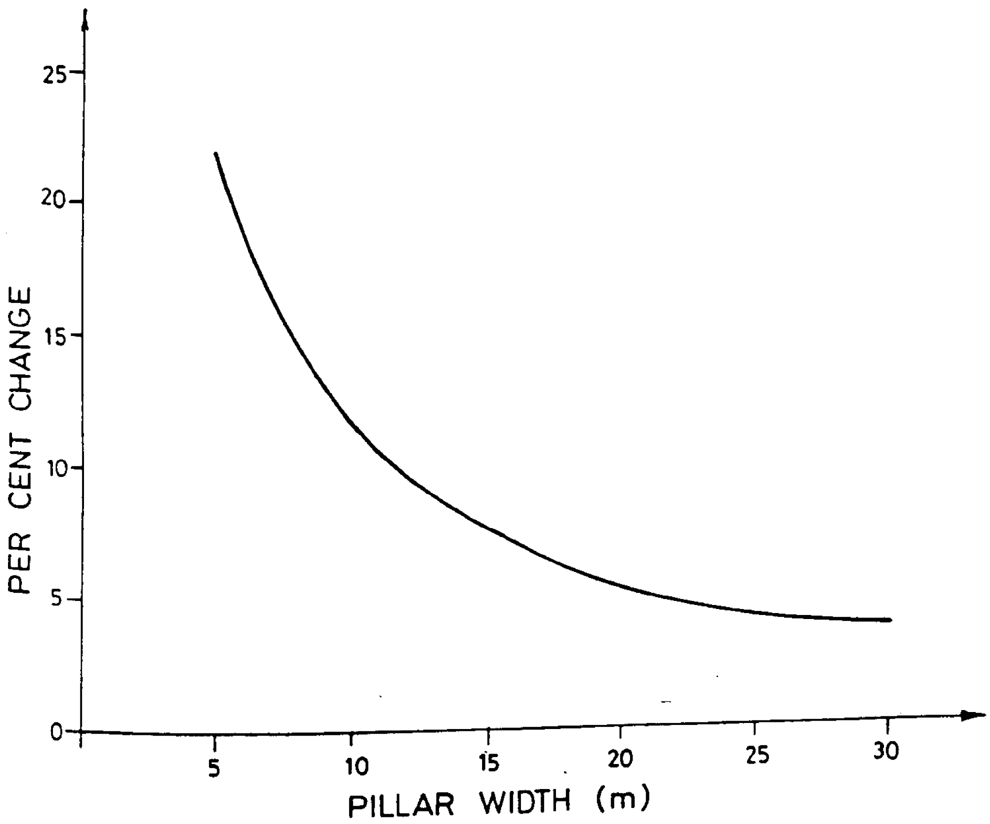

Figure 5.26 Percentage change in area of blast damage zone over pillar area.

C H A P T E R 6

SQUAT FORMULA LABORATORY TESTS

6.1 INTRODUCTION

The literature survey and the results from Chapter 3 suggest that the Salamon and Munro pillar strength formula underestimates pillar strength when the width to height ratio exceeds about four or five. To account for the anticipated increase in strength, Salamon (1982) suggested a formula, termed the squat pillar formula, which is an extension of his well established strength formula. Results of investigations to verify the assumption that the squat pillar formula realistically predicts the strength increase of high width to height ratio pillars are presented in the following two chapters.

Before a full scale field trial that could have placed men's lives at risk was undertaken, an extensive laboratory testing programme was conducted to assess the influence of specimen width to height ratio on its strength and deformation characteristics. The results obtained in the laboratory were used to examine the suitability of Salamon's squat pillar formula in predicting specimen strength.

6.2 EXPERIMENTAL DETAILS

6.2.1 Material Tested

Most information regarding the influence of width to height ratio on the strength of a pillar is based on laboratory experiments with specimens having width to height ratios less than 5,0, Greenwald (1941), Steart (1954). Experiments on specimens with width to height ratios greater than five by Bieniawski (1967b) and Hudson et al (1971) indicated an increased strength as well as a change in the post peak stress-strain curve. However, few results were presented by these investigators.

Many authors have studied the strength of coal specimens to obtain a relationship between strength and the specimen's width to height ratio. However, coal as a material is difficult to work with as it is susceptible to weathering, is anisotropic (even in a small range within one seam), and is difficult to prepare in specimens; the volume of the specimen also affects the strength more than in other rock types.

To overcome these difficulties an isotropic, fine-grained, Karoo sandstone was used for the present series of tests thus limiting many of the unknown factors associated with the testing of coal. The strength properties of this material have been well established by Stavrapoulou (1982) and are summarized in Table 6.1.

Table 6.1 Strength and Material Properties of Karoo Sandstone.

Uniaxial compressive strength	80,8 MPa
Poisson's ratio	0,34
Young's modulus	22,0 GPa

The isotropy of the sandstone was examined by testing three specimens parallel and perpendicular to the bedding. The difference in mean strength was approximately seven per cent, Stavropoulou (1982).

6.2.2 Design of the Experiment

The experiment was designed to determine the width to height ratio effect of cylindrical specimens on strength and to establish whether pronounced size effects occur in the range of specimens tested. For this purpose six sets of specimens with diameters ranging from 24 to 100 mm were prepared. In each of these sets the width to height ratio from 1,0 to 8,0 was obtained by varying the height of the specimen. Figure 6.1 shows the range of specimen sizes and width to height ratios covered by the experiment.

In the larger specimens the upper limit of width to height ratio was governed by the space and load restrictions of the testing machine, while in the small specimens the grain size of the material limited the minimum height of the squat specimen giving a width to height ratio of 8,0.

The specimens were drilled to a diameter greater than required and the sides surface-ground to the test diameter. This was to ensure that the sides were perpendicular and that the core barrel grinding did not influence the specimen's shape. The specimens were prepared to within dimensional tolerances such that the final diameter was ±0,6 per cent of the designed diameter while the length was approximately two per cent of the designed length. The width to height ratio of the specimens were within two per cent of the designed ratio. Table 6.2 shows specimen size and the number of tests conducted for each specimen width to height ratio. In total 222 specimens were tested.

Table 6.2 Specimen Size and the Number of Tests Conducted for Each Specimen Width to Height Ratio.

Series	Diameter Size	Number of Tests								Total Number Per Series
A	24 mm	0	X	0	X	0	X	0	0	42
B	36 mm	0	X	0	X	0	X	0	0	42
C	48 mm	0	X	0	X	0	X	0	0	42
D	60 mm	0	X	0	X	0	X	0	0	42
E	80 mm	0	X	0	X	0	X	0	0	42
F	100 mm		X	X						12
Specimen width to height ratio		1	2	3	4	5	6	7	8	
0 represents three specimens tested X represents nine specimens tested										

In an attempt to study the fracture development within the specimens, 11 specimens were confined by one, two or three rubber bands for the purpose of keeping the fractured slabs in place. After subjecting the specimen to a predetermined load level, they were taken from the testing machine and impregnated with resin. The specimens were dissected, after curing, and the fracture zone within the specimen was examined.

The lateral expansion of three specimens was determined by measuring the increase in circumference during testing. The load-deformation curve of each specimen was also recorded. A video film was taken of each test conducted on specimens with diameters of 60,0 mm, 80,0 mm and 100 mm and used to study fracture development. Photographs of the specimens, after testing, were taken for a permanent record of the test results.

6.2.3 The Testing Machine

As mentioned earlier, this investigation was not only concerned with the effect of width to height ratio on the strength of a specimen, but also on the specimen's deformation characteristics both pre and post failure. In order to obtain an accurate picture of the post failure deformation of the specimen, a stiff 1,0 MN testing machine was used for these experiments. To maintain the maximum stiffness of the machine over the entire height range of the specimens, platens of different thicknesses were used to keep the amount of hydraulic fluid in the machine's piston to a minimum over the entire range of tests. The rate of loading was kept constant at 0,0762 mm/min. The load and axial displacement were recorded with an x-y recorder.

6.2.4 Platens

Platens of hardened mild steel, with a surface ground finish to ISRM standards, Brown (1981), were used in all the tests. The average static friction between the platen and sandstone specimen as determined from 10 tests was 0,35 ± 0,03. The combinations of platens used for the series of tests are summarized in Table 6.3.

Table 6.3 Combination of Platen Sizes Used in the Tests.

Test Series	Platen combination							
A	AA	-----	----	----	---	---	----	AA
B	AA	-----	----	----	---	---	----	AA
C	AA	-----	----	----	---	---	----	AA
D	BB	-----	-BB	CC	---	---	----	CC
E	CC	-----	----	----	---	---	----	CC
F	-	CC	-	-	-	-	-	-
w/h	1	2	3	4	5	6	7	8

Platen A 100 x 120 x 20 mm
Platen B 90,5 mm dia., 40 mm height
Platen C 100,0 mm dia., 100 mm height

w/h is the specimen width to height ratio.

The ratio of the platen diameter to specimen diameter is given in Table 6.4.

Table 6.4 Platen Diameter to Specimen Diameter Ratios.

Platen diameter (Pl) mm	Specimen diameter (Sl) mm	Ratio (Pl/Sl)
100	24	4,17
100	36	2,78
100	48	2,08
90,5	60 (w/h 1-3)	1,51
100	60 (w/h 4-8)	1,67
100	80	1,25
100	100	1,00

6.2.5 Calibrations

Previous laboratory tests had indicated a change in the mode of failure with increasing width to height ratio, (Hudson et. al. 1971). Therefore, careful calibrations of the load and displacement of the machine were recorded. The load was found to be within 0,5 per cent of the recorded load and the displacement to be within 1,0 per cent. The recorded displacement value was corrected for the deformation of the hardened mild steel platens and the indentation of the specimen and platen into the body of the machine. Details of the correction procedures are given in Appendix I.

6.3 RESULTS

6.3.1 Stress-Strain Curves

The stress-strain relationships for specimens of width to height ratios ranging from 1,0 to 8,0 for the six diameter sizes studied in this investigation are shown in Figures 6.2 to 6.7. Representative curves for each group of width to height ratios within a given specimen size are plotted in the figures. The stress-strain curves change with an increase in the specimen's width to height ratio. Figure 6.8 shows typical stress-strain curves obtained in the testing of the sandstone specimens.

The curve OABCD (Figure 6.8) is described by Jaeger and Cook (1976), where O-A is the settling in and void closure region, A-B the linear elastic region, B the yield point and B-C the area where irreversible changes are induced in the rock. At C, the compressive strength of the specimen, the curve has its minimum radius of curvature (MRC) point. The points C, C1 and C2 show how the MRC changes with width to height ratio; C-D is the brittle region where the ability of the specimen to resist load decreases with increasing deformation. A specimen with this stress-strain curve is considered to be brittle. The sandstone specimens with width to height ratios between 1,0 and 4,0 display stress-strain characteristics of this kind. Violent failure is often associated with rapid loss of load-carrying capacity and with increased deformation in the C-D region.

Specimens with larger width to height ratios follow a similar load-deformation trend up to the strength value at the MRC to that followed by the low width to height ratio specimens. Beyond this point, in the intermediate width to height ratio, i.e. 6,0 to 7,0, there is a loss of load with further deformation until the point F is reached. At this point the fractured particles or slabs are considered to consolidate and the specimen is again capable of resisting load with further deformation. This resistance is maintained or increases with deformation.

Specimens with width to height ratios greater than 7,0 were found to maintain their strain hardening characteristics without an intermediate strain softening. For the latter groups of width to height ratios, no definite strength value can be defined as strength is a function of the percentage compression of the specimen. One of the most significant results, apart from the increase in strength with increasing specimen width to height ratio, is the gradual transition from brittle behaviour at low specimen width to height ratios to ductile behaviour at large specimen width to height ratios. This transition occurs between the width to height ratios of 5,0 and 6,0 for the cylindrical sandstone specimens.

6.3.2 The Influence of a Cylindrical Specimen's Width to Height Ratio on Strength

Figue 6.9 shows the strength value at the MRC for 24 mm diameter specimens with width to height ratios less than 6,0, together with strength values corresponding to two per cent, five per cent, 10 per cent and 15 per cent compression of the specimens with specimen width to height ratios greater than 6,0.

A straight line function could describe the strength values for the specimens with a width to height ratio of 5,0 and less. The values recorded for the specimens with width to height ratios between 6,0 and 8,0 show an exponential increase in the specimen's ability to carry load with increasing deformation.

6.3.3 The Influence of Volume on Strength

The relationship between the volume of the specimen and strength is shown in Figure 6.10. The specimens of similar width to height ratio are grouped together. The strength value of specimens with width to height ratios greater than 6,0 was taken as the strength at two per cent axial deformation.

The figure shows that, for the same volume of specimen, the strength increases with increasing specimen width to height ratio. The strength value for specimens with width to height ratios 1,0, 2,0 and 3,0 seems unaffected by volume, while the specimens with greater width to height ratios show an increase in strength with decreasing volume.

6.3.4 Modulus of Deformation and Observed Fractures

A post failure modulus was defined as the ratio of the "peak" pillar stress (minimum radius of curvature for specimens with width to height ratios 6,0 to 8,0) to the corresponding strain. The value of the post failure modulus for a specimen decreases with an increase in the width to height ratio, Figure 6.11. Wagner (1974) reported a similar trend from tests on in situ coal pillars.

Figure 6.12 shows the observed fractures as a percentage of the uniaxial compressive strength or strength at the MRC value. It was noted that the amount of fracturing that took place during the linear-elastic region, that is before the yield point, was more pronounced with specimens of width to height ratio of 6,0 or greater.

6.3.5 Fracture Patterns

The fracture spacing was noted for specimens with width to height ratios ranging from 2,0 to 6,0 and several specimens were impregnated with clear resin after testing and then dissected. The shape of the specimens after testing is shown in Figure 6.13. The conical shape typifying specimens with width to height ratios 1,0 to 3,0 is shown in Figure 6.13a, and the numerous slabbed fragments surrounding the inner core typifying specimens with width to height ratios 6,0 to 8,0 can be seen in Figure 6.13b.

6.3.6 Effect of Confining the Specimens

For the purpose of the fracture analysis the specimens were confined with rubber bands to maintain their integrity. An interesting observation was that the load-deformation characteristics of the specimens with width to height ratios greater than 2,0 were influenced by the soft rubber bands after the deformation exceeded the point of MRC. No such influence was found for specimens having width to height ratios less than 2,0 as shown in Figure 6.14.

Figure 6.15 shows the stress-strain curves for unconfined 60,0 mm diameter specimens having a width to height ratio of 4,0. Also plotted in this figure is specimen D14 which had a width to height ratio of 3,0 and was confined by rubber bands. Note that the load-deformation characteristic of this specimen is the same as that of specimens of the higher width to height ratio.

Specimen D18, width to height ratio 4,0, on the same figure was also confined by rubber bands and maintained a higher load at the same deformation as the other specimens of the same width to height ratio. This trend of a confined specimen exhibiting a similar load-deformation curve as an unconfined specimen of higher width to height ratio was evident in all the confined specimens with width to height ratios greater than 2,0.

6.3.7 Observations of Specimen Expansion

Three specimens were surrounded loosely by string to observe the lateral expansion of the specimen with axial deformation. These observations were done on specimens with a width to height ratio of 6,0 and the circumferential expansion was noted on the load-deformation curve.

Figure 6.16 shows a typical stress/lateral strain versus axial strain curve. Point A is the yield point and no increase in circumference was noted up to this point. However, some fractures were observed before the yield point. Between points A and B rapid lateral expansion (25 milli-strain) occurred. After point B a decrease in load was noted an the specimen expanded diametrically by another 15 milli-strain. At point C consolidation took place and the specimen expanded by only a further three milli-strain to point D, while the stress rose from 136 MPa, at point C, to 207 MPa at point D and was still rising at the end of the test. The specimen deformed axially during the whole process.

6.3.8 Strain Energy

In order to deform a specimen or pillar by a certain amount, work or energy has to be expended by the loading system. Some of this work is recoverable in the form of elastic strain energy, with the remainder having been used in the form of heat loss during frictional movements or in the creation of new fractures. The strain energy density (SED) is the area under the stress-strain curve up to a given value of strain:

$$SED = \int_0^{\epsilon} \sigma d\epsilon . \qquad (6.1)$$

Figure 6.17 shows the strain energy density in MJ/m^3 as a function of the width to height ratio of specimens ranging in diameter from 24,0 to 80,0 mm. The strain energy values have been calculated for a maximum specimen compression of five per cent.

As the specimen's width to height ratio increases, the amount of work required by the system to deform the specimen to a certain value of strain increases. This increase in work can be described by the polynomial equation

$$SED = 0,185R^2 - 0,203R + 0,529 \quad MJ/m^3 \quad , \qquad (6.2)$$

where SED is the strain energy density and R is the width to height ratio of the specimen. The equation is valid for five per cent compression of the cylindrical sandstone specimens.

6.4 DISCUSSION OF RESULTS

6.4.1 Stress-Strain Relationships

Relationships between stress and strain for specimen width to height ratios less the 6,5 have been obtained by previous researchers, including Greenwald et. al. (1939), Holland (1962), and Skelly et. al. (1977).

However, the dramatic increase in the load-carrying capacity after the strength value at the point of MRC has been reached for specimens with width to height ratios exceeding 6,0 has not been observed. However several authors have suggested that this would occur, Holland (1962), Vutukuri et. al. (1974), Salamon and Oravecz (1976).

The influence of the frictional resistance between the platen and the specimen on the strength of a specimen, in the form of lateral confining stress, increases with increasing specimen width to height ratio. Thus the surface between the platen and specimen plays an important part in the generation of confining stresses and will vary depending on the angle of friction between different materials.

6.4.2 Mode of Fracture

The typical conical wedge-shaped end segments of the failed specimen, due to end constraints by the loading platens, were observed in the laboratory experiment where the specimens had a width to height ratio between 1,0 and 3,0, Figure 6.13. This type of failure is also observed underground with pillars of similar width to height ratio. The fracture angle appeared to remain fairly constant in all the specimens dissected and the fracture slab seemed proportional to the specimen's height. Figure 6.18 shows the slab width, S, when the fracture angle, ψ, is constant.

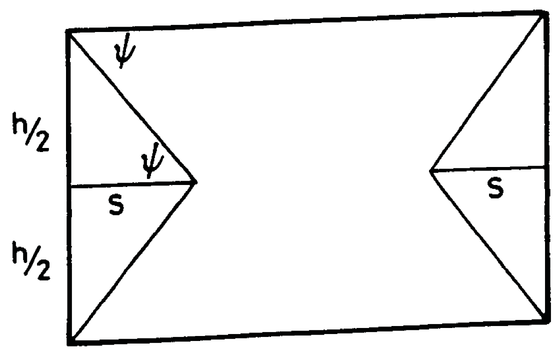

Figure 6.18 Cross-Section of Specimen. Slab Width S, Angle of Fracture ψ and Specimen Height h.

Thus,

$$S = \frac{h}{2\tan\psi}. \tag{6.3}$$

If ψ is constant, this may be expressed as

$$S = Qh, \tag{6.4}$$

where

$$Q = \frac{1}{2\tan\psi}.$$

To examine if this assumption is reasonable, the average slab width, measured after testing, was plotted against the specimen half height as shown in Figure 6.19. Based on the results from 20 specimens which covered the range of width to height ratios from 2,0 to 8,0, an average fracture angle of 51° was obtained.

Given a constant fracture angle, the amount of slabbed material formed on the circumference of the specimen has been calculated as a percentage of the total volume and plotted against the specimens having width to height ratios ranging from 1,0 to 8,0 in Figure 6.20. The figure shows the larger proportion of fractured material per total volume occurs with specimens with low width to height ratios. This proportion decreases as the specimen's width to height ratio increases. From a width to height ratio of about 6,0 further change in width to height ratio becomes insignificant.

Thus, when the initial slab forms within specimens of width to height ratio greater than 6,0, the overall area of the specimen left to carry the load is not unduly affected by the slabbing. As slabs continue to form in the specimen, increasing areas of fractured surfaces are made available. Thus the frictional resistance between the fractured slabs increases. This resistance together with the frictional forces at the platen-specimen contact must be overcome for the specimen to deform further.

Figure 6.21 shows the frictional forces within a fractured specimen. The frictional resistance is primarily a result of the platen-specimen contact and as a result of this force the resistance between the fractured slabs increase. This provides a normal component of force to the fractured slab contact and gives lateral confinement to the central core of the specimen.

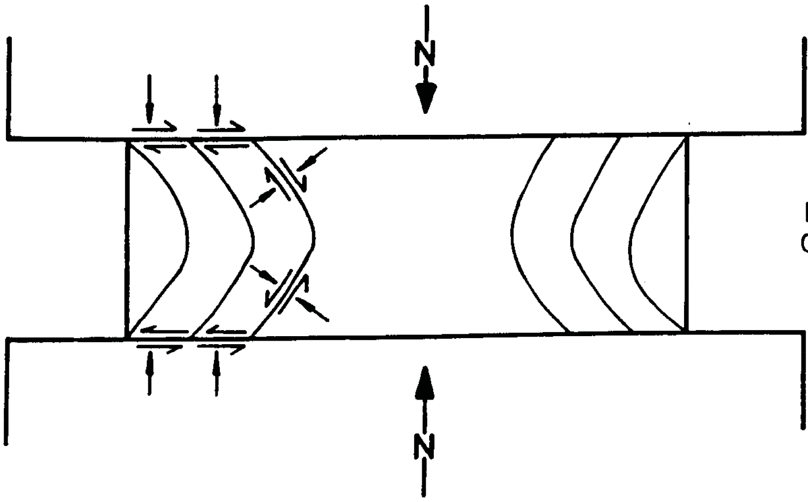

Figure 6.21 The Frictional Forces Within a Fractured Specimen.

The effect of the consolidation of the slabs and their confinement of the central core was shown in Figure 6.16, where, after expanding laterally, the slabs consolidated and the load carrying capacity of the specimen increased even though deformation was taking place. Galvin (1982) showed that even small confinement generated by placing ashfill around a coal pillar increases the strength of the pillar.

6.4.3 Influence of Confinement

The influence of the slabs confining the central core of a specimen is similar to the confinement of a specimen in a triaxial test. This influence becomes more pronounced at higher width to height ratios. Figure 6.22 shows stress-strain curves obtained by Stavropoulou (1982) on the same Karoo sandstone in triaxial compression.

The peak or MRC strength value does not follow the same increase but the load carrying characteristics of the specimens, after this strength value has been reached, are very similar to the triaxial curves. The latter is because the greater the specimen's width to height ratio, the greater the frictional resistance between the platen and the specimen causing an increase in the interaction of the slabs confining the central core. The cores of specimens with width to height ratios greater than 6,0 were sheared and crushed indicating the high stresses generated in the core.

The influence of the soft rubber bands and string around the specimens was considerable and changed the load carrying characteristics when the specimen's width to height ratio exceeded 2,0. This shows that slabs at a pillar's side, although fractured, may still carry some load and provide confinement to the core of the pillar, and therefore influence the strength of the pillar.

Remedial measures, such as wire mesh and bolting, applied to a pillar that has excessive sidewall slabbing, can therefore help reinforce the slabs and provide confinement to the central core of the pillar, thus increasing the load carrying capacity of the pillar. Alternatively, in the design of pillars with large width to height ratios a reduction in pillar width may be considered if confinement of the pillar is included in the design. The benefits of the additional gain in extraction would have to be compared to the cost of supporting the pillar. The design of the artificial confining system has to be such that it does not lose its effectiveness with time.

6.4.4 Strength versus Width to Height Ratio of the Specimen

In Figure 6.9 it was shown that the strength values as determined at the point of MRC increase linearly for specimens with a width to height ratio less than 5,0. Beyond this ratio it was found that the increase in strength is governed largely by the amount of compression that can be tolerated.

In the case of the cylindrical sandstone specimens the critical width to height ratio (R_o) appears to be reached when the strength value increases at a greater rate than that predicted by the straight-line equation. Table 6.5 summarizes the critical width to height ratio (estimated from the graphs) and the straight-line equations obtained for values less than the critical width to height ratio.

Table 6.5 Summary of Results Obtained From the Straight-Line Section of the Strength Versus Specimen Width to Height Ratio Graphs.

Specimen Diameter Size	Critical Width to Height Ratio (R_o)	Equation strength (MPa)
A 24 mm	5-6	Strength = 86,7+14,1 (w/h)
B 36 mm	6	Strength = 84,4+13 (w/h)
C 48 mm	6	Strength = 88 +10 (w/h)
D 60 mm	5-6	Strength =105,1+ 4,1 (w/h)
E 80 mm	5	Strength = 90 +10 (w/h)

The equations, apart from that for series D 60 mm diameter, show a very similar form. The average equation for strength is:

$$strength = 88 + 12\left(\frac{w}{h}\right) \quad MPa. \tag{6.5}$$

Hustrulid (1976) shows that most strength versus specimen width to height ratio plots can be approximated by a straight-line equation. The results were obtained on specimens with a width to height ratio less than 6,5.

Similarly for full size coal pillars, the equation for calculating the strength of South African coal pillars is:

$$strength = k\frac{w^{0.46}}{h^{0.66}} \quad MPa. \tag{6.6}$$

Figure 6.23 shows the strength versus pillar width to height ratio for a 3,0 m high coal seam. In the region where the specimen width to height ratio is between 2,0 and 5,0 the curve is fairly linear and could be described by the equation

$$strength = 6{,}55 + 1{,}39\left(\frac{w}{h}\right) \quad MPa. \tag{6.7}$$

Dividing equation (6.5) by the unconfined compressive strength of the sandstone gives:

$$\frac{\sigma_c}{\sigma_{s1}} = \frac{88}{100} + \frac{12}{100}(w/h) \quad , \tag{6.8}$$

$$\frac{\sigma_c}{\sigma_{s1}} = 0{,}88 + 0{,}12(w/h) \quad . \tag{6.9}$$

Similarly, dividing the average coal strength into equation (6.7)

$$\frac{\sigma_c}{\sigma_{s2}} = \frac{6{,}55}{7{,}2} + \frac{1{,}39}{7{,}2}(w/h) \quad , \tag{6.10}$$

$$\frac{\sigma_c}{\sigma_{s2}} = 0{,}91 + 0{,}19(w/h) \quad , \tag{6.11}$$

where sandstone σ_{s1} = 100 MPa and coal σ_{s2} = 7,2 MPa.

When the sandstone specimen test results in the lower width to height ratio range are normalized with respect to uniaxial compressive strength and the strength of coal from the pillar formula is equated to a straight-line relationship and normalized with respect to the unit strength of coal, the normalized parameter that describes the strength of the specimens of different width to height ratios is not dissimilar.

It was established from the literature survey that an over proportional increase in strength with increasing specimen width to height ratio has been suggested by numerous investigators, although experimental evidence has been scarce.

Salamon (1982) has proposed that the strength of a squat pillar can be described by the formula

$$\sigma_p = k\frac{R_0^b}{V^a}\left[\frac{b}{\epsilon}\left[\left(\frac{R}{R_0}\right)^{\epsilon} - 1\right] + 1\right], \tag{6.12}$$

where σ_p is the strength,

- k is the unit strength of a cube,
- V is the pillar's volume,
- R is the pillar's width to height ratio,
- R_o is the critical width to height ratio where the curve deviates from the straight-line equation,

a is a constant,
b is a constant,
ϵ is a material constant.

This formula is a consistent extension, for pillars of larger width to height ratios, of the existing pillar strength formula which has been in use for many years in South African coal mines.

From the research presented in this thesis it was found that the formula is also well suited to describe the relationship between the strength and width to height ratio of squat sandstone specimens studied in this investigation.

However, it was found that the critical parameters, namely R_o and ϵ, depend on the amount of pillar compression at which the strength was measured. Table 6.6 gives the least squares estimates for these constants at 2,0 and 5,0 per cent compression of the sandstone specimens.

Table 6.6 Least Squares Estimates for Constants at Two Per Cent and Five Per Cent Specimen Compression.

Specimen compression	R_o	ϵ
2 per cent	4,5	4,5
5 per cent	4,0	4,5

6.5 CONCLUSIONS

6.5.1 Strength

This investigation showed that there is a marked change in the influence of the width to height ratio of a specimen on strength beyond a certain critical width to height ratio (R_o). For width to height ratios smaller than R_o, the strength properties can be described by a linear relationship similar to that found by other authors. For specimen width to height ratios greater than R_o there is a very rapid increase in strength with increasing specimen width to height ratio. More importantly it is no longer possible to define a strength value, as the strength value is dependent on the compression that the specimen can tolerate.

The strength value for the sandstone specimens below a width to height ratio of 6,0 can be described by the linear equation

$$Strength = 88 + 12\left(\frac{w}{h}\right) \quad MPa. \qquad (6.5)$$

The formulation of the extended pillar strength formula by Salamon (1982) is well suited to describe the increase in strength found in this investigation for sandstone specimens with width to height ratios of 4,5 and above.

	R_o	ϵ
2 per cent compression	4,5	4,5
5 per cent compression	4,0	4,5

6.5.2 Load-Deformation of Cylindrical Sandstone Specimens

As far as the load-deformation characteristics of small cylindrical sandstone specimens are concerned, it was found that there was a gradual transition from brittle behaviour, at low specimen width to height ratios, to ductile behaviour at large specimen width to height ratios. This transition occurred at a width to height ratio between 5,0 and 6,0.

This change in load-deformation behaviour of sandstone specimens with larger width to height ratios is of great practical consequence as far as the stability of pillar workings is concerned. The results suggest that sudden unstable pillar collapse is most unlikely in the case of squat pillars.

6.5.3 Confinement of Pillar Circumference

Limited experimental evidence suggests that even small amounts of confinement provided to the fractured circumference of specimens has a significant influence on the strength and load-deformation characteristics of those pillars. The effect of providing confinement can be described as similar to that of a specimen with a higher width to height ratio. This observation can be of great practical significance as far as the stability of bord and pillar workings and the design of pillars at great depth is concerned.

6.5.4 Fracturing

The tests have shown that, even in the case of large width to height ratios, initial fracturing of the pillar material at the circumference occurs at comparatively low stress levels. The subsequent slabbing can significantly reduce the strength of pillars with small width to height ratios but is of decreasing importance as the pillar's width to height ratio increases. Removal of the fractured slabs can have an adverse effect on the ultimate load-deformation behaviour of the pillar as was demonstrated by the benefit of even small amounts of confinement to the pillar sides.

6.5.5 Energy Considerations

Energy required to strain cylindrical sandstone specimens by a certain amount increases proportionally with increasing specimen width to height ratio. The strain energy density required to deform the specimen by five per cent was given by the function

$$SED = 0{,}185R^2 - 0{,}203R + 0{,}529 \quad MJ/m^3 \qquad (6.2)$$

where SED is the strain energy density,
R is the specimen width to height ratio.

6.5.6 Volume Effect

The effect of volume on strength was not pronounced although the specimens with a width to height ratio greater than 4,0 showed an increase in strength with decreasing volume. For the same volume of specimen the strength increased with increasing width to height ratio.

Although the results of the tests on the small cylinderical sandstone specimens cannot be applied directly to the design of in situ coal pillars, they have helped to clarify a number of important points particularly as far as the load-deformation behaviour of squat pillars is concerned.

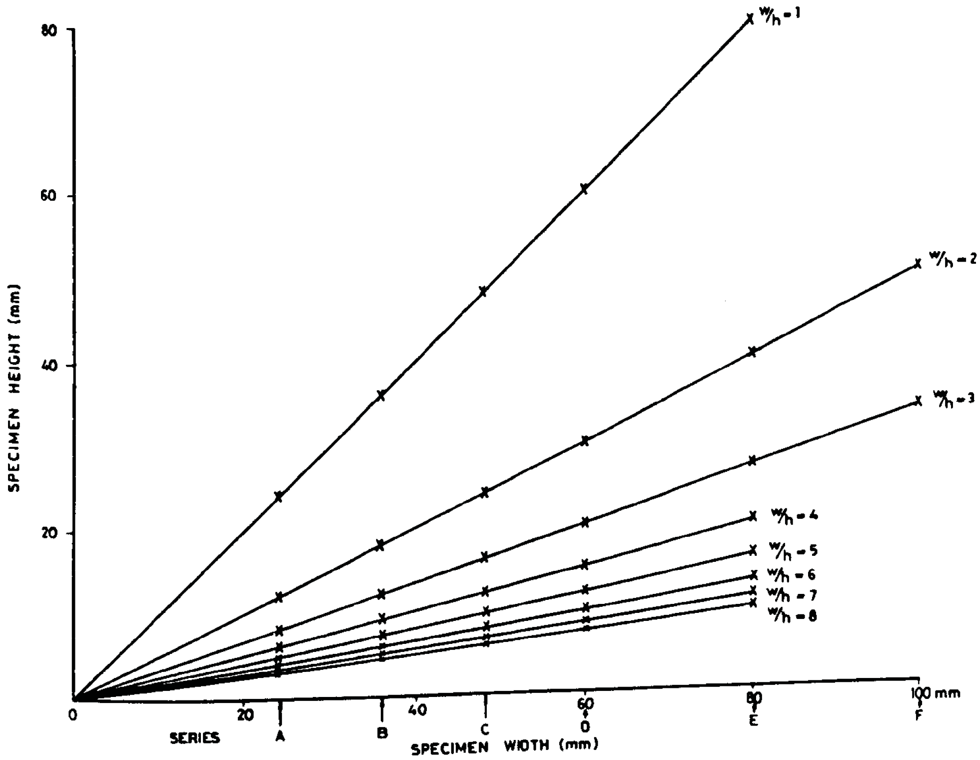

Figure 6.1 Range of specimen sizes and width to height ratios in the experiment.

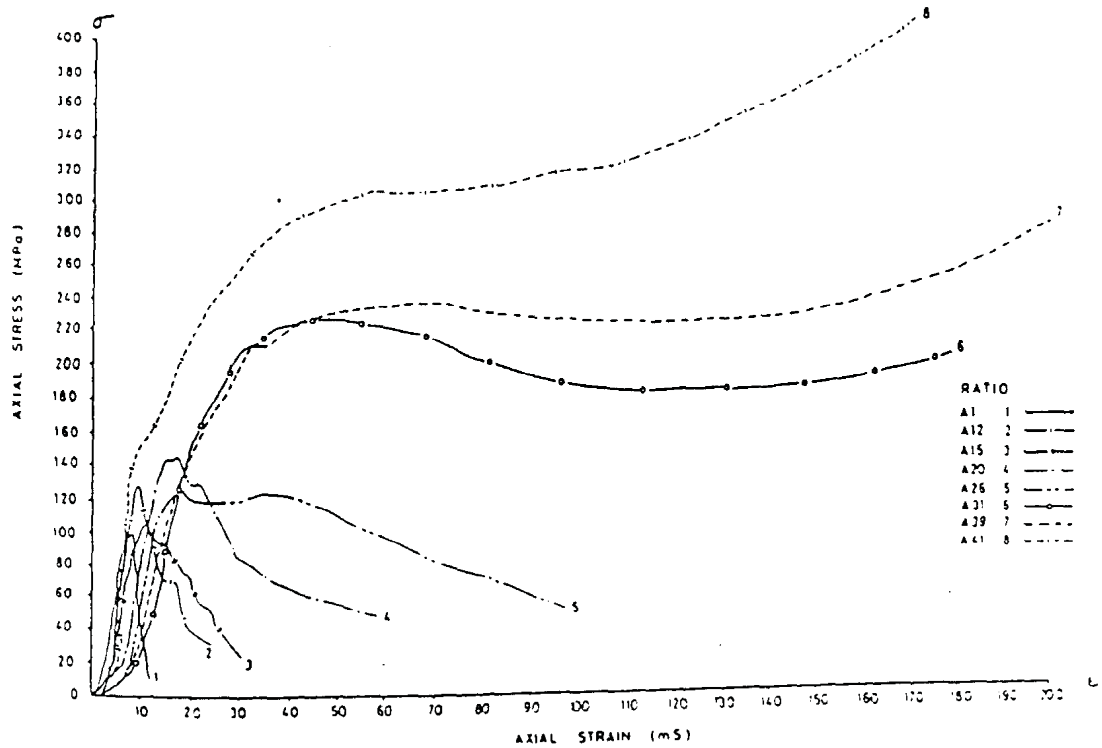

Figure 6.2 Series "A" stress-strain curve, 24 mm diameter.

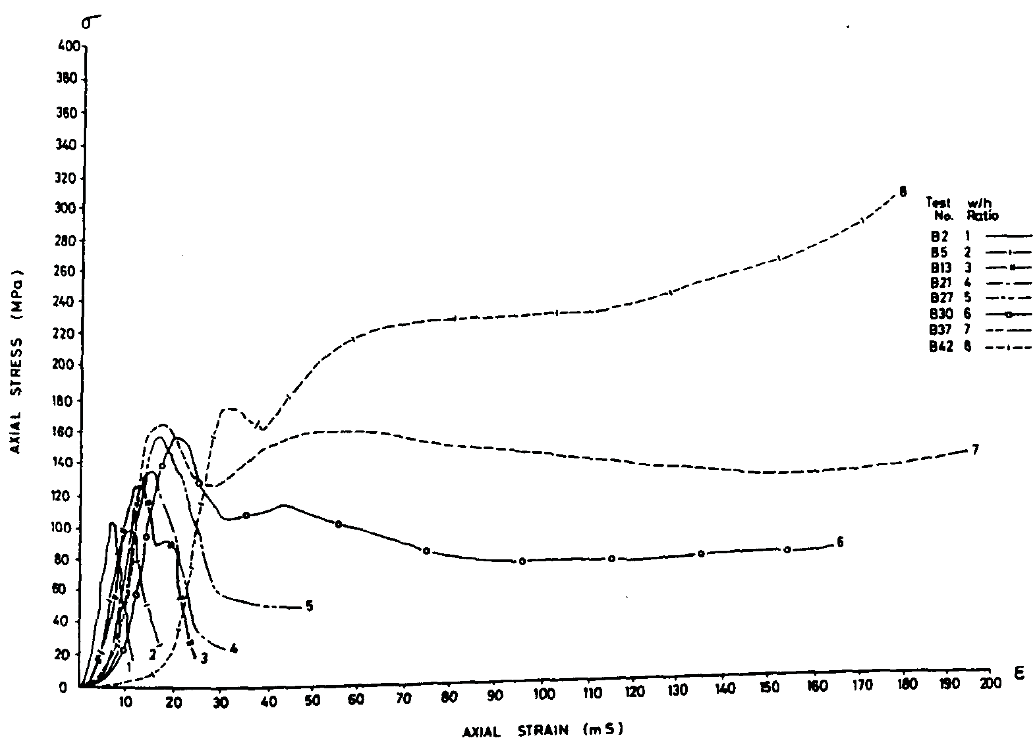

Figure 6.3 Series "B" stress-strain curve, 36 mm diameter.

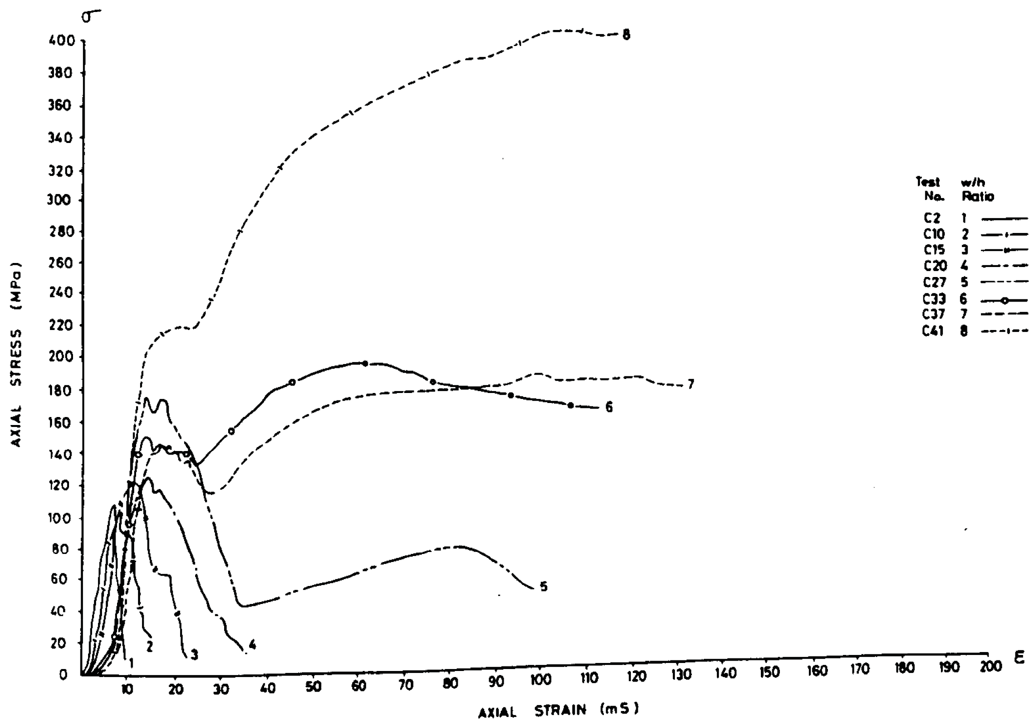

Figure 6.4 Series "C" stress-strain curve, 48 mm diameter.

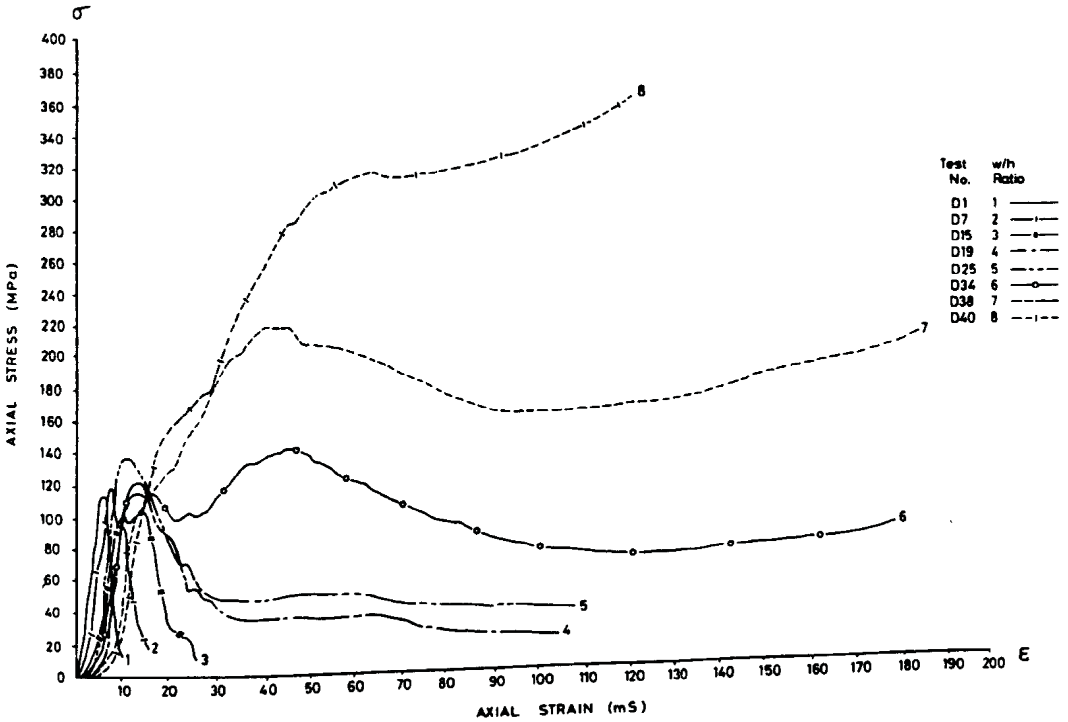

Figure 6.5 Series "D" stress-strain curve, 60 mm diameter.

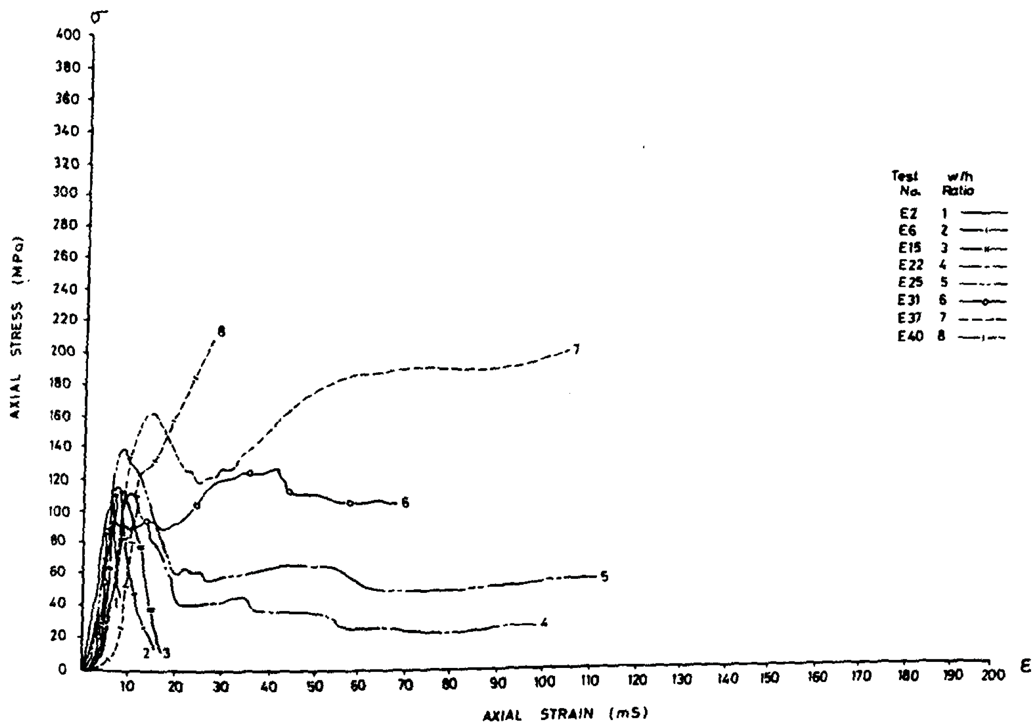

Figure 6.6 Series "E" stress-strain curve, 80 mm diameter.

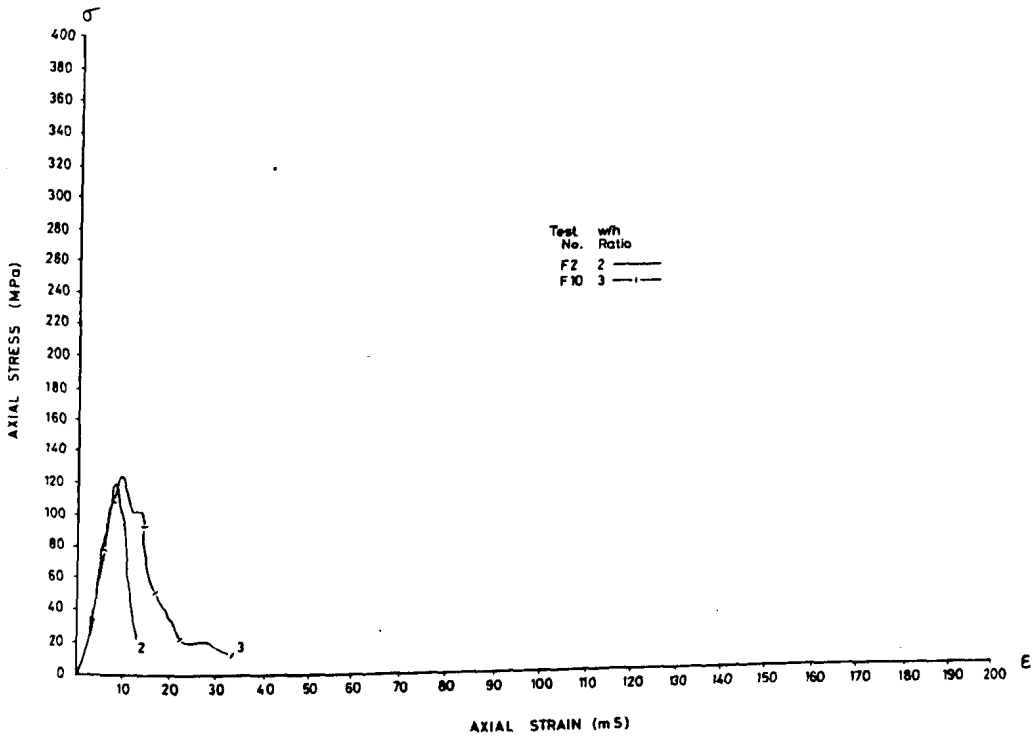

Figure 6.7 Series "F" stress-strain curve, 100 mm diameter.

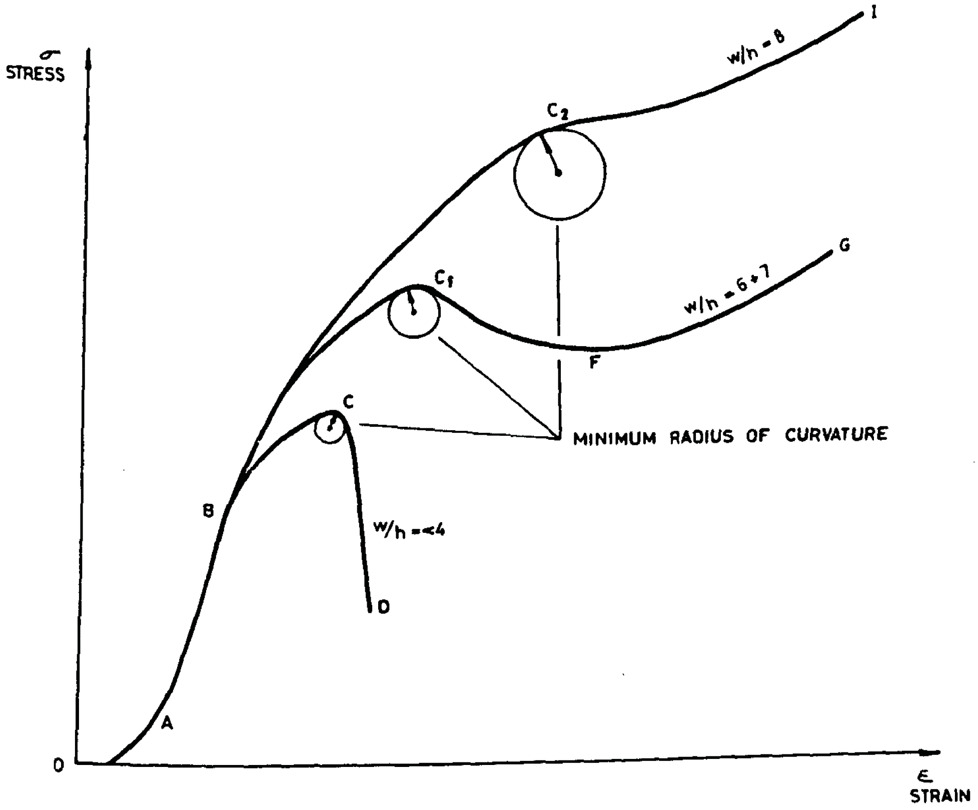

Figure 6.8 Typical stress-strain curves from Figures 6.2 to 6.7 .

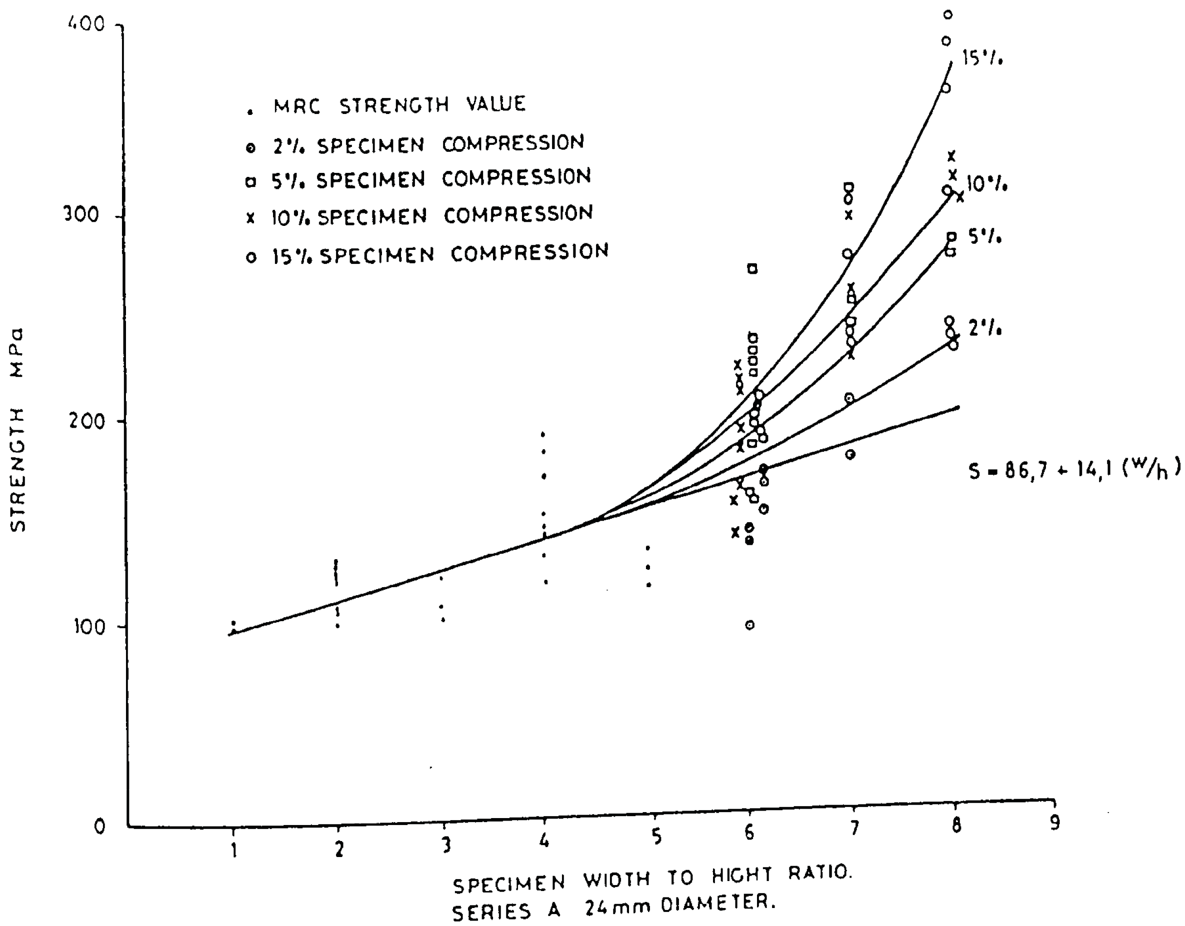

Figure 6.9 Strength versus specimen width to height ratio, 24 mm diameter.

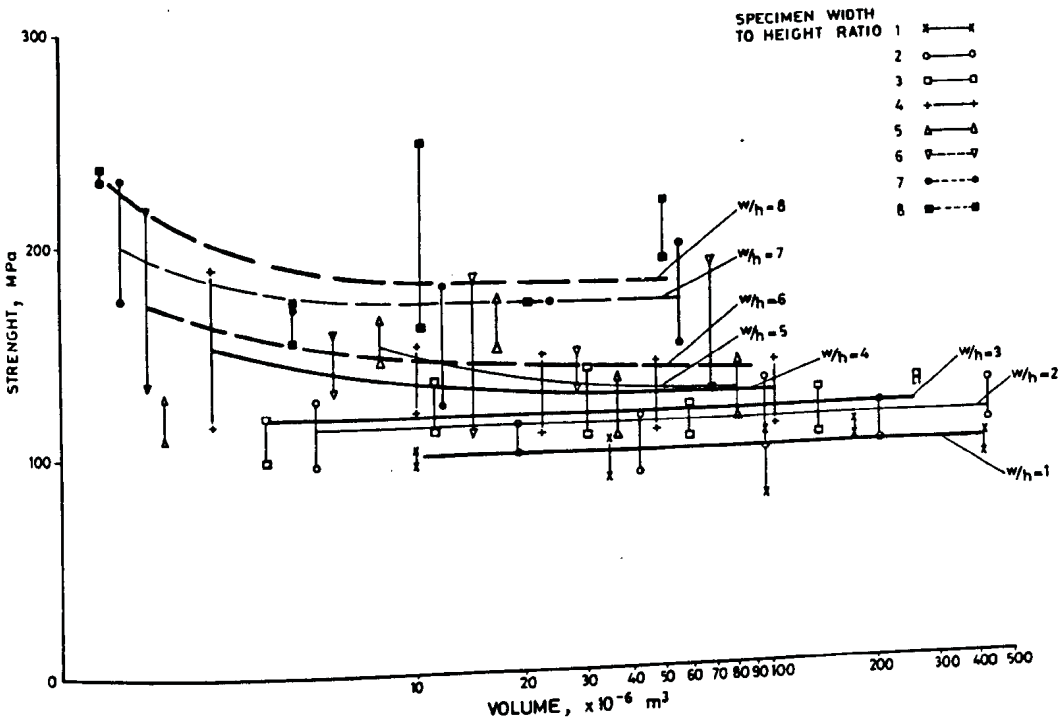

Figure 6.10 Influence of volume on specimen strength.

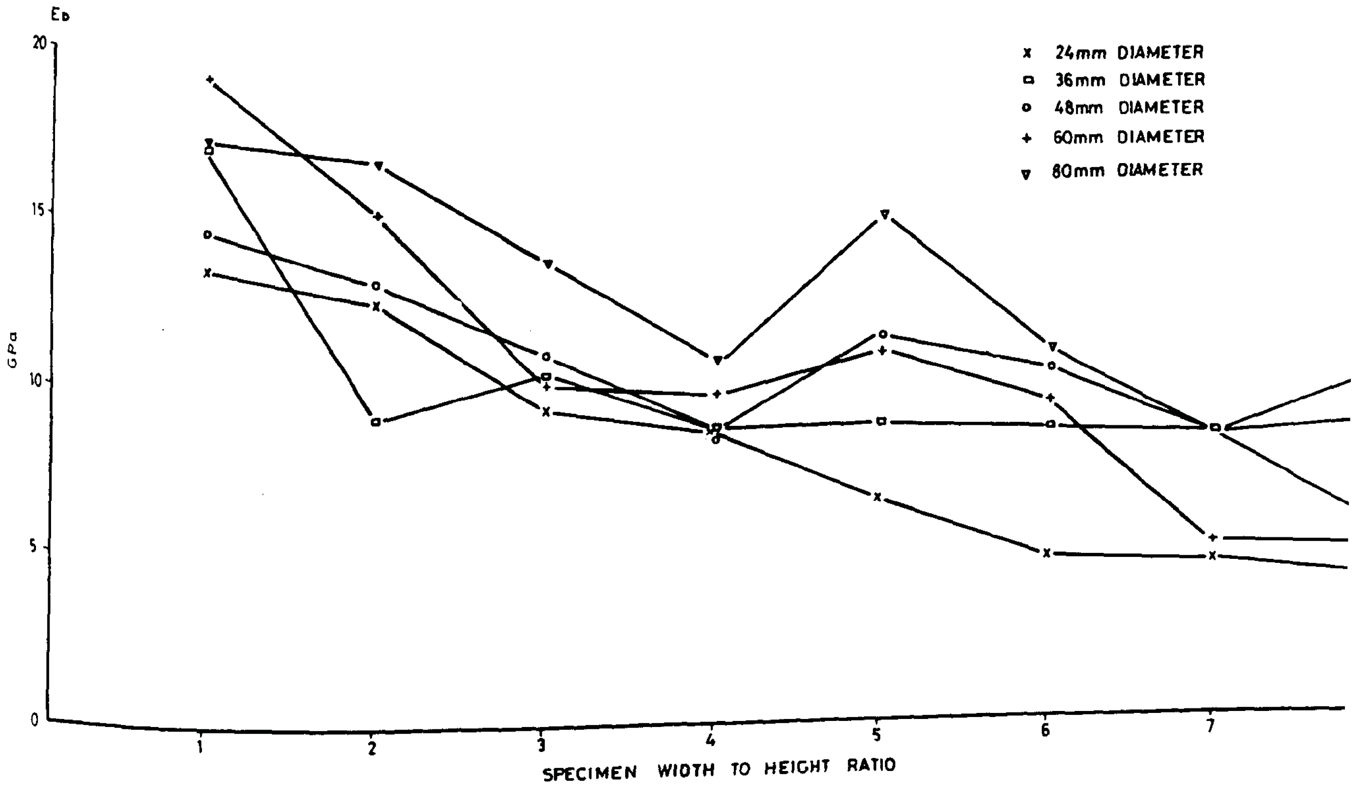

Figure 6.11 Post failure modulus of deformation versus specimen width to height ratio.