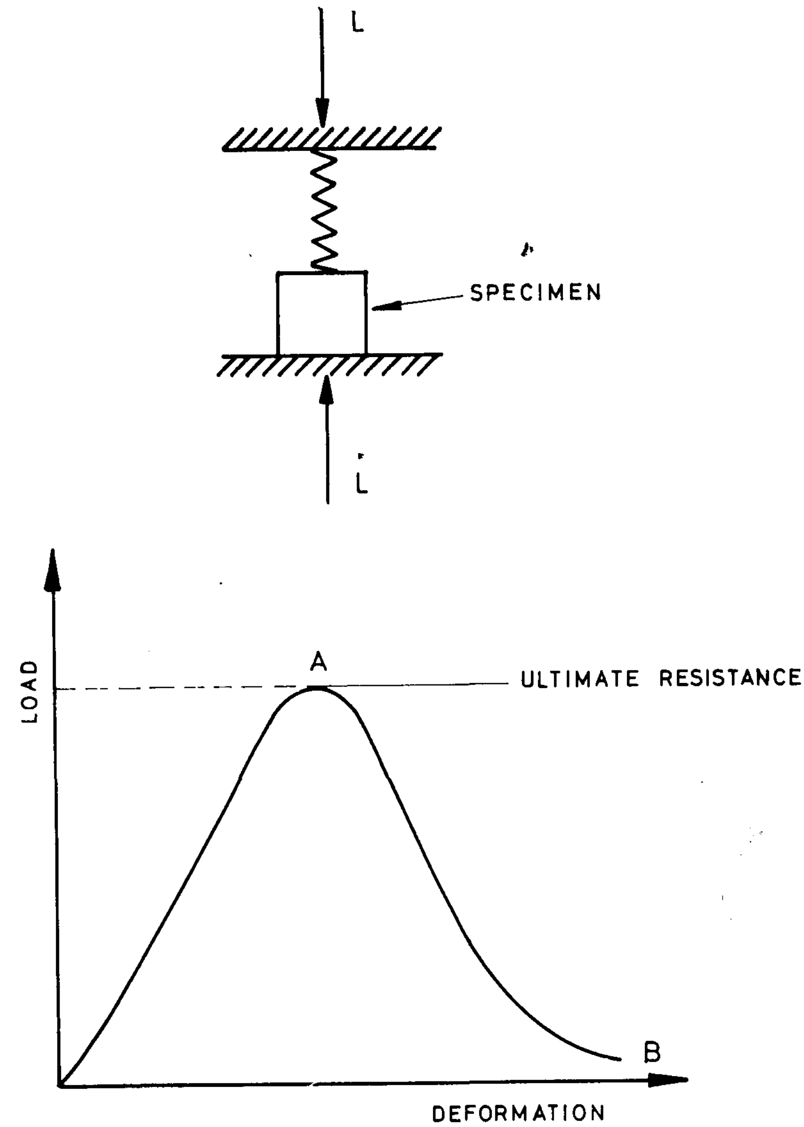



**Fig. 1—Diagrammatic representation of specimen deformation under compression**

### Specimen Size

Due to the fact that actual rock and coal masses are usually discontinuous, tests conducted on small specimens in the laboratory generally do not yield strength and deformation data directly applicable to the coal mass from which the specimens were taken. A small specimen is usually a continuous structure or, at any rate, approaches such a state. The smaller the specimen, the fewer the discontinuities present and hence the stronger the specimen. This was foreseen more than twenty years ago by Denkhaus[6] when he pointed out that, for metals, the strength is constant from a specimen size of about 20 mm onwards, so that large structures such as boilers, bridges, and ships are designed on the basis of strength tests on steel specimens of much smaller sizes. Bieniawski[2] found that this critical size for coal is about 1,5 m, as will be clear from Fig. 2, where his results are plotted.

Since there is no reliable method of predicting the strength and deformation characteristics of actual large coal pillars from the results of laboratory tests on small specimens, *in situ* tests on large specimens are necessary. For coal, specimens of a size of about 1,5 m side length should be tested. Such *in situ* tests have the additional advantage that the coal is tested at the same environmental conditions to which actual coal pillars are subjected.

### Specimen Shape

The main object of *in situ* compression tests on large specimens is to estimate the strength and deformation behaviour (also after strength failure for the yielding-pillar concept) of structures such as mine pillars. For this purpose an empirical formula, which includes parameters describing the shape (usually the width-to-height ratio) and the coal material strength of the specimen, is usually derived from the data obtained from large specimens. The coal material strength in this connection is understood as the strength obtained from an *in situ* cube specimen of at least 1,5 m side length as discussed previously. Various types of empirical formulae will be dealt with later. No relationship between post-failure deformation characteristics and width-to-height ratios of specimens have been derived so far.

## TEST REQUIREMENTS

Tests on large specimens are aimed at determining, *in situ*, the complete load-deformation characteristics of specimens with width-to-height ratios of up to 3,5 under conditions of natural constraint. Natural constraint means the constraint due to contact with the roof and the floor of the mine in the case of an actual coal pillar. Any method of testing must reproduce natural loading conditions as accurately as possible if the measurements are to be meaningful for pillars actually used in mining.

In order to define the loading conditions, one considers one of the many pillars compressed by a uniform, normal convergence between the roof and the floor of the mine. In this case, tilting of the roof and floor is sufficiently small to be ignored, and the deformation of the pillar between roof and floor is uniformly distributed. Obviously, indentation of the roof and the floor by the pillar will also occur.

It is clear, then, that the following requirements must be met by *in situ* tests if the measurements are to be meaningful.

1. Lateral restraint must be provided at the top of the specimen

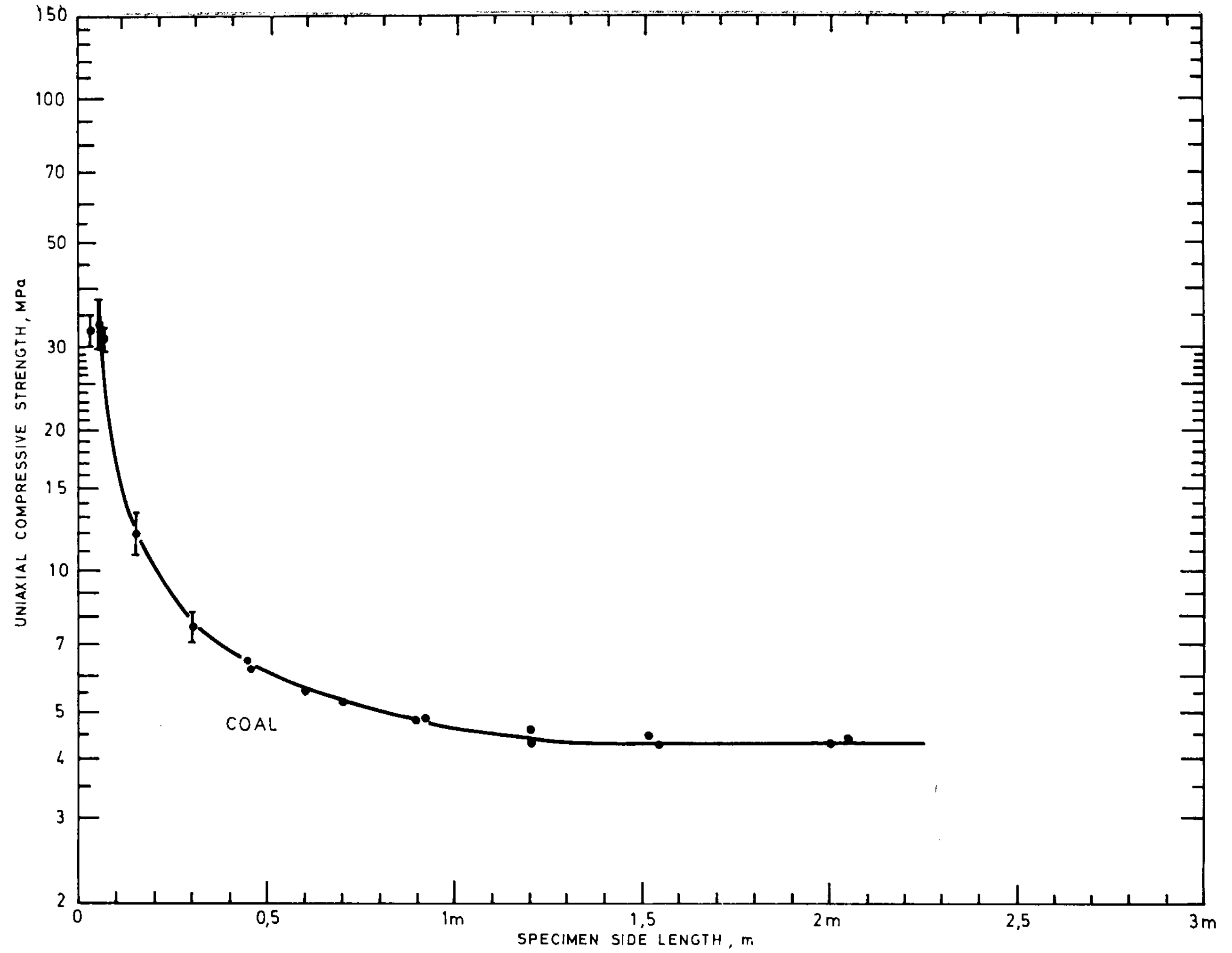



**Fig. 2—The phenomenon of the strength approaching asymptotically a constant value (after Bieniawski[3])**

to simulate the effect of the roof on an actual pillar.

2. Lateral restraint must be provided at the bottom of the specimen to simulate the effect of the floor on an actual coal pillar.
3. The loading of the specimen must be such that the deformation of the specimen is uniform and that tilting of the loaded surfaces is not possible. This clearly requires the adoption of displacement-controlled, rather than stress-controlled, loading.
4. The loading system must be stiff in comparison with the elastic stiffness of the coal so that the complete load-deformation behaviour of the specimen can be determined, as already explained.
5. Finally, the loading equipment must have sufficient loading capacity for all the specimens to be loaded to complete failure.

## TEST METHODS USED

The different test methods and equipment used for the testing of large coal specimens *in situ* have been described in detail elsewhere[1-4]. However, to make the development of the latest method clear, it is necessary to describe the different methods briefly.

### Uniform Stress Loading (Stress-controlled Loading)

The first *in situ* testing of coal specimens[1,2] was conducted using hydraulic jacks according to the method illustrated in Fig. 3(a). In this method, all the jacks were connected in parallel to a pump unit, and the *stress (oil pressure) was controlled* during the test. A thin concrete slab was cast on top of the specimen to provide end constraint* and to ensure uniform deformation of the specimen during loading. These tests were aimed at the determination of the strength and deformation characteristics up to strength failure only. The loading system was therefore not designed with a high stiffness in mind. In fact, the large volume of hydraulic fluid in the loading system[2] and the wooden packing on top of the jacks resulted in a low stiffness that made it impossible

*Alternative arrangements, like a steel band round the top part of the specimen, to provide end constraint have also been used in some tests.

to obtain complete load-deformation data by this method[7]. Another disadvantage of the method was that tilting of the loaded top surface of the specimen was difficult to control. Although this method was acceptable for the original tests, it could not satisfy all the five requirements mentioned previously.

## Uniform-deformation Loading (Deformation-controlled Loading)

The uniform-deformation loading method[4] is illustrated in Fig. 3(b), where the jacks are arranged in the midplane of the specimen, which in fact produces two specimens. Each jack was supplied with oil by an independent pump. By setting the volume of oil delivered by each pump to the same value, the displacement of the loaded surfaces could be kept uniform during the test. The loading system was designed in such a way as to minimize the amount of hydraulic fluid in the system and so increase the stiffness of the system. It is believed that requirements 1 and 2 were reasonably satisfied in the test because the specimen remained attached to the roof and the floor as in the case of an actual mine pillar. The tests conducted with the equipment also proved that all the other requirements could be satisfied for practical purposes except 5 — the last one. In fact, it was found that specimens with width-to-height ratios of greater than 2,2 could not be loaded to complete failure with this equipment because of its insufficient loading capacity. The reason for this lies in the fact that the specimen first failed at the corners; thereafter different parts of the specimen failed successively and reduced the number of jacks available to apply load to the strong central section of the specimen[5]. Near the end, after the corners and sides of the specimen had failed, only a few jacks were left to break the strongest part of the specimen and for this the capacity of these few jacks was found insufficient.

Obviously, the total loading capacity of all the jacks is much greater, but they must all contribute to the load right up to the end of the test as in the next method described below.

## Latest Method

The same loading equipment just mentioned was used in the latest method, which is illustrated in Fig. 3(c), the difference being that the jacks were arranged on top of the specimen and not in the midplane as in Fig. 3(b). In addition, the arrangement was modified by the casting of a thick reinforced concrete slab on each specimen so that the loading capacity of all the jacks was available to break the strong central portion of the specimen. Another purpose of the concrete slab was to provide end constraint to the top of the specimen, which was no longer attached to the roof as in the previous method. It will also be noticed from Fig. 3(c) that the coal above the jacks was replaced by concrete right up to the roof of the seam so as to avoid the use of timber packing for filling this gap.

Of major importance is the extent to which such a test method satisfies the five test requirements. Since the

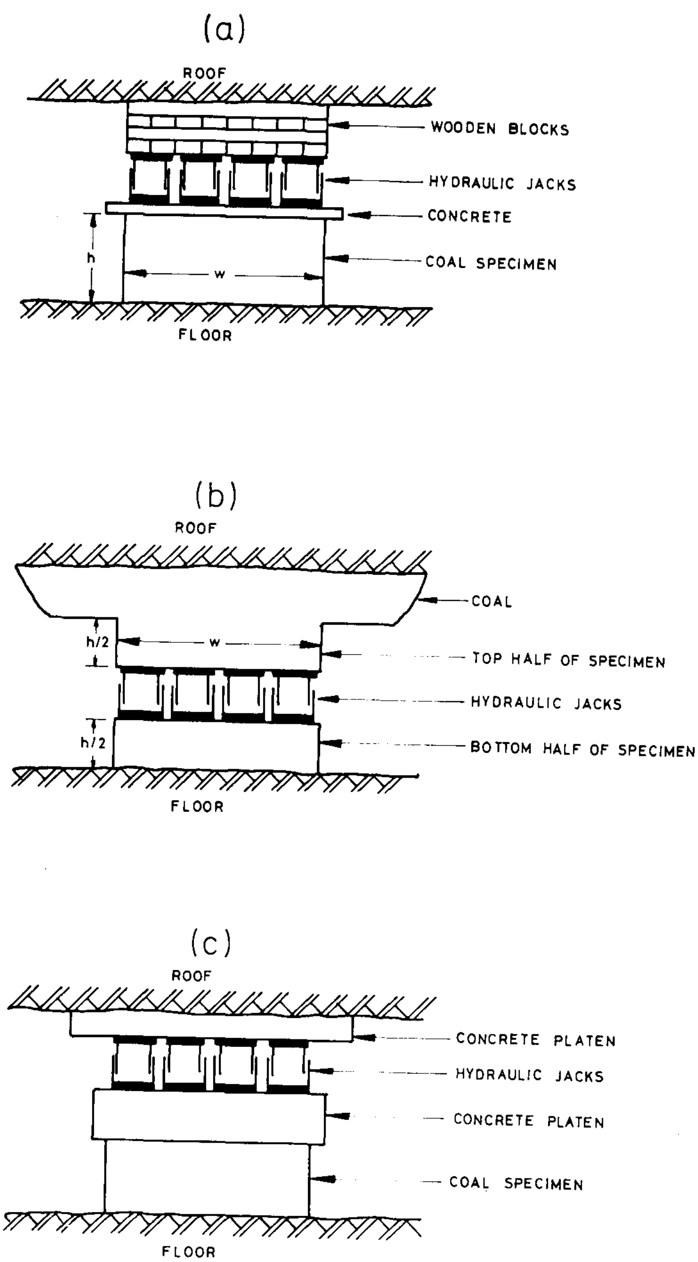
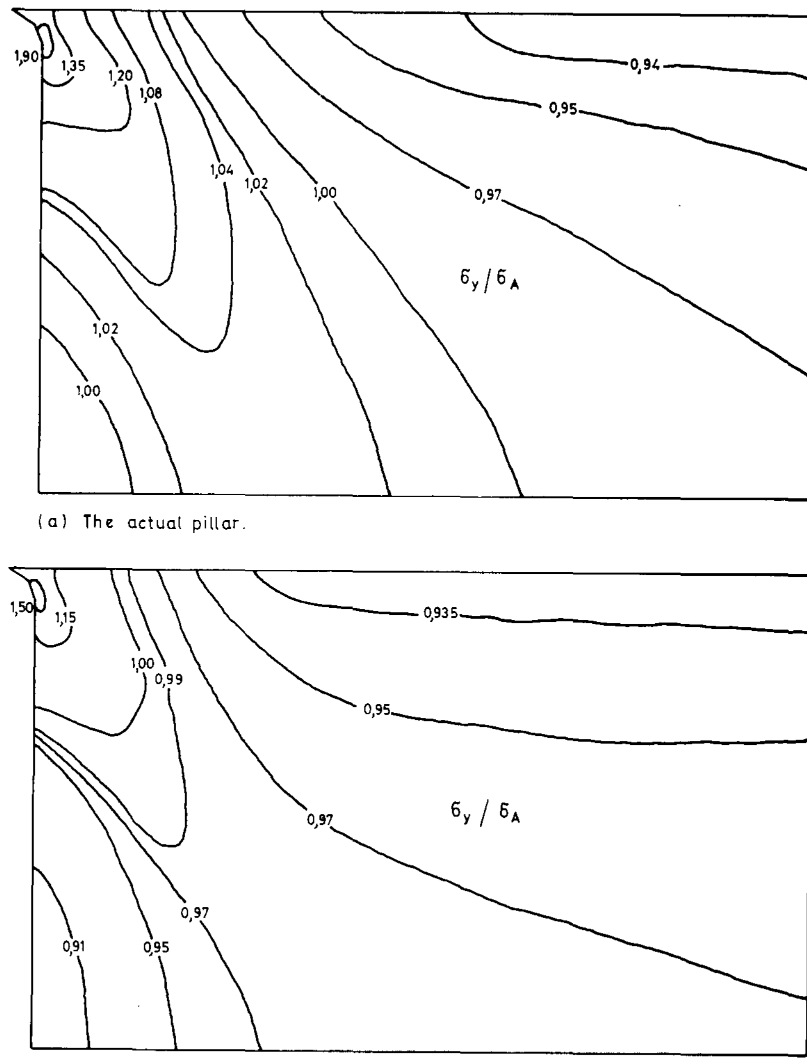



**Fig. 3 (a) Stress-controlled loading of coal specimens (after Bieniawski[2])**
**(b) Method of uniform-deformation loading (after Cook et al[4])**
**(c) Modified uniform-deformation loading (present method)**

same equipment was used as for the previous method, it satisfied the requirements of uniform-deformation loading and stiffness. In addition to this, the specimen remained attached to the floor so that the bottom end constraint was correct and, since all the jacks were used right up to the end of the test, the loading capacity requirement (5) could be satisfied. This left only requirement 1 to be satisfied, namely, that the properties of the concrete on top of the specimen had to be such that the constraint due to the concrete block was the same as that provided to an actual pillar by its direct contact with the roof of the mine.

It was decided that, when the stress distribution in the specimen was the same as that in an actual pillar, this requirement would be satisfied. Two-dimensional finite element analysis was therefore employed to compare the stress distribution in an actual pillar with that in a coal specimen. The properties of the concrete and the size of the block were varied within certain limits until a practical size of block was found for which the stress distribution in the specimen was approximately the same as in an actual pillar. On this basis, a block measuring 1,5 m in width and 1,0 m in height was selected. The concrete had the uniaxial compressive strength of 40 MPa, modulus of elasticity of 37,9 GPa, Poisson's ratio of 0,15, and density of 2500 kg/m$^3$.

Fig. 4 shows contours of the ratio of vertical-stress component to applied stress both in the specimen with a concrete block, as specified above, on top and in an actual coal pillar. It will be seen that the stress distribution in the specimen is very close to the stress distribution in an actual pillar. Similar good agreement was also evident for the horizontal- and shear-stress components. Certain differences are apparent only near the corners, but the volume of coal affected by these differences is a very small percentage of the total volume of the specimen. Consequently, under such conditions, the natural end constraint was considered to be well simulated in the specimen.




(a) The actual pillar.

(b) The specimen.

**Fig. 4—Contours showing the ratio of vertical normal stress to applied stress**

The method was used in the testing of ten coal specimens in New Largo Colliery, near Witbank. All the specimens had a cross-sectional area of 1,4 m by 1,4 m, and five different heights were used: 1,2 m, 1,0 m, 0,7 m, 0,5 m, and 0,4 m. Two specimens of each height were tested as a cross-check of the results. A specimen ready for testing is shown in Plate I.

## STRENGTH AND DEFORMATION CHARACTERISTICS

All specimens failed in a symmetrical double-pyramid fashion, indicating that the lateral restraint at the top of the specimen was about the same as at the bottom of the specimen. Typical complete stress-strain curves are shown in Figs. 5 and 6. A summary of the test results is given in Table I.

The strength data obtained from this investigation are plotted in Fig. 7. Also plotted there are the test results obtained by the Chamber of Mines[5] at Usutu Colliery, a relationship derived by Salamon[8] from a survey of full-size pillars and plotted for the size of the specimens tested in the present investigation, and the test results obtained by the CSIR at Witbank Colliery[2, 3] from earlier tests.

The formula by Salamon reads:

$$\text{Strength (MPa)} = 7{,}2 w^{0{,}46} / h^{0{,}66}, \qquad \ldots (1)$$

where $w$ and $h$ are measured in metres.

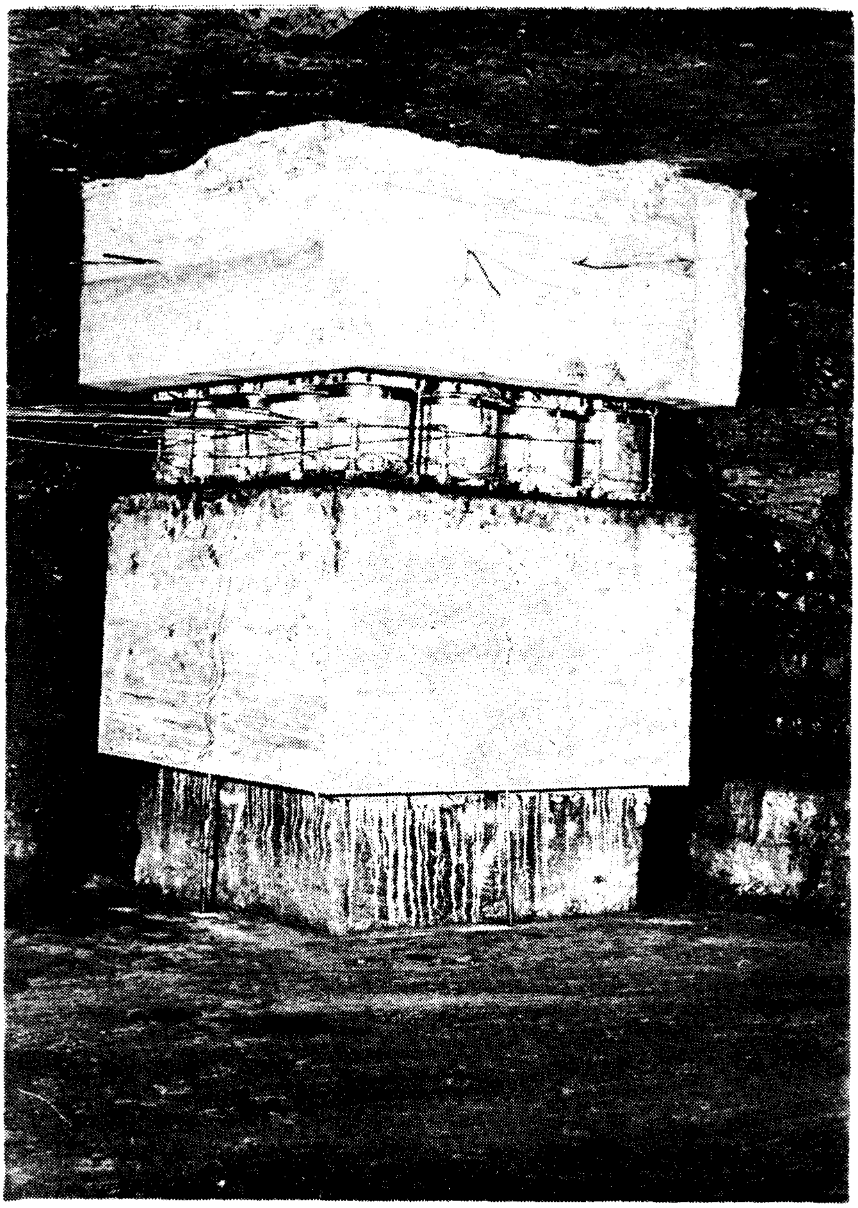


**Plate I—A specimen with all the jacks and measuring equipment installed**

The general form of this formula is

Strength (MPa)$=kw^a/h^b$, . . . (2)

where $k$, $a$, and $b$ are constants.

Analysing the results obtained by the Chamber of Mines, Wagner[5] fitted a strength formula:

$$\text{Strength (MPa)} = 11{,}0\sqrt{w/h} \quad . . . (3)$$

This is just a special case of equation (2) with $k=11{,}0$ and $a=b=0{,}5$.

Using the type of expression in equation (2), the results obtained by Bieniawski[2,3] can be described by the following formula:

$$\text{Strength (MPa)} = 4{,}5\sqrt{w/h} \quad . . . (4)$$

and those obtained in the present investigation by

$$\text{Strength (MPa)} = 13{,}3\sqrt{w/h} \quad . . . (5)$$

It is clear from Fig. 7 that equation (1) lies approximately in the middle between the Witbank results and the Usutu results. Such a large difference between the test results from two collieries is not surprising if one considers the large scatter of results from the Usutu Colliery alone.

The numerical factors in equations (3) to (5) represent the strength of a cube ($w/h=1$) of the material tested, the 'coal material strength' of 1,5 m cubes. Comparison of this factor for various collieries reveals that coal is particularly weak at Witbank Colliery (4,5 MPa), while it is the strongest, as tested to date, at New Largo Colliery (13,3 MPa). Equation (1) gives the strength of a 1,5 m cube as 6,7 MPa and, since equation (1) was derived from average data from all the collieries, it stands to reason that coal from some collieries will yield higher strength values and coal from others will yield much lower values. Although it was shown[9] that, for small coal specimens, the strength of coal *material* obtained from different South African collieries does not differ excessively, in a large block of coal the influence of joints and beddings on the strength can be great[10], so that large strength differences can be expected between large coal specimens from different collieries.

Although equations (3) to (5) seem to fit the available data, in the range of width-to-height ratios between 1,0 and 3,4 the scatter of the results is such that the results can be represented equally well by other empirical mathematical relationships. This is clear from Fig. 8, where the same data — including points derived from equation (1) — are shown to fit equations representing a straight line. Fig. 8 shows that a straight line is equally satisfactory over the region of width-to-height ratios between 1,0 and 3,5. Thus, the strength results of the present tests can also be described by the following equation:

Strength (MPa)$=10+4{,}2\ w/h$ . . . (6)

Although the straight-line equation mentioned above is easier to use than other more complicated equations, it has the disadvantage that it is applicable only to the area where the actual tests were carried out. This will be clear from Fig. 8, where different formulae are shown to fit the data from different collieries. The reason for this lies in the fact that a formula of the

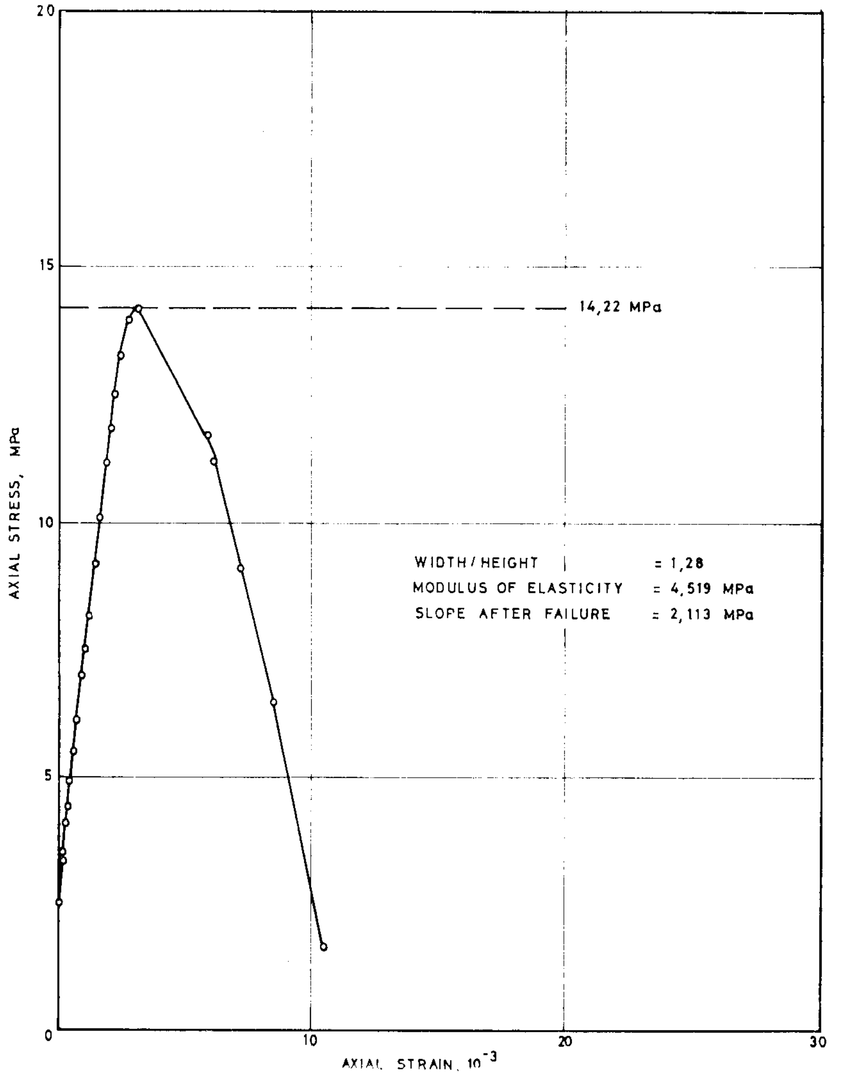



**Fig. 5—Complete stress-strain curve obtained for specimen No. 3**

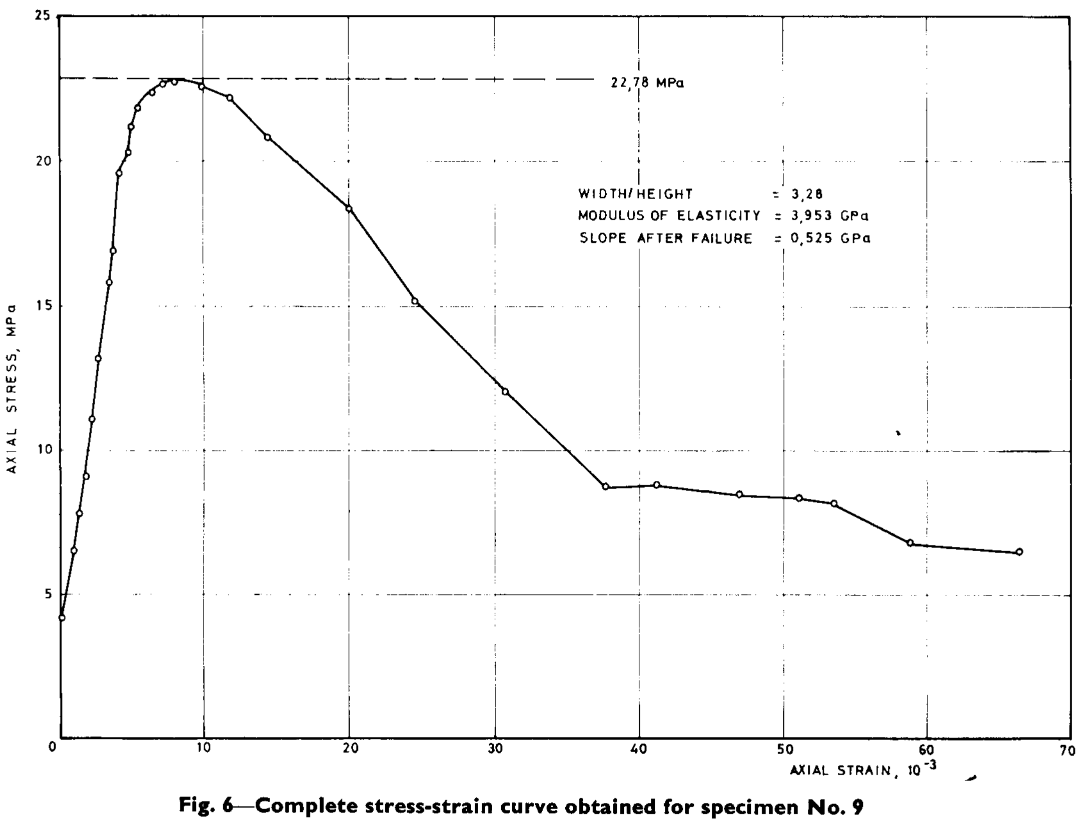



**Fig. 6—Complete stress-strain curve obtained for specimen No. 9**

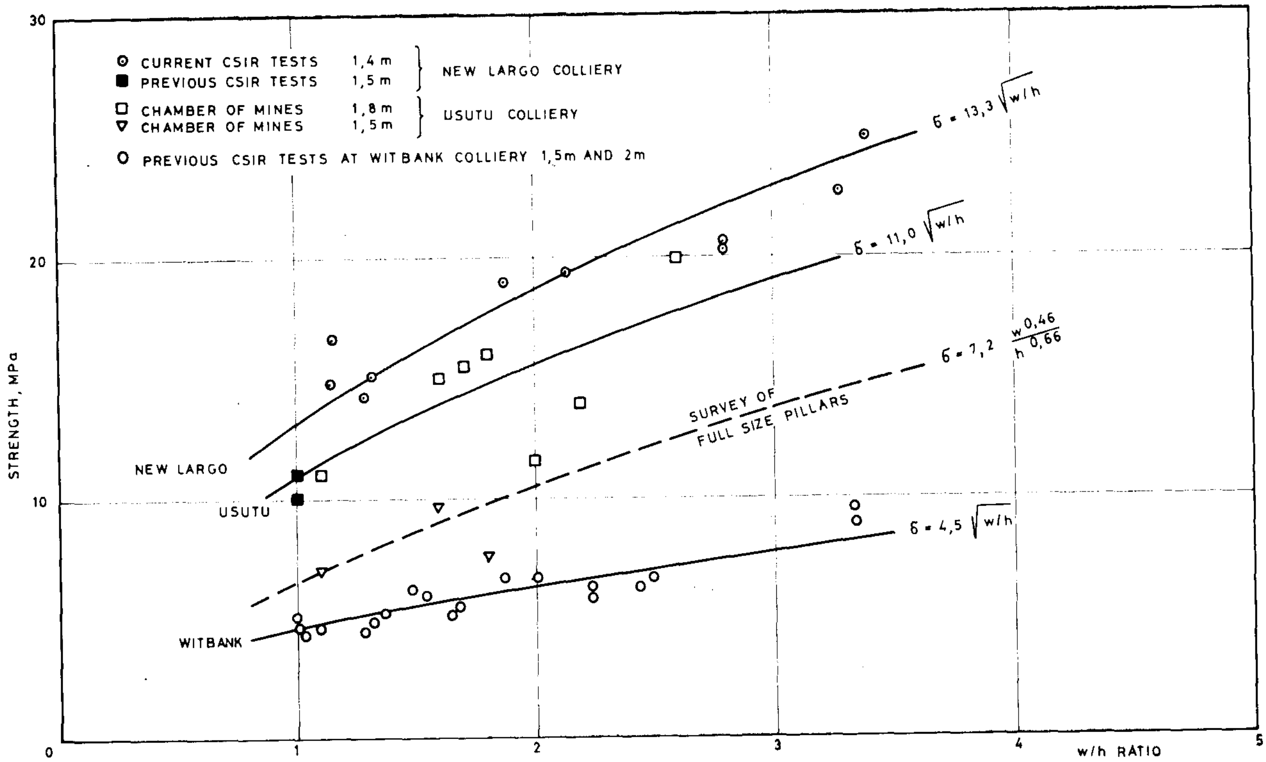



**Fig. 7—Comparison of current strength data with those of previous tests**

TABLE I
SUMMARY OF RESULTS

| Specimen no. | Height ($h$) (mm) | Width ($w$) (mm) | $w/h$ | Strength (MPa) | Modulus of elasticity (GPa) | Slope after failure (GPa) |
|---|---|---|---|---|---|---|
| 1 | 1240 | 1413 | 1,14 | 14,82 | 3,71 | 2,00 |
| 2 | 1230 | 1415 | 1,15 | 16,69 | 4,59 | 0,87 |
| 3 | 1115 | 1428 | 1,28 | 14,22 | 4,52 | 2,11 |
| 4 | 1062 | 1394 | 1,31 | 15,14 | 3,33 | 1,72 |
| 5 | 755 | 1408 | 1,87 | 19,02 | 3,75 | 1,14 |
| 6 | 650 | 1383 | 2,13 | 19,40 | 4,26 | 0,91 |
| 7 | 492 | 1373 | 2,79 | 20,26 | 3,86 | 0,52 |
| 8 | 507 | 1415 | 2,79 | 20,58 | 3,62 | 0,70 |
| 9 | 427 | 1401 | 3,28 | 22,78 | 3,95 | 0,53 |
| 10 | 410 | 1390 | 3,39 | 25,05 | 4,29 | 0,55 |

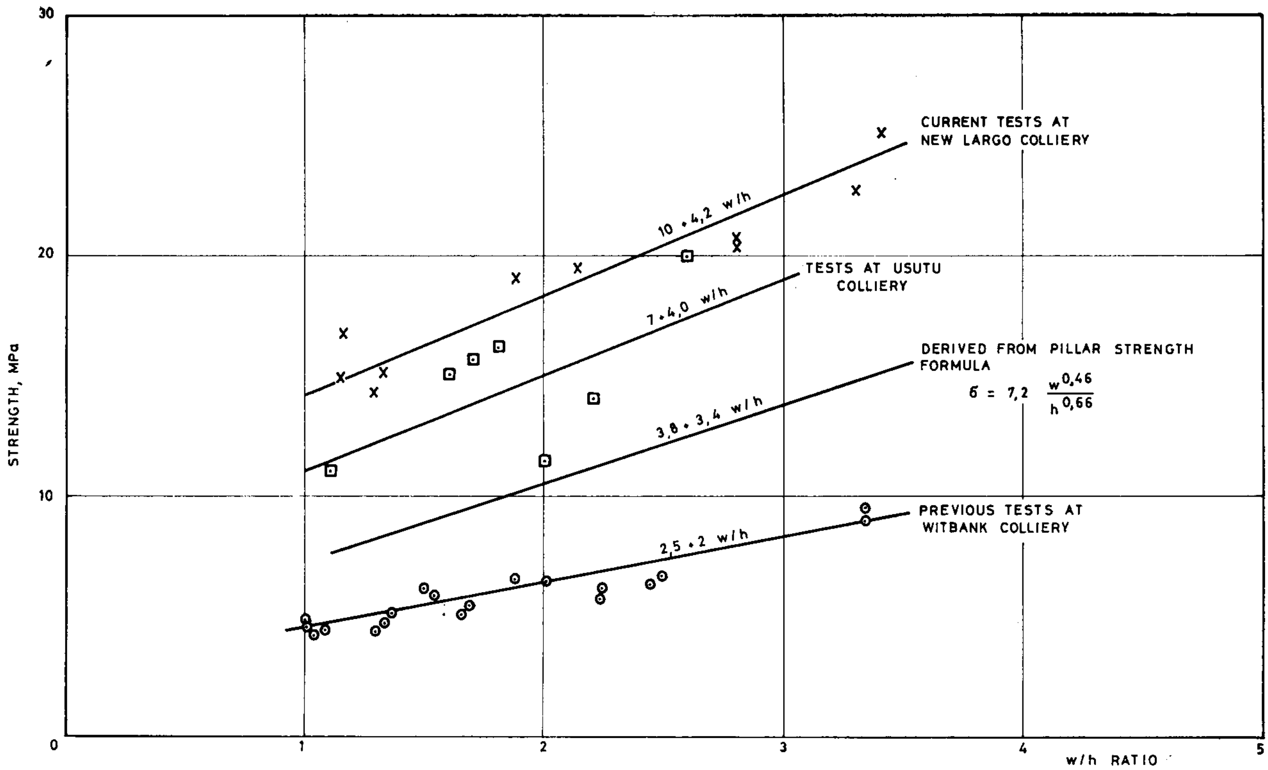



**Fig. 8—Representation of strength data by a straight line**

type

Strength (MPa)$=A+B(w/h)$

depicts not only the influence of width-to-height ratio but also the influence of structural differences (joints, bedding planes, etc.) in the different coal seams.

This problem can be overcome if the strength results are plotted in a dimensionless form. Fig. 9 shows a plot of width-to-height ratio versus the dimensionless ratio of strength to the strength of a cubical specimen ($w/h=1$) of the size tested. All the results from Fig. 8, which were obtained at different collieries, are plotted, and it can be seen that the results fall close to a single straight line. The equation of this line is

$$\sigma/\sigma_1=0,64+0,36\ (w/h), \quad . . . (7)$$

where $\sigma$ is the strength of the specimen and $\sigma_1$ is the strength of a cubical specimen of the size tested. This formula is now applicable to different collieries because it depicts only the shape effect. The influence due to the different properties of different coal seams is included in the value of $\sigma_1$, which must be determined for each locality before equation (7) can be applied. When equation (7) is to be applied to the design of full-size pillars, a cubical specimen with a side length of at least 1,5 m must be tested to eliminate the size effect mentioned before.

For the yielding-pillar concept, the deformation characteristics of the specimen, particularly after strength failure, are of equal importance to the strength characteristics.

The slope of the stress-strain curve before the ultimate resistance of the specimen is reached, that is the modulus of elasticity of the specimen, is not influenced by its width-to-height ratio. In fact, values ranging between 3,33 and 4,59 were measured for all the tests, the variations being due to scatter in the results. The average value for all tests is 4,0 GPa, which is in agreement with previous test results[2-5] that were obtained with specimens of various sizes and different test methods. This indicates that the modulus of elasticity of coal does not depend upon the shape and size of the specimen or on the test method.

On the other hand, the slope of the portion of the stress-strain curve beyond the ultimate resistance of the specimen is influenced by the width-to-height ratio of the specimen. This influence is shown in Fig. 10, where the post-failure modulus versus the width-to-height ratio of the specimen is plotted. These are the first results obtained *in situ* for coal where a definite trend could be established for this property.

Since it was shown[3] that, for coal, the influence of size is negligible for sizes from about 1,5 m upwards, the results of the present investigation are applicable to full-size pillars.

The curve in Fig. 10 is thus important from a practical point of view because, if the yielding-pillar concept is to be used in coal mining, the stiffness of the pillars (the slope of the stress-strain curve after failure) must be less than the stiffness of the strata. It has been reported* that the typical stiffness of the strata is about 0,5 GPa. The present results confirm what has already been feared, that the yielding-pillar concept cannot, unfortunately, be applied in practice, even for pillars with width-to-height ratios of as

*Coal Mining Research Controlling Council, Rock Mechanics Research Programme 1972, Sept. 1971.

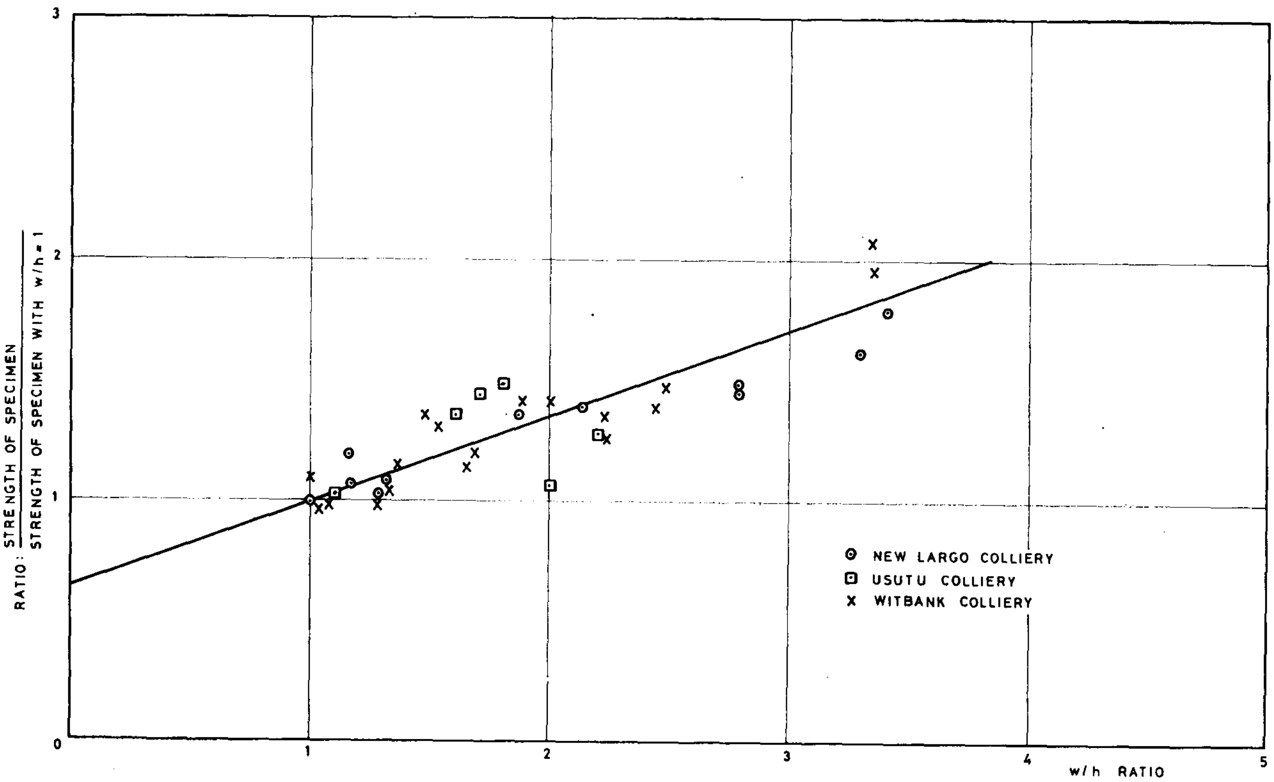



**Fig. 9—Representation of strength data in dimensionless form**

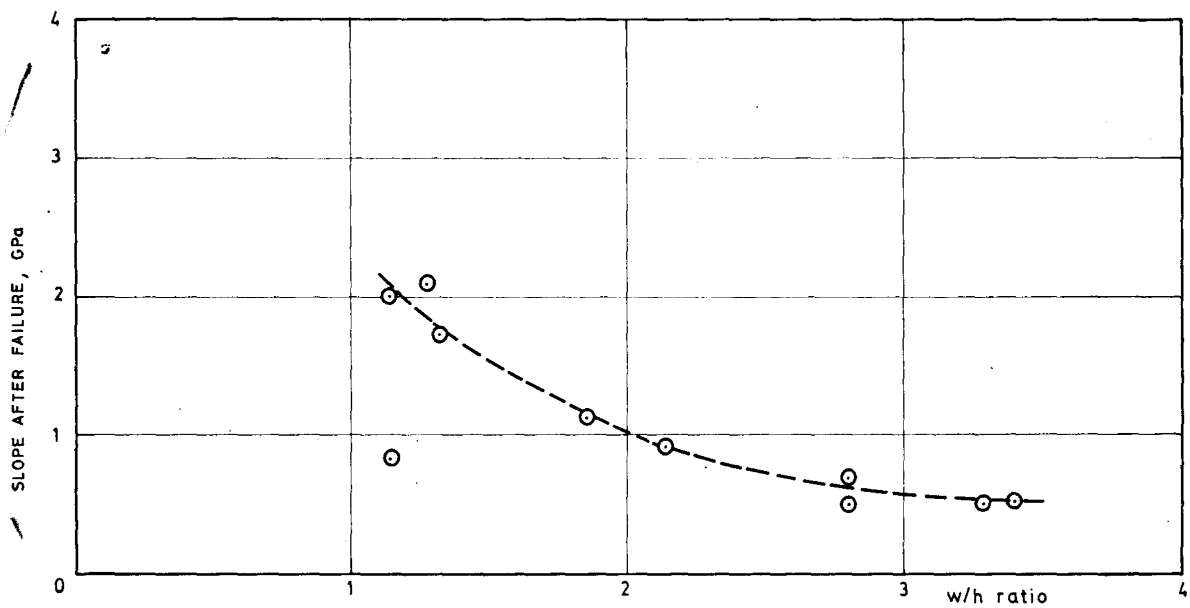



**Fig. 10—Influence of *w/h* ratio on the slope of the stress strain curve after failure**

high as 3,5. In addition, Fig. 10 seems to indicate that the situation cannot be improved, even if pillars with width-to-height ratios of more than 3,5 are used, because the curve approaches a horizontal straight line for high width-to-height ratios.

## CONCLUSIONS

1. The testing of coal specimens with high width-to-height ratios is feasible using the method described in this paper and the available hydraulic loading equipment. It is believed that even specimens with width-to-height ratios of greater than 3,5 can be tested with this equipment because at no time was the loading capacity exceeded in any of the tests.

2. The influence of width-to-height ratio on the strength of coal can be expressed by a linear equation that is valid for different collieries if the strength data are presented in dimensionless form. This equation is:

$\sigma/\sigma_1=0{,}64+0{,}36\ (w/h)$,

where $\sigma_1$ is the strength of a cubical specimen of the size tested. This equation can be used for the design of full-size pillars provided $\sigma_1$ is determined from tests on cubical specimens with a side length of 1,5 m.

3. The modulus of elasticity of the coal specimen was found to be about 4,0 GPa, which is the same as the modulus obtained from previous *in situ* tests. It was confirmed that the modulus is independent of the size and shape of the specimens.

4. The slope of the stress-strain curve after strength failure decreases with increasing $w/h$ ratio of the specimen, but it approaches a constant value of about 0,5 GPa at a width-to-height ratio of about 3,0. This slope of 0,5 GPa may not be sufficiently low for the yielding-pillar concept to be used with an acceptable margin of safety.

## ACKNOWLEDGEMENTS

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# Thermal analysis

The Fourth Thermal Analysis School organized by the Thermal Methods Group of The Society for Analytical Chemistry (Analytical Division of the Chemical Society) is to be held at the University of Salford, from 7th to 11th April, 1975. This school aims to provide an introduction to the techniques of thermal analysis and their applications in various fields. The course is designed to give scientists and technologists sufficient background of theory and practice to enable them to evaluate critically the uses of these techniques in relation to their own analytical, testing, or research requirements.

The First European Symposium on Thermal Analysis is to be held, also at the University of Salford, from 20th to 24th September, 1975. It is envisaged that all aspects of thermal analysis will be covered, including instrumentation and techniques; aspects of physical, inorganic, organic, and polymer chemistry; and the application of thermal methods in the applied sciences such as mineralogy, corrosion, pharmaceuticals, ceramics, building materials, and glass technology.

Address your enquiries to the University of Salford, Salford M5 4WT, England: to Miss A. M. Tonks, Administrative Assistant (Short Courses) for the School, and to Dr D. Dollimore, Reader in Physical Chemistry for the Symposium.

# Council of Commonwealth Mining and Metallurgical Institutions

The Council announces that preliminary arrangements have been made for the Eleventh Commonwealth Mining and Metallurgical Congress to be held in India in November 1978. It is expected that arrangements will also be made for optional visits to other countries in the Far East to fit in with, or follow, the Congress in India. A further announcement giving details will be made in 1976.

The Council announces also that Sir Ronald Prain, O.B.E., who has been Chairman since 1961, retired on 31st December, 1974, and has been succeeded by Sir Val Duncan, O.B.E.