Table 2.4 Comparison of Coal Strength Data for Collieries Representing All Major Coalfields in South Africa, After Bieniawski (1968d).

Coalfield	Colliery	Locality	Uniaxial Compressive Strength		Number of Specimens Tested	Strength Index
			Mean MPa	Standard Deviation		
C	Coalbrook	2nd Seam	40,8	14,1	54	103,9
C	Cornelia	Berth Sec.	43,8	16,9	60	111,5
B	DNC	Section 5	34,5	10,0	52	87,7
B	DNC	Section 40	38,4	16,7	72	97,8
A	Kendal	-	44,1	22,6	40	112,4
C	Sigma	-	37,9	14,3	39	96,5
D	Springfield	-	40,5	16,9	100	103,0
A	Wolvekrans	No 4 Seam	39,3	18,1	35	100,0
A	Wolvekrans	No 2 Seam	48,7	27,4	78	108,9
A	Wolvekrans	No 1 Seam	36,5	16,3	49	143,9

NOTE: (i) All specimens were one inch cube in size
(ii) Coalfields

A Witbank
B Klip River Coalfield, Natal
C Vereeniging Coalfield, Orange Free State
D Balfour Coalfield, Transvaal

Kruger (1968) reports the results of tests on 40 specimens from the No. 4 Seam and 200 specimens from the No. 2 Seam of Witbank Coalfield. All specimens were two inch cubes and were loaded normal to the bedding. Figure 2.7 summarizes the frequency versus uniaxial compressive strength. Again, standard deviations of up to 28 per cent are quoted.

Merten (1969) reports that results of six tests on one foot cubes, from the No. 4 Seam at New Largo Colliery, Witbank Coalfield, were within four per cent (7,65 MPa compared to 7,98 MPa) of tests on one foot cubes from the No. 4 Seam, Witbank Colliery.

The laboratory investigations into the strengths of individual South African coal seams show that, while quantitative differences occur, the determination of individual seam strength is influenced by many factors including specimen transportation, preparation, moisture content, position in the seam and size.

These conclusions are confirmed in similar research conducted overseas. Koifman et al (1969), in an investigation into the strength of coals from the USSR, found that while a reduction in compressive strength with increasing specimen size was noted, a scatter of approximately 50 per cent was recorded.

Sorensen and Pariseau (1978) discussed the results of 371 unconfined compressive tests performed on cylindrical specimens of USA Coal with diameters of 1,0; 2,0; 4,0; 6,0; 8,0 and 12,0 inches and width to height ratios of 0.5; 0,75; 1,0; and 2,0. It is stated that the interpretation of laboratory tests is not without ambiguity, particularly in the post peak strength region, and that strength results often show a standard deviation in excess of 30 per cent. They also state that coal is one of the most frequently tested material types in rock mechanics because of the problem of calculating the size of production pillars from laboratory tests and adequately taking into account the effect of size. This size effect is partly due to end effects and the friction between the platen and specimen. If this end condition cannot be scaled, laboratory tests cannot be extrapolated to coal mine pillars. However, laboratory test results provide the determination of material properties necessary for pillar design based on principles of rock mechanics.

In examining the problem of predicting the strength of a mine pillar from small laboratory tests, Panek (1979) suggested the use of a mathematical model that expresses the strength of a typical mine pillar as a function of relevant structural parameters. The effects of size, shape and end conditions are discussed and the influence of size on strength is stated as being the greatest controlling variable. However, in the paper it is concluded that the size effect for South African coal is small, based on work reported by Bieniawski (1969) and Salamon (1967). One complicaion of Panek's formula, as stated in the paper, is that the floor, seam and roof material values of the modulus of elasticity, Poisson's ratio and the coefficient of friction have not been determined with sufficient accuracy. To overcome this, Panek suggested that either the end-constraint conditions must be modelled so that the test specimen and mine pillar satisfy similar requirements or the end-constraint must be characterized and measured. Neither suggestion is simple to execute.

These results confirm those found in South Africa that laboratory tests, while valuable in identifying general trends and material properties, cannot be used to determine individual seam strengths. Table 2.5 provides a summary of formulae derived from laboratory tests.

Table 2.5 Formulae Derived From Laboratory Tests.

Authors	Formula	Remarks
Johnson (1897)	$\frac{\sigma_{prism}}{\sigma_{cube}} = 0.778 + 0.222\frac{w}{h}$	quoted Bunting (1911)
Carpenter (1901)	$\sigma_p = \frac{k}{\sqrt{h}}$	
Rice (1929)	$\sigma_p = k\sqrt{\frac{w}{h}}$	
Steart (1954)	$\sigma_p = k\frac{\sqrt{w}}{h}$	
Gaddy (1956)	$\sigma_p = \sigma_c\sqrt{w}$	
Evans et al. (1961)	$\sigma_p = kw^{-0.32}$ $\sigma_p = kw^{0.17}$	Deep Duffryn Coal Barnsley Hards Coal
Holland Gaddy (1956)	$\sigma_p = k\frac{\sqrt{w}}{h}$	
Bieniawski (1967c)	$\sigma_p = k\frac{w^{0.16}}{h^{0.55}}$	
Hustrulid (1976)	$\frac{\sigma_p}{\sigma_1} = 0.778 + 0.222\frac{w}{h}$	if h > 36"
	$\sigma_p = \frac{k}{\sqrt{36}}$	if h < 36"
	$\sigma_p = \frac{k}{\sqrt{h}}$	
Jeremic (1979)	$\sigma_p = 2.4 + k\frac{w}{h}$	if w/h > 5
	$\sigma_p = k\frac{w}{h}$	if w/h < 5

2.3.2 In situ tests

Problems associated with laboratory tests initiated the testing of samples in situ. The first test results were obtained in the USA where a total of 12 tests were performed between 1939 and 1941.

Rice (1929) noted that differences of up to 50 per cent in strength had been recorded in laboratory tested coal specimens and he stated that, for realistic tests, specimens should model actual geometries of mine pillars which have width to height ratios between five and 10. He also suggested an in situ method whereby pillars in a remote panel could be designed to be loaded by the surrounding strata.

This method was first used by Greenwald et al (1939). Seven pillars in the US Bureau of Mines experimental mine were formed, capped by a layer of concrete and loaded using hydraulic jacks. The pillars varied between 30 and 63 inches wide having a width to height ratio between 0,5 and 1,03 and all, except two, had square bases. Although most of the production pillars had width to height ratios of between five and 15, it was noted that, in retreat mining, some ribs had width to height ratios as low as one.

Systematic measurements of vertical and lateral movements were recorded giving the first in situ stress-strain curves up to the pillar's peak strength. The loading of each pillar took several days with incremental loading every one or two days until no further movement could be detected. Although two pillars failed due to a 12-15 inch layer of fireclay in the floor, the other results show remarkable similarity in the stress-strain profiles. The experiment, which took over 18 months to complete, was a significant contribution to the knowledge of the mechanical behaviour of in situ coal despite the limited number of pillars tested.

Extensive in situ testing was conducted in South Africa during the period 1966 to 1974 with 91 in situ tests being completed. The results are summarized in Table 2.6.

Table 2.6 Summary of the Results of South African In Situ Tests.

Reference	Colliery	Seam	Number of Tests	Cube Size	Result
Hoek (1966)	Witbank	No. 4	5		
Bieniawski(1967a)	Witbank	No. 4	14	2, 3 and 4 ft	Fig 2.8-10
Bieniawski& Mulligan(1967)	Witbank	No. 4	8	upto 5 ft	
Bieniawski(1968e)			8	upto 6,6 ft	
Bieniawski(1968c)	Witbank	No. 4	3		Fig 2.14
Cook et al.(1971)	Usutu	?	5	3 ft	Fig 2.11
V Heerden(1971)	New Largo	?	5	1 m	
Wagner(1974)	Usutu	?	33	upto 2 m	Fig 2.13
V Heerden(1974)	New Largo		10	1,4 m	
		TOTAL	91		

The feasibility of conducting large scale in situ tests in South Africa was investigated at the Wolvekrans Section, Witbank Colliery in the No. 4 Seam by Hoek (1966). Five sample pillars were tested in situ with the aim of assessing the testing method. The in situ results were compared to results from five laboratory specimens and the trend of a significant reduction in strength with increasing size was noted, although Hoek (1966) stated that the number of samples was too small for meaningful results. However, the tests proved the testing method was feasible.

Following on from this report, a substantial in situ testing programme was conducted over an eight year period by the CSIR and summarized by Bieniawski and van Heerden (1975). Initial tests, Bieniawski (1967a), were conducted on 14 samples, 2,0 foot, 3,0 foot and 4,0 foot square with width to height ratios between 0,5 and 2,0 in the No 4. Seam of the Wolvekrans Section, Witbank Colliery, Witbank Coalfield. The samples were loaded with a total of 16 hydraulic jacks. Several corners failed during the experiment and it was concluded that the lateral constraint applied at the sample-jack contact was not effective and that a stronger constraint should be provided in future experiments. The results are shown in Figures 2.8 and 2.9 where the influence of sample width and height on strength is indicated. Figure 2.10 shows the reduction in strength with increasing cube size. It should be noted that these tests were a significant advance in the knowledge of the strength of in situ coal pillars. Although only two tests on cubes of each size were performed, the results are remarkably close considering the scatter obtained in the laboratory.

Pillar cubes of 2,0 foot, 3,0 foot, 4,0 foot, and 5,0 foot were tested by Bieniawski and Mulligan (1967) who concluded that there would be no increase in the strength of a sample beyond 5,0 foot cube. As a result the usual assumption that strength of coal pillars can be represented as a power function of their width to height ratio was stated by Bieniawski (1968b) not to be valid since coal strength reaches an asymptotic value at 5,0 feet. To confirm this, Bieniawski (1968e) reported tests on eight 6,6 foot wide in situ samples with two samples each having heights of 2,0 feet, 3,3 feet, 5,0 feet and 6,6 feet.

Cook (1967) was critical of the results obtained by Bieniawski's testing procedure since, he suggested that, in large scale tests, it was essential not to disturb the contact between the hangingwall, footwall and pillar as the end constraints are an important factor affecting pillar strength. He further suggested that the middle of the pillar be used as an axis of symmetry and that uniform displacement rather than uniform load be applied. The jacking units should be free to allow lateral movement and be expanded by a fixed amount irrespective of resistance. In this way the complete load-displacement curve of the pillar could be obtained.

Supplementary in situ tests on 3,0 foot cube coal samples were conducted by Bieniawski (1968c) to investigate the effects of end constraint on strength. Three samples in the No. 4 Seam, Wolvekrans Section of the Witbank Colliery were prepared in situ and a reinforced concrete cap 3,0 inches thick and extending over the sample sides by 9,0 inches was placed on each sample. The results gave well over a 100 per cent increase in strength over the results previously obtained on 3,0 foot cube samples, also tested by the same jacking system, in the No. 4 Seam, Wolvekrans Section Witbank Colliery. The previous tests were restrained by steel straps around the top of the sample and wooden shuttering between the jacks and the top coal layer.

Bieniawski (1974) felt that this discrepancy, although anticipated, was too large to be due to the influence of lateral end constraint only and that the difference could be explained by differences in the coal strata tested. However, the fact that a difference in strength values of over 100 per cent was recorded using the same testing system in the same locality as in previous tests, whether this difference was due to changes in geology, lateral end constraint or a combination of both, is cause for concern in the extrapolation of results to full size pillars.

The practical implementation of the uniform deformation testing system, Cook (1967), was discussed by Bieniawski (1968a), who expressed some concern over aspects of the system.

Concurrent with the CSIR testing programme, in situ tests were conducted by Cook et al (1971) and Wagner (1974) and Bieniawski's criticisms were answered by Cook et al (1971) in tests at Usutu Colliery in the Ermelo Breyton Coalfield where results showed that the testing of in situ pillars using the uniform displacement system was possible and the complete average stress-compression curves for coal pillars were obtained for the first time, Figure 2.11. However, samples with width to height ratios greater than 2,2 could not be loaded to complete failure owing to the insufficient loading capacity of the jacking system. Van Heerden (1971) tested one metre cube samples at New Largo Colliery, Witbank Coalfield, using both the uniform stress and uniform displacement methods, however most of the jacks attained their maximum capacity before the sample failed. The results showed that both the uniform stress (two samples) and uniform displacement tests (three samples) gave the strength of the one metre cubes as greater than 8,0 MPa. This is nearly twice the value of 4,5 MPa in the tests reported by Bieniawski (1967a). Van Heerden (1971) suggested that the increased strength is a result of the coal seam being stronger.

During van Heerden's experiment several corners failed before the jacks had reached their maximum load. Also the surface contact between the sample and floor revealed a "shiny oily material" in one sample leading van Heerden (1971) to conclude that the end constraint effect was very much smaller than thought previously.

The determination of the complete load-deformation characteristics of coal pillars was reported by Wagner (1974). Thirty-three tests were conducted at Usutu Colliery using the uniform deformation technique; thus the important boundary conditions between the ends of the pillar and the roof and floor remained unaltered. Both rectangular and square pillars with widths and lengths between 0,6 to 2,0 m and width to height ratios from 0,6 to 2,2 m were tested. The number of jacks varied from four to 25. Figure 2.12 shows the strength values obtained versus the pillar width to height ratios. The wide spread of results was partly attributed to the area beneath the jack compared to the total area of the sample. This assists in confinement of smaller pillars but in the larger pillars this confinement falls away at the early stages of the test when the pillar circumference starts to fail. The stress profiles at various stages of pillar compression could be plotted using the uniform deformation technique (Figure 2.13). A major finding of this work was the realization that the centre portion was capable of withstanding extremely high stresses even when the pillar had been compressed beyond its maximum resistance, which is traditionally regarded as the strength of the pillar. Other important findings were that the circumferential portions of a pillar were virtually independent of the sample width to height ratio whereas the strength of its centre increases with an increasing width to height ratio. In addition, it was found that the modulus of elasticity was a true material property and independent of geometry. However, the post failure modulus was markedly affected by width to height ratio, which indicated that the post-failure behaviour of a pillar is a structural or system property and not an inherent material property.

Using uniform deformation loading, Cook et al (1971) obtained the complete stress-strain curves for in situ samples, for the first time.

The in situ and laboratory strength of Indian coal was compared by Lama (1970). Twenty in situ tests were performed, 10 in uniaxial compression and 10 under constrained conditions. The in situ samples were approximately 650 mm square with a height of about 1,65 m and a width to height ratio of approximately 0,4. Some 218 specimens, with base dimensions of 50 and 100 mm square and heights from 10 to 200 mm, were tested in the laboratory. Lama (1970) concluded that the fracture strength of coal is greaty influenced by the presence of cracks and other planes of decreased cohesion and that constraint increases the specimen strength by about 50 per cent.

Experiments by Hazen and Artler (1976) and Skelly et al (1977) on in situ pillars in the USA were conducted by instrumenting two pillars in each investigation and monitoring deformation as the pillars were reduced in size. Hazen and Artler concluded that the in situ pillars were composed of a highly stressed inner zone surrounded by a perimeter region which had lost its elasticity. From the tests a considerable scatter of results was obtained and they suggested that cubes get stronger as they increase in size which contradicts the findings of Bieniawski (1968d), Greenwald et. al. (1939) and Wagner (1974). The general nature of both findings may be attributed to the limited experimental samples.

The complex behaviour of a coal sample in a large scale in situ compression test in a USA colliery was discussed by Cyrul (1986). An experiment on a 1,5 m cube of coal using the uniform deformation loading method and extensively instrumenting the sample showed that local strain fluctuation, regional and global bending and torsion were measured in the sample. These effects occur in heterogenous strata like coal and result from differences in local stiffness, and anisotropy within the stratification leading to a complex deformation process including bending torsion and local strain fluctuations. It is these variations that lead to a scatter of results obtained in large scale in situ tests.

The in situ testing of coal resulted in an increased knowledge of the behaviour of coal pillars, particularly as far as the stress-strain behaviour is concerned. However, similarly to the laboratory investigations, a wide scatter of results was obtained. In addition, in situ experiments were limited by the capacity of the loading system applied to the pillar and proved to be time-consuming, elaborate and expensive. However, within larger width to height ratio samples a confined core surrounded by a failed fractured zone was found to be capable of carrying load even when the sample pillar had passed its average peak strength. Formulae derived from in situ experiments are shown in Table 2.7.

Table 2.7 Formulae Derived From In Situ Experiments.

Authors	Formula	Remarks
Greenwald et al(1939)	$\sigma_p = k\sqrt{\frac{w}{h}}$	psi
Greenwald et al(1941)	$\sigma_p = \frac{\sqrt{w}}{6\sqrt{h^5}}$	psi
Bieniawski(1967c)	$\sigma_p = 400 + 220\frac{w}{h}$	psi
Bieniawski(1969c)	$\frac{\sigma_p}{\sigma_c} = 0.64 + 0.36\left(\frac{w}{h}\right)$	ifw/h>1, w>1,5m
Van Heerden(1974)	$\sigma_p = 10 + 4.2\frac{w}{h}$	MPa
Wagner(1974)	$\sigma_p = k\sqrt{\frac{w_{eff}}{h}}$	k= 11 MPa $w_{eff} = 4AC$
Wang et al(1977)	$\frac{\sigma_p}{\sigma_c} = 0.78 + 0.22\frac{w}{h}$	

2.3.3 Field Measurement

The displacement of strains on pillars induced by bord and pillar mining in two collieries at 11,6 m and 25,5 m depth to the seam were monitored by Salamon and Oravecz (1966). The findings were compared to theoretical results using both a homogeneous and a transversely isotropic elastic model. The former gave a good description of the observed displacement. Conclusions from the investigation showed that the in situ Young's Modulus of coal measure strata was considerably lower at low stresses than values determined by laboratory experiments. Hence the stress concentration in the pillars could be smaller than previously suspected. These field measurements were invaluable because they showed that observed in situ results could be explained using elastic theory. Hence, at a low stress environment, the behaviour of coal pillars could be predetermined.

An in situ penetrometer to investigate the cuttability of South African coal seams was developed and used to measure initial identation, mean and peak cutting force and specific energy, Whyte and Grant (1979). Such measurements can give an indication of the strength of coal seams as the strength of coal is related to the force necessary to cut it.

Results from 13 seams in 17 collieries using the penetrometer were recorded by Grant and Whyte (1981). General strength results are implied in the conclusion that the South Rand Seam was the easiest to cut and the Orange Free State Seams 1, 2A, 2B and 3 showed "much" variation. In the Witbank Coalfield, the No. 4 Seam was easier to cut than the No. 5 Seam and the No. 2 Seam was the hardest. They equated the No. 4 Seam with the No. 2 Seam from the Orange Free State. The Ermelo-Breyten Seams B, C Upper and C Lower were regarded as harder requiring twice the force to cut the C Lower Seam compared to that required to cut the South Rand Seam.

The results of further tests on the seams in the Witbank Coalfield recorded by Grant (1981) correlated with the previous investigation, while tests on seams in the Natal Coalfields showed a great variation in rank, from blend coking coal to anthracite; no trend was noted, however, for either physical properties or cutting forces with rank. The Natal seams were generally easier to cut than the No. 4 Seam, Witbank Coalfield.

2.3.4 Mining Method

Wagner (1980) suggested that the method of mining may affect the strength of the coal pillar as a pillar formed by a continuous miner would not be subjected to blast induced damage of the pillar side as in conventional drilling and blasting methods. Although not quantifying the extent of the blast induced damage, Wagner (1980) proposed a method of altering the strength formula of Salamon and Munro (1967) to take into account the increased strength of a continuous miner formed pillar.

2.4 THE STRENGTH OF SPECIMENS WITH HIGH WIDTH TO HEIGHT RATIOS.

2.4.1 Theoretical and Laboratory Investigations

Most investigations, both in the laboratory and in situ, have been conducted on specimens with low width to height ratios. However, it was noted that the effect of geometry had an important influence on strength and, after a certain ratio, the strength value was greater than that predicted by extrapolating the results from low width to height ratio specimens.

The effect of geometry on strength was first investigated by Lawall and Holland (1932). Holland (1942) reported that the laboratory results of Lawall and Holland (1932) were extremely erratic with some specimen failing abruptly and others failing gradually. Some specimens with width to height ratios greater than 4,9 deformed but there was no point at which it could be stated that failure definitely occurred. It was also stated that the coal specimen dented the steel bearing plates and that the coal specimen was "forced" into a plastic state. Some specimens were described as failing by "squeezing", the transition from abrupt failure to squeezing being gradual. It was stated that specimens with width to height ratios of 4,9 or greater are closer to the width to height ratio of coal pillars.

Friction has an important influence on strength. Denkhaus (1962) stated that the frictional forces at the specimen-platen contact influence the strength result, hence the shape and size of the specimen will affect the strength result.

Holland (1942) indicated that friction between a specimen and the top and bottom platens was directly responsible for the apparent increase in specimen strength as the specimen width to height ratio increased. This was confirmed by the strength reductions of between 30 and 40 per cent which resulted when the specimen-platen contact was lubricated with a graphite-grease layer, Meikle and Holland (1965).

From an investigation into the compressive strength of rectangular blocks of UK coal, Evans and Pomeroy (1957) concluded that the strength is determined by the specimen's height provided the height is not less than the minimum lateral dimension. Friction between the specimen and platens was the important factor regarding the increased strength of "squat" specimens.

The phenomenon of strength increasing at an increased rate after a certain width to height ratio was noted by Bieniawski (1968c), Figure 2.14. Bieniawski (1967b) reported compression test results on sandstone specimens with width to height ratios between one and 10. These results showed that, beyond a width to eight ratio of five, the strength of a specimen increases rapidly with increasing width to height ratio. The strength of mine pillars was examined theoretically by Grobbelaar (1968) who concluded that the strength of a pillar is highly dependent on the slope of the failure criteria diagram, the co-efficient of lateral stress and the width to height ratio. He suggested that the strength of the material in the pillar varies with distance from the pillar edge; but an exceedingly high value of vertical stress may develop in the centre of wide pillars, he stated, and proposed that the strength increase would be an exponential function.

Vutukuri et al (1974) stated that the stress distribution in specimens with large width to height ratio tends to be triaxial and the specimens exhibit very high compressive strength.

Borecki and Kidybinski (1970) tested concrete blocks ranging in width to height ratios from 1,0 to 20,0. Because of the continued build-up in load with deformation, they had difficulties in determining the ultimate load bearing capacity of the concrete blocks with width to height ratios greater than 10,0. Specimens with "large" width to height ratios were crushed without loss of load, i.e. with an ever-increasing resistance as a result of the increased frictional resistance in the central part of the pillar.

Hudson et al (1971) examined the influence of geometry in the laboratory and showed that the post peak region of the stress-strain curve of a specimen changes with increasing width to height ratio.

Wilson (1972) proposed that the centre of pillars, over a certain pillar size, is composed of a central core subjected to triaxial stress surrounded by a fractured and yielding zone. The average stress of a pillar is given by:

$$\sigma = 488R\,(p.s.i) \qquad (2.4)$$

or

$$\sigma = 3.37R\,(MPa)$$

where R is the pillar width to height ratio.

He compared equation 2.4 to one developed by Bieniawski (1967c), Table 2.7, and found that equation 2.4 predicted a greater increase in strength with increasing width to height ratio. However, this equation underestimates the strength of pillars with width to height ratios greater than 10 (Bieniawski (1983)).

Barron (1978) examined Wilson's proposal by using an air injection technique to identify the extent of the fractured zone and thus estimate the integrity of pillars and barriers in coal mines; as mining depth increases, fracturing of the sidewall occurs and the stress profile changes resulting in a zone of high stress further from the pillar edge. Although the method was subjective in the interpretation of the results, it showed that a central core was surrounded by a zone of fractured rock and that this zone extended into the pillar over time.

The extent of fracturing in a coal pillar was estimated using a sonic velocity logging probe by Snodgrass and Neuman (1985). This probe showed that the extent of pillar fracturing could be delineated owing to changes in compressional and shear wave velocities between the fractured zone and the elastic unfractured core.

Singh (1980) proposed multiplying the strength formula by a factor that varied between five and six depending on the width to height ratio, although no experimental evidence was presented. Theoretical studies by Bauer (1980), using an analytical solution comprising equilibrium equations for the plane state of strain, a Mohr-Coulomb criterion and boundary conditions between the seam floor and the roof contacts, found that the pillar strength was chiefly dependent on the internal friction angle; when this value exceeded 30 °, very high strengths were obtained when the width to height ratio exceeded 5,0.

Bieniawski (1984) quoted the modified formula of Bieniawski and Van Heerden (1975) by Belesky (1981):

$$\sigma_p = \sigma_1[0,64+0,36(w/h)]^{\eta} \qquad (2.5)$$

The component η takes into account the constraining effects of wider pillars, and when the width to height ratio is greater than 5,0 it is taken as 1,4 and equals 1,0 when the width to height ratio is 5,0 or less.

The formula was dismissed by Bieniawski for the sake of safety and because of the lack of experimental data.

Salamon and Oravecz (1976) stated that it is important to note that the equation proposed by Salamon and Munro underestimates the strength of pillars when the pillar's width to height ratio exceeds 5,0 or 6,0 and that the pillar would be indestructible when the ratio exceeds 10. Salamon (1982) proposed an extension to the formula that takes account of the rate of strength increase with increasing width to height ratio, after a certain ratio.

The formula of Salamon and Munro (1967) can be written in terms of volume and width to height ratio.

Thus $\sigma_p = kV^a R^b$ (2.3)

where $a = -0{,}0667$
$b = 0{,}5933$
V = pillar volume $w^2 x h$.

It is interesting to note that the volume of full size pillars decreases by the exponent $a = 0{,}0667$.

Salamon (1982) suggested that equation (2.3) should be expressed in the form

$$\sigma_p = kV^a(\gamma R^\epsilon + \delta) \qquad (2.6)$$

where γ, δ and ε are dimensionless parameters. Parameters γ and δ can be determined from two conditions of continuity. It was postulated that at $R = R_0$

where R_0 is the critical width to height ratio

$$\sigma_p = \sigma_s \quad ; \quad \frac{\partial \sigma_p}{\partial R} = \frac{\partial \sigma_s}{\partial R}.$$

These relationships permitted the reformulation of equation 2.3 to

$$\sigma_s = k\frac{R_0^b}{V^a}\left\{\frac{b}{\epsilon}\left[\left(\frac{R}{R_0}\right)^\epsilon - 1\right] + 1\right\} \qquad (2.7)$$

where σ_s is the strength of a squat pillar
ε is the rate of strength increase.
a is 0,0667
b is 0,5933.

Salamon and Wagner (1985) suggested values of 5.0 for R_0 and 2,5 for ε.

An experiment on six Indian Coals by Das (1986) showed the stress-strain curves on cylindrical, 54 mm diameter, coal specimens with width to height ratios from 0,5 to 13,5. The post failure slope becomes positive after reconsolidation of the failed material when the width to height ratio exceeds 6,75.

Strength formulae that account for high width to height ratio pillars are shown in Table 2.8.

Table 2.8 Formulae Accounting For the Increased Strength of Squat Pillars.

Authors	Formula	Remarks
Wilson (1972)	$\sigma_p = \sigma_{cr} + \sigma_3 \tan\beta$ $\sigma_p = 488w/h$	
Panek (1979)	$\frac{\sigma_2}{\sigma_1} = \left(\frac{A_1}{A_2}\right)^{a}\left(\frac{E_2}{E_1}\right)^{b}\left(\frac{V_2}{V_1}\right)^{c}\left(\frac{\theta_2}{\theta_1}\right)^{d}\left(\frac{\mu_2}{\mu_1}\right)^{e}\left(\frac{\mu_2}{\mu_1}\right)^{f}$	
Bielesky (1981)	$\frac{\sigma_p}{\sigma_1} = [0.64 + 0.36(w/h)]^n$	where η is 1,4
Salamon (1982)	$\sigma_p = k\frac{R_0^a}{V^b}\left\{\frac{b}{\varepsilon}\left[\left(\frac{R}{R_0}\right)^{\varepsilon} - 1\right] + 1\right\}$	where R_0 is 5 ε is 2,5 a is 0,0667 b is 0,5933 R is w/h

2.4.2 Summary

Laboratory experiments conducted on specimens with width to height ratios exceeding 5,0 indicate an increased strength beyond that predicted by formulae based on specimens with width to height ratios less than about 5,0. Results from in situ tests on coal pillars with large width to height ratios showed that a fractured perimeter surrounds an unfractured core. The resulting confinement results in the pillar being capable of sustaining load while the pillar deforms.

Both laboratory tests and in situ experiments on coal pillars suggest that using Salamon and Munro's strength formula to design large width to height ratio pillars will result in underestimating the strength of the pillar. Although several strength formulae that account for the increased strength of squat pillars have been suggested, none have been validated by full scale field experiments.

2.5 CONCLUSION

A survey of the literature regarding the strength of coal and the determination of an economic pillar design method reveals extensive investigations by many research teams throughout the past 100 years. The strength calculation versus pillar width to height ratio of predictive formulae from some of these investigations is shown in Figure 2.15. The figure indicates the wide variation in strength values which deviate increasingly with increasing pillar width to height ratio.

General trends have been noted and these have greatly added to the knowledge of coal behaviour. However, these research efforts, both in South Africa and abroad, are characterized by a wide scatter of results, thus the determination of coal strength is difficult and extrapolating them to full size pillars impossible.

Salamon and Munro's pillar strength formula remains the most reliable design method as it is based on full size intact and collapsed coal pillars. However, the assumption of one average seam strength for all seams and the fact that the formula is based on empirical data, require investigation. This is particularly true considering the expansion in the exploitation of South African coal reserves.

For example, there is evidence both from the laboratory and field investigations that the strength of pillars rapidly increases after a certain width to height ratio is exceeded.

It is also suggested that the effect of the mining method used to form the coal pillar is a possible cause of the difference in coal pillar strength; however this effect has not been quantified.

This thesis critically reviews the coal pillar strength formula of Salamon and Munro in the light of its performance over the past 22 years. The assumption of one average strength for all coal seams is investigated by alternative methods to traditional laboratory and in situ testing. The effect of mining method on pillar strength is quantified and the validity of extending Salamon and Munro's pillar strength formula beyond its empirical range is examined as is an alternative strength formula that accounts for the strength of squat pillars.

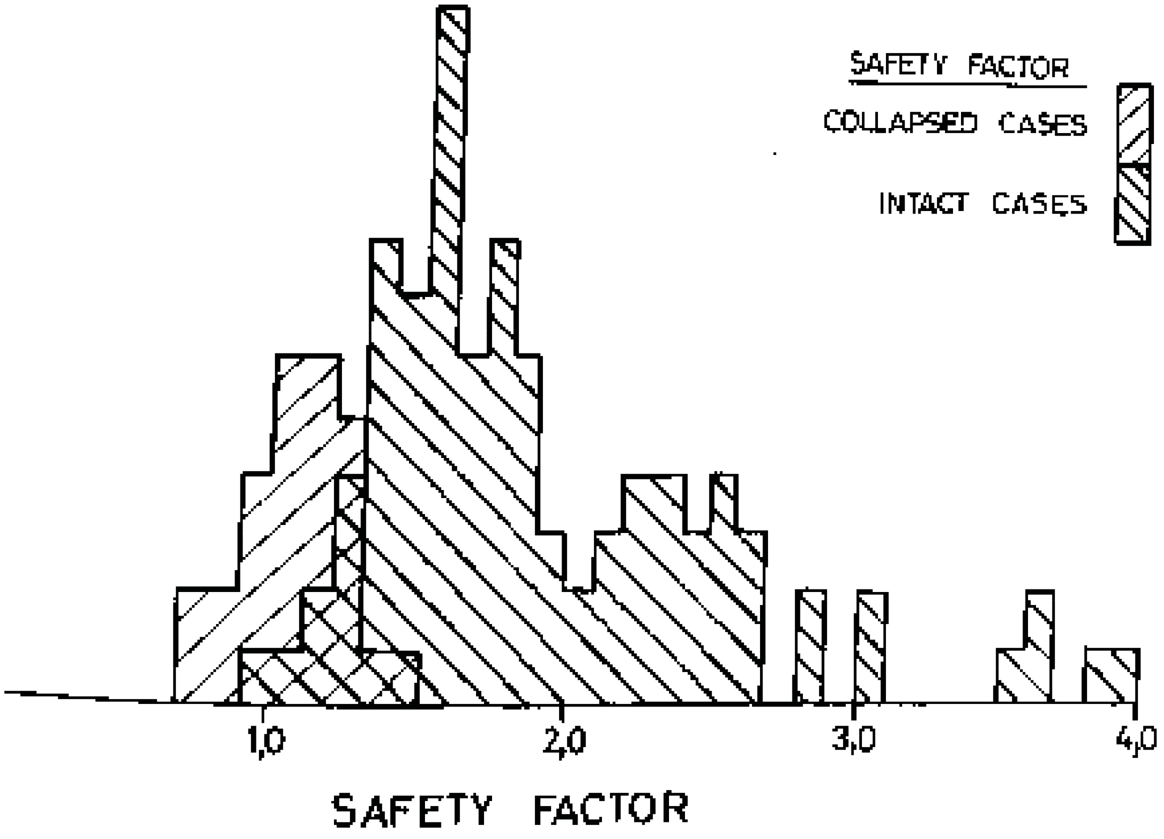

Figure 2.1 Histogram of safety factors for stable and collapsed cases. After Salamon (1967).

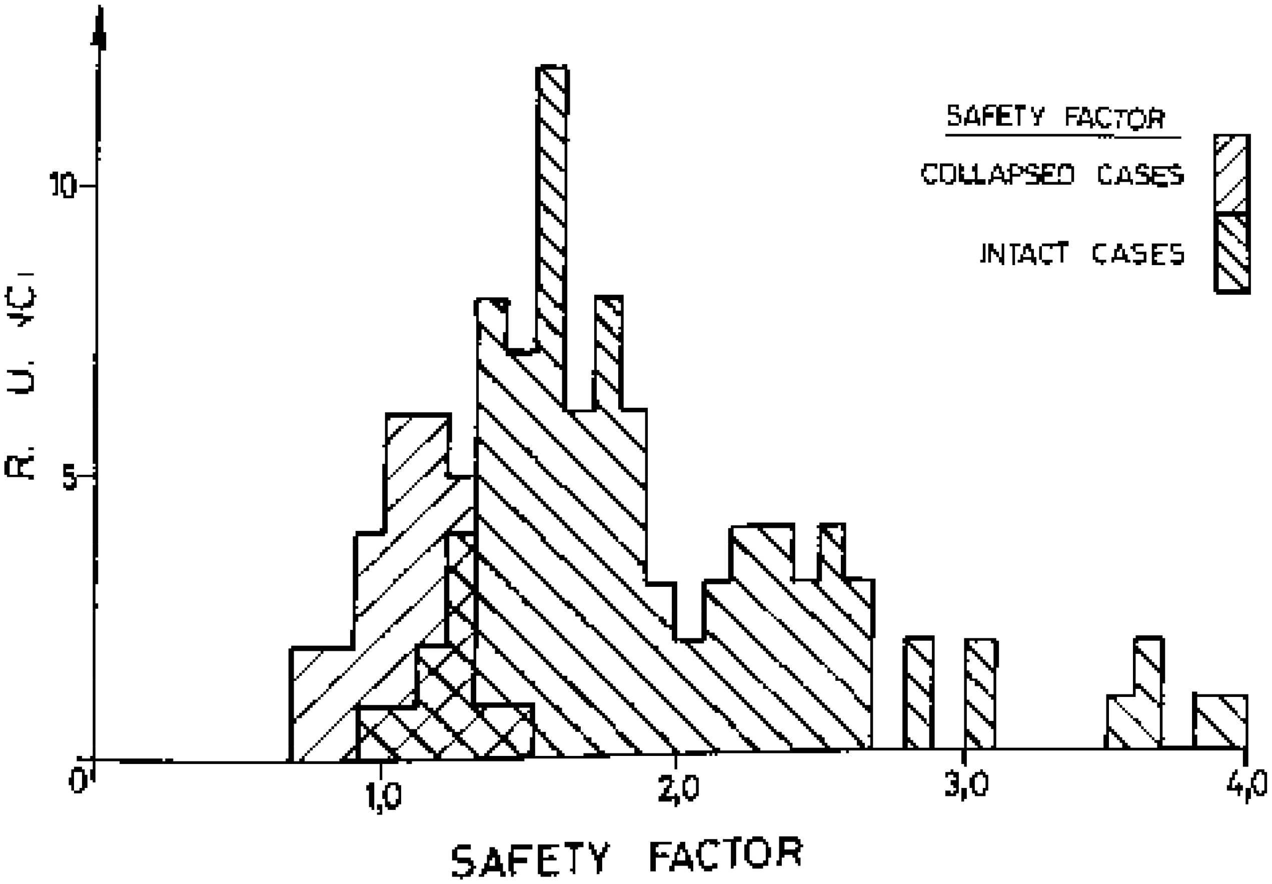

Figure 2.1 Histogram of safety factors for stable and collapsed cases. After Salamon (1967).

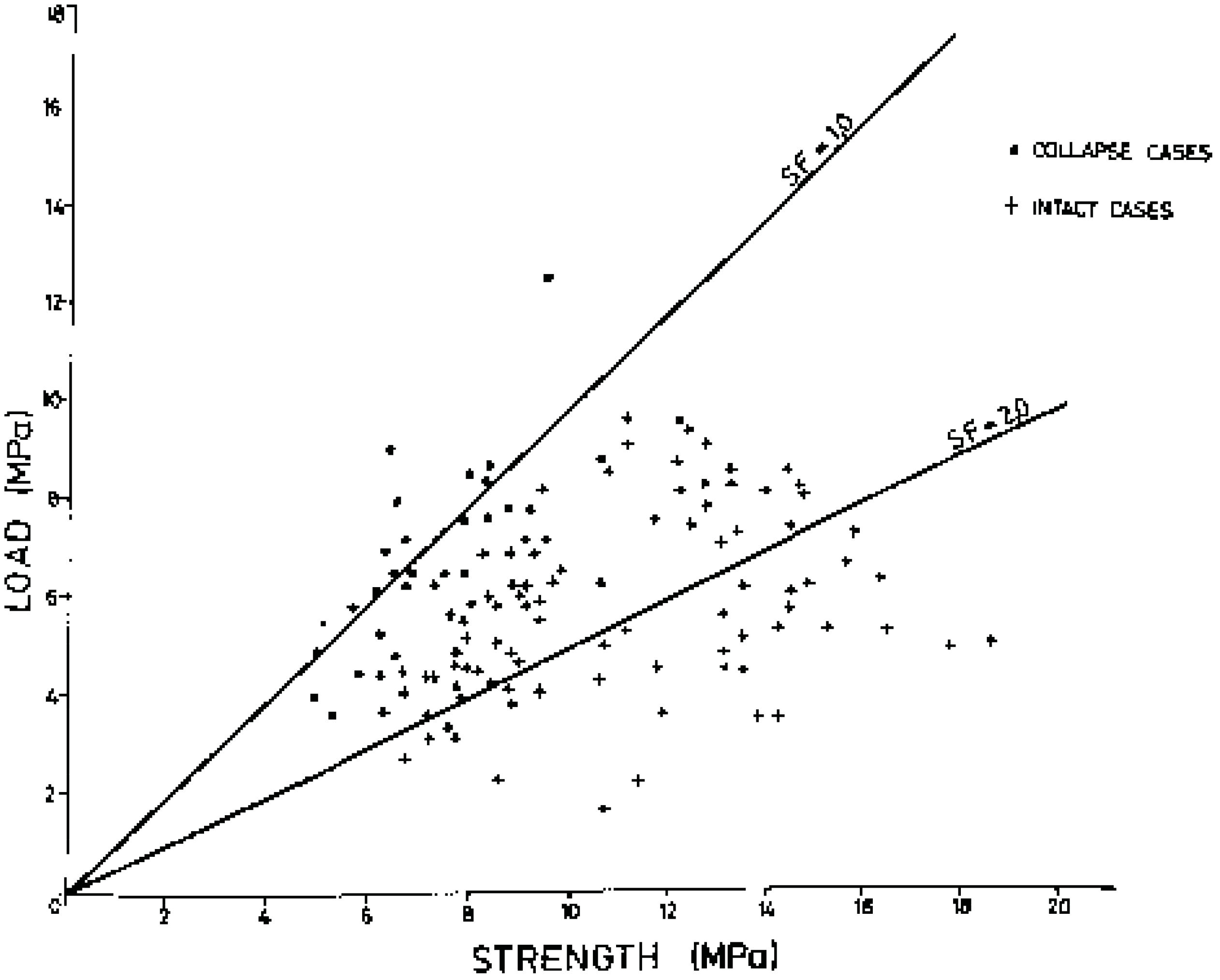

Figure 2.2 Observed pillar loads as a function of calculated pillar strengths for collapsed and stable areas of mining. After Salamon and Munro (1967).

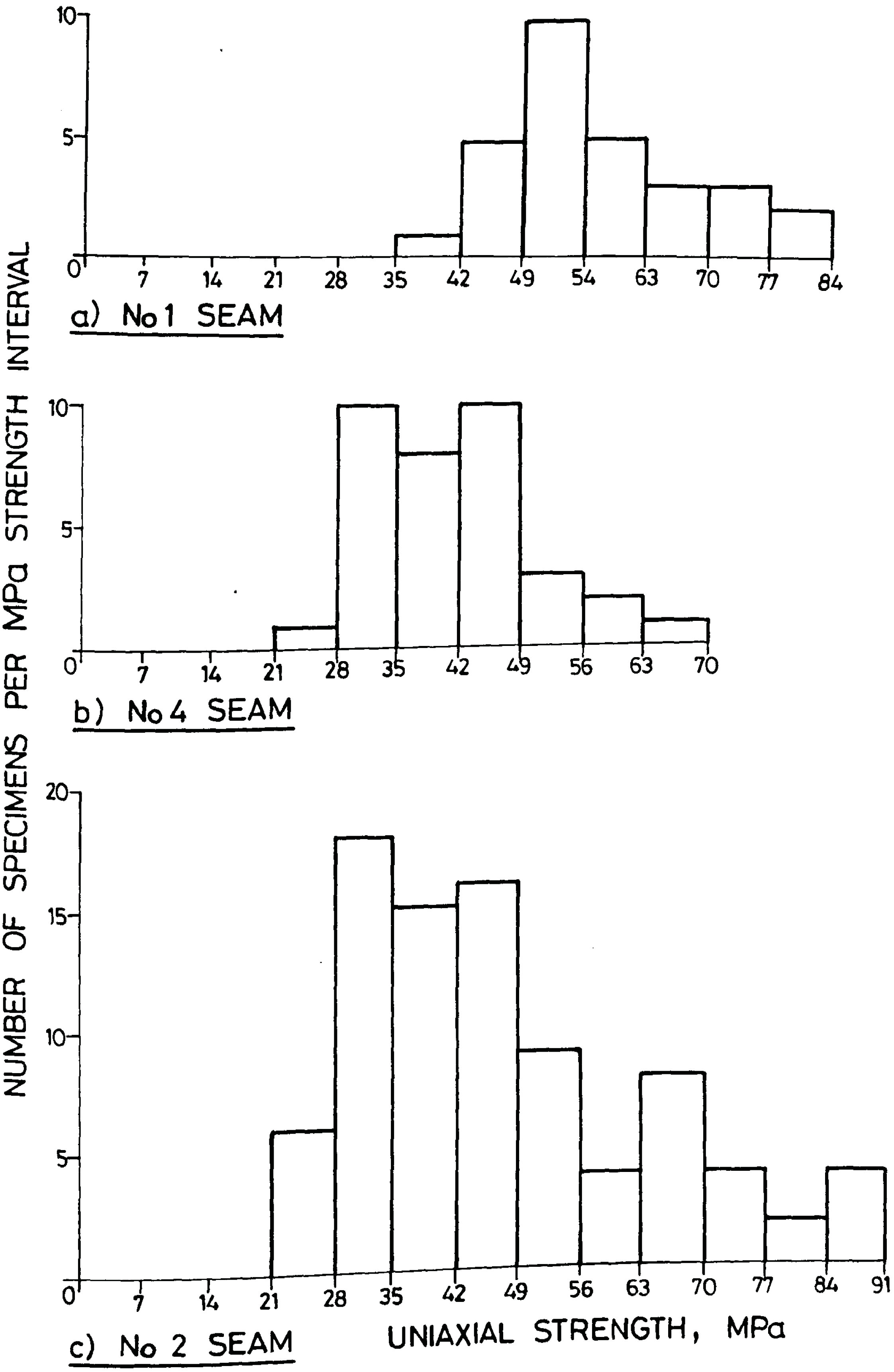

Figure 2.3 Histograms showing the distribution of uniaxial compressive strength values for coal test specimens from No. 1, 2 and 4 Seams Witbank Colliery. After Wiid (1963).

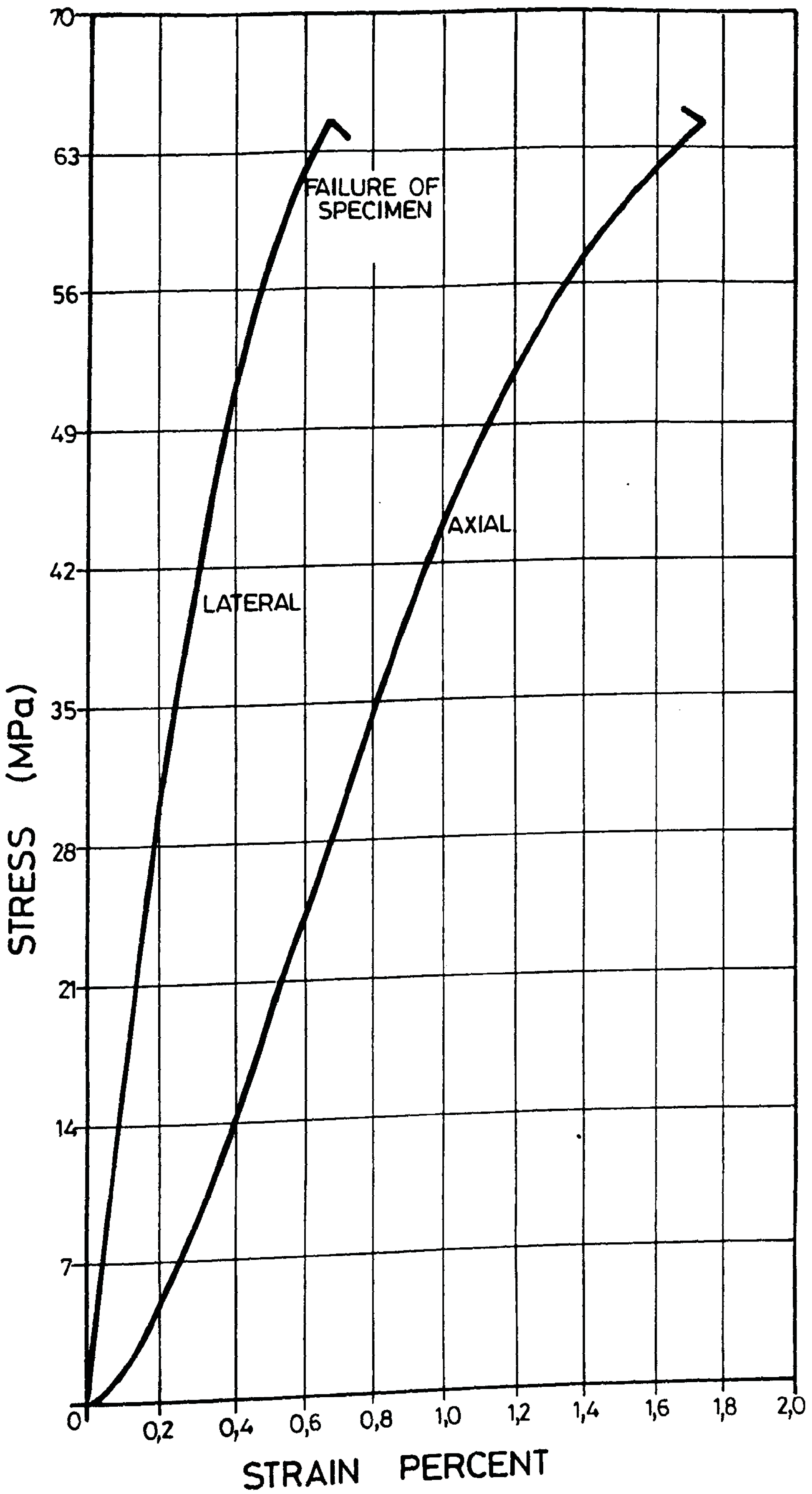

Figure 2.4 "Typical" stress - strain curves for one inch coal cubes from No. 2 Seam, Wolvekrans Section, Witbank Colliery. After Wiid (1963).

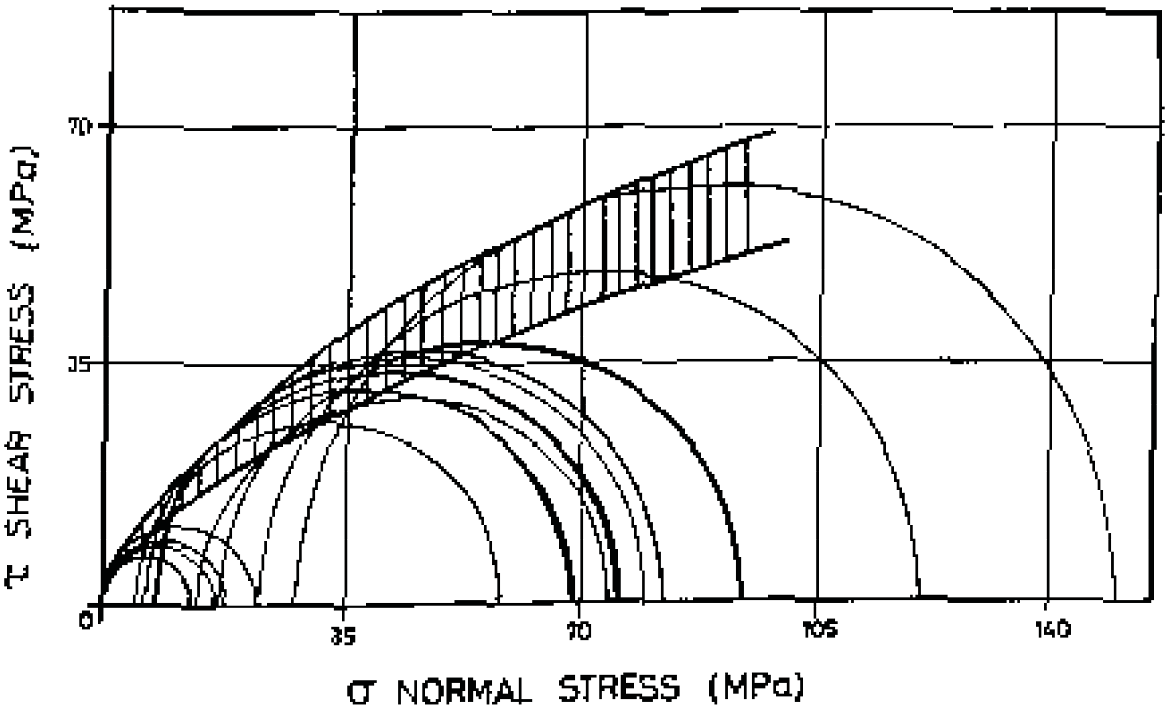

Figure 2.5 Mohr's diagram for BX-Size cylindrical coal specimens parallel to the bedding plane (No. 2 Seam Wolvekrans Section, Witbank Colliery). *After CSIR report (1965).*

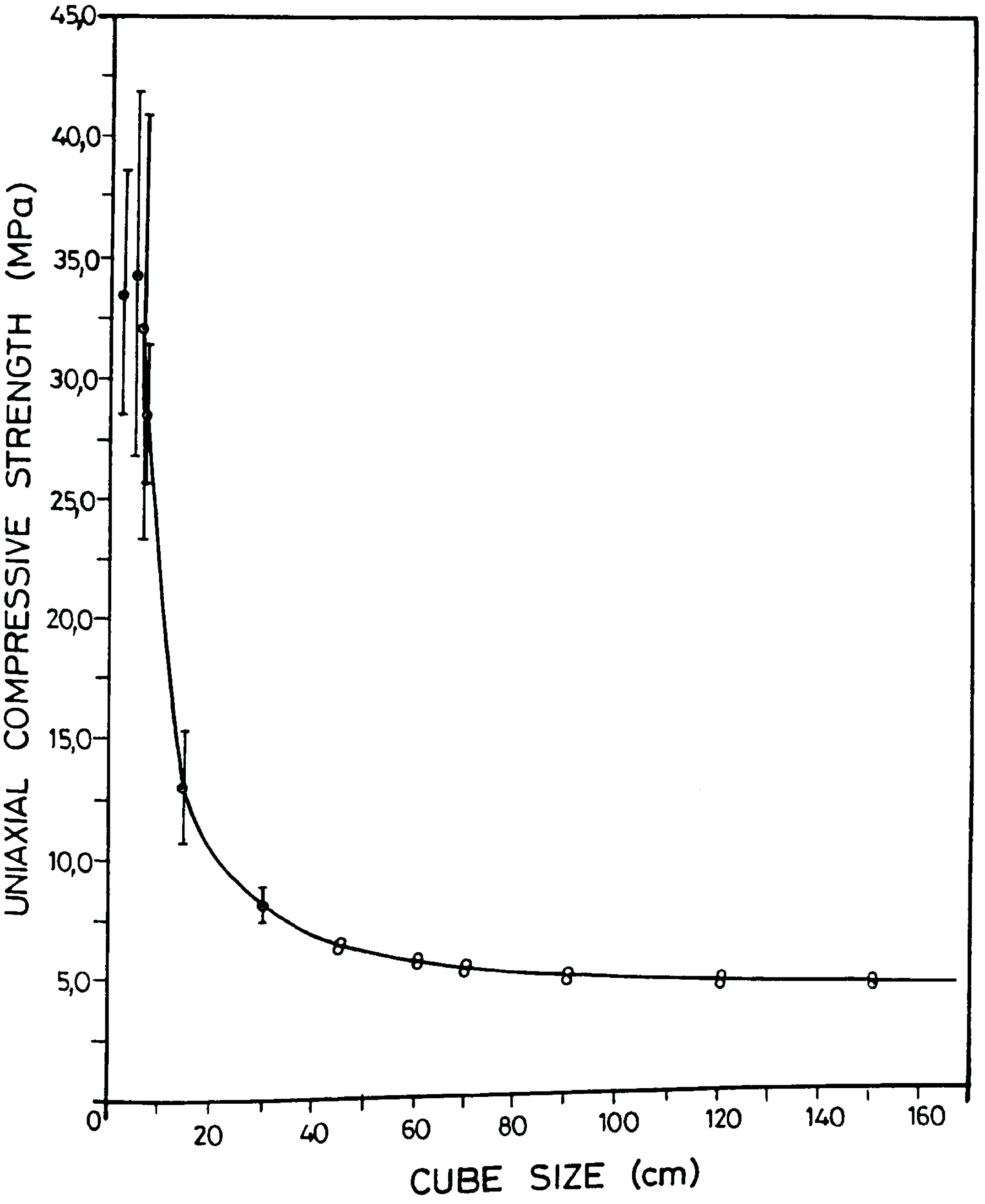

Figure 2.6 The effect of specimen size on the strength of coal. After Bieniawski (1968d).

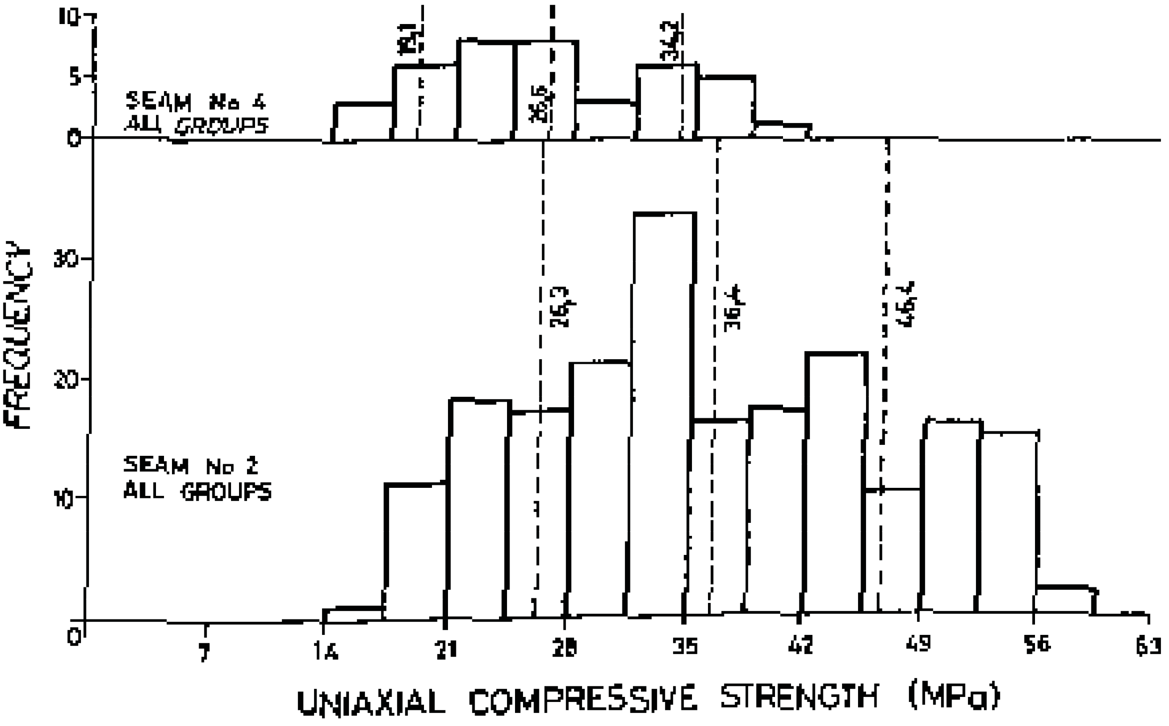

Figure 2.7 Histograms for seam data of No. 2 and No. 4 Seams. After *Kruger (1968)*.

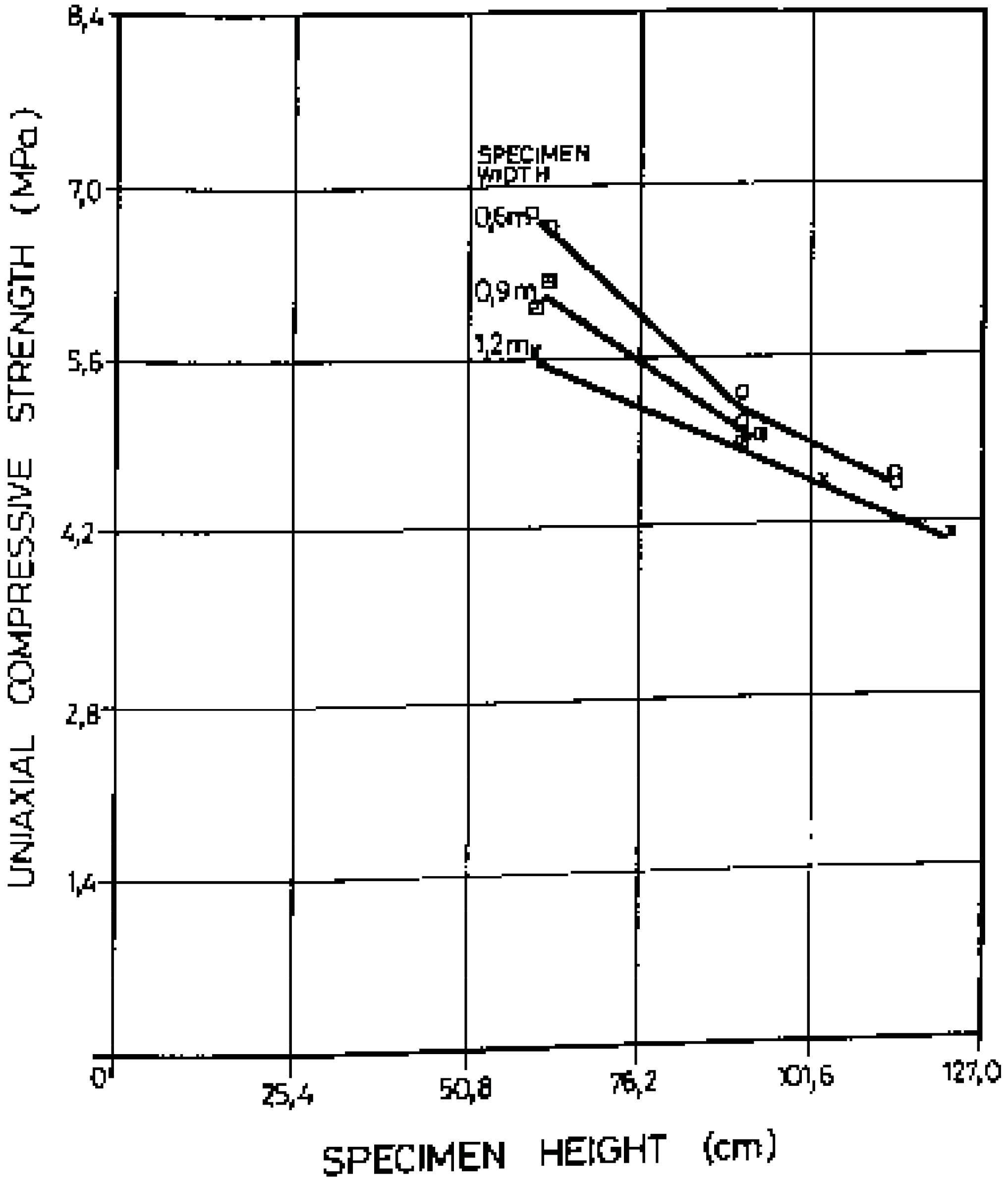

Figure 2.8 Relationship between strength and width of square coal specimens. After Bieniawski (1967a).

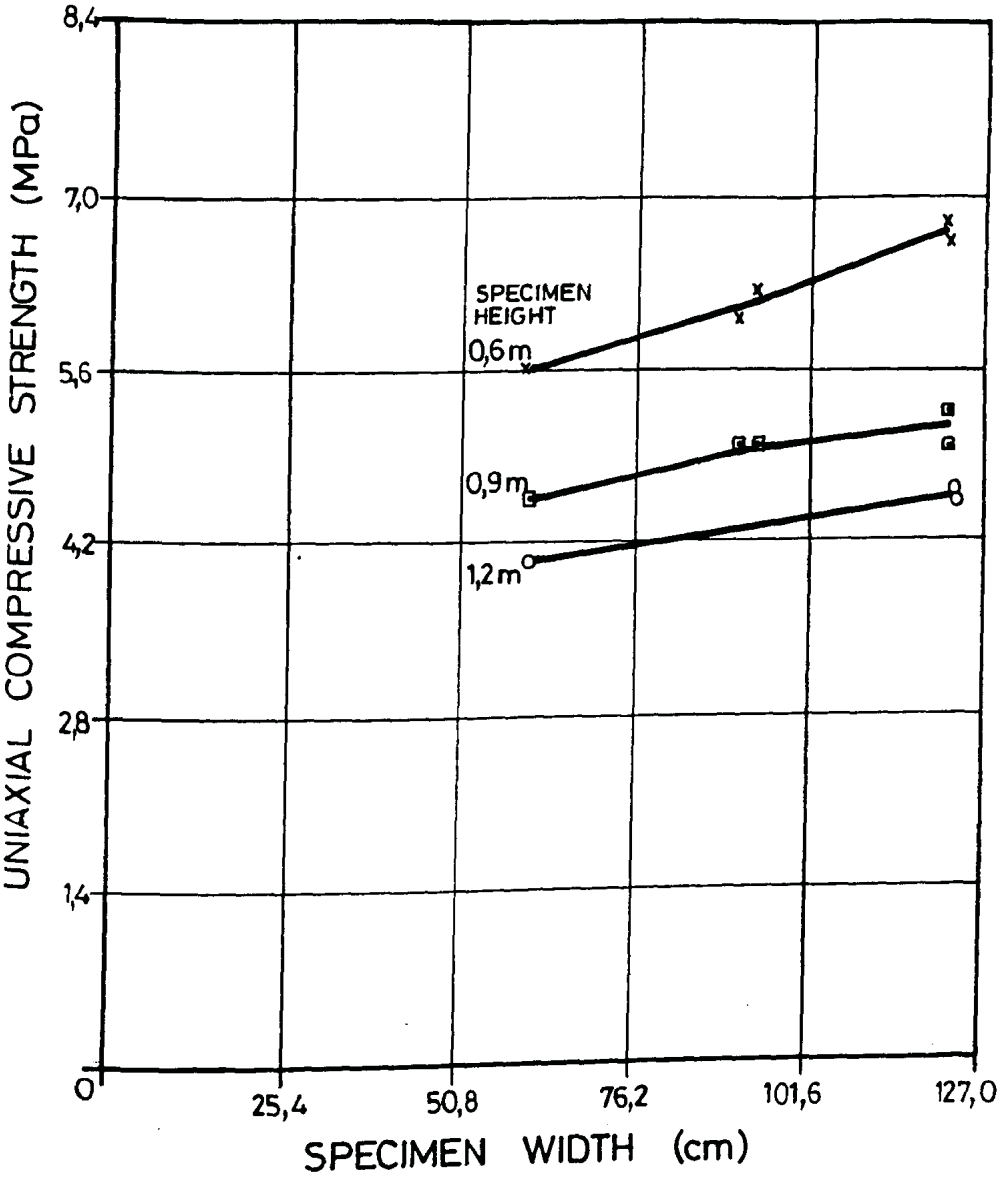

Figure 2.9 Relationship between strength and height of square coal specimens. After Bieniawski (1967a).

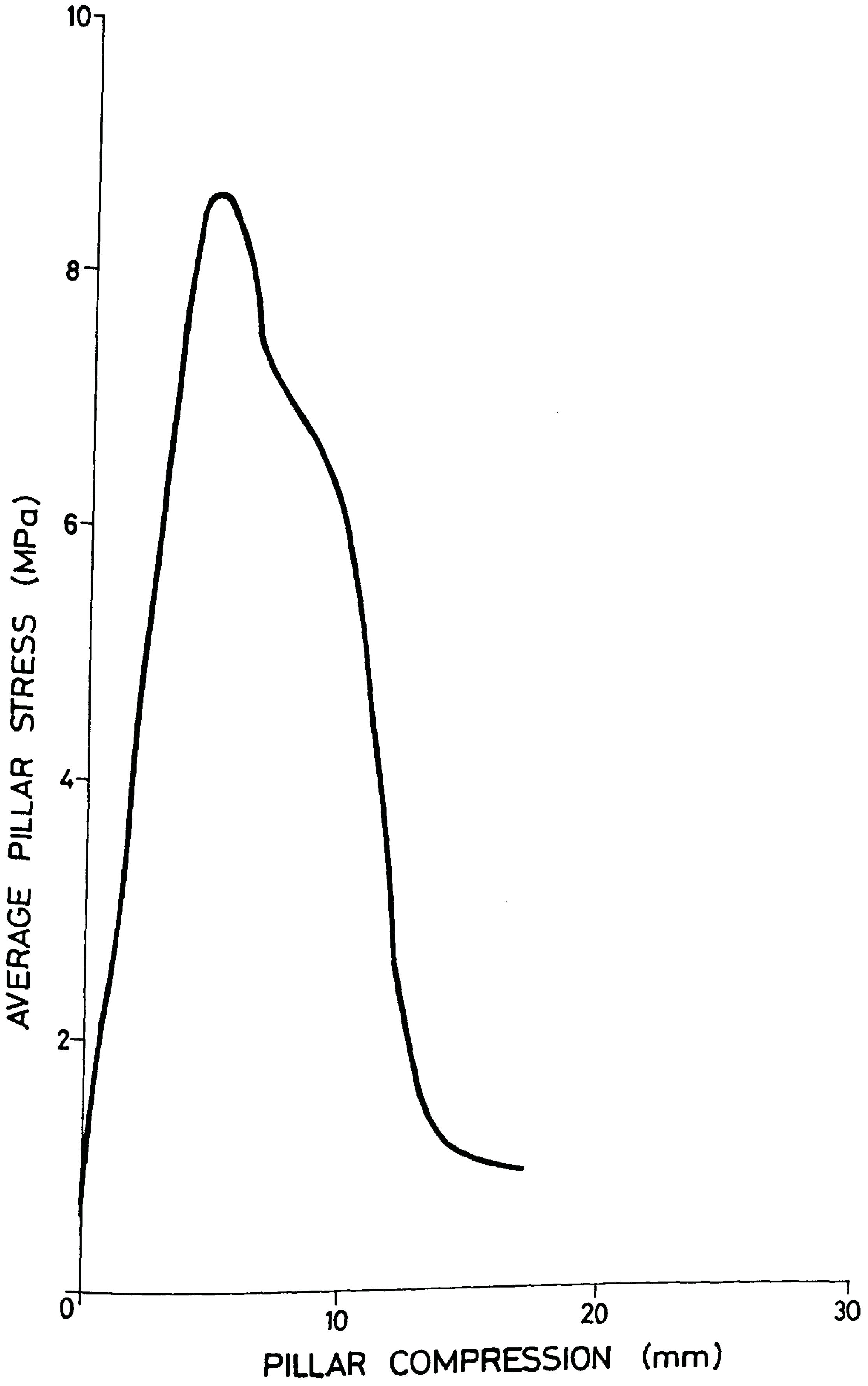

Figure 2.10 Relationship between strength and cube size of large scale coal specimens. After Bieniawski (1967a).