INVESTIGATIONS INTO THE EFFECT OF SIZE AND WIDTH TO HEIGHT RATIO ON THE STRENGTH OF THE LABORATORY SIZED COAL SPECIMENS

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Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Dated this 15 day of OCTOBER 1996

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ABSTRACT

The design of bord and pillar working in South African collieries is based on the pillar strength formula developed by Salamon and Munro in 1967 and which has been used widely since then for designing pillars. This formula is based on the statistical analysis of 27 collapsed and 98 intact coal pillar cases from collieries located in the Transvaal and the Free State.

The main objective of this study is to establish the difference in the strength of the coal material in different seams by means of laboratory testing. In this manner, some 753 coal samples from 10 collieries from 4 seams were tested.

The size and width to height ratio effects on strength were analysed. The size effect showed that the difference between the seams was obvious, with a difference of 59,4 per cent between the strongest and weakest coal.

The statistical re-analysis showed that the strength of the six blocks from the No 2 Seam, Witbank Coalfield occurred in a fairly tight strength range; and that laboratory coal strengths from individual seams or mines could deviate to a significant although relatively small extent from the overall average.

ACKNOWLEDGEMENTS

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To my wonderful wife,

Semsa

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List of Symbols

σ_p	pillar strength
α	height effect exponent, -0,66
β	width effect exponent, 0,44
h	mining height, or height of test sample
w	width
w/h	width to height ratio
H	mining depth
B	bord width
V	volume
C	centre distance
SF	safety factor
S_c	critical safety factor
a	volume effect power, -0,0667
b	width to height ratio effect exponent, 0,5933
σ_c	unconfined compressive strength of 2,5 cm cubes of coal
γ	unit rock pressure
r	cube:cylinder strength ratio
k	strength of a unit cube of coal
S_{cyl}	strength of a cylindrical test specimens with a width to height ratio of 1
D	specimen diameter

σ_l	the variation in unconfined compressive strength
L	specimen length
σ	strength of coal
σ_1	strength of a cubical pillar at the critical specimen size
σ_s	strength of a squat pillar
σ_L	laboratory strength of coal
R_0	critical width to height ratio
ε	rate of strength increase
P	overburden load

CHAPTER 1.

INTRODUCTION

1.1. Defining the problem

The strength of coal has been investigated since the beginning of this century, with some research having been conducted into the factors influencing the strength of coal, such as size and width to height ratio effects.

It is well known that coal is not a solid material and contains discontinuities such as cracks, cleats and bedding planes. Since these discontinuities have an effect on the strength of coal, it is difficult to extrapolate laboratory strength data to determine the in situ strength of underground coal pillars. Discontinuities, cracks and cleats affect the strength of coal, depending on how many and what types of discontinuities are present (Bieniawski, 1968). The effect of these discontinuities increases with increasing specimen size until a critical size is reached [Bieniawski (1968), Lama (1971)].

This dissertation therefore does not provide a coal pillar strength formula, but rather a basic understanding of factors influencing coal strength aspects. The results obtained provide additional information for the understanding of coal behaviour in laboratory conditions and facilitate comparisons between the strength characteristics of different coal seams.

In South Africa, the pillar design formula developed by Salamon and Munro has been successfully used since 1967. Salamon's formula is based on a statistical analysis of collapsed and intact pillar cases, mainly from the No 2 Seam and assumes one strength value for all seams in South Africa. But, as known, the strength of the coal layers varies considerably both from seam to seam and laterally and vertically within the same seam. This dissertation aims to establish effects of size and shape on strength under laboratory conditions, and the strength variance of coal tested in the laboratory.

The size and strength relationship has been investigated since the research on coal pillar strength has started the general trend establish such as decrease in strength with increasing size.

In addition to the size effect, coal strength is also found to depend on specimen geometry. Many formulae have been proposed in the past, with two types of pillar strength expressions predominating:

$$\sigma_p = \sigma_1\left(A + B\frac{w}{h}\right) \qquad (1.1)$$

and

$$\sigma_p = k\frac{w^\beta}{h^\alpha} \tag{1.2}$$

where σ_p is the pillar strength, σ_1 is the strength of a cubical pillar at the critical specimen size, k is a constant characteristics of a pillar rock while α and β are constants.

The detailed results of, linear and non-linear, size-strength and width to height ratio-strength are summarized in Chapters 4 and 5.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Coal pillar design is of primary importance for the safe, economic extraction of a valuable national resource. Initially pillar dimensions and road widths were based on experience obtained through trial and error. This approach, having some inherent errors, can have disastrous consequences in terms of loss of life, equipment and coal reserves. Research efforts worldwide have therefore concentrated on the development of an effective design procedure that can be used by collieries.

Since the turn of the century, a number of investigators have studied the effect of the sample size and shape on the compressive strength of coal specimens in the laboratory. General trends were quickly established, such as a decrease in the specimen strength with increasing height and size, and an increase in strength with increasing width. From these studies a number of predictive equations have emerged, some of which have been suggested as applicable for coal pillar design and to determine the strength of different coal seams.

Initially laboratory testing of small coal samples was carried out. This method is relatively simple and cheap.

Following these studies, tests were conducted on large coal specimens underground. Although these in situ tests can overcome some of the shortcomings of laboratory tests, such as influence of moisture, transportation etc., these experiments are time-consuming, costly and are limited with respect to the size of pillar that can be tested.

The third method is the statistical analysis of pillars which have remained stable and those pillars which have collapsed. This method includes the effect of time on the strength of the pillar, although up to now, this effect has not been explicitly determined.

2.2 The Estimation of strength from failed and stable cases

An area of over 2,5 square kilometres of bord and pillar workings collapsed suddenly in January 1960 at Coalbrook Colliery in South Africa. This disaster resulted in the loss of 437 lives (Bryan et al, 1964), but served to highlight the critical need to develop a safe and rational method for the design of pillar workings.

A statistical study was initiated in 1963 by Salamon and Munro from which a formula, which defines the approximate strength of coal pillars in South African collieries, was derived.

This study was based on the statistical analysis of 27 collapsed and 98 intact cases from collieries located in the Transvaal and the Orange Free State. The analysis of the pillar design procedure was based on the concept of a safety factor ,SF, defined as:

$$SF = \text{strength}/\text{load} \tag{2.1}$$

The values substituted for strength and load must be regarded as approximations which are subject to error. The load was calculated using the tributary area theory. The calculated value of SF, in general, does not represent the true safety factor.

Hence the critical safety factor (S_c), calculated from the predicted strength and the load at failure, is either smaller or greater than unity.

The strength was defined as the strength of coal pillars, not the strength of the coal, and the load as the average stress acting on the pillar. The strength of a pillar was considered to be dependent on the material of which it is composed, its volume and its shape. The shape effect was defined by the constraint imposed on the pillar through friction or cohesion provided by the roof and floor contacts. The volume and shape of square pillars were completely defined by their width and height.

The general formula for strength was defined by Salamon and Munro as :

$$\sigma_p = k h^{\alpha} w^{\beta} \qquad (2.2)$$

Where k, α and β are appropriately chosen constants, w is the pillar width in meters and h is the pillar height in meters. Salamon and Munro determined the values for k, α and β to be 7176 kPa, -0,66 and 0,46 respectively.

It was noted that k is defined as the strength of a unit cube of coal, and the numerical value of k should be taken as the strength of a one foot cube of coal. It is likely, however, that the value of k does not represent the actual strength of such a specimen and one value of k was used in the analysis to represent the strength of all seams mined in the various collieries.

Salamon and Munro's data are summarized in Table 2.1.

Salamon and Munro have re-written the strength formula in terms of volume to examine the size and shape effects. Substituting V = hw^2, and pillar width to height ratio, R = w/h, in equation 2.2 gives

$$s_p = k V^{a} R^{b} \qquad (2.3)$$

where a=-0,0667 and b=0,5933.

Table 2.1. The Range of Parameters in the Data for both the Stable and the Collapsed Cases (After Salamon and Munro, 1967)

Group	Stable	Collapsed
Number of cases in the group	98	27
Depth (H), m	20-220	21-192
Height (h), m	1,2-5	1,5-5,5
Pillar width (w), m	2,7-21	3,4-16
Extraction ratio per cent	98-37	91-45
Width to height ratio (w/h)	8,8-1,2	3.6-0.9

The value of "a" suggests that the effect of size diminishes above a critical volume.

Salamon emphasised that the pillar strength formula was essentially empirical, hence it should not be used much beyond the range of data which were used to derive it.

In 1987, Sheorey et al attempted to develop a new strength formula using the same statistical method. The strength formula they proposed was based on the width to height ratios of 23 failed and 20 stable pillar cases in India's coalfields.

The data from this study are summarized in Table 2.2

The load on these pillars was obtained using a computer program. In this investigation, the first equation was found as indicated below, which was assumed to be linear and proportional to the depth.

$$\sigma_p = \sigma_c h^{-\alpha} + am\gamma cH\left(\frac{W}{h} - 1\right) \qquad (2.4)$$

where, a is the triaxial parameter that was obtained from triaxial tests, m is the virgin stress ratio that was estimated from in situ stress measurements, γ is the unit rock density, and H is the depth of cover.

Table 2.2 Data from Sheorey et al.

Group	Collapsed	Stable
Number of cases in the gr.up	23	20
Depth (m)	30-450	30-450
Height (m)	1,8-8,4	3,0-6,0
Pillar width (m)	3-24,1	5,4-40
Roadway width (m)	3,15-6	3,9-6
Width to height ratio	0,6-6,67	1,4-8,3

Because of the somewhat complicated nature of this equation, an alternative and simpler equation was determined, based on slender pillar cases. This formula which fits the first 14 collapsed cases is:

$$\sigma_p = 0{,}27\sigma_c\left[\frac{\sqrt{w}}{h^{0{,}86}}\right] \qquad (2.5)$$

where

w = pillar width

h = pillar height

σ_c = unconfined compressive strength of 2.5 cm cubes of coal

σ_p = pillar strength

The formula is not recommended however for use in seams where the width to height ratios are greater than 4 and for depths greater than about 200 m.

According to the new strength formula a new safety factor formula which was defined with depth of cover and width to height ratio of pillars was also developed by Sheorey et al.

$$S = \frac{0{,}27\sigma_c h^{-0{,}36} + \frac{H}{160}\left(\frac{W}{h} - 1\right)}{0{,}025H(L/W)^2} \qquad (2.6)$$

where B is roadway width and L=W+B.

They concluded that the new pillar strength equation would fit the available case studies of failed and stable mine pillars, and could possibly be used for all practical values of width to height ratio.

In 1991 Madden examined the South African pillar collapses with the same criteria used by Salamon and Munro (1967) to select those cases that represent pillar failure as a result of the strength of the coal pillar being exceeded by the load imposed upon it. A total of 31 pillar collapses were recorded since the introduction of the pillar design formula in South Africa. Of the 31 cases, 17 satisfied the criteria. These collapses were analysed, together with Salamon and Munro's 27 collapses, to show whether there were any new trends in the collapse of bord and pillar workings.

Table 2.3 shows the summary of data used in this analysis, which indicates that there was little variation between the later and the earlier collapses.

The new strength formula from these statistical analyses was described as

$$\sigma_p = 5{,}24 \frac{w^{0,63}}{h^{0,78}} \qquad (2.7)$$

Table 2.3. Comparison of the two Analyses of Collapsed Coal Pillars (After Madden, 1991)

Group	Stable	Collapsed (1904-1965)	Collapsed (1966-1988)
Number of cases in the group	98	27	17
Depth (H), m	20-220	21-192	22-205
Height (h), m	1,2-5	1, [illegible] 5,5	1,35-5,94
Pillar width (w), m	2,7-21	3,4-16	3,50-17
Extraction ratio per cent	98-37	91-45	88-44
Width to height ratio (w/h)	8,8-1,2	3.6-0.9	3,7-1,3

Madden stated that, when the strength was calculated from both formulae, there was little variation between Salamon's and his (Madden) strength data over the empirical range covered by the formulae. This confirms that the strength formula of Salamon and Munro can be successfully used for the design of stable bord and pillar workings. Furthermore, when the data on individual seams were used, the statistical analysis showed that, although the strength of individual seams differed, the difference was not statistically significant and therefore the average strength could represent all seams.

Madden suggested that, at depths less than 40 m, pillar widths should preferably be greater than 5 m, the width to height ratio should be in excess of 2, and the percentage extraction less than 75 per cent. In addition, a safety factor of more than 1,6 should be maintained.

In 1993 Van der Merwe attempted to re-analyse the pillar design formula for the Vaal basin, as the pillar width to height ratios were less than 5.

Van der Merwe analysed pillar collapses that occurred only in the Vaal basin Coalfield and identified these collapses as a separate group which were characterized by higher safety factors and shorter lifespans than the other failures.

This study showed that the rest of the country indicates no failure above a safety factor of approximately 1,6, and that the value for the Vaal basin is 2,3. It is also noted that scaling is much more common than roof falls in the Vaal basin and in most areas virtually all the pillars scale, while roof falls tend to be restricted in extent and in occurrence. It is observed that more roof falls occur in the Vaal basin than elsewhere but, even in that area, only some pillars are affected by roof falls, while virtually all pillars are affected by scaling.

Van der Merwe then recalculated the safety factors with k=4,5 instead of 7,2 MPa and concluded that, for the Vaal basin, k=4,5 should be used and the strength of pillars in the Vaal basin should then be calculated by use of the expression

$$\sigma_p = 4{,}5\frac{w^{0,46}}{h^{0,66}} \tag{2.8}$$

In this study the load was calculated by tributary area theory.

The Salamon and Munro pillar-design formula was based on the designed mining dimensions of workings which have been mined by the drill and blast method. The skin of the coal pillars which are formed by drill and blast is damaged by the blasting vibrations and the gases which penetrate existing joints.

The depth of blast damage into the side of a pillar has been quantified as being between 0,25 to 0,3 m, Madden (1990). The effect on the safety factor of a pillar formed by a continuous miner was estimated on the assumption that the effective pillar width increases by the depth of the fractured zone over that of a pillar mined by conventional methods. If the nominal pillar width, *w*, results in a safety factor η ,then the safety factor of bord-and-pillar workings developed by means of a continuous miner, η_o, was calculated from the following expression given by Wagner and Madden (1984):

$$\eta_0 = \eta\left(1+\frac{2\Delta w_0}{w}\right)^{2,46} \qquad (2.9)$$

Thus, if the pillar width, w, was 10 m, the designed safety factor 1,6, and the blast-damage zone 0,3 m, the safety factor of a pillar formed by a continuous miner would be 1,85.

2.3. Laboratory tests

Coal is an important economic mineral and thus its strength has been examined since the early 1900's.

Laboratory tests were first performed by Daniels and Moore (1907) on 45 anthracite coal specimens and 12 bituminous coal specimens with the purpose of gathering data for the design of bord and pillar workings. They stated that the crushing strength per square inch of small cubes was greater than that for larger cubes. With a constant base area and increasing height, the crushing strength became smaller. Moreover, in these tests on anthracite no uniformity was found with respect to the compressive strengths of the specimens taken as a whole, or between specimens from the same seam. The per cent compression of the bituminous specimens showed a greater uniformity.

In 1911, Bunting performed compressive strength tests on anthracite coal samples of various dimensions from several mines.

Using 17,3 MPa as the average compressive strength for coal cubes with side lengths of 2 to 6 in, he characterised the laboratory data in terms of the equation

$$\sigma_L = 1750 + 750\, w/h \quad \text{psi} \qquad (2.10)$$

Bunting also plotted the loads (P), which were calculated using the weight of the overburden and the extraction ratio for six mine pillars with which he was familiar and of varying width to height ratios. These data are plotted in Figure 2,1. From these two curves it would appear that, by applying a safety factor (actually a scale factor) of 2,5 to the equation, the pillar crushing strength could be predicted. The appropriate equation would be

$$\sigma_p = 700 + 300 w/h \tag{2.11}$$

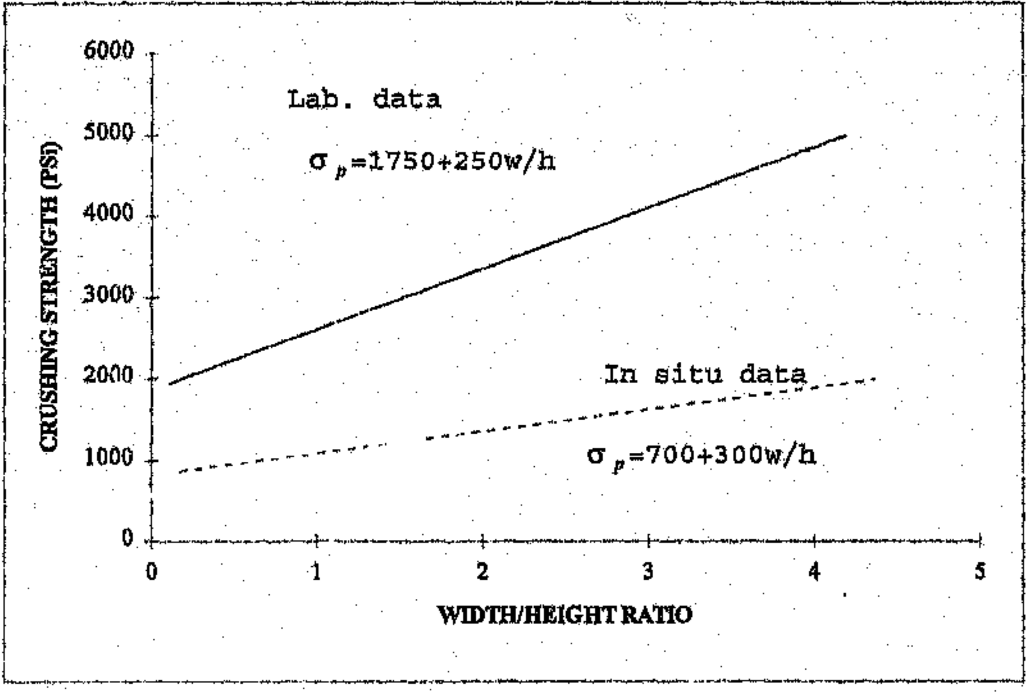

Figure 2,1. Crushing Strength as a Function of Width to Height Ratio for Anthracite Coal (After Bunting, 1911)

The strength of South African coal seams was initially discussed by Steart (1954). He tested on : foot square specimens of varying height from 4 to 27 inches taken from Durban Navigation Colliery. In these tests the pillar width was held constant and the height changed. It was found that the seams in the Ermelo and Breyton districts were very hard and hence a large number of tests would be necessary to arrive at the approximate strength of the coal. Small test specimens of coal were invariably more homogeneous than the entire section of a large, tall underground pillar. Steart therefore formulated the following three rules to predict the strength of mine size pillars on the basis of miniature coal pillars.

1. *The strength of pillars of the same width vary in inverse ratio to their height.*

This principle, when applied to the strength of pillars of the same width but of different height, implies that the strengths of such pillars vary in inverse ratio to height, so that doubling the height of a pillar, whilst the width remains the same, reduces its strength by half. Similarly the reduction of height by half, doubles the pillar strength.

2. *The strengths or resistance to crushing of square pillars of the same height varies as the square root of their widths.*

The strength increases with increase in width when the height is unaltered, but the increase is not in direct proportion to width. Rather, the strength appears to vary as the square root of width, where pillars are square in plan.

3. The strength of pillars of cubical form varies in inverse ratio to the square root of their dimensions.

Steart also noted that, when the dimensions of a cube were increased, both rules 1 and 2 were involved. If height was increased rule 1 operated, and when the width was increased then rule 2 comes into effect as well.

Other relevant work on coal pillar dimensions was carried out by Borecki and Kidybinski. Tests on concrete blocks of width to height ratios ranging from 1 to 20 were performed . The blocks were compressed to complete crushing, and it was found that, with values of width to height ratio of up to about 5, there was a sensible decrease in the force required to exceed the strength of the specimen.

In 1975 Townsend et al. investigated the relationship between the unconfined compressive strength of cubes and cylinders of coal specimens, obtained from nearly all major deep coal seams in the USA.

Over 200 cubes and cylinders with loading area ranging in size from specimens 3 to 16 in^2 were tested and the technique chosen to analyses the data was to normalize cylinder strengths using an average cube strength for specimens of equal area.

It was found that there was a maximum average difference in strength of 30 per cent for the smaller specimens (1,7 inches in diameter), and that this difference diminished with increasing specimen size. The following three factors were presented as possible causes for this difference:

1. The cored specimens were disturbed more during preparation and thereby weakened.
2. The boundary conditions and material properties may cause the stress distribution to vary, not only with shape (w/h) but also with size of specimen.
3. The corners of the larger cubical specimens fail prematurely, causing the cubes to lose strength more rapidly than the cylinders.

The results for individual seams group around an average line, as shown in Figure 2.1. The greatest variation from this line occurred for specimens with an area of 6,4 in^2 but confidence in this portion of the curve was low because of the small number of specimens.

Townsend et al. concluded that the difference in cube and cylinder strengths was found to be maximum 30% for all materials tested, and thus the line shown in Figure 2.2 can be used to relate cube and cylinder strengths.

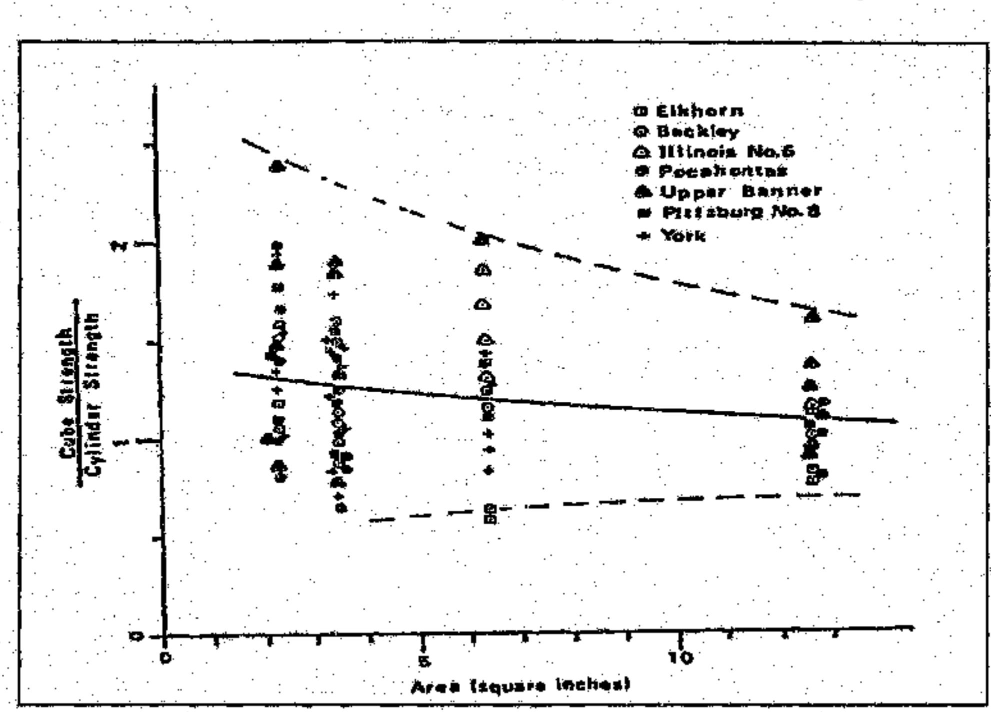

Figure 2.2. Composite Plot of the Cube Cylinder Strength Ratio vs. Area for all Seams Sampled. (After Townsend et al.)

Skelly et al.(1977) presented results of a study which included measurement of pillar strength and deformation in situ, as well as laboratory compression tests of small specimens. A total of 155 tests were conducted on coal specimens, using various diameters: 1, 2, 4, 6, 8 and 12 inches. and width to height ratios: 0,5, 0,67, 1,0 and 2,0. Laboratory results were examined statistically and the variation in unconfined compressive strength (σ_1) with specimen diameter (D), for specimens of equal width and height, was best described by equation:

$$\sigma_1 = 2360(D)^{-0,21} \quad \text{(psi)} \qquad (2.12)$$

Similarly the variation in specimen strength (σ/σ_1) with ratio dimensions (D/L) observed in the laboratory data was best described by equation:

$$\frac{\sigma}{\sigma_1}=\left(\frac{D}{L}\right)^{0,45} \qquad (2.13)$$

In 1978, Sorensen and Pariseau presented the results of 371 unconfined compressive tests performed by Hustrulid et al (1977)on cylindrical specimens with diameters of 1, 2, 4, 6, 8 and 12 inches and width to height ratios of 0,5; 0,75; 1,0 and 2,0. They stated that the results showed a tendency for strength (defined as the peak load divided by the original cross sectional area of the cylinder) and the modulus to increase with an increase in diameter to height ratio. The same trend was obtained from computer simulations of the laboratory tests and it was due to end effects, that is, to frictional contact between testing machine platens and test specimens having different elastic properties. It was also stated that a laboratory test for strength is not a scale model of a mine pillar, laboratory results provide the properties data necessary for pillar design based on the principles of mechanics and as much of the variability observed in the laboratory test data as was desired can be incorporated directly into an otherwise deterministic design analysis.

In 1979 a number of sets of data taken from the literature were analysed by Panek. He defined the load-bearing capacity of a square, rectangular, or cylindrical prism of brittle material such as rock, coal or concrete. He also discussed the effects of size, shape and end conditions on strength and it was stated that the closely related effects of size and shape can be expressed in several ways. Because the fundamental equation is expressed as a product of powers of dimensionless ratios, the height effect exponent is equal to the sum of the size effect exponent and the width effect exponent, which in turn is a constant equal to 1/3, in accordance with the geometric relation: $(\text{pillar area})^{1/2}/(\text{pillar volume})^{1/3}$. This implies that, with pillar height and lateral configuration (b/w) constant, the pillar compressive strength is proportional to the cube root of pillar width. A further finding was that the size effect appears not to be a constant, but a characteristic that varies with the pillar material, as the size effect exponent ranges from 0 to 0,5. The height effect can thus be characterised as the result of superimposing (multiplicatively) a variable size effect on the constant width effect.

The squat pillar formula for South African collieries was developed by Madden in 1989. A laboratory experiment was carried out to determine the width to height ratio effect of cylindrical sandstone specimens on strength, and to establish whether pronounced size effects occur in the range of specimens tested. For this purpose six sets of 222 specimens with diameters ranging from 24 to 100 mm were tested.

Field trials and in situ measurements were also conducted to observe the performance of squat coal pillars. This was achieved by examining the extent of fracturing on the pillar sides as well as monitoring pillar dilation and the stress profile of pillars designed to the squat pillar formula with the assumptions that the critical width to height ratio (R_0) is 5 and that the rate of strength increase(ε) is 2,5.

Madden stated that the squat pillar formula was found to fit the laboratory results well, and although these laboratory results cannot be related directly to coal pillars because of the difference in the material, scale, and time taken to test the samples, the general trend can be assumed to be similar.

The squat formula used was given as:

$$\sigma_s = k\frac{R_0^b}{V^a}\left\{\frac{b}{\varepsilon}\left[\left(\frac{R}{R_0}\right)^{\varepsilon}-1\right]+1\right\} \qquad (2.14)$$

where σ_s is the strength of a squat pillar

R_0 is the critical width to height ratio

ε is the rate of strength increase

a is -0,0667

b is 0,5933

The assumption that the critical width to height ratio to be equal to 5 was based on the fact that no pillar had collapsed with a width to height ratio greater than 3,75.

The benefits of the squat pillar formula were stated as increased extraction of coal and increased production.

In 1986, six cylindrical coal specimens of 54 mm diameter with width to height ratios from 0,5 to 13,5 were tested by Das at a constant strain rate of 10^{-3} sec^{-1}. The results showed that the post failure slope becomes positive after reconsolidation of the failed material when the width to height ratio exceeds 6,75.

Ozbay (1994) conducted tests on 216 cylindrical samples, of diameter 25, 54, 100 and 300 mm and with width to height ratios between 0,4 and 4,0, from the No 2 Seam Delmas Colliery and the No 2A Seam Sigma Colliery. He aimed to determine the effect of size and width to height ratio on the strength of coal obtained from seams with different strength characteristics.

All the cores were drilled perpendicular to the seam plane. The tests were carried out using an MTS 815 hydraulic servo-controlled stiff testing machine. The tests were displacement controlled, and both load and deformation were recorded during testing. The effect of size and width to height ratio for each of the coal types are summarized by the following relationship:

	Size effect	w/h ratio effect	
Delmas	$171,2\ D^{-0,34}$	$0,52+0,48(w/h)$	(2.15)
Sigma	$240,5\ D^{-0,50}$	$0,65+0.35(w/h)$	(2.16)

where D is the specimen diameter.

Ozbay concluded that the strength of the coal from Sigma Colliery varied considerably for the specimen sizes of 25, 54 and 100 mm but was consistent for the 300 mm diameter specimens. The results from the Delmas coal were relatively consistent for sample sizes of 54 mm and higher.

An assessment of the influence of discontinuities has been proposed by Esterhuizen (1995) whereby the amount and type of discontinuity occurring within the coal pillar can be classified by a simple mapping technique. The importance of the technique is that [illegible] influence of discontinuities, particularly slips, can drastically reduce pillar strength. This effect is significant at low pillar width to height ratios of say less than 3,0. As the pillar geometry changes and the pillar width to mining height ratio increases the pillar strength is increasingly determined by the increased surface contacts between the coal and surrounding strata as well as the triaxial effects within the pillar. The material strength and effects of discontinuities become less significant as the pillar width to mining height increases. However, Esterhuizen (1995) found that the strength of a pillar with a pillar width to height ratio of 2,0 can be reduced by 77 per cent due to joints dipping at 45°, while the same joints reduce the strength of a pillar with a width to mining height ratio of 6,0 by only 17 per cent.

2.4 In situ tests

In 1939 the first large in situ compressive tests were conducted in the USA by Greenwald et al. Seven pillars were formed and tested with the aim of determining the strength and deformation characteristics of large coal specimens. The tested specimens were all square in plan with widths between 0,8 and 1,6 m and with width to height ratios from 0,5 to 1,03. All, except two, had square bases. The specimens were prepared with hand tools without using explosives. A thick concrete block was cast on top of each specimen and loading was achieved by means of one or two large hydraulic jacks inserted between the concrete and the roof. The load increase was carried out in stepped increments. Systematic measurements of vertical and lateral displacements were recorded giving the first in situ stress-strain curves up to the pillar's peak strength. The load increase was halted at each increment until no further deformation of the specimen was noted.

The authors derived a relationship between the strength and width to height ratio, as given in Table 2.7. Additional tests were carried out by the same authors in 1941. This resulted in the derivation of the second formula presented in Table 2.7.

In 1967, a long term in situ testing program was initiated by Bieniawski. Initially Bieniawski performed in situ uniaxial compressive strength tests on 14 coal specimens in No 4 Seam of Wolvekrans Section, 4 SE2-S4 Panel. The sizes of the specimens were 2, 3 and 4 ft in width, with their heights from 2 to 4 ft. A total of 16 hydraulic jacks were used to load the samples.

In three cases corner failure of the specimen had occurred, resulting in damage to the jacks. This failure was disregarded as it was due to the fact that the lateral constraint applied at the sample jack contact was not effective.

The relationship between the strength of the specimens and their height or width was obtained and illustrated in Figure 2.3 and Figure 2.4. Figure 2.3 shows that the strength increases with increasing width. Figure 2.4 shows strength decreases with increasing height.

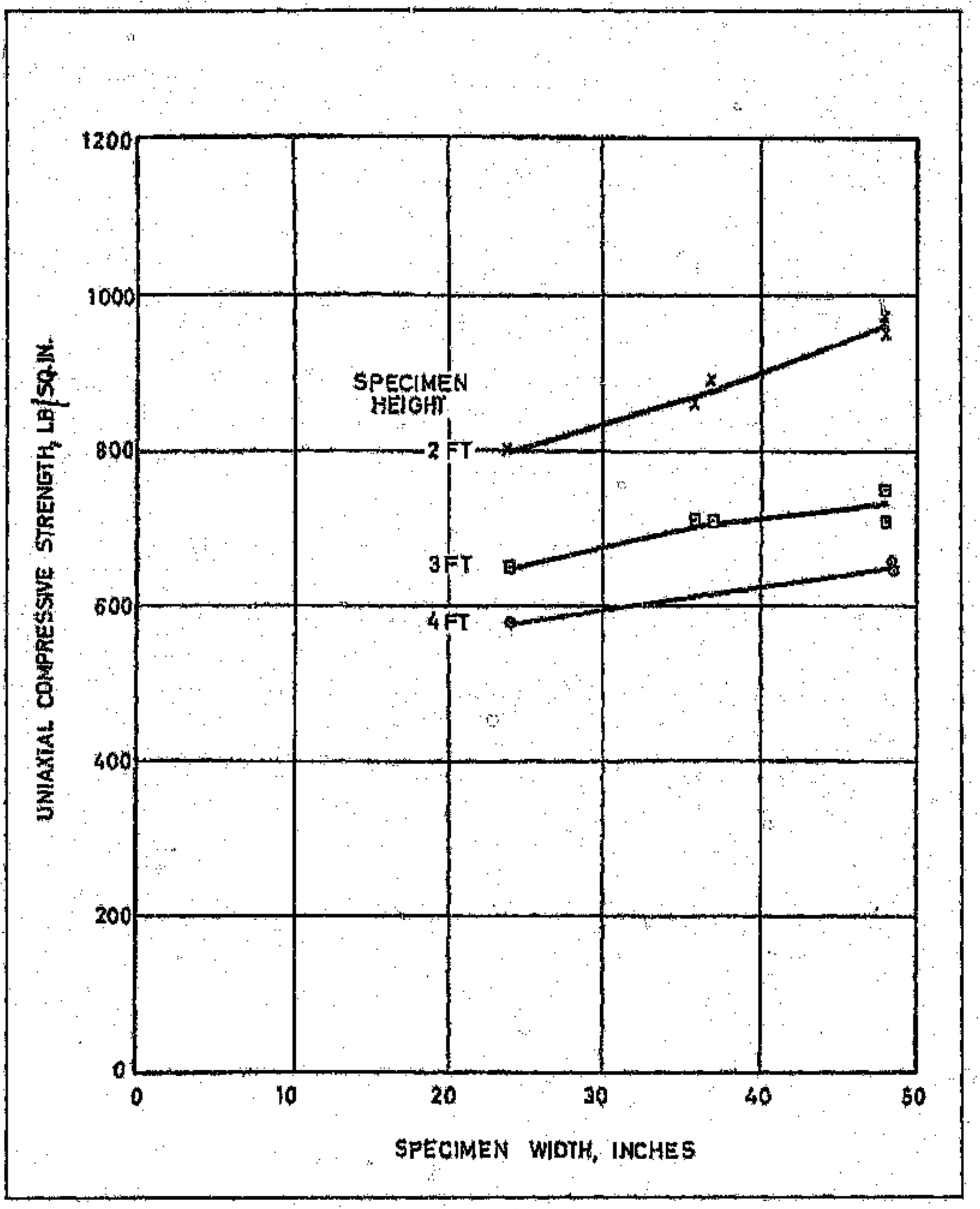

Figure 2.3. Relationship between Strength and Width of Square Coal Specimens (After Bieniawski)

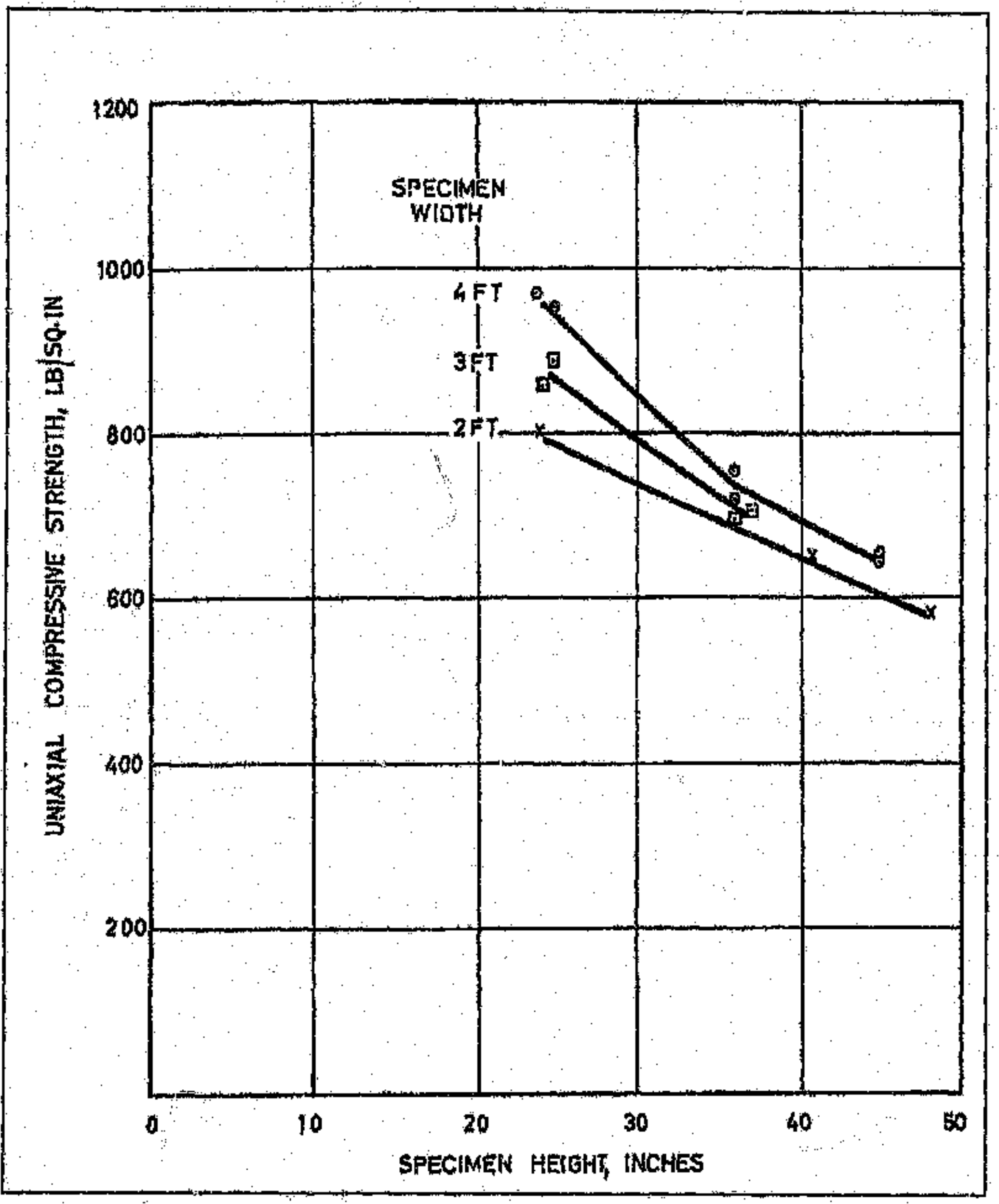

Figure 2.4. Relationship between Strength and Height of Square Coal Specimens (After Bieniawski)

Four small samples, of varying diameter from 10 to 6 inches and height for 9 to 5.4 inches, were also tested and results included in the data. The relationship between the data is summarized in Figure 2.5, which includes data derived from small size tests. It can be seen from this figure that

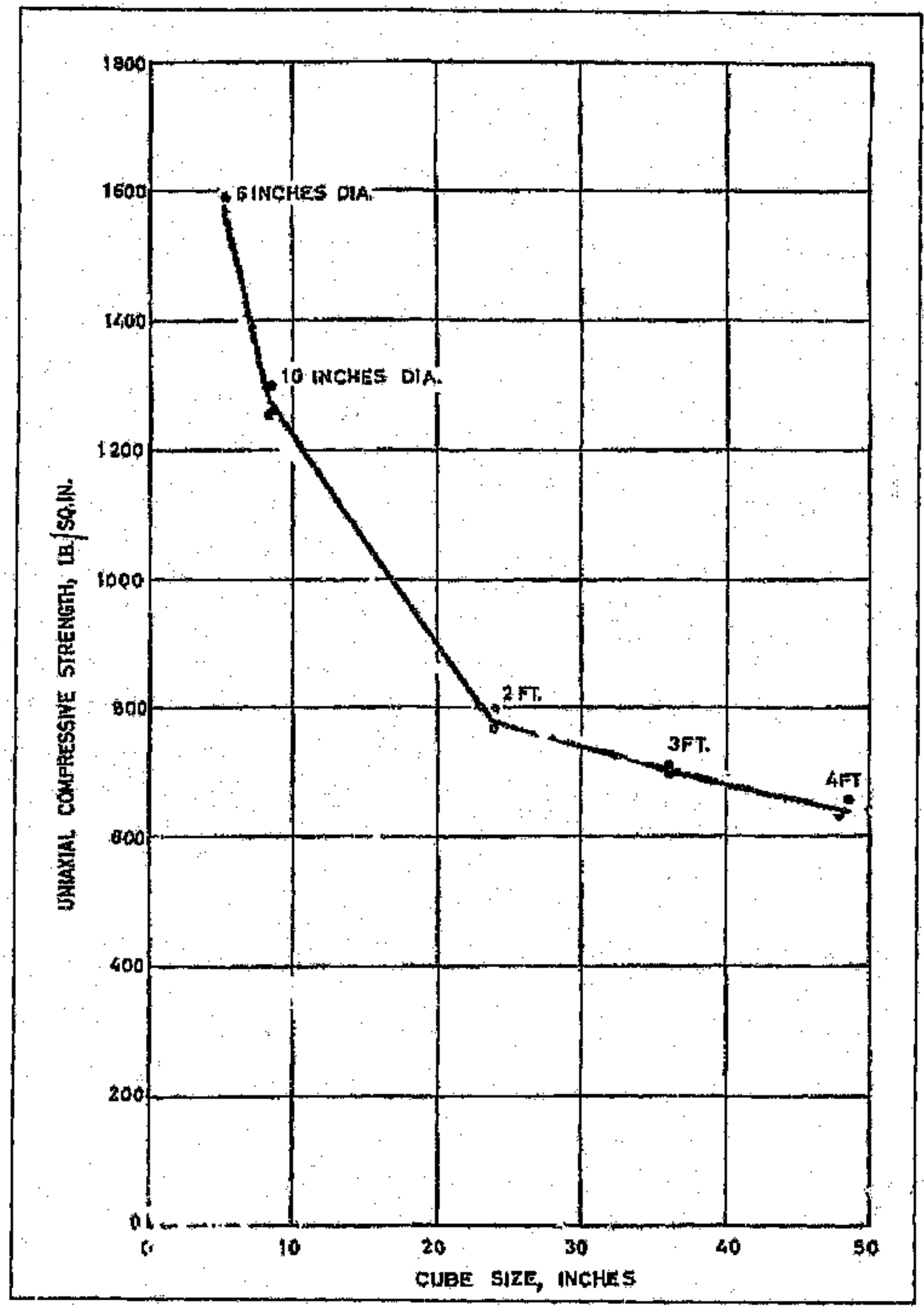

Figure 2.5 Relationship between Strength and Cube Size of Large Scale Coal Specimens (After Bieniawski)

the strength decreases with increasing size, but the curve flattens out possibly tending to some asymptotic value. The curve could be flat once the size of 6 ft is reached.

An attempt was made to derive a strength formula, based on the these results. Applying a logarithmic transformation and using a least square fit of a linear equation to the results from the tests, the following formula was derived

$$\sigma = 1100 w^{0,16} h^{-0,55} \tag{2.17}$$

where σ is the pillar strength, ib/sq.in.
h is the pillar height, in feet (ft)
w is the pillar width, in feet (ft)

In July 1968 Bieniawski conducted in situ tests underground on four 1 ft and two 1,5 ft cube coal specimens to examine the testing method used in the previous tests. The tests were conducted in the Wolwekrans Section of Witbank Colliery. It was concluded that the testing method used in these and previous tests proved satisfactory for the purpose of underground tests. It was also stated that the experimental results were described by an empirical relationship that had been derived previously.

In 1967, Bieniawski and Mulligan tested eight square coal specimens measuring 5 ft in width and 2 ft, 3 ft and 4 ft in height. The tests were conducted in the No 4 Seam of Wolvekrans Section at Witbank Colliery. The results obtained showed that,

- there is no strength reduction beyond a specimen size of about 5 feet, which implies that a 20 feet cubic pillar would be of the same strength as a 5 feet,

- the testing techniques used for large scale in situ tests of coal specimens was considered to be field-proven,
- while the moduli of elasticity decrease with increasing specimen size no definite relationship was determined or their limiting values found, and
- there appears to be no distinct effect of size on Poisson's ratio.

Bieniawski analysed the results of previous underground tests in 1967. It was concluded that the strength of pillars cannot be expressed as a power function of their width and height as there exists a critical pillar size above which the strength does not change with an increase in pillar size. This critical size was defined as 5 ft and it was stated that there can be no further effect on the specimen strength for heights of 5 ft and over. The linear relationship between the strength and width to height ratio was given as

$$\sigma_p = 400 + 200w/h \qquad (2.18)$$

Bieniawski also performed underground tests on the coal specimens, measuring from 2 to 6,6 ft in size, in the No 4 Seam of Volwekrans Section, Witbank Colliery. All specimen preparation and testing were done underground using the same testing method that had been used in previous tests. From these tests Bieniawski concluded that the results of these in situ tests generally confirmed the strength and deformation data previously derived, however it was found that the relationship between strength, width and height is valid up to the width to height ratios of 2,5 only.

The comparison of 579 one inch cubic specimens is given In Table 2.4, after Bieniawski (1967), using a strength index based on the strength of No 4 Seam, Witbank Coalfield. Bieniawski stated that while these results do not represent the in situ strength of coal they can, however, be used for comparative purpose. This table shows that all the results are within 12,5 per cent of the No 4 Seam values, with the exception of No 1 Seam Witbank Coalfield.

Table 2.4 Comparison of Coal Strength Data for Collieries Representing all Major Coalfields in South Africa (After Bieniawski, 1967).

Coalfield	Colliery	Locality	UCS (MPa)	Standard deviation	Number of specimen tested	Strength index
C	Coalbrook North	2. Seam	40,8	14,10	54	103,90
C	Cornelia	Bertha Sec.	43,8	16,90	60	11,50
B	Durban Navigation	Section 5	34,5	10,00	52	87,70
B	Durban Navigation	Section 40	38,5	16,70	72	97,80
A	Kendal		44,1	22,60	40	112,40
C	Sigma		37,9	14,30	39	96,50
D	Springfield		40,5	16,90	100	103,00
A	Witbank, Wolvekrans	No 4 Seam	39,3	18,10	35	100,00
A	Witbank, Wolvekrans	No 2 Seam	42,8	27,40	78	108,90
A	Witbank, Wolvekrans	No 1 Seam	56,6	16,30	49	143,90

Note: (i) All specimens were one inch cube size
(ii) Coalfields
A Witbank - Breyten Coalfield, Transvaal
B Klip River Coalfield, Natal
C Vereeniging Coalfield, Orange Free State
D Balfour Coalfield, Transvaal

Supplementary in situ tests on three 3 ft cube coal samples were performed by Bieniawski (1968) at the same site. The specimens were provided with lateral end constraint in the form of reinforcing concrete. The reinforced concrete capped specimens yielded much higher strength values in fact, well over 100% more than the previously used specimens with wooden shuttering. Bieniawski also noted that, while an increase in the strength of the specimen with reinforced concrete capping was expected, no such large differences were anticipated and it was thought that this discrepancy was too large to be due to the influence of lateral end constraint only.

Van Heerden (1971) tested one meter cubic samples at New Largo Colliery, Witbank Coalfield. The tests were aimed at obtaining the complete load-deformation characteristics of one meter cubic coal specimens using the method of uniform deformation loading. Nine hydraulic jacks, each loading an area of 305 by 305 mm, were used to apply load to the specimens; however most of the jacks attained their maximum capacity before the sample failed. The results of these tests showed that the strength of a one meter cubic coal specimen is greater than 8 MPa.

The results of previous large scale tests (Bieniawski, 1967), carried out in another colliery and using the conventional method of uniform stress loading, gave the strength of a one meter cubic coal specimen as 4,5 MPa. This was considerably less than the strength of a one meter cubic coal specimen tested in van Heerden's investigation. Van Heerden (1971) suggested that the increased strength was as a result of the coal seam being stronger.

In 1974 a set of rectangular and square coal pillar samples, ranging from 0,6 to 2 m in side, length and width to height ratios from 0,6 to 2,2, were tested by Wagner. A total of 33 coal samples were tested in situ using a uniform deformation technique. In this loading system each of up to 25 hydraulic jacks were connected to a separate pump with constant delivery. A wide spread of strength values were obtained. It was stated that the strength of the test pillars were found to be 50 per cent higher than that predicted by Salamon's formula.

The stress profiles at various stages of pillar compression as determined by Wagner are plotted using the uniform deformation technique Figure 2.6. The important finding of this work was the realization that the central portion of the pillar 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.

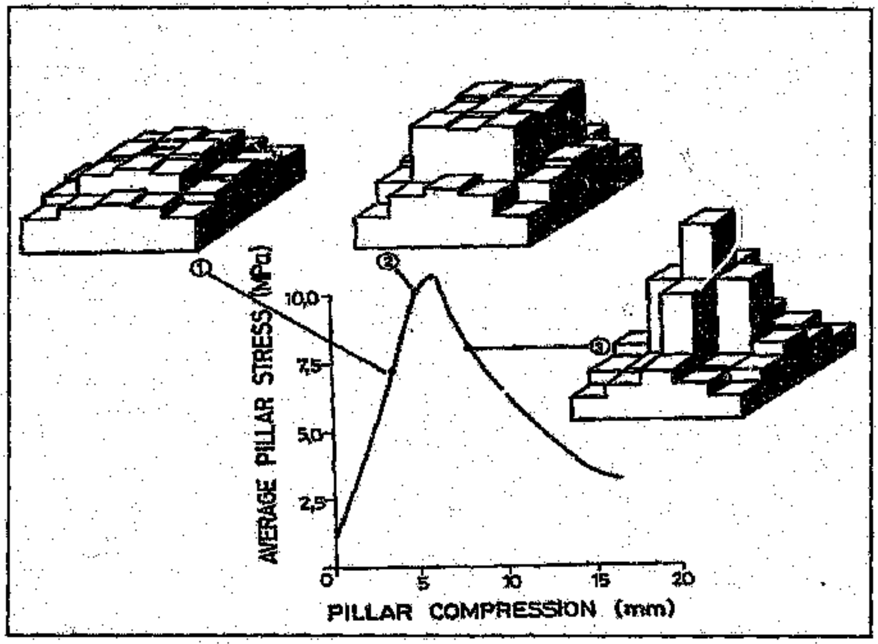

Figure 2.6. Stress-Profiles at Various Stages of Pillar Compression (w/h=1)

A large scale in situ test of a laminated coal cube was conducted by Cyrul (1986). The studies were conducted on a 1,5 m coal cube isolated from the 504 seam in the Gottwald Mine in Poland by using the uniform deformation loading method. Cyrul presented a method of strain measurements which provides extensive data from one test. This study demonstrated the complex behaviour of laminated and heterogeneous samples under uniform uniaxial loading. It includes local strain fluctuations, regional and global bending, as well as regional and global torsion.

2.6 Conclusion

The strength of pillars has been discussed by a number of authors. Different methods were used to determine pillar strength, including back analysis, laboratory testing and in situ tests, on laboratory size small samples and in situ size large coal samples.

Salamon and Munro's pillar design formula has been used successfully since 1967. However, pi collapses still occur. It has to be rememb Salamon used only 27 of 50 collapsed and Mad (1991) found 31 collapsed cases between 1967 and 1988 but excluded 14 cases on the same grounds. Therefore of the 81 collapsed cases up to 1988 only 44 to 54 per cent were included in the analyses. While some of these cases were excluded due to unreliable data there is a need to re-examine this information.

The laboratory investigations into the strengths of individual South African coal seams showed 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 of sample. However, in the larger specimens there was less scatter in the test results obtained.

The knowledge obtained from testing of coal has resulted in increased understanding of the behaviour of coal pillars, particularly as far as their stress-strain behaviour is concerned. However, as in 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.

The results from the literature are summarized in Tables 2.5-2.7.

Table 2.5. Formulae Derived from the Back Analysis

AUTHORS	FORMULA	REMARKS
Salamon & Munro (1967)	$\sigma_p = 7{,}17 \frac{w^{0,46}}{h^{0,66}}$	South Africa
Sheory et al	$\sigma_p S = 0{,}27 \sigma_c \frac{\sqrt{w}}{h^{0,86}}$	India
Madden (1990)	$\sigma_p = 5{,}24 \frac{w^{0,63}}{h^{0,78}}$	South Africa
van der Merwe	$\sigma_p = 4{,}5 \frac{w^{0,46}}{h^{0,66}}$	South Africa Vaal basin

Table 2.6. Formulae Derived From Laboratory Tests

AUTHORS	FORMULA	REMARKS
Bieniawski (1967)	$\sigma_p = 1100 \frac{w^{0,16}}{h^{0,55}}$	
Bunting (1911)	$\sigma_L = 1750 + 750 w/h$ psi $\sigma_p = 700 + 300 w/h$ psi	
Skelly et al. (1977)	$\sigma_1 = 2360\, D^{-0,21}$ psi $\frac{\sigma_p}{\sigma_1} = \left(\frac{D}{L}\right)^{0,45}$	
Madden (1991)	$\sigma_s = k \frac{R_0^b}{V^a} \left\{ \frac{b}{\varepsilon} \left[\left(\frac{R}{R_0} \right)^{\varepsilon} - 1 \right] + 1 \right\}$	w/h>5
Ozbay (1994)	Delmas $171{,}2\, D^{-0,34}$ $\quad 0{,}52 + 0{,}48 w/h$ Sigma $240{,}5\, D^{-0,50}$ $\quad 0{,}65 + 0{,}35 w/h$	

Table 2.7. Summary of Strength Formulae Proposed from Large Scale In Situ Tests in Compression

AUTHORS	FORMULA	REMARKS
H.P Greenwald H.C. Howarth I. Hartmann 1937-1939 USA	$\sigma_p = 700\sqrt{w/h}\ psi$	Pittsburgh
H.P Greenwald H.C. Howarth I. Hartmann 1939-1941 U.S.A	$\sigma_p = 2800(\sqrt{w}/\sqrt{h^5})\ psi$	Pittsburgh
Z.T Bieniawski 1965-1966 South Africa	$\sigma_p = 7.6\,w^{0.16}/h^{0.55}$	Witbank
Z.T Bieniawski 1967-1968 South Africa	$\sigma_p/\sigma_c = 0{,}64 + 0{,}36w/h$	Witbank
W.L. van Heerden 1973 South Africa	$\sigma_p = 10 + 4{,}2w/h$	New Largo

CHAPTER 3.

DESCRIPTION OF TESTS

3.1. Introduction

In South Africa, the pillar design formula developed by Salamon and Munro has been successfully used since 1967. This formula is based on the statistical analysis of collapsed and intact pillar cases, mainly in No 2 Seam located in the Orange Free State and Transvaal regions. This formula assumes one strength value for all coal seams in South Africa. However, as has been shown in the literature survey, the strength of the coal changes from seam to seam and mine to mine.

This and the following chapters present the description and the results of an extensive laboratory study to determine the effect of the size and the width to height ratio and to show the difference in strength between the different coal seams.

3.2. Material tested

Many authors have studied the strength of coal samples to obtain a relationship between strength

and the specimen's width to height ratio. However, as coal is both anisotropic and susceptible to weathering it is difficult to prepare suitable samples for testing. Thus all together 753 laboratory based strength tests from ten blocks taken from four seams in ten collieries and nine coalfields were conducted in order to investigate the effect of size and width to height ratio.
A summary of the samples tested is provided in Table 3.1. However it should be noted that no 200 and 300 mm samples were tested from the Z.A.C. block and that only a certain number of specimens and width to height ratios were obtained from the blocks Bank and Goedehoop, due to the blocks of coal received from these collieries being too small and heavily jointed.

Table 3.1. The blocks tested.

Colliery	Seam	Number of Specimens
Z.A.C.	Main	83
Goedehoop	NO 2	61
Bank	No 2	40
Delmas	No 2	104
Arnot	No 2	104
Greenside	No 2	85
Khutala	No 2	74
Kriel	N 4	68
Secunda	4C Lower	68
Blinkpan	No 2	66

3.3. Sampling procedure and test matrix

Specimens of 25, 60, 100, 200 and 300 mm diameter were drilled from the large blocks obtained from seven different collieries. All the cores obtained were drilled perpendicular to the seam plane.

The test matrix used in this study is shown in Table 3.2.

Table 3.2. The test matrix used for the experiments.

w/h D	0,4	1	2	3	4	5	6	7	8
25	4*	31*	31*	28*	30*	19*	27*		
60		33*	31*	30*	32*	30*	29*	28*	20*
100	3*	23*	23*	26*	27*	20*	22*	23*	19*
200		17*	14*	12*	14*	9*	10*		
300		14*	17*	16*	17*	13*	9*		

D= Diameter (mm), w/h= Width/Height, *= Number of Specimen

Size effect tests were conducted on specimens measuring 25x25, 60x60, 100x100, 200x200 and 300x300 mm. The width to height ratios of the specimens were 1, 2, 3, 4, 5, and 6 for the 25, 200 and 300 mm diameter specimens, and 1, 2, 3, 4, 5, 6, 7, and 8 for the 60 and 100 mm diameter specimens.

3.4. Sample preparations

The 25, 60 and 100 mm diameter samples were cut to length using a lathe in which the cores were placed in a sleeve driven opposite to the direction of blade rotation. After being cut to the approximate length, the 25, 60 and 100 mm diameter samples were placed in a special grinder machine and the ends ground using a surface grinder. The 200 and 300 mm diameter samples were cut using a large rock cutting saw and a large surface grinder machine was used to grind the samples to size. The sample drilling, cutting and preparation were done dry using a vacuum system for dust collection. After grinding, the samples were removed and checked with a dial gauge for parallelism to within 0,002 mm.

All the blocks obtained from the different collieries were protected from weathering by being painted with a bituminous paint and covered with plastic sheeting. The moisture content of the block was not determined at the colliery, due to ingress of moisture during transportation. Therefore the moisture content of the two test specimens from each w/h ratio of each size was determined after the block had been drilled and the specimen tested. In addition to this, the block was stored on surface for a week prior to drilling. To identify whether the block moisture content changed during storage, preparation and testing, small samples were obtained from the appropriate area underground. The difference between the average moisture of the tested and in-situ samples was found to be 18%. The moisture test results are summarised in Appendix I.

3.5. Testing Procedures

Samples of 25, 60 and 100 mm diameter were tested in a 1,2 MN Seidner testing machine; while the larger 200 and 300 mm diameter samples were tested in the 25 MN testing machine at the CSIR, Division of Mining Technology. The testing machines were not inherently stiff nor were they servo-controlled. However by using a special testing procedure, it was possible to obtain more accurate results.

The small size specimens were tested by using a spherical head, and machine displacement was avoided by placing the LVDT's on the spherical seat. The standard end pieces were used to test the small size specimens.

Special end pieces were designed and made for the 200 and 300 mm specimens.

A special data acquisition program "MATS2" was used to monitor all the tests, with both load and deformation being recorded during the testing.

In 1984 Madden presented the strength and load-deformation characteristics of cylindrical sandstone specimens with diameters ranging from 24 to 100 mm and width to height ratios ranging from 1 to 8. This investigation showed that there was a marked influence of the width to height of a specimen on strength beyond a certain critical width to height ratio. Above the critical width to height ratio there was a very rapid increase in strength with increasing specimen width to height ratio. This critical width to height ratio is described as 5 for sandstone specimens.

In this study the tests were carried out with the width to height ratios varying up to 8. The width to height ratios bigger than 6 affect the results dramatically in terms of strength as stated by Madden, 1984. Therefore it was assumed that the width to height ratios bigger than 6 fall into the range of application of the squat pillar formula. Linear regression analysis were therefore performed only on samples having a width to height ratio less than 6. Thus the w/h ratios bigger than 6 were used in the statistical analysis.

CHAPTER 4.

LINEAR REGRESSION ANALYSIS

4.1 Size Effect on Strength

A summary of the results from the size effect tests is graphically illustrated in Figures 4.1-4.10, where unconfined strength is plotted against specimen size for the width to height ratios used for the tests.

The curves presented in Figures 4.1-4.10 were obtained after applying power regression analysis to the data from the test results. In all cases, power regression analysis gave the best correlations. Other regression analyses, namely linear, logarithmic and exponential resulted in relatively poor correlations. The general trend is found to be that the strength increases with decreasing specimen diameter and increasing w/h ratio. The results show a large scatter of strength values as expected.

The relationships between the size and the strength of the specimens tested are shown in Table 4.1.

In Table 4.1, the equations shown against each width to height ratio represent the best fit of the power regression line applied through the each width to height ratios for each sample diameter.

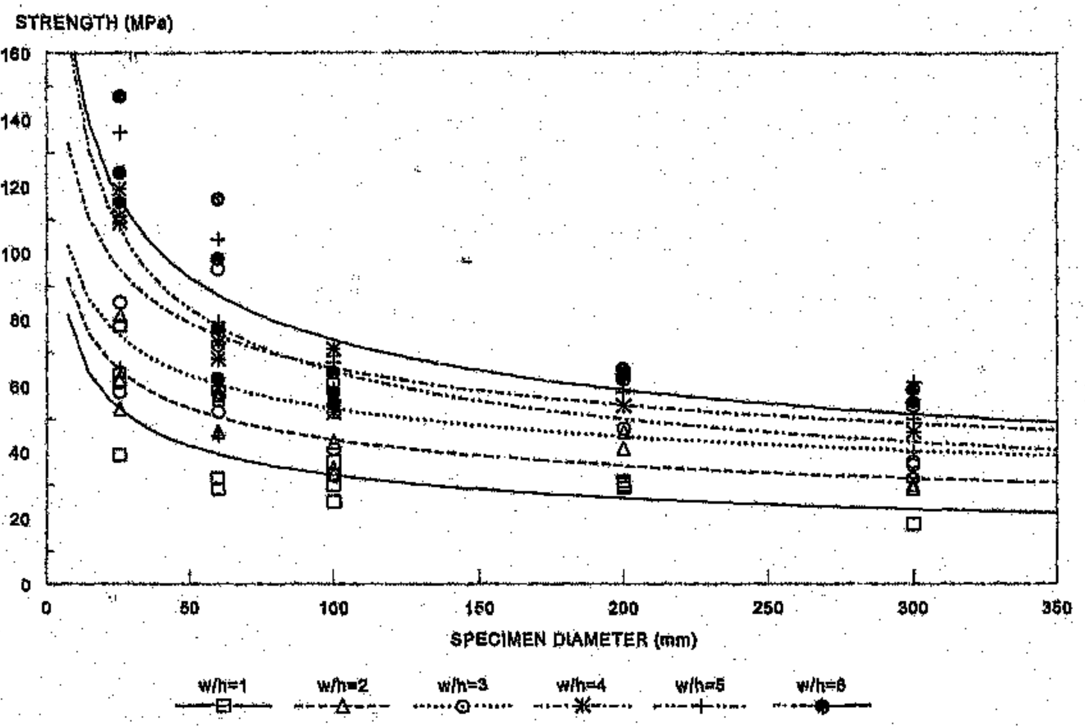

Figure 4.1. Arnot Colliery Size Effect Test Results

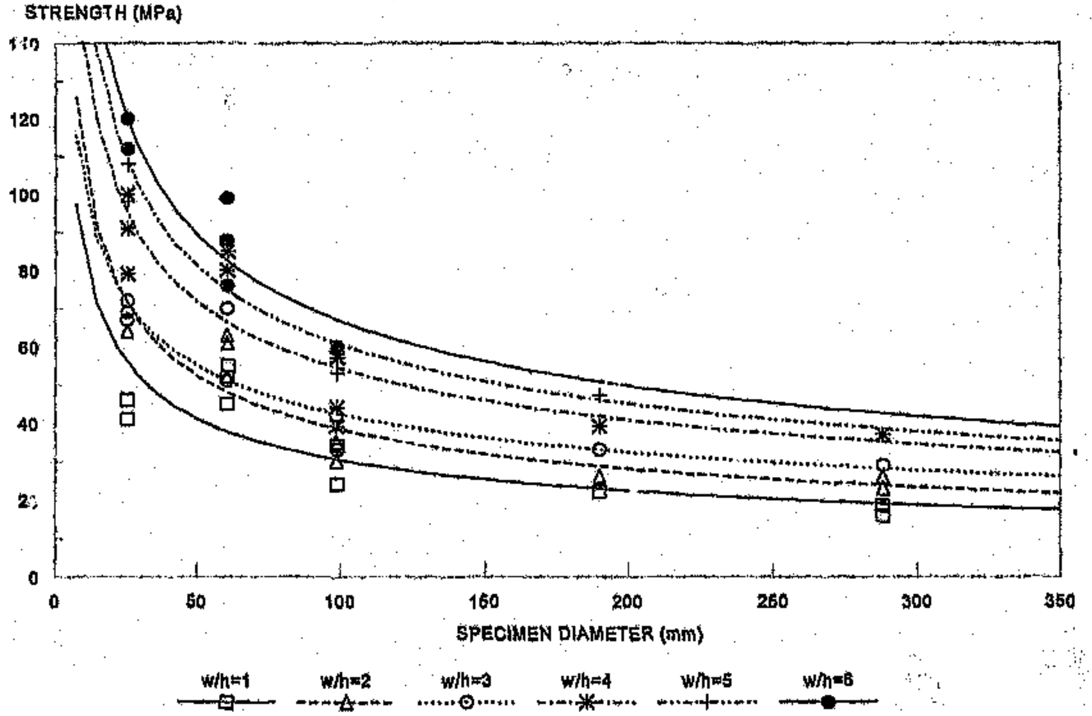

Figure 4.2. Blinkpan Colliery Size Effect Test Results

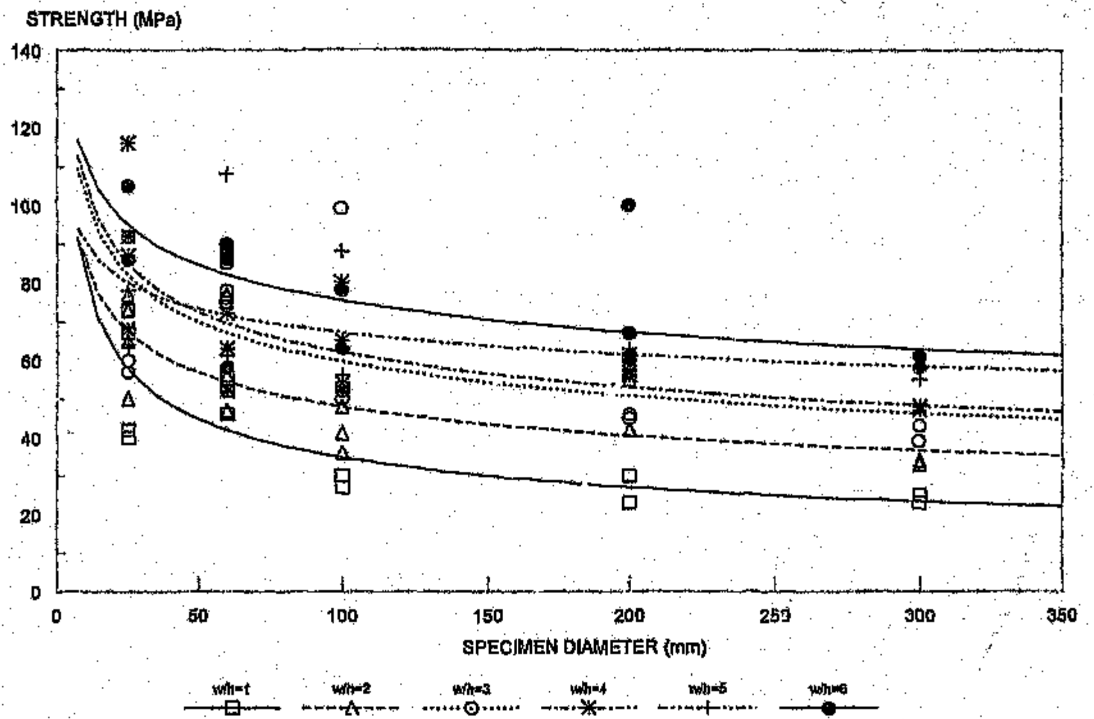

Figure 4.3. Delmas Colliery Size Effect Test Results

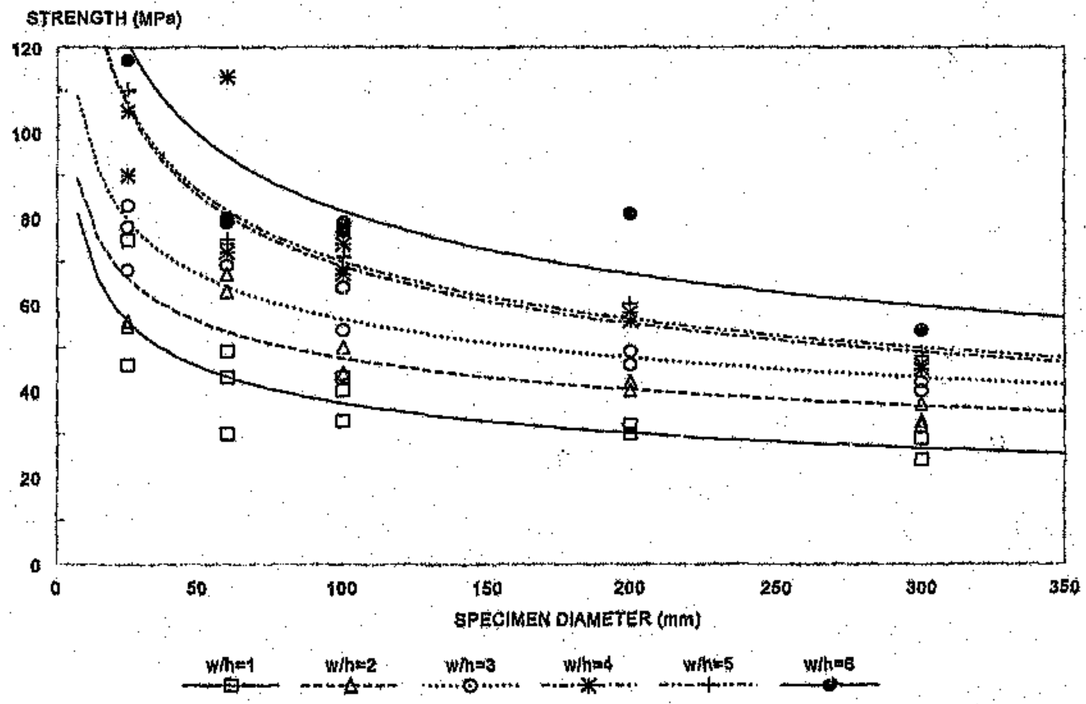

Figure 4.4. Khutala Colliery Size Effect Test Results

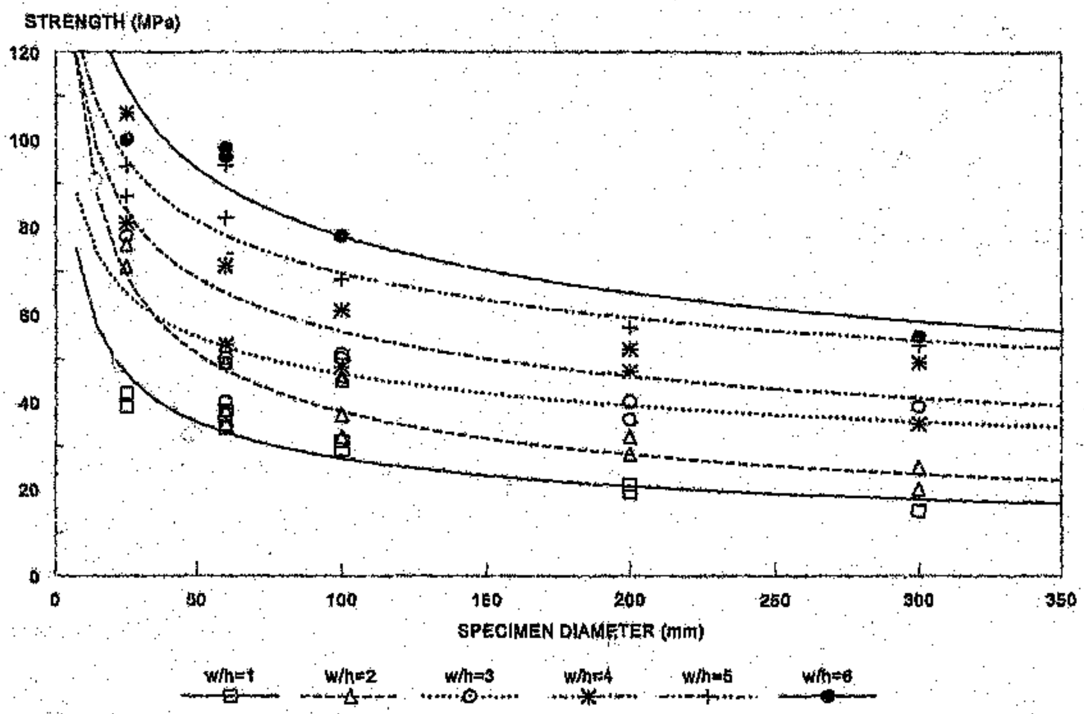

Figure 4.5. Kriel Colliery Size Effect Test Results

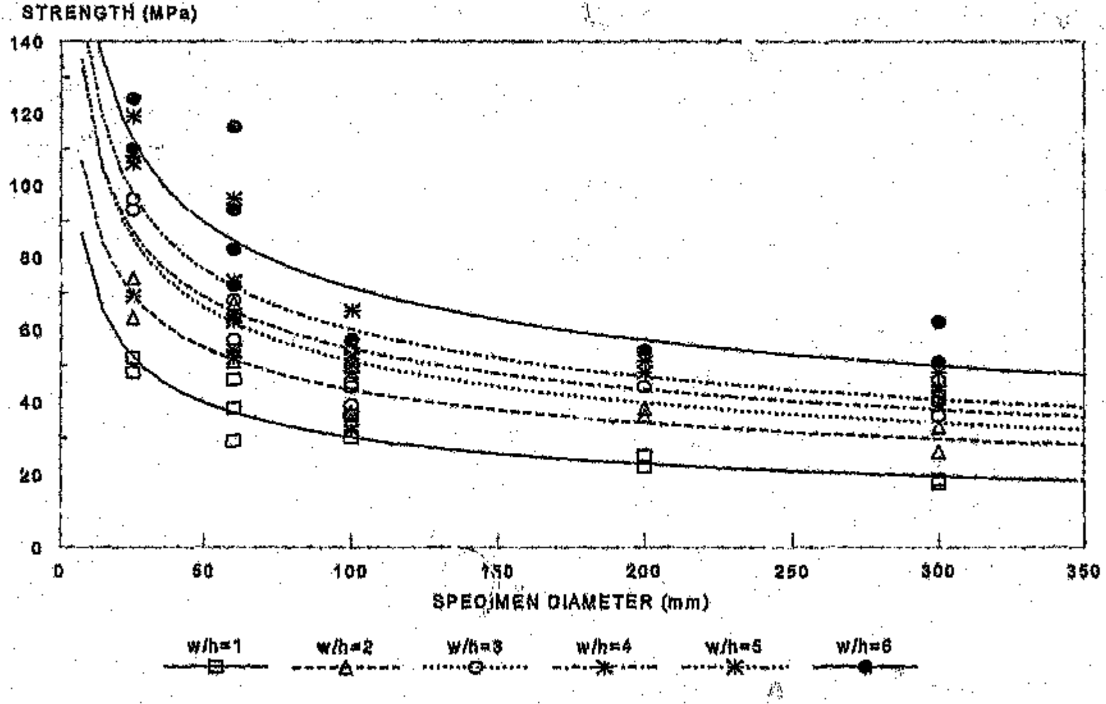

Figure 4.6. Greenside Colliery Size Effect Test Results

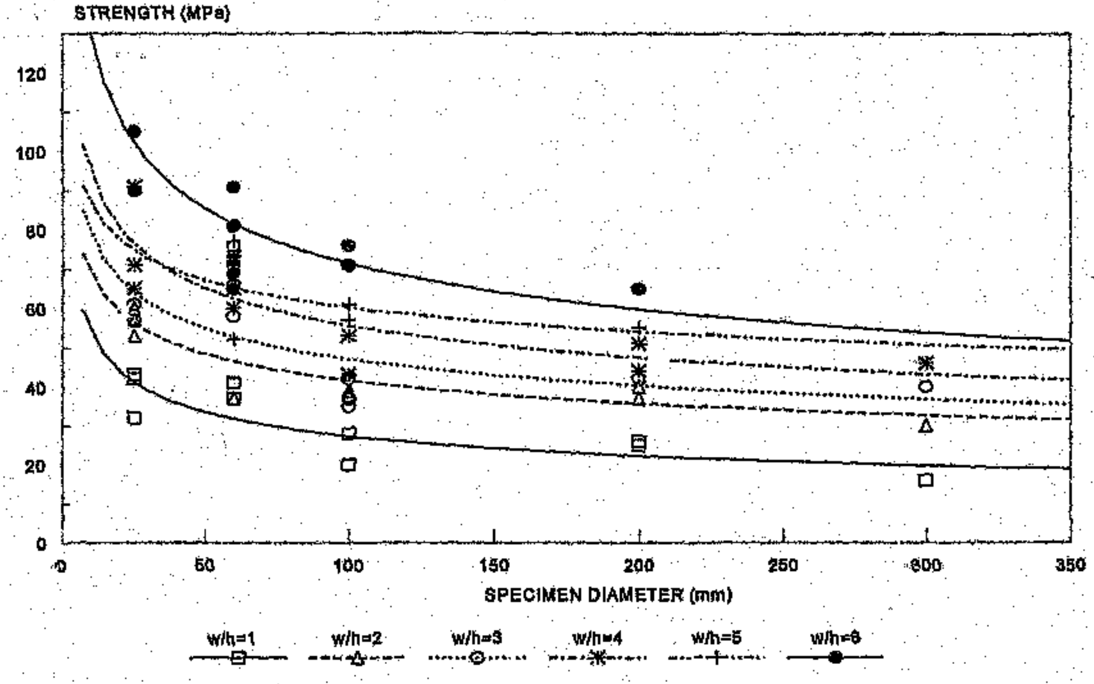

Figure 4.7. Secunda Colliery Size Effect Test Results

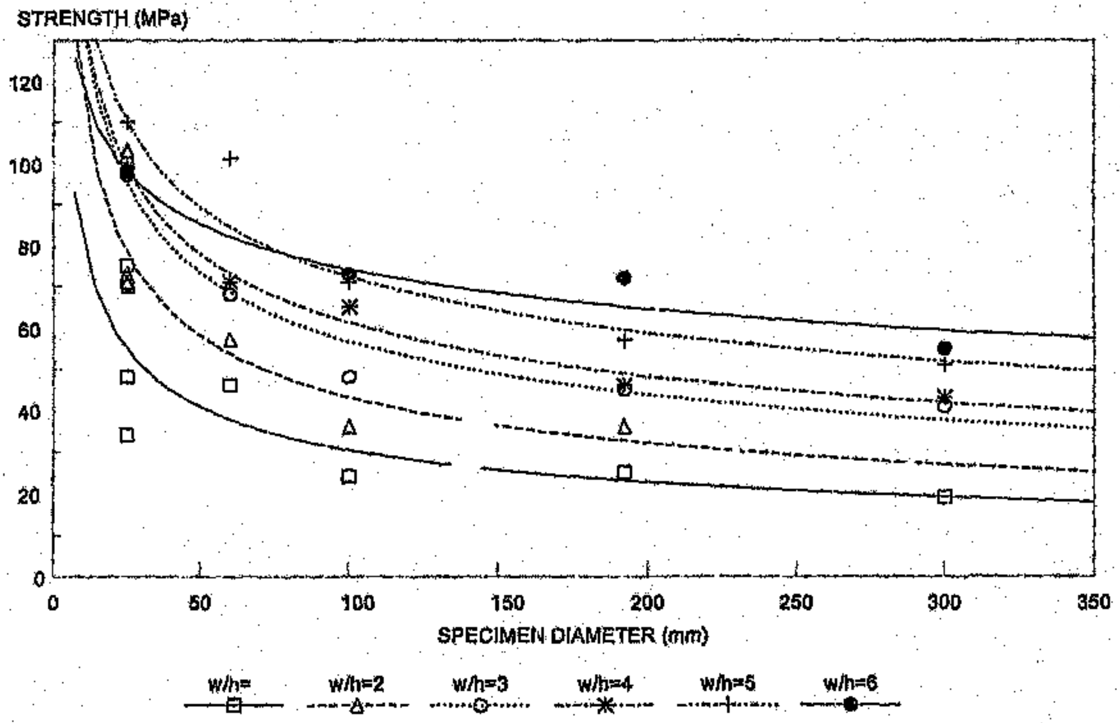

Figure 4.8. Bank Colliery Size Effect Test Results

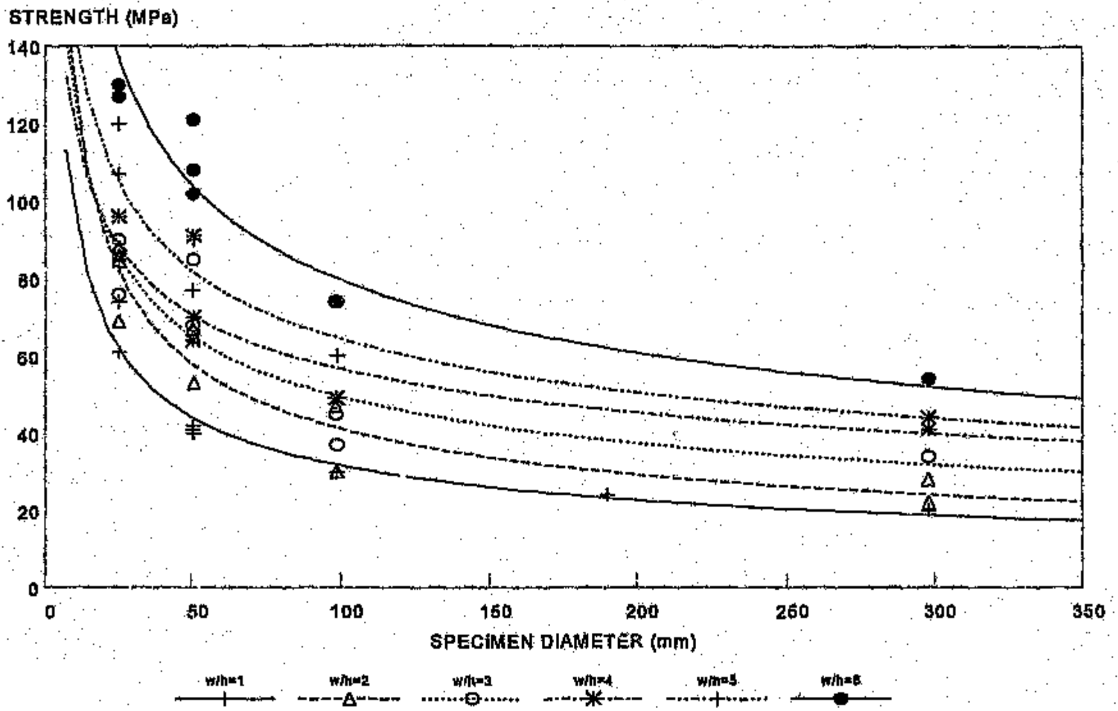

Figure 4.9. Goedehoop Colliery Size Effect Test Results

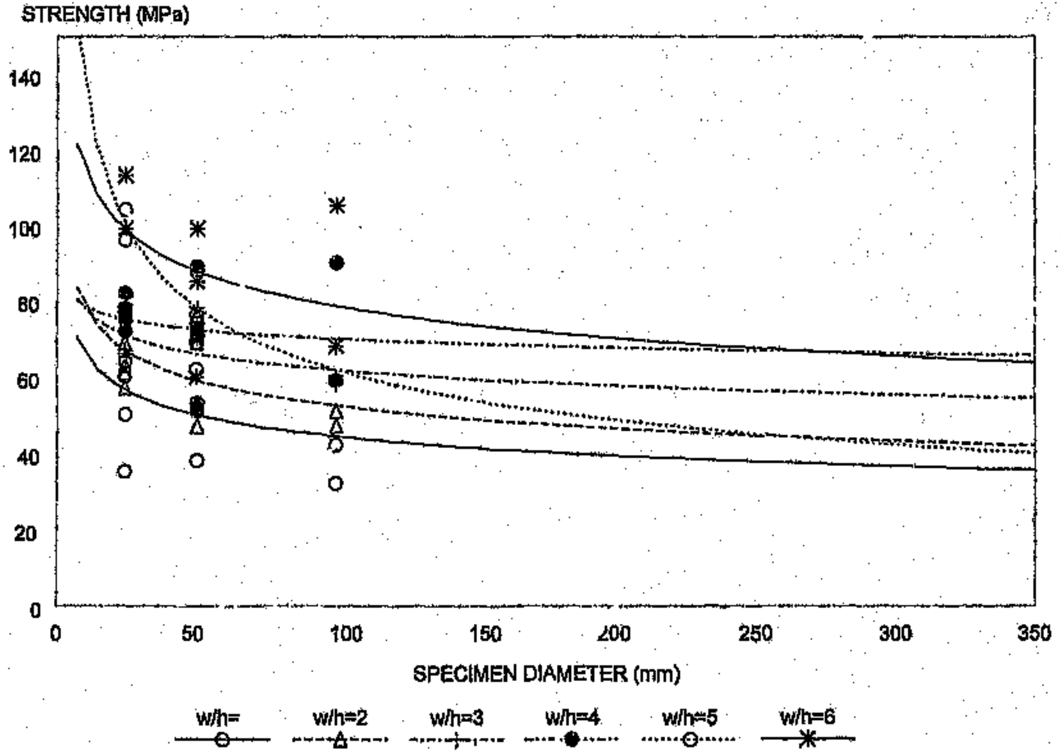

Figure 4.10. Z.A. Colliery Size Effect Test Results

Table 4.1 Results of the size effect tests (D = Sample diameter)

COLLIERY	w/h	STRENGTH (MPa)	COR. COEFF. (R^2)
ARNOT No 2 Seam	1	$158{,}9D^{-0{,}342}$	0,58
	2	$160{,}7D^{-0{,}283}$	0,71
	3	$166{,}8D^{-0{,}249}$	0,58
	4	$347{,}2D^{-0{,}366}$	0,90
	5	$225{,}7D^{-0{,}269}$	0,49
	6	$332{,}3D^{-0{,}327}$	0,69
BLINKPAN No 2 Seam	1	$231{,}5D^{-0{,}441}$	0,73
	2	$304{,}9D^{-0{,}451}$	0,85
	3	$245{,}0D^{-0{,}382}$	0,85
	4	$353{,}9D^{-0{,}408}$	0,81
	5	$427{,}9D^{-0{,}425}$	0,88
	6	$470{,}1D^{-0{,}424}$	0,82
DELMAS No 2 Seam	1	$185{,}9D^{-0{,}364}$	0,69
	2	$147{,}6D^{-0{,}244}$	0,57
	3	$171{,}9D^{-0{,}230}$	0,45
	4	$176{,}0D^{-0{,}221}$	0,62
	5	$120{,}4D^{-0{,}127}$	0,24
	6	$161{,}8D^{-0{,}166}$	0,43
KHUTALA No 2 Seam	1	$145{,}9D^{-0{,}288}$	0,68
	2	$143{,}1D^{-0{,}240}$	0,73
	3	$176{,}3D^{-0{,}247}$	0,90
	4	$287{,}7D^{-0{,}311}$	0,81
	5	$286{,}1D^{-0{,}306}$	0,93
	6	$303{,}5D^{-0{,}285}$	0,68
KRIEL No 4 Seam	1	$161{,}1D^{-0{,}388}$	0,88
	2	$279{,}1D^{-0{,}434}$	0,83
	3	$141{,}4D^{-0{,}242}$	0,66
	4	$210{,}1D^{-0{,}267}$	0,72
	5	$198{,}2D^{-0{,}228}$	0,85
	6	$259{,}1D^{-0{,}261}$	0,88

COLLIERY	w/h	STRENGTH (MPa)	COR. COEFF.
GREENSIDE No 2 Seam	1	$189,6D^{-0,399}$	0,88
	2	$208,6D^{-0,342}$	0,82
	3	$276,8D^{-0,367}$	0,84
	4	$255,7D^{-0,336}$	0,64
	5	$301,8D^{-0,342}$	0,65
	6	$321,2D^{-0,327}$	0,71
SECUNDA 4C Lower	1	$106,1D^{-0,294}$	0,67
	2	$113,6D^{-0,218}$	0,66
	3	$131,5D^{-0,223}$	0,43
	4	$159,9D^{-0,229}$	0,68
	5	$123,8D^{-0,156}$	0,24
	6	$234,6D^{-0,258}$	0,61
BANK No 2 Seam	1	$213,3D^{-0,423}$	0,73
	2	$309,4D^{-0,427}$	0,85
	3	$313,7D^{-0,372}$	0,85
	4	$299,9D^{-0,344}$	0,81
	5	$289,1D^{-0,301}$	0,88
	6	$186,3D^{-0,201}$	0,82
GOEDEHOOP No 2 Seam	1	$291,9D^{-0,482}$	0,73
	2	$400,0D^{-0,493}$	0,85
	3	$311,0D^{-0,393}$	0,85
	4	$246,9D^{-0,319}$	0,81
	5	$322,2D^{-0,349}$	0,88
	6	$477,1D^{-0,389}$	0,82
Z.A.C. Main Seam	1	$123,8D^{-0,227}$	0,73
	2	$118,1D^{-0,176}$	0,85
	3	$98,1D^{-0,100}$	0,85
	4	$87,9D^{-0,05}$	0,81
	5	$305,4D^{-0,347}$	0,88
	6	$167,2D^{-0,163}$	0,82

COLLIERY	w/h	STRENGTH (MPa)	COR. COEFF.
OVERALL	1	$207,55D^{-0,411}$	0,87
	2	$193,21D^{-0,326}$	0,86
	3	$188,87D^{-0,282}$	0,84
	4	$200,43D^{-0,272}$	0,89
	5	$219,17D^{-0,264}$	0,77
	6	$293,63D^{-0,369}$	0,75

The critical size strength for rock masses is very important in design [Bieniawski (1968), Hustrulid (1976)]. The critical size is defined as that specimen size at which a continued increase in specimen size causes no significant decrease in strength. For South African coal, Bieniawski (1968) stated that 1,5 m cubic specimens constitute the critical size. Hustrulid (1976) pointed out that a critical size of 0,9 m would be generally applicable to coal for practical engineering purposes. To enable the comparison of the strengths of different coal seams, the results were extrapolated, for a w/h ratio of 1, to a sample diameter of 500 mm. This analysis yielded a value of 12,14 MPa for a laboratory sized specimen. Note that the strength values of 7,17 MPa given by Salamon is the k value as given in his pillar strength formula which includes structural effects as well as time dependent strength decay.

Table 4.2 shows the predicted strength values of the data assuming that the critical size is 1000 mm, using the equations for w/h=1.

Table 4.2. Predicted strength values of each set of data

Colliery	Seam	Predicted strength (MPa) (D=1000 mm)	(R) Squared
Arnot	No 2	14,96	0,58
Blinkpan	No 2	11,00	0,73
Delmas	No 2	15,04	0,69
Khutala	No 2	18,6	0,68
Kriel	No 4	11,04	0,88
Greenside	No 2	12,04	0,88
Secunda	4C Lower	13,83	0,67
Bank	No 2	11,47	0,72
Goedehoop	No 2	10,4	0,96
Z.A.C.	Main	25,6	0,16

As can be seen from the Table 4.2 that, Z.A.C. block shows the greatest strength value compare to others, this is due to effect of sample size tested on Z.A.C. block as explained earlier. It can also be seen that the strength of the coal changes from seam to seam even in same seam and while the strength of Khutala No 2 Seam block is 18,6 MPa, the strength of Goedehoop block, from the same seam, is 10,4 MPa. These results indicate the seam specific size effect on strength. The difference between the strongest (Z.A.C. Main Seam) and the weakest coal (Goedehoop No 2 Seam) is found to be 59,4.

Figure 4.11 shows the strength values (w/h=1) as obtained from the size effect tests against specimen size together with predicted strengths from Salamon and Bieniawski.

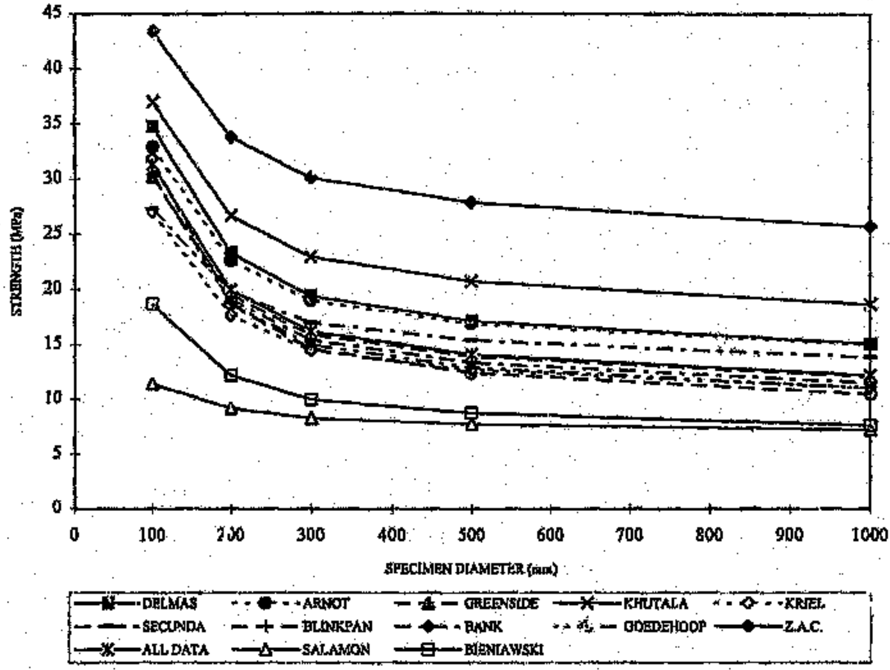

Figure 4.11 The Data as Obtained from the Size Effect Test together with Data Salamon and Bieniawski (w/h=1)

It will be seen from the experimental results plotted in Figure 4.11 that the strength values obtained using the Salamon and Bieniawski formulae are lower than the laboratory test data. This would be expected because the laboratory data has a greater size effect due to the effect of discontinuities on the strength of laboratory samples. The strongest coal to be found is the Z.A.C. Main Seam coal while the weakest coal is Goedehoop No 2 Seam. As mentioned earlier, the Z.A.C. block was not large enough to obtain a full suite of size samples and only the 25, 50 and 100 mm size samples were obtained. However, the 200 and 300 mm sample strengths had a significant effect on the calculation resulting in the Z.A.C. coal being the strongest coal tested.

4.2 Width to Height Ratio Effect on Strength

As the depth of mining increases the support pillars are designed to have larger width to height ratios. The design of these support pillars requires a knowledge of the strength of the pillar, which is considered to be determined by the strength of the pillar material, the shape or geometry of the pillar and the volume of the pillar.

This chapter basically summarizes the width to height ratio effect on the strength of coal specimens.

The testing technique used was that the sample diameter was kept constant and the heights varied. This technique has been used by many investigators in the past, but as is well known the actual height of coal pillars is normally controlled by the seam thickness and the strength is varied by changing the width.

Samples of varying width to height ratio's (i.e. 1:1, 2:1, 3:1, 4:1, 5:1 6:1, 7:1, 8:1) were tested from each coal block except that from the Z.A.C. block. For this block the sample diameters were 25, 60, 100.

The width to height (w/h) ratio tests are graphically summarized in Figures 4.12-4.21, where unconfined strength values are plotted against width to height ratios for the diameters used in the tests. For each block from each colliery an increase in strength with increasing w/h ratio is observed for each diameter. It is also found that after a certain width to height ratio is achieved the width to height ratio has a marked influence on the specimen's strength.

The relationships between the strengths and width to height ratios are given in Table 4.3. The equations presented against the correlation coefficients were obtained after applying a linear regression analysis which gave better correlation coefficients than the other regression analyses for the strength versus width to height ratio. These results are presented in Appendix II and summarized in Table 4.3 and are based on the equation C = A(w/h) + B, where A and B are the slope and the intercept of the regression line.

It is interesting to note that the scatter of the results is gradually reduced as the size of the tested specimens increase and the number of specimens decrease. Also the correlation coefficients for the each individual diameter give better results than the overall results.

Table 4.3. Shape effect test results

Colliery	Diameter (mm)	Strength/K	Cor.Coeff (R^2)	Overall Strength/K	Cor.Coeff (R^2)
ARNOT	25	0,72+0,28(w/h)	0,60	0,79+0,31(w/h)	0,29
	60	0,88+0,12(w/h)	0,35		
	100	0,82+0,18(w/h)	0,64		
	200	0,80+0,20(w/h)	0,96		
	300	0,70+0,30(w/h)	0,71		
BLINKPAN	25	0.67+0,33(w/h)	0,94	0,72+0,28(w/h)	0,42
	60	0,80+0,20(w/h)	0,85		
	100	0,71+0,29(w/h)	0,84		
	200	0,67+0,33(w/h)	0,97		
	300	0,64+0,36(w/h)	0,98		
DELMAS	25	0,87+0,13(w/h)	0,41	0,84+0,16(w/h)	0,33
	60	0,83+0,17(w/h)	0,62		
	100	0,82+0,18(w/h)	0,51		
	200	0,75+0,25(w/h)	0,65		
	300	0,70+0,30(w/h)	0,96		
KHUTALA	25	0,68+0,32(w/h)	0,84	0,73+0,27(w/h)	0,49
	60	0,84+0,16(w/h)	0,53		
	100	0,82+0,18(w/h)	0,82		
	200	0,70+0,30(w/h)	0,98		
	300	0,79+0,21(w/h)	0,92		
KRIEL	25	0,78+0,22(w/h)	0,76	0,59+0,41(w/h)	0,60
	60	0,63+0,37(w/h)	0,90		
	100	0,73+0,27(w/h)	0,90		
	200	0,51+0,49(w/h)	0,98		
	300	0,31+0,69(w/h)	0,91		

Colliery	Diameter (mm)	Strength/K	Cor.Coeff (squared)	Overall Strength/K	Cor.Coeff (squared)
GREENSIDE	25	0,77+0,23(w/h)	0,63	0,74+0,26(w/h)	0,30
	60	0,60+0,40(w/h)	0,70		
	100	0,85+0,15(w/h)	0,63		
	200	0,78+0,22(w/h)	0,89		
	300	0,65+0,35(w/h)	0,91		
SECUNDA	25	0,64+0,36(w/h)	0,88	0,72+0,28(w/h)	0,59
	60	0,79+0,21(w/h)	0,69		
	100	0,68+0,32(w/h)	0,89		
	200	0,73+0,27(w/h)	0,95		
	300	0,43+0,57(w/h)	0,97		
BANK	25	0,88+0,12(w/h)	0,53	0,82+0,18(w/h)	0,34
	60	0,72+0,28(w/h)	0,90		
	100	0,62+0,38(w/h)	0,95		
	200	0,71+0,29(w/h)	0,96		
	300	0,59+0,41(w/h)	0,96		
GOEDEHOOP	25	0,83+0,17(w/h)	0,71	0,73+0,27(w/h)	0,48
	60	0,74+0,26(w/h)	0,87		
	100	0,34+0,64(w/h)	0,81		
	300	0,64+0,36(w/h)	0,96		
Z.A.C.	25	0,83+0,17(w/h)	0,73	0,84+0,16(w/h)	0,70
	60	0,86+0,14(w/h)	0,69		
	100	0,70+0,30(w/h)	0,88		
ALL DATA	25	0,79+0,21(w/h)	0,62	0,79+0,21(w/h)	0,44
	60	0,81+0,19(w/h)	0,60		
	100	0,77+0,23(w/h)	0,61		
	200	0,72+0,28(w/h)	0,78		
	300	0,64+0,36(w/h)	0,83		

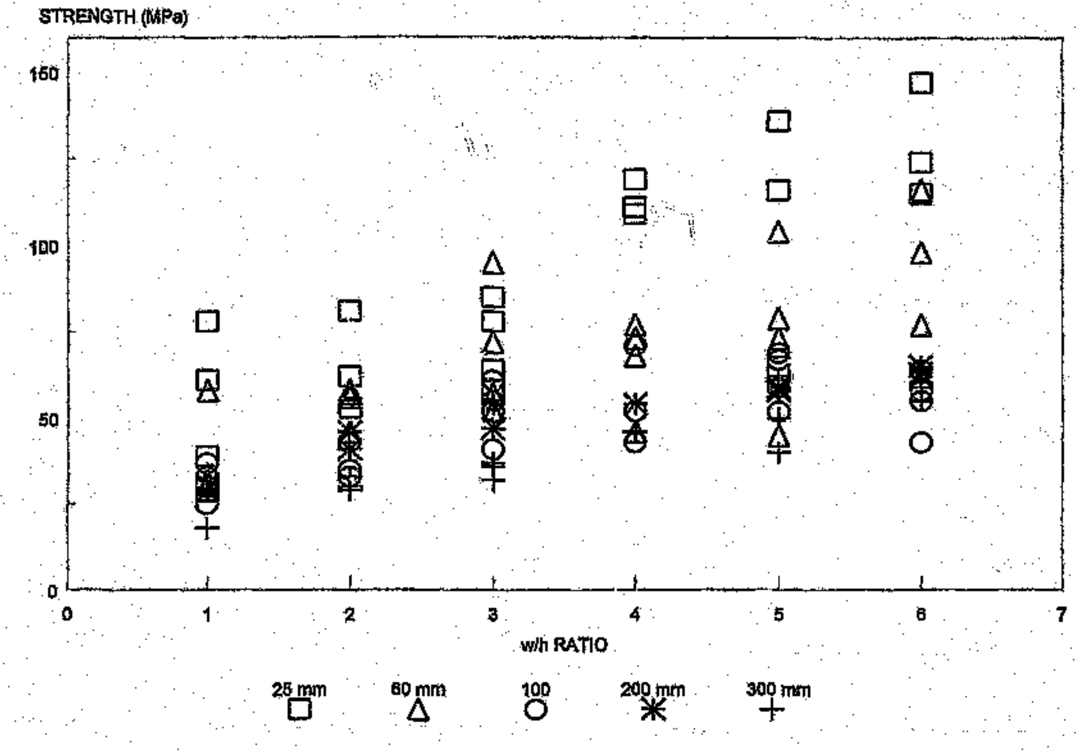

Figure 4.12. Strength Results, Arnot Colliery

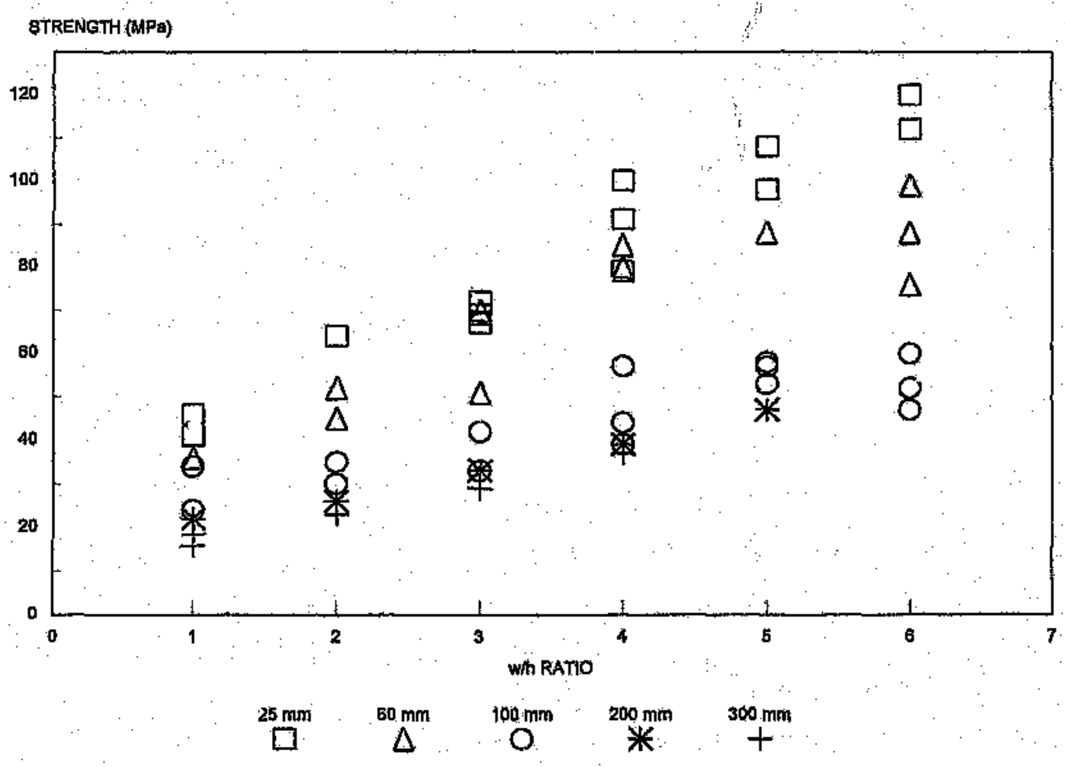

Figure 4.13. Strength Results, Blinkpan Colliery

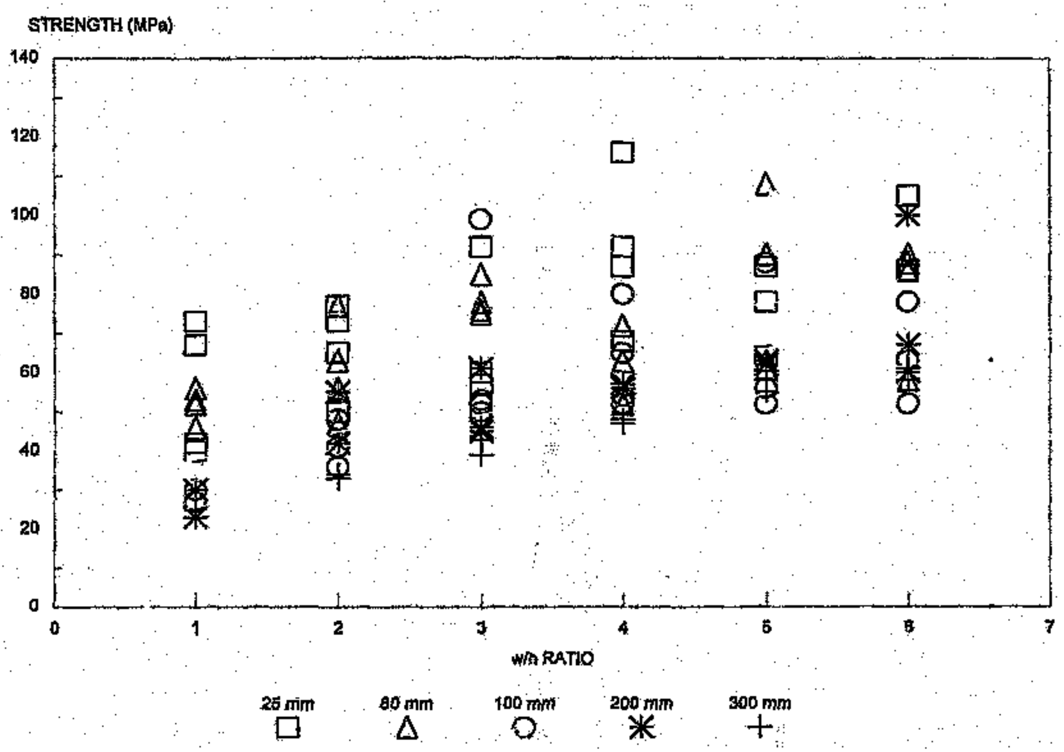

Figure 4.14. Strength Results, Delmas Colliery

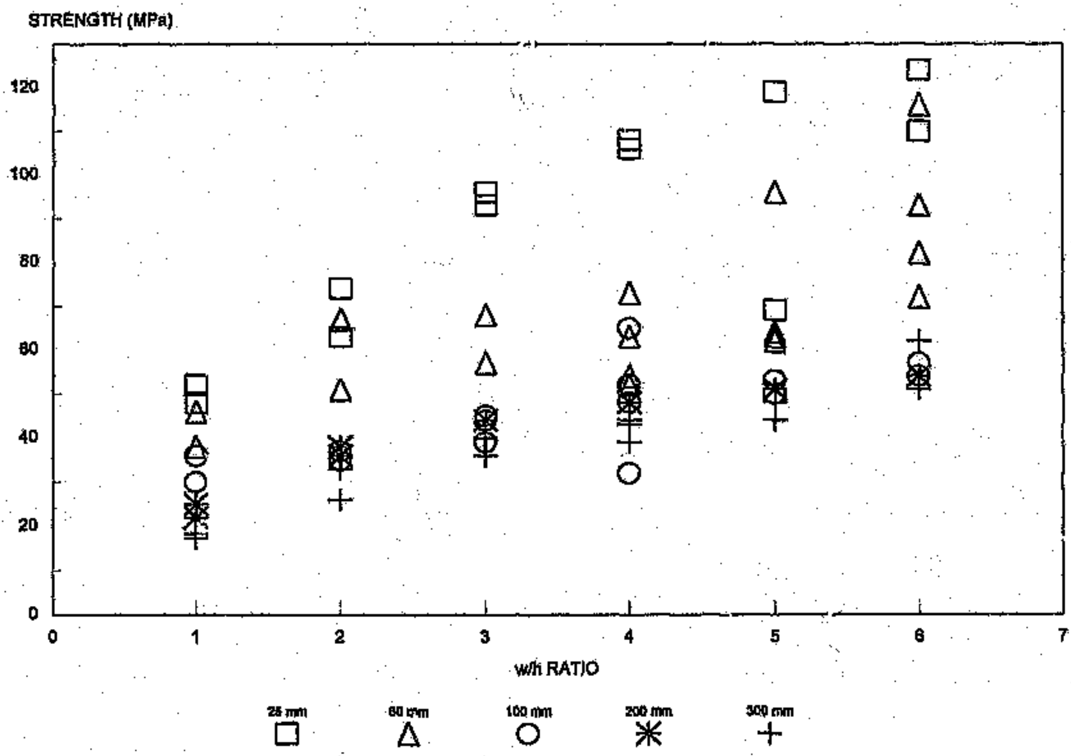

Figure 4.15. Strength Results, Greenside Colliery

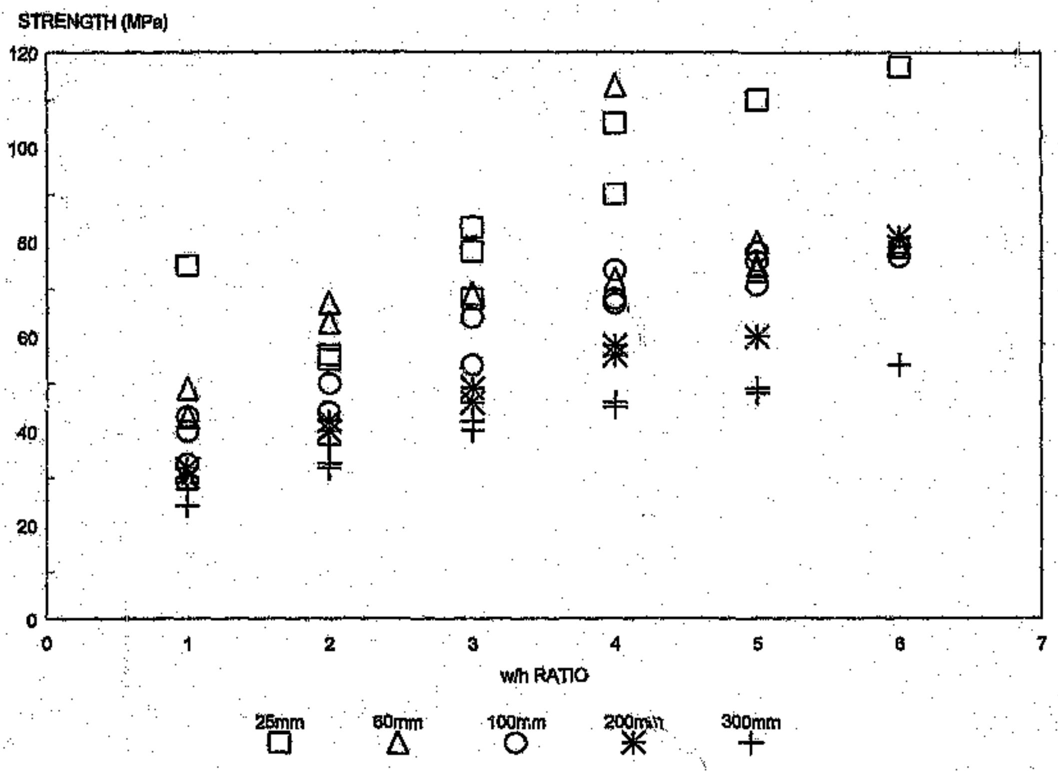

Figure 4.16. Strength Results, Khutala Colliery

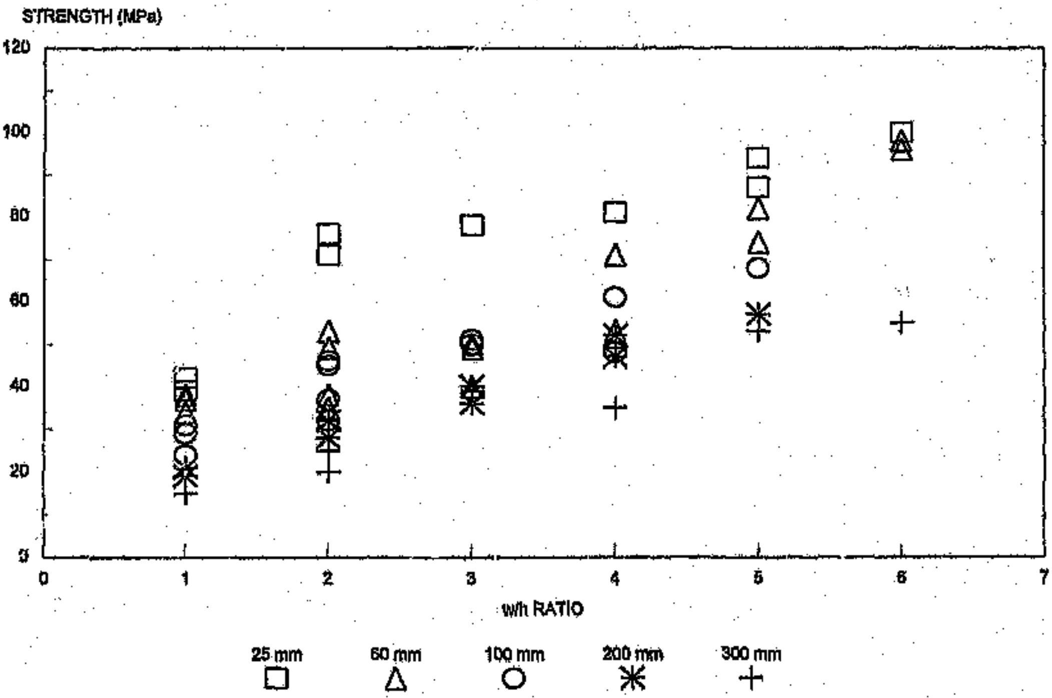

Figure 4.17. Strength Results, Kriel Colliery

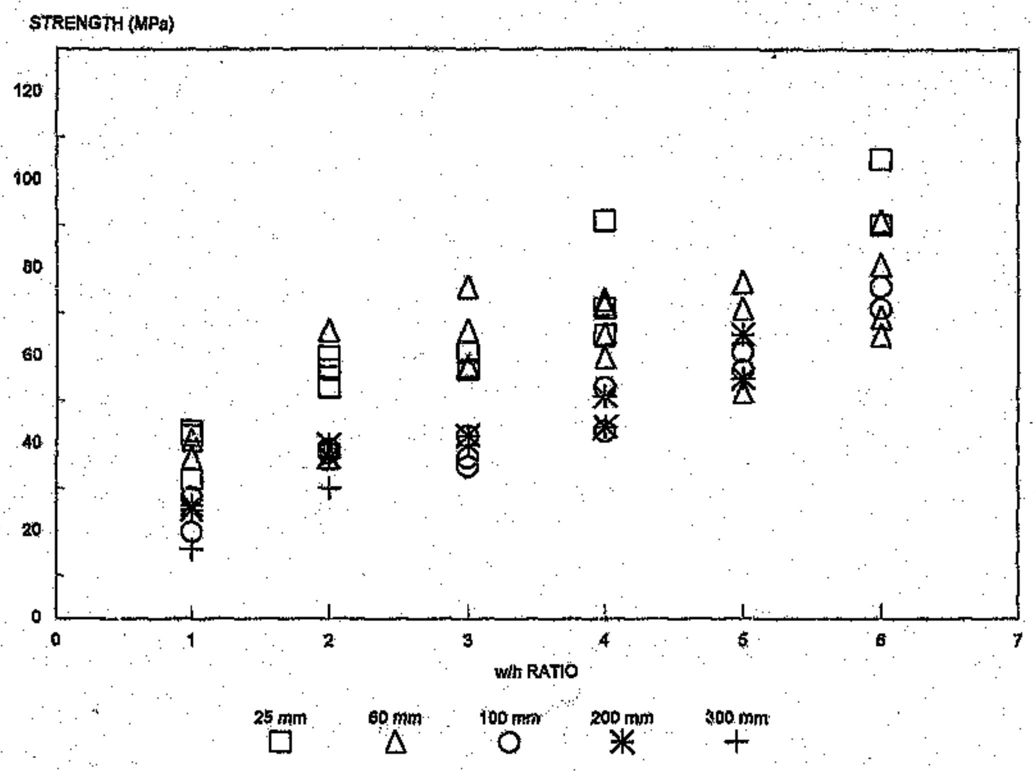

Figure 4.18. Strength Results, Secunda Colliery

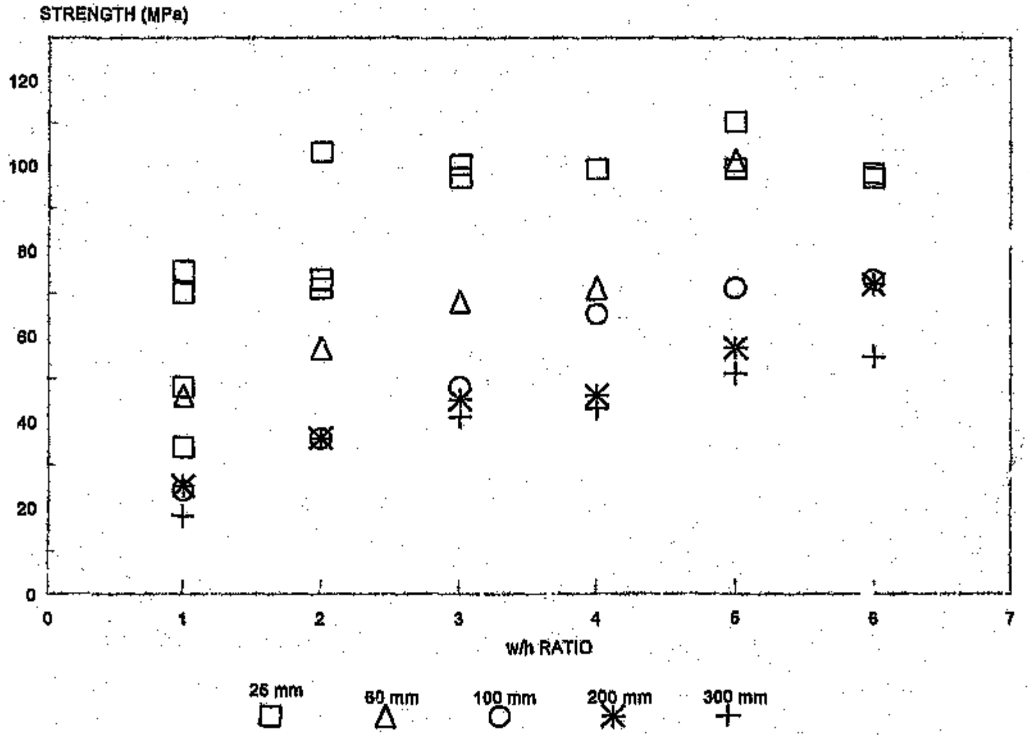

Figure 4.19. Strength Results, Bank Colliery

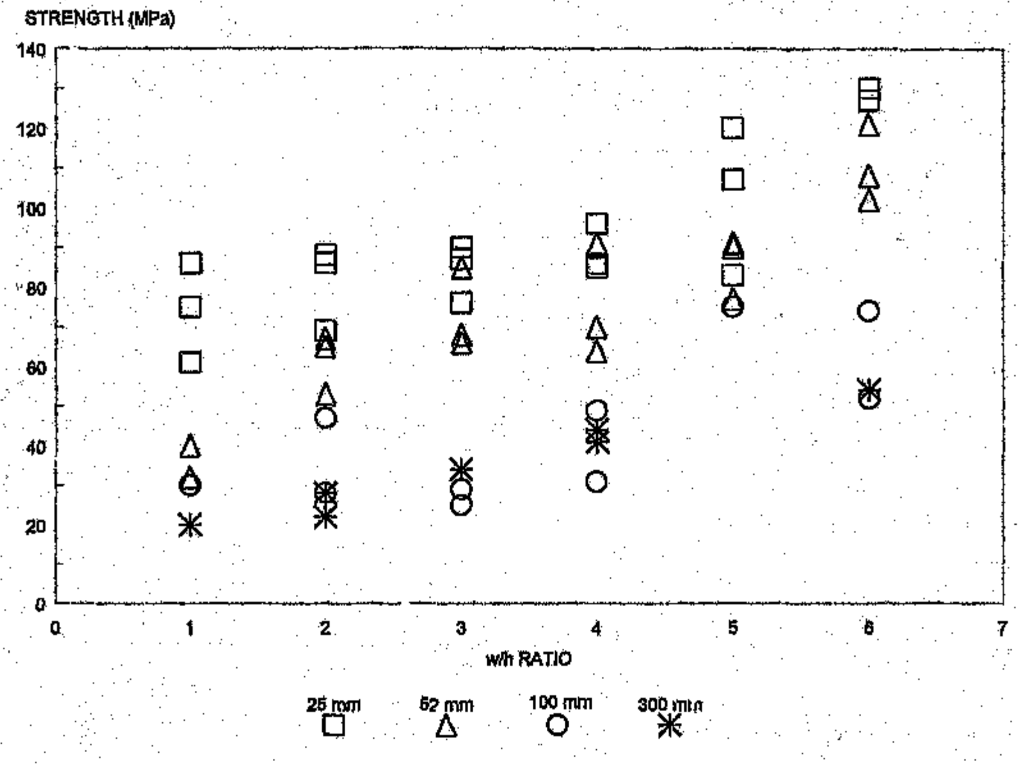

Figure 4.20. Strength Results, Goedehoop Colliery

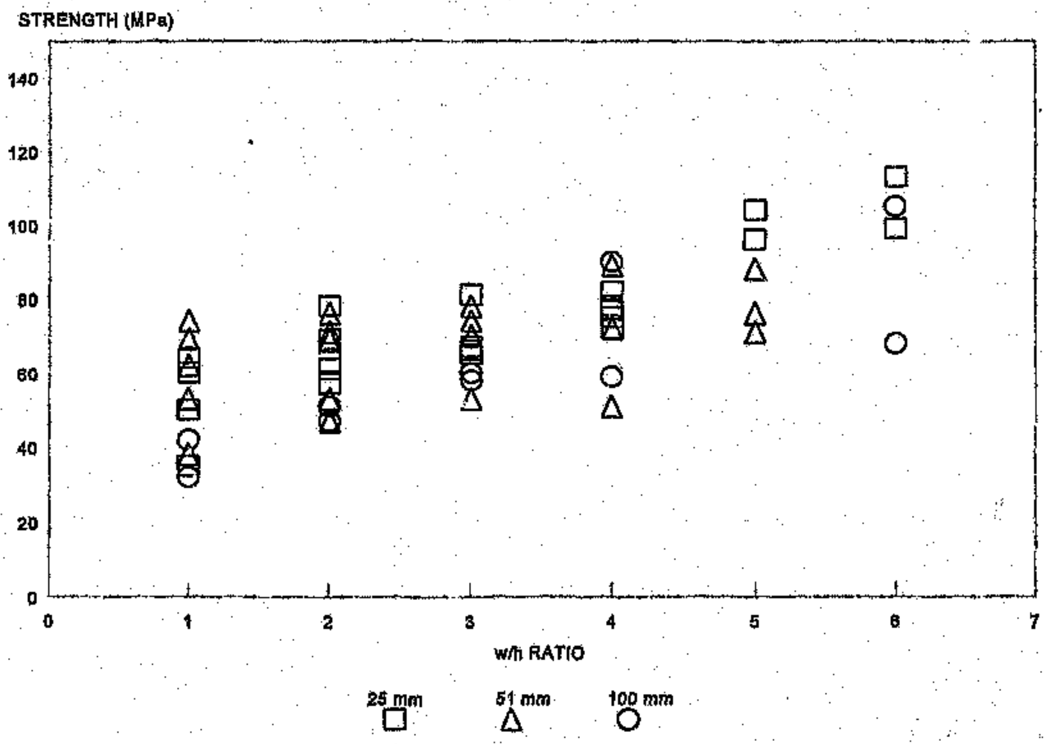

Figure 4.21. Strength Results, Z.A.C.

The normalized strength values against w/h ratio are shown in Figure 4.22. It will be seen from the Figure 4.22 that, Kriel coal shows the greatest rate of strength increase with increasing w/h ratio.

Note that the equations obtained from the linear regression analyses were the same for the Secunda-Blinkpan, Z.A.C.-Delmas and Goedehoop-Khutala data. Therefore these two data sets plotted on top of the each other.

Figure 4.23 shows the normalized strength values plotted against the width to height ratio, together with data from Bieniawski and Salamon's analyses assuming a constant height. Similarly Figure 4.23 shows the normalized strength values plotted against the width to height ratio together with data from Bieniawski and Salamon's analyses assuming a constant width. However in Figure 4.24, while the results of the study shows good agreement, at w/h=2 and greater, with Salamon's formula, Beinawski's formula shows a slower rate of strength increase with increasing width to height ratio. Also in Figure 4.24, it is seen that while Bieniawski's formula closely approximates the results obtained from this study, Salamon's formula shows a greater rate of strength increase with increasing width to height ratio.

This difference can be explained by considering the effect of volume on strength. In other words, as the pillar height is kept constant the volume of the pillar gets bigger than would be the case if the width were to be kept constant. While this volume increase results in a big difference on strength in Salamon's and Bieniawski's equations, it does not affect the results obtained from this study because the linear relationship between the width and height does not take the volume effect into account.

In general the results show that holding width constant while varying height leads to a stronger effect on the width to height ratio than the reverse procedure.

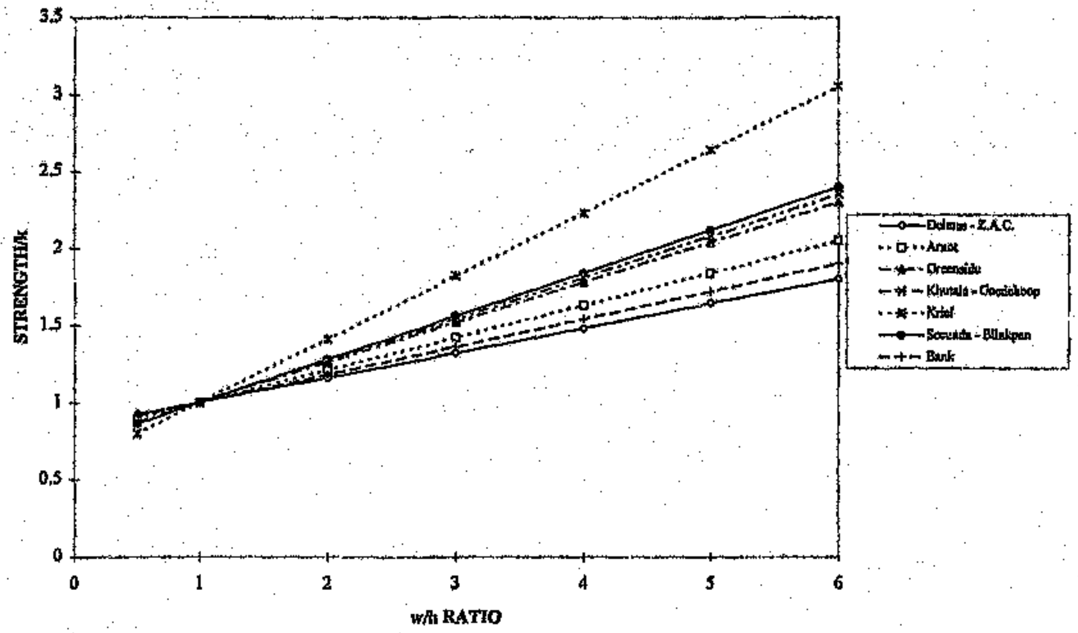

Figure 4.22. The Normalized Strength Values for each Data.

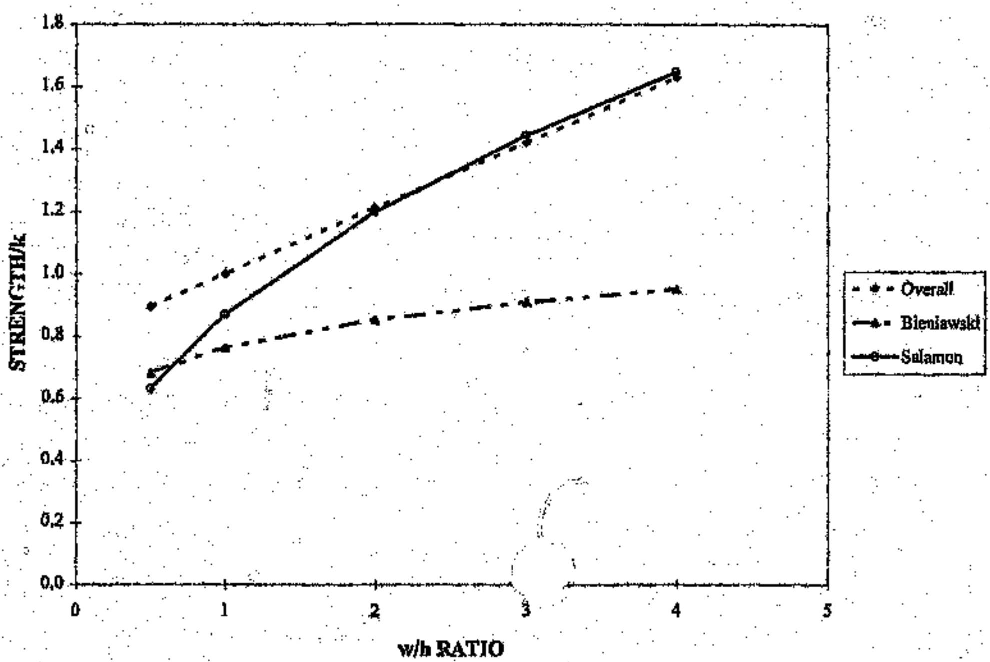

Figure 4.23. The Normalized Strength Values Plotted against data from Bieniawski and Salamon, (h is constant)

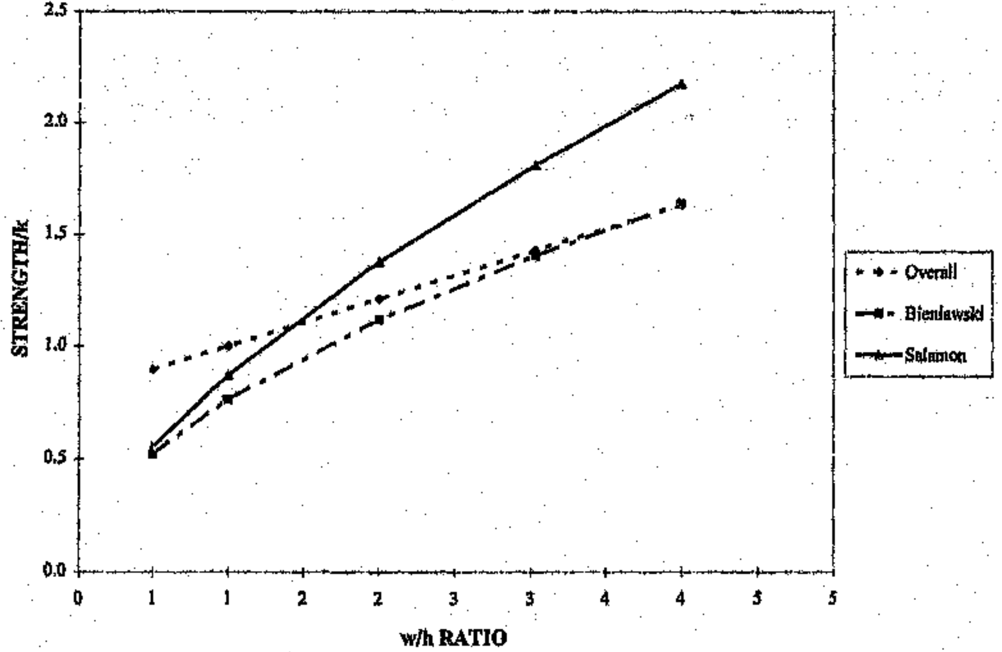

Figure 4.24. The Normalized Strength Values Plotted against data from Bieniawski and Salamon, (w is constant).

CHAPTER 5.

STATISTICAL ANALYSIS

5.1 Statistical analysis of the data

Extensive laboratory testing of coal samples was conducted during the project. Data from some 753 tests from 4 seams in 10 collieries. The test sample sizes ranged in diameter from 0,025 - 0,3 m and in the width to height ratio over the range 0,4 - 8,0.

As seen in the linear regression analyses, the correlation coefficient is found to be relatively poor. Therefore, it was decided to analysis the data statistically. The results of the statistical analyses are presented in this chapter.

Initially the methodology was aimed at determining site specific strength formulae which incorporated the testing of samples prepared from a block of coal selected from a seam within a colliery. Site specific strength formulae based on laboratory testing has been extensively debated in the past. One of the main problems with this approach is the danger of dilution of the substantial data base of experience. The approach was therefore shifted to examining the potential of laboratory testing to distinguish between seam strengths and to relate the results to the field design procedure.

To achieve this, the laboratory test results were re-analysed statistically. The re-analysis initially combined all the test results and relationships between predicted strength and sample width and height were obtained. In this manner a coefficient of strength for each block was determined. The mean strength and variance for the samples tested from each block were then compared and the relative variation in strength between each block was obtained.

The laboratory test results were then analysed by fixing the constants for width and height to those obtained by Salamon from the statistical analysis of collapsed and intact pillar cases. A comparison was made between the two methods of evaluating the strength of the coal blocks.

The potential bias of the laboratory testing process and how the results can be of practical use were examined as were the relationship between the laboratory test results and those obtained by Salamon and Munro from their analysis of full sized pillars.

To gain additional insight into the results from the laboratory tests was re-analysed by statistical methods. The key points arising were as follows:-]

1 - A common relationship across the blocks to provide A common form of relationship with width and

width to height ratio across blocks provides an adequate fit to the data with a coefficient varying according to the strength of the coal. The form of the relationship is

$$\text{Strength} = \delta \times \text{width}^{0,124}/\text{height}^{0,449} (\text{MPa}) \quad (5.1)$$

and the width and height of the laboratory samples are in metres.

The coefficient delta (δ) varied as shown in Table 5.1 for the various collieries (the overall average value being 15,7 MPa).

Table 5.1 Delta (δ) Values For The Coal Blocks With "Optimized" α and β

Colliery	Seam	δ
Arnot	No 2	15,3
Bank	No 2	16,0
Blinkpan	No 2	13,3
Delmas	No 2	16,7
Goedehoop	No 2	15,1
Greenside	No 2	13,7
Khutala	No 2	17,1
Kriel	No 4	12,9
Secunda	4C Lower	13,7
Zululand Anthracite	Main	17,6
Overall Average		15,7

2 - The strength of the different blocks exhibits consistent variation. The analysis of variance for between-blocks variability is presented below. The variance between blocks is a highly significant effect.

Table 5.2. Variance between Blocks

Source	Sum of squares	degrees of freedom	Mean square
Between blocks	3,30	9	0,3667
Residual	34,14	745	0,0464
TOTAL	37,43	754	0,0502

3 - The strength of the different seams exhibits consistent variation, with No 2 Seam, Witbank Coalfield being stronger than the other blocks tested. The analysis of variance for between-seams variability is presented below. This variance between seams is a highly significant effect as shown in Table 5.3

Table 5.3. Variance between Seams

Source	Sum of squares	degrees of freedom	Mean square
Between seams	1,89	3	0,6300
Residual	35,54	751	0,0473
TOTAL	37,43	754	0,0496

4 - The analysis of variance for between-blocks variability for all blocks drawn from the No 2 Seam, Witbank Coalfield, is presented below. This effect is also highly significant, although the variability is lower than for all blocks. This implies that blocks drawn from within the No 2 Seam, Witbank Coalfield are somewhat more similar in strength than blocks drawn at random.

Table 5.4. Variance between No 2 Seam Blocks

Source	Sum of squares	degrees of freedom	Mean square
Between blocks	1,41	5	0,4500
Residual	25,22	531	0,0518
TOTAL	26,63	536	0,0497

5 - The analysis of variance for between-blocks variability for all blocks drawn from seams other than the No 2 Seam, Witbank Coalfield is presented overleaf. This effect is also highly significant, and the variability between blocks is similar to that for all blocks including the No 2 Seam.

Table 5.5. Variance between non No 2 Seam Blocks

Source	Sum of squares	degrees of freedom	Mean square
Between blocks	1,47	2	0,735
Residual	9,02	215	0,0420
TOTAL	10,49	217	0,0483

6 - The improvement which can be achieved by fitting a separate form of model to each block, i.e. different exponents for width and width/height ratio, is relatively small. The reduction in the residual mean square, or error variance, varies from 0,0528 for the common form of model to 0,0473 to the separate form of model. The common form of model is probably preferable as it is more robust, simpler to apply and there is limited evidence for specifying a different form of model for each block. Considering that the common model is also based on far more observations, the predictions which can be made using it are subject to a lower error variance.

7 - In order to establish the relative strength of a new coal block to ±10% at a 95% confidence level, 23 samples would have to be tested. To reduce the uncertainty range by a factor of 2, the number of samples would have to be multiplied by 4. In the current set of tests, the 95% range for coal strength was generally of the order of ±5 or 6%.

8 - The range for predicting the strength of a 1 m cube block at the 95% level is ±8% for most mines.

Individual cubes of this dimension would be expected to exhibit a variation in strength of ±60%. However, these results should be treated with caution as they involve extrapolation well outside the range of the data, and different physical behaviours may come into play.

The series of samples from 10 coal blocks were tested for strength as a basis for establishing a relationship between geometrical properties (width or diameter and length or height), coal type and the strength. For each block, a balanced experiment was conducted with respect to the width (diameter) and width/height ratio of the samples. These variables were therefore used as the basis for defining the geometry of the sample.

The relationship previously fitted to accommodate geometrical variations as well as differing coal properties between the different blocks was given in equation (5.1).

$$\text{Strength} = \delta \text{ x width}^{0,124}/\text{height}^{0,449}\text{(MPa)} \quad (5.1)$$

On the suggestion of Professor Salamon, it was decided to fit a model for strength based on fixed parameters α and β. The values selected for these parameters were 0,46 and 0,66 which are the values determined from the statistical analysis of coal pillar failures conducted by Salamon and Munro. The model fitted in this way was as follows.

$$\text{Strength} = \delta^1\text{x width }^{0,46}/\text{height }^{0,66} \text{ (MPa)} \quad (5.2)$$

δ^1 values for the various collieries are shown in Table 5.6.

Table 5.6. δ^1 Values For The Coal Blocks With "Salamon" α and β

Colliery	Seam	δ	δ^1
Arnot	No 2	15,3	15.8
Bank	No 2	16,0	17.6
Blinkpan	No 2	13,3	15.3
Delmas 2	No 2	16,7	17.0
Goedehoop	No 2	15,1	17.3
Greenside	No 2	13,7	15.4
Khutala	No 2	17,1	17.8
Kriel	No 4	12,9	15.6
Secunda	4C Lower	13,7	14.9
Zululand Anthracite	Main	17,6	19.9

In all cases, the "Salamon" model predicts a higher strength for blocks of pillar size than the "optimized" model. While extrapolation outside the range of experimental data is considered to be a dangerous practice, the "optimized" model has the merit of providing what may be regarded as conservative estimates of pillar strength considering that the Salamon and Munro model was derived for large volumes of coal (greater than 3,0 m, whereas the present laboratory sample range was only 0,025 - 0,3 m.).

It should also be noted that the predictions provided by the "optimized" model are not entirely dissimilar from Salamon's original formula. Salamon's smaller k value coupled with different α and β give rise to a similar function over the range of meaningful pillar sizes. Table 5.7 gives a comparison between the average "optimized" model strength predictions and the original Salamon formula over a range of widths and width to height ratios. At a width of 5,0 m and a width to height ratio of 5, the percentage difference in predicted strength is 27%, at a width of 10 m the difference drops to 16,4% and at a width of 20 m the difference is 6,8%.

The reasons for the difference in α and β between the "optimized" model and the "Salamon" model can only be speculated on given the statistical evidence available. However, possible explanations lie in some or all of the following areas:

- circular cross section blocks follow a different relationship than square section blocks.
- preferential extraction of competent elements from within the coal seam lead to different failure modes of the blocks than in bulk composition.
- a different form of relationship applies to smaller widths and heights which cannot be scaled up, (e.g. the "scale effect is much stronger for small specimens than it is for pillar sized blocks").

- loading characteristics in experimental tests differ from field loading conditions.

Table 5.7. Comparison of Optimized Model with Original Salamon Formula

		Strength (MPa)	
Width (m)	Width/Height	Optimized	Salamon original
0,1	1	33,2	11,4
0,1	2	45,3	18,0
0,1	5	68,3	32,9
0,2	1	26,5	9,9
0,2	2	36,2	15,6
0,2	5	54,6	28,6
0,5	1	19,7	8.2
0,5	2	26,8	13,0
0,5	5	40,5	23,8
1,0	1	15,7	7,2
1,0	2	21,4	11,3
1,0	5	32,3	20,8
2,0	1	12,5	6,2
2,0	2	17,1	9,9
2,0	5	25,8	18,1
5,0	1	9,3	5,2
5,0	2	12,7	8,2
5,0	5	19,2	15,0
10,0	5	15,3	13,1
20,0	5	12,2	11,4

In conclusion, the "optimized" α and β model should be preferred to predict the failure strength of laboratory sized samples (widths from 0,1 to 0,3 m and width to height ratios from 1,0 to 8,0). However, this does not provide any evidence that the

"Salamon" α and β are inappropriate for blocks of realistic pillar size.

The relative differences between the predictions obtained from extrapolated laboratory results using the optimized model and Salamon's field data on mine scale pillars represents encouraging, though not conclusive, evidence that the laboratory strength results could provide a useful input to coal pillar design procedures, in particular to distinguish coals of inherently different strengths.

5.2 Representative Sampling for Pillar Strength Determination

The sampling method to obtain the laboratory samples was a two stage process, firstly involving selection of a block of coal, and secondly involving extraction of test samples from each block. In each of these stages, there is a possibility that the sampling process is not representative.

Non-representative sampling may arise in two fundamentally different ways, as follows:

A *bias* may arise in the selected samples due to a *consistent* method of non-representative sampling. For example, in the block selection stage of the process, it may only be possible to extract blocks consisting of particularly strong coal, or the blocks may always be extracted from the middle of the seam where particular geological properties apply. It is considered less likely that a bias would arise in extracting samples from each block as this process is under close control. However, an example of such a bias could arise from the extraction of samples of each width to be tested from different coal layers within the block. This could give rise to an incorrect assessment of the effect of width on strength. However, since several blocks are involved, it is unlikely that this same selection bias would be made on all the blocks.

A *variance* will arise in the selected samples due to *inconsistent* departures from the average strength for the coal seam. Examples of pure variances would be inhomogeneities within the coal block being studied or random fluctuations in the instrumentation used to do tests. This type of error can be reduced by taking a greater number of independent samples. However, taking more samples from a block will not reduce any variance associated with the blocks not being representative of coal seam strength (such additional samples would not be independent as they would be from the same block).

It is frequently difficult to identify bias in experimental results on a rigorous basis from the data available since there is not always a benchmark value available against which to identify a bias Examples of benchmarks which are available to identify the potential for bias are mainly the calibrations of the instruments used to perform the strength tests. This allows a confident assertion that the recorded sample strengths are an unbiased reflection of the real sample strength. Since there are no other benchmarks with which to test for bias, careful attention to the design of the experimental work to avoid (or, if unavoidable, enable quantification) of possible bias is important.

A further important consideration about bias is that, if the magnitude of the bias in the experimental results is known, the data can be used to provide an unbiased predictor by using appropriate factors. One such example of this would be the use of a strength downgrading factor to accommodate for the difference in strength between relatively unjointed samples with relatively more heavily jointed or fractured rock in the coal seam.

Although the current work is intended to expand on Salamon's formula by making provision to consider different coal types, Salamon's field strength results give the possibility of indirect validation to determine the overall bias. Such an exercise could be used to provide a factor by which to multiply predicted field strength to obtain an unbiased predictor. The range of coal types considered in the current work is unlikely to be too dissimilar from the range in Salamon's data, and so a comparison of the entire experimental data set with Salamon's formula for strength could be appropriate.

The variance between blocks can be estimated quite precisely as there are 10 degrees of freedom for this statistic. However, there is some concern that the variance statistic may be an underestimate for the overall block strength distribution, as the blocks may share a common attribute, for example being only higher strength blocks. This is a matter of speculation, since there is no data to either confirm or deny this. However, since both the mean and the variance of the distribution of pillar strengths are critical inputs into the safety factor calculation, a bias giving rise to too high an estimate of the mean and too low an estimate of the variance will give rise to an underdesign. Merely correcting for bias will reduce the extent of the underdesign, but the underestimate of variance will still contribute towards underdesign.

A further note of caution in this area revolves around the possible dependence of variance in strength on the dimensions of the sample (as size is increased from single sample to block to pillar).

There is little statistical information available from the data on which to estimate this effect, but it is of great importance for the establishment of a reliable safety factor methodology. By considering Salamon's field data on pillar strengths in conjunction with the experimental data, it may be possible to obtain some insights in this area.

Based on these concepts on representative sampling, it is possible to address certain points.

There is no statistical evidence to suggest that the larger diameter samples are subject to a significantly different logarithmic variance than other diameter samples. Taking this into account, it is considered most appropriate that a comparison between blocks should be based on all samples, as this provides the most powerful test for a difference in strength. Using only a sub-set of samples would reduce the significance level of any difference which may exist.

The laboratory samples actually exhibit a shallower trend in strength with diameter than the relationship based on Salamon's field data. As a result of this, at small sample diameters, the formulae based on laboratory data estimate a far higher strength than extrapolations from Salamon and Munro's formula would indicate. At meaningful size pillar widths, the difference between the formulae is much smaller.

One possible explanation is that the weaker width relationship obtained from laboratory data incorporates a mathematical representation of "downgrading" in the lower width exponent. If Salamon's exponents are applied to the laboratory data, it is necessary to apply a significantly higher downgrading of the delta strength factor to obtain agreement with field observations. However, with the optimized exponents, the downgrading is relatively smaller. The observed factor with the optimized relationship could possibly be used to correct for selection bias in extracting blocks. There is, however, no evidence to prove this contention over many other possible explanations.

Figure 5.1 shows the laboratory and in situ data together with field strength versus pillar width for a constant width to height ratio of 2,0 on a log scale. Similarly Figure 5.2 shows strength versus pillar height, again with a constant width to height ratio of 2,0. It is interesting to note that a similar variation between the laboratory and the field was found in an extensive study by Martin (1995) on Canadian granite, Figure 5.3. Martin stated that "these results demonstrate that there is not an unique strength-scaling law that can be applied to both laboratory and in situ failure." The down-grading from the laboratory to the field is contained in the exponents for width and height. Figures 5.4 and 5.6 show the comparison between laboratory and field predictions. The aspect of down grading can be significance in that each data set may be calibrated with each other, allowing comparative assessment of seams via laboratory testing.

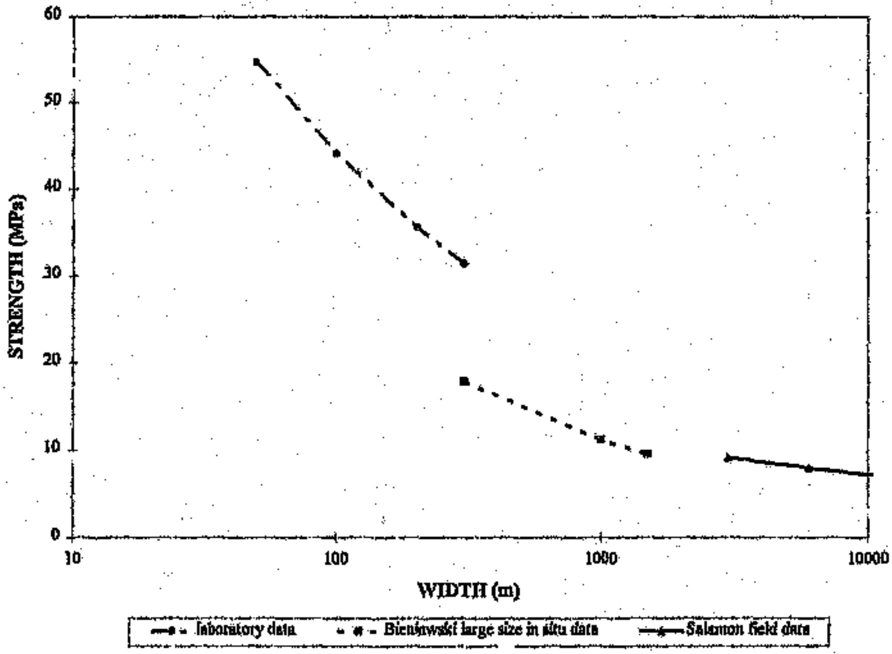

Figure 5.1. The Laboratory, In Situ and Field Strength versus Pillar Width for a Constant Width to Height Ratio

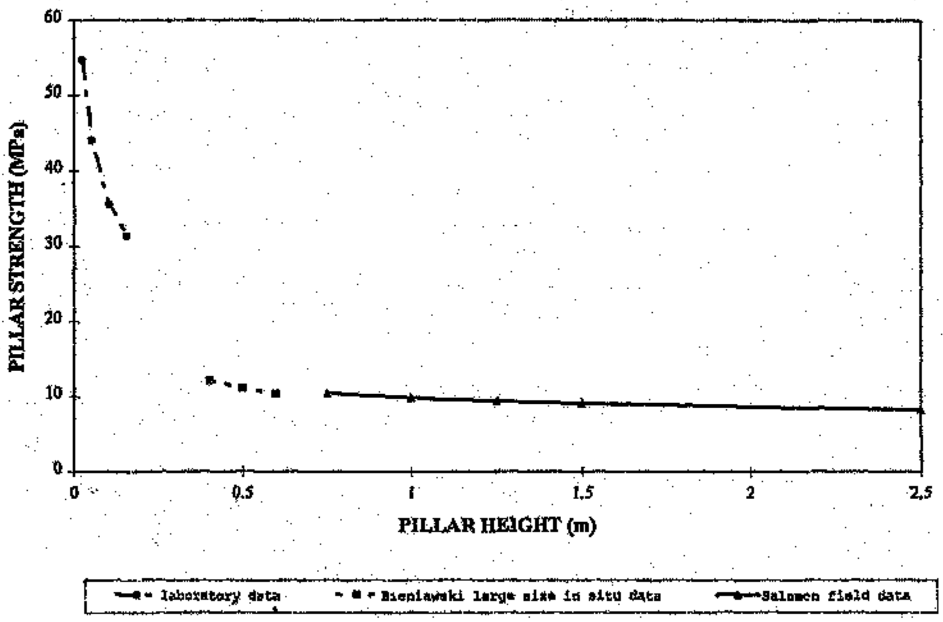

Figure 5.2. The Laboratory, In Situ and Field Strength versus Pillar Height for a Constant Width to Height Ratio of 2,0

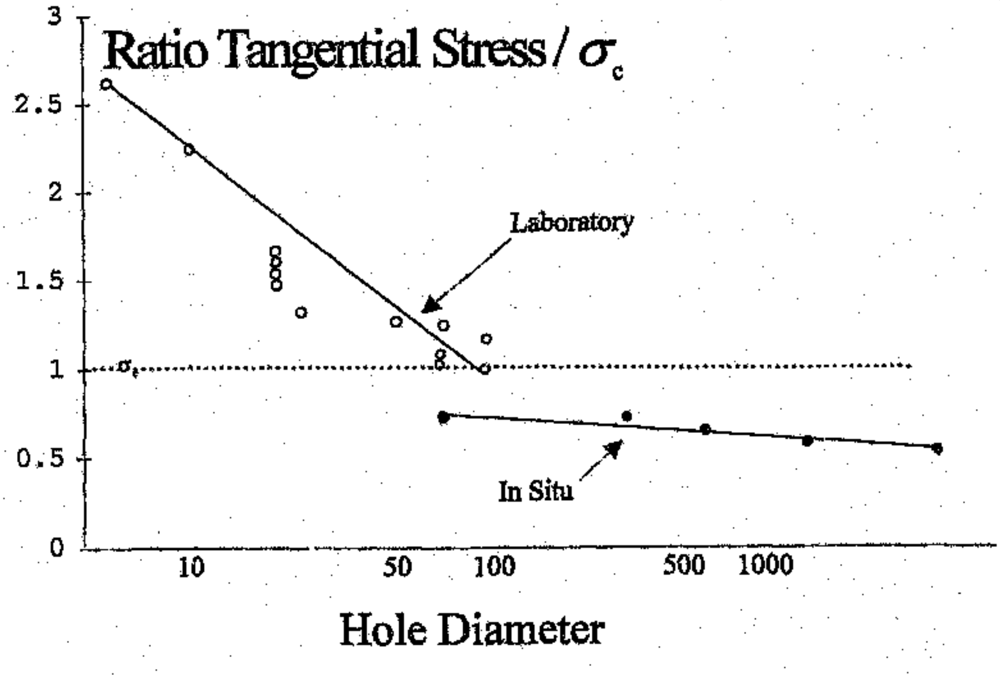

Figure 5.3. Strength versus Hole Diameter (Log Scale), after Martin (1995)

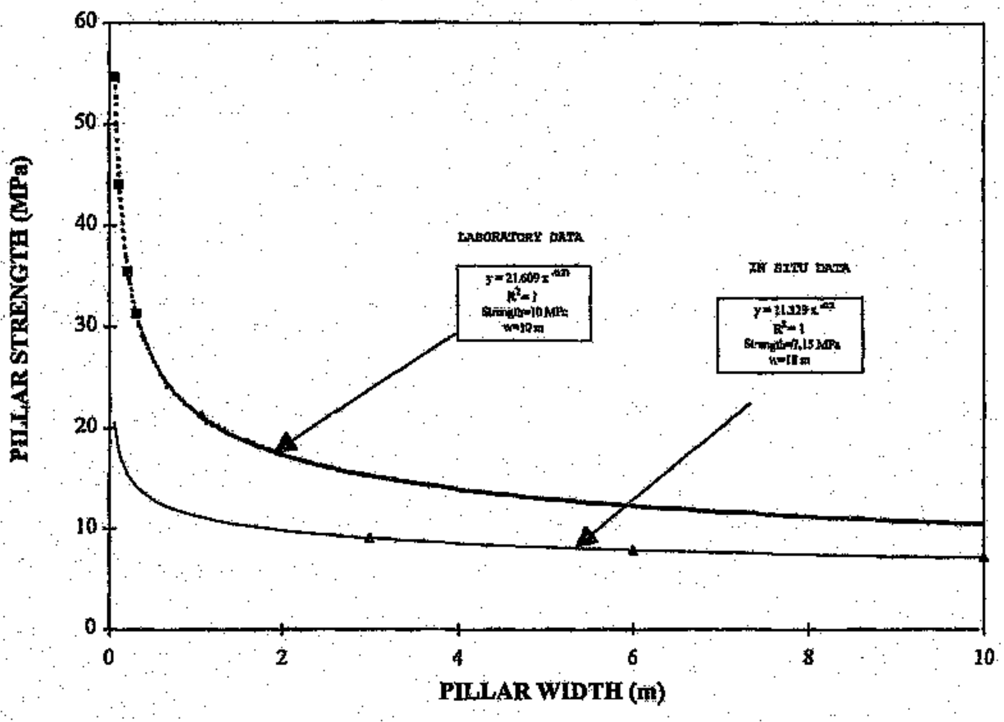

Figure 5.4. Comparison between Laboratory and Field Predictions

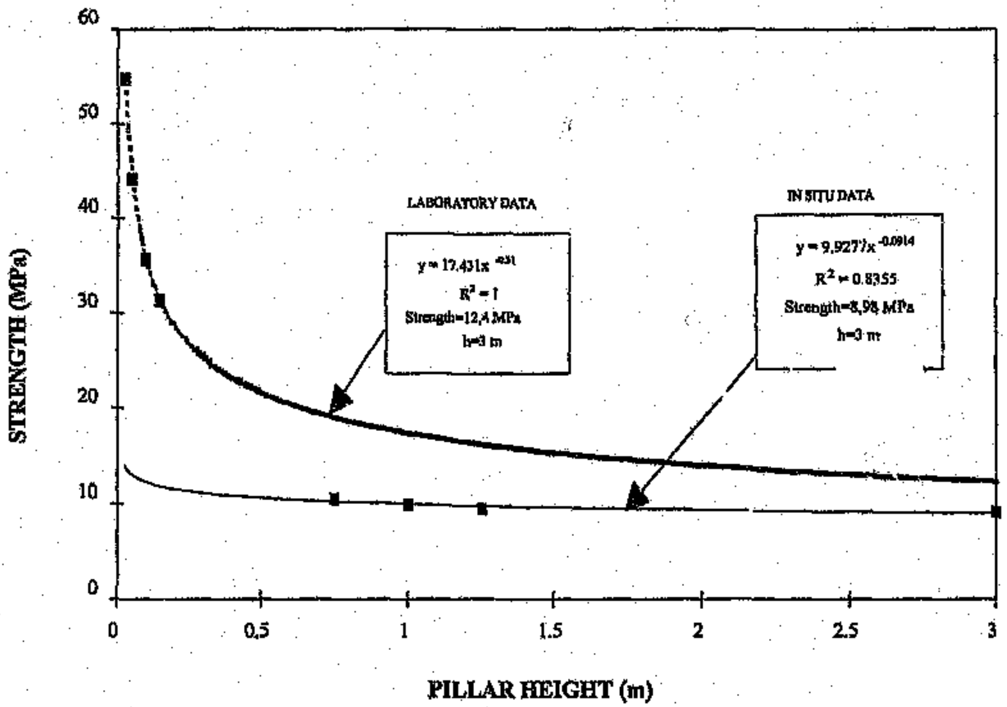

Figure 5.5. Comparison between Laboratory and Field Predictions

There is statistical evidence in the data that blocks from the No 2 Seam have a higher strength than blocks from other seams. It is also understood that there is some field evidence that other seams suffer from a greater percentage of pillar failures than the safety factor calculation based on a common strength relationship would indicate. It could therefore be validly proposed that the No 2 Seam should be regarded as having a higher strength than the other seams tested. However, the number of blocks tested from other seams is relatively low and the difference in strength is relatively small.

The standard deviation between blocks within a seam is estimated at 7,4% of the mean (when extracted using the selection scheme adopted for these experiments), and the standard deviation between samples from within a block is estimated at 21,4% of the block mean. As discussed above, a strategy involving the testing of 5 blocks, analysing 25 samples per block would give rise to a 95% confidence range between 92,4% and 107,6% of the mean for the seam. This may be an appropriate basis on which to estimate the distribution of pillar strength which would be expected.

A number of observations are extremely important in this context.

Firstly, although the current experimental results displayed a greater degree of homogeneity within the No 2 Seam than for the total experimental dataset, it is suggested that a study should be initiated to assess the geological characteristics of the coal and to see whether there are differences in the physical attributes of the coal which would give rise to a relatively consistent strength within the seam, with other seams displaying different physical attributes. Such modelling exercises based on physical relationships can be used with greater confidence than purely empirical data. Another seam's behaviour may be different because of different geological processes responsible for its formation and subsequent history etc. Development of such a model would require the recording of geological attributes of the coal blocks when conducting the test programme, and also an assessment of the condition and make up of the coal seam as a whole.

Secondly, with respect to a new coal seam, it is strongly advised that borehole data alone should not be used to provide comparisons with the current set of results. Any biases in the block selection process would be radically changed with the result that the factor to apply to strength in order to scale up to pillar size would be unknown. For example in this work it appears that the selection process which was adopted in extracting the blocks may have resulted in overstrength blocks being used. Testing of borehole samples would probably therefore lead to lower (unbiased) strength results. Application of a factor to reduce strength estimates would then lead to the true strength of the coal being undervalued, thereby resulting in overdesign of pillars. The potential error is probably a conservative situation, but it is recommended that extreme caution should be adopted in this area with appropriate statistical expertise being used to evaluate the results.

Thirdly, the more blocks and samples that are processed, the more precisely can the strength of the coal be determined, such that it may become possible to base the safety factor calculations on a higher average strength of the coal. However, it would be necessary to be conservative in this calculation and perhaps to take the confidence limit as the average strength. This would achieve the same predicted probability of pillar failure, but based on more comprehensive testing. The statistical calculations underlying this approach are not trivial and there would be a need to optimize the extent of testwork which should be carried out.

The results from the testing of coal blocks supports the contention that the average strength of coal is within a fairly tight band, with the possible exception as indicated by Madden (1985) and van der Merwe (1993) where the Vaal Basin Coal was shown to be significantly weaker.

CHAPTER 6.

CONCLUSIONS AND PROPOSED FURTHER STUDIES

6.1 Conclusions

In this study, with respect to sample preparation, it was found that coal as a material is difficult to work with and is susceptible to weathering, and is also anistropic. It is difficult to prepare samples. However, an extensive laboratory testing program, on 10 coal blocks from 10 collieries, was carried out and valuable information on the laboratory strength of South African coals has been obtained.

The results clearly show that specimen strength, size effect and width to height ratio effect are seam specific and related to coal structure.

From the size effect test results it is indicated that the strength increases with decreasing specimen diameter and increasing width to height ratio. Also as shown in Figure 4.11 the strength values obtained from this study vary from seam to seam. However, these strength values cannot be used for in situ pillar design, because of the effects of the variables on strength, such as discontinuity, weathering and roof and floor contacts geometry nature of the coal. Nevertheless the tests provided valuable information on the comparative strength of South African coal seams and the difference between the strongest and weakest coal tested was found to be 59,4 per cent.

A linear regression analysis showed that normalized strength values against the width to height ratio, together with data from current design formula (e.g. the Salamon design formula) gave a poor relationship with a constant height. In addition the height of in situ coal pillars is controlled by the seam thickness and the strength is varied by changing the pillar width. Therefore, the data from this study was compared to data from Bieniawski and Salamon with various seam heights at a constant width. The results showed that the linear regression analysis does not take the volume effect into account, for instance, it gives the same strength values for an in situ pillar of dimension w=8 m, h=2 m, w/h=4 and a laboratory size sample w=100 cm, h=25 cm, w/h=4. Thus laboratory tests overestimates the strength values, mainly because of discontinuity effects on the strength of coal.

From linear regression analysis the relationships between the strength and width to height ratio are obtained for each block. These relationships are summarized Table 7.1.

Table 6.1 Results from the Linear Regression Analysis

Colliery	Diameter (mm)	Strength	R^2	Strength/K	R^2
Z.A.C.	60	$123{,}8D^{-0{,}227}$	0,73	0,84+0,16(w/h)	0,70
GOEDEHOOP	60	$291{,}9\,D^{-0{,}482}$	0,73	0,73+0,27(w/h)	0,48
KHUTALA	100	$145{,}9\,D^{-0{,}298}$	0,68	0,73+0,27(w/h)	0,49
KRIEL	100	$161{,}1\,D^{-0{,}388}$	0,88	0,59+0,41(w/h)	0,60
BLINKPAN	100	$231{,}5\,D^{-0{,}441}$	0,73	0,72+0,28(w/h)	0,42
GREENSIDE	100	$189{,}6\,D^{-0{,}399}$	0,88	0,74+0,26(w/h)	0,30
BANK	100	$213{,}3\,D^{-0{,}423}$	0,73	0,82+0,18(w/h)	0,34
SECUNDA	100	$106{,}1\,D^{-0{,}295}$	0,67	0,72+0,28(w/h)	0,59
ARNOT	100	$158{,}9\,D^{-0{,}342}$	0,58	0,79+0,21(w/h)	0,29
DELMAS	100	$185{,}9\,D^{-0{,}364}$	0,69	0,84+0,16(w/h)	0,33
OVERALL	100	$207{,}55\,D^{-0{,}411}$	0,87	0,79+0,21(w/h)	0,44

The statistical analysis showed that the strengths of the six blocks from the No 2 Seam, Witbank Coalfield was constrained in a fairly tight strength range; and that laboratory coal strengths from individual seams or mines could deviate to a significant although relatively small extent, from the overall average.

While the laboratory results cannot be directly applied to the field measurement, a methodology for the estimation of relative strength between coal seams has been established. This could be of significance when mining a greenfield region.
It is interesting to note that the form of the equation derived from laboratory test results was

$$\text{Strength} = \delta\, w^{0,124}/h^{0,449} \qquad (\text{MPa}) \qquad (3.1)$$

while the form found by Bieniawski (1967) after an extensive program of laboratory tests on South African coal from the No. 2 Seam, Witbank Coalfield was

$$\text{Strength} = \delta\, w^{0,16}/h^{0,59} \qquad (\text{MPa}) \qquad (3.6)$$

Bieniawski's results were obtained in a laboratory installed underground within the mine section where the samples were obtained. This procedure was conducted to overcome the potential difficulties of transportation, the effects of moisture content and the time between sample collection and testing.

The statistical analyses also showed that borehole data alone should not be used to provide comparisons with the current set of results. Any biases in the block selection process would be radically changed with the result that the factor to apply to strength in order to scale up to pillar size would be unknown. and the more blocks and samples that are processed, the more precisely can the strength of the coal be determined, such that it may become possible to base the safety factor calculations on a higher average strength of the coal.

The major difficulty with laboratory testing is the extrapolation [illegible] results to full size pillars, and how to account for the variability of strength in the layers within the coal seam and the effects of cleats and discontinuities.

6.2 Recommendations for future work

Bord and pillar workings in South Africa showed that in general the Salamon pillar design is very successful for design of stable workings. However, local conditions such as a very weak floor, excessive slips or weak bands within the seam, can affect the overall pillar strength. Likewise, variation in seam strength can result in changes to strength and hence influence the design confidence. Considering that between 100 000 and 200 000 pillars are formed annually in South African collieries the performance of these pillars gives the best assessment of the design. The significance of a large empirical data base is that as the number of observations increase the confidence in the predicted value also increases. This is in terms of anomalies as well as in satisfactory performance. The further collection and evaluation of collapsed pillar cases could be useful to highlight any anomalies in current design procedures and point to any significant missing design parameters.

Further laboratory testing could expand on the existing data base. Strata material properties and their relation to index tests could assist in establishing the type of mining environment and the potential for foundation failure. Using a classification system and the incorporation of structural discontinuities into this classification system for improved assessment of similar geotechnical areas could be a major contribution to the design of safe pillar systems in South Africa.

The extensive laboratory testing programme indicated that there is a variation in strength between seams. Panels of pillars designed according to Salamon's formula have been standing in excess of 25 years, although collapses have also occurred. These collapses should be examined to gain further knowledge of individual pillar strengths. For example, examination of pillars standing for periods greater than say five years could yield valuable data with respect to their performance. In the case of in situ pillars the seam contacts and environment effects are implicitly incorporated into the analysis, which is not the case with laboratory based testing. The factors leading to anomalies in performance should be detailed so that these factors can be incorporated into the design of workings.

Field trials to investigate the pillar and surrounding strata behaviour, could assist to obtain information on pillar stability in situ.

The use of geophysical and photographic techniques, together with conventional instrumentation could provide useful methodologies for future monitoring programmes.

Examination of pillars with heights in excess of Salamon's empirical range could be useful. Numerous areas where considerable research has been conducted have not been included in this thesis, such as research into surface subsidence, roof support, ash filling, caving and sidewall support systems.

The effects of different geological and structural factors as well as the influence of the surrounding strata could be investigated and taken into account.

Coal pillar research is, because of its complex nature, time consuming. However, the benefits from such work are far reaching in terms of worker safety and the better understanding of the behaviour of pillars, which in turn would enable greater extraction of coal from current and future coal mines.

APPENDIX I

RESULTS FROM MOISTURE TESTS

Greenside Colliery Moisture Content Test Results on Coal Samples Obtained Later from the Mine

SAMPLE NO:	WRAPPED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	494.36	481.22	2.66
S2	923.90	913.13	1.17
S3	769.05	745.65	3.04
S4	1036.57	1012.04	2.37
S5	261.86	255.18	2.55
AVERAGE MOISTURE CONTENT %			2.36
STANDARD DEV.			0.71

Khutala Colliery Moisture Content Test Results on Coal Samples Obtained Later from the Mine

SAMPLE NO:	WRAPPED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	597.26	591.20	1.01
S2	312.40	298.34	4.50
S3	612.08	597.69	2.35
S4	477.09	456.93	4.23
S5	295.13	287.74	2.50
S6	168.11	160.34	4.62
AVERAGE MOISTURE CONTENT %			3.20
STANDARD DEV.			1.47

Secunda Colliery Moisture Content Test Results on Coal Samples Obtained Later from the Mine

SAMPLE NO:	WRAPPED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	692.55	660.13	4.68
S2	803.00	767.32	4.44
S3	504.04	476.15	5.53
S4	529.88	501.04	5.44
S5	732.70	694.86	5.16
AVERAGE MOISTURE CONTENT %			5.05
STANDARD DEV.			0.48

Arnot Colliery Moisture Content Test Results on Coal Samples Obtained Later from the Mine

SAMPLE NO:	WRAPPED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	782.04	689.16	11.88
S2	459.30	432.19	5.90
S3	367.19	343.88	6.35
S4	620.53	583.31	6.00
S5	478.46	455.97	4.70
S6	341.28	324.60	4.89
AVERAGE MOISTURE CONTENT %			6.62
STANDARD DEV.			2.66

Kriel Colliery Moisture Content Test Results on Coal Samples Obtained Later from the Mine

SAMPLE NO:	WRAPPED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	648.75	609.05	6.12
S2	669.12	629.49	5.92
S3	1014.61	968.14	4.58
S4	324.31	306.91	5.37
S5	337.69	315.63	6.53
S6	984.70	930.09	5.55
AVERAGE MOISTURE CONTENT %			5.68
STANDARD DEV.			0.68

Blinkpan Colliery Moisture Content Test Results on Coal Samples Obtained Later from the Mine

SAMPLE NO:	WRAPPED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	572.35	555.87	2.88
S2	797.05	770.57	3.32
S3	258.77	249.05	3.76
S4	277.11	265.25	4.28
S5	540.44	525.15	2.83
AVERAGE MOISTURE CONTENT %			3.41
STANDARD DEV.			0.61

Kriel Colliery Moisture Content Test Results on Coal Samples Obtained after the Test

SAMPLE NO:	TESTED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	3.47	3.28	5.48
S2	3.74	3.66	2.14
S3	2.42	2.31	4.55
S4	0.82	0.78	4.88
S5	1.85	1.76	4.86
S6	2.17	2.08	4.15
S7	38.12	36.45	4.38
S8	29.90	29.00	3.01
S9	26.98	25.81	4.34
S10	17.80	17.04	4.27
S11	77.07	73.53	4.59
S12	17.99	17.24	4.17
S13	20.13	19.24	4.42
S14	56.31	53.52	4.95
S15	38.29	36.35	5.07
S16	17.11	16.40	4.15
S17	56.95	54.45	4.39
S18	55.64	54.66	1.76
S19	38.82	36.80	5.20
S20	33.02	32.20	2.48
S21	21.10	20.47	2.99
S22	35.22	33.70	4.32
S23	189.18	181.25	4.19
S24	161.61	153.79	4.84
S25	111.38	106.86	4.06
S26	80.72	77.20	4.36
S27	128.75	122.24	5.06
S28	90.20	85.88	4.79
S29	139.02	132.76	4.50
S30	71.52	68.08	4.81
S31	152.29	144.80	4.92
AVERAGE MOISTURE CONTENT %			4.26
STANDARD DEV.			0.89

Blinkpan Colliery Moisture Content Test Results on Coal Samples Obtained after the Test

SAMPLE NO:	TESTED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	3.47	3.28	5.48
S2	3.74	3.66	2.14
S3	2.42	2.31	4.55
S4	0.82	0.78	4.88
S5	1.85	1.76	4.86
S6	2.17	2.08	4.15
S7	38.12	36.45	4.38
S8	29.90	29.00	3.01
S9	26.98	25.81	4.34
S10	17.80	17.04	4.27
S11	77.07	73.53	4.59
S12	17.99	17.24	4.17
S13	20.13	19.24	4.42
S14	56.31	[illegible]	4.95
S15	38.29	[illegible]	5.07
S16	17.11	[illegible]	4.15
S17	56.95	[illegible]	4.39
S18	55.64	[illegible]	1.76
S19	38.82	36.[illegible]	5.20
S20	33.02	32.20	2.48
S21	21.10	20.47	2.99
S22	35.22	33.70	4.32
S23	189.18	181.25	4.19
S24	161.61	153.79	4.84
S25	111.38	106.86	4.06
S26	80.72	77.20	4.36
S27	128.75	122.24	5.06
S28	90.20	85.88	4.79
S29	139.02	132.76	4.50
S30	71.52	68.08	4.81
S31	152.29	144.80	4.92
AVERAGE MOISTURE CONTENT %			4.26
STANDARD DEV.			0.89

Khutala Colliery Moisture Content Test Results on Coal Samples Obtained after the Test

SAMPLE NO:	TESTED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	696.58	678.43	2.61
S2	2.02	1.92	4.95
S3	563.89	548.40	2.75
S4	538.18	522.51	2.91
S5	922.22	896.17	2.82
S6	1.86	1.78	4.30
S7	396.38	387.30	2.29
S8	264.55	256.01	3.23
S9	370.33	364.28	1.63
S10	24.92	24.37	2.21
S11	336.20	332.28	1.17
S12	13.79	13.52	1.96
S13	74.79	73.22	2.10
S14	69.32	67.36	2.83
S15	12.90	12.45	3.49
S16	2.88	2.77	3.82
S17	8.76	8.54	2.51
S18	2.75	2.64	4.00
S19	30.07	29.13	3.13
S20	1.36	1.33	2.21
S21	29.85	28.94	3.05
S22	21.91	21.28	2.88
S23	3.84	3.76	2.08
S24	2.82	2.80	0.71
S25	12.79	12.51	2.19
S26	31.05	30.35	2.25
S27	67.60	65.61	2.94
S28	23.17	22.64	2.29
S29	3.28	3.21	2.13
S30	23.26	22.64	2.67
S31	26.39	26.13	0.99
S32	77.01	74.82	2.84
S33	40.74	39.57	2.87
S34	47.10	45.64	3.10
S35	10.70	10.49	1.96
S36	15.42	15.06	2.33
S37	18.75	18.26	2.61
AVERAGE MOISTURE CONTENT %			2.62
STANDARD DEV.			0.85

Greenside Colliery Moisture Content Test Results on Coal Samples Obtained after the Test

SAMPLE NO:	TESTED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	92.67	91.01	1.79
S2	194.92	191.50	1.75
S3	252.32	249.02	1.31
S4	69.53	68.33	1.73
S5	133.68	131.80	1.41
S6	111.94	109.99	1.74
S7	86.40	85.19	1.40
S8	118.54	116.40	1.81
S9	60.41	58.62	2.96
S10	98.27	97.10	1.19
S11	34.27	33.69	1.69
S12	63.81	62.82	1.55
S13	76.61	75.52	1.42
S14	58.87	57.93	1.60
S15	60.98	60.19	1.30
S16	54.30	53.00	2.39
S17	29.75	29.22	1.78
S18	54.02	53.06	1.78
S19	43.97	43.18	1.80
S20	36.42	35.67	2.06
S21	22.13	21.81	1.45
S22	68.43	67.21	1.78
S23	39.84	39.35	1.23
S24	10.65	10.51	1.31
S25	22.81	22.41	1.75
S26	22.66	22.39	1.19
S27	12.30	12.02	2.28
S28	21.94	21.58	1.64
S29	8.55	8.38	1.99
S30	12.04	11.86	1.50
S31	24.23	23.58	2.68
S32	8.60	7.90	8.14
S33	2.38	2.35	1.26
S34	4.24	4.15	2.12
S35	1.35	1.31	2.96
S36	3.50	3.47	0.86
S37	2.11	2.07	1.90
S38	1.77	1.70	3.95
S39	7.50	7.44	0.80
S40	2.50	2.45	2.00
S41	3.61	3.55	1.66
S42	1.74	1.70	2.30
AVERAGE MOISTURE CONTENT %			1.93
STANDARD DEV.			1.14

Secunda Colliery Moisture Content Test Results on Coal Samples Obtained after the Test

SAMPLE NO:	TESTED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	96.84	92.04	4.96
S2	89.28	84.97	4.83
S3	76.77	73.33	4.48
S4	104.05	99.68	4.20
S5	89.38	85.90	3.89
S6	95.24	90.90	4.56
S7	49.96	47.47	4.98
S8	62.97	60.93	3.24
S9	57.97	55.82	3.71
S10	53.87	51.73	3.97
S11	47.91	45.90	4.20
S12	105.16	100.23	4.69
S13	53.81	51.58	4.14
S14	77.44	73.70	4.83
S15	14.99	14.31	4.54
S16	11.85	11.11	6.24
S17	29.85	28.36	4.99
S18	12.57	12.07	3.98
S19	33.04	31.51	4.63
S20	19.98	19.09	4.45
S21	10.33	9.91	4.07
S22	17.97	17.19	4.34
S23	48.46	46.13	4.81
S24	16.41	15.66	4.57
S25	14.07	13.37	4.98
S26	25.90	24.75	4.44
S27	19.50	18.66	4.31
S28	32.16	30.67	4.63
S29	17.51	16.76	4.28
S30	6.73	6.52	3.12
S31	1.90	1.81	4.74
S32	6.78	6.52	3.83
S33	3.44	3.29	4.36
S34	6.71	6.47	3.58
S35	3.32	3.21	3.31
S36	2.63	2.52	4.18
AVERAGE MOISTURE CONTENT %			4.36
STANDARD DEV.			0.59

Arnot Colliery Moisture Content Test Results on Coal Samples Obtained after the Test

SAMPLE NO:	TESTED SAMPLE	DRIED SAMPLE	% MOISTURE CONTENT
S1	10.41	10.07	3.27
S2	17.24	16.52	4.18
S3	29.68	28.50	3.98
S4	5.28	5.13	2.84
S5	14.23	13.65	4.08
S6	21.14	20.39	3.55
S7	43.17	41.40	4.10
S8	14.42	13.93	3.40
S9	18.24	17.89	1.92
S10	41.38	39.68	4.11
S11	7.95	7.69	3.27
S12	14.37	13.81	3.90
S13	13.70	13.15	4.01
S14	22.81	21.83	4.30
S15	23.13	22.16	4.19
S16	14.42	13.88	3.74
S17	20.84	17.54	15.83
S18	2.93	2.86	2.39
S19	4.25	4.10	3.53
S20	4.75	4.62	2.74
S21	1.04	1.01	2.88
S22	1.52	1.50	1.32
S23	25.01	24.11	3.60
S24	79.16	76.03	3.95
S25	87.61	84.12	3.98
S26	113.80	109.21	4.03
S27	85.51	82.26	3.80
S28	39.59	38.05	3.89
S29	75.01	72.27	3.65
S30	65.25	62.80	3.75
S31	60.21	57.82	3.97
S32	67.22	64.60	3.90
S33	97.30	93.37	4.04
S34	22.94	22.06	3.84
S35	117.68	113.16	3.84
S36	131.97	126.73	3.97
S37	52.97	51.02	3.68
S38	132.47	127.11	4.05
AVERAGE MOISTURE CONTENT %			3.93
STANDARD DEV.			2.09

APPENDIX II

RESULTS FROM WIDTH TO HEIGHT RATIO TESTS

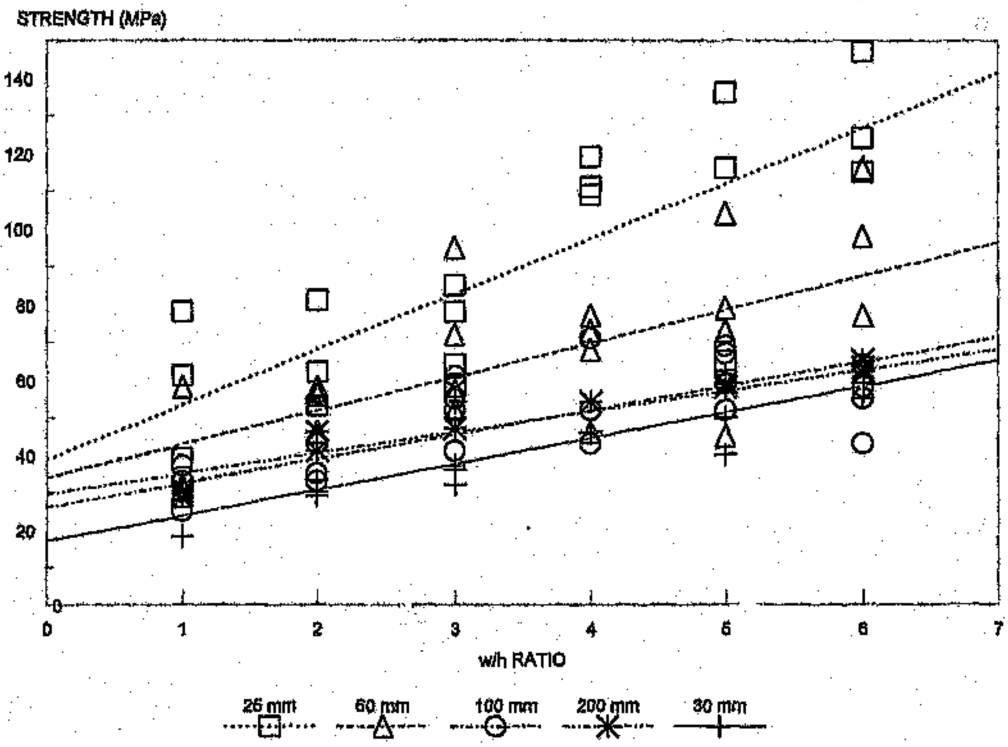

Figure 5.8. Arnot Colliery w/h Ratio Effect Test Results

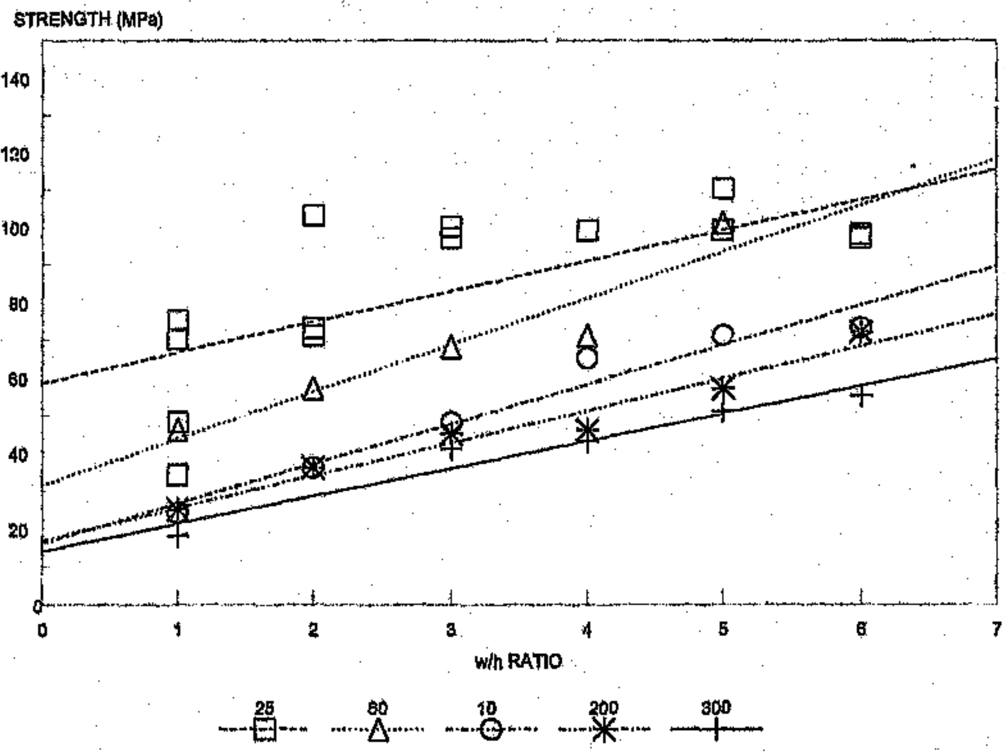

Figure 5.9. Blinkpan Colliery w/h Ratio Effect Test Results

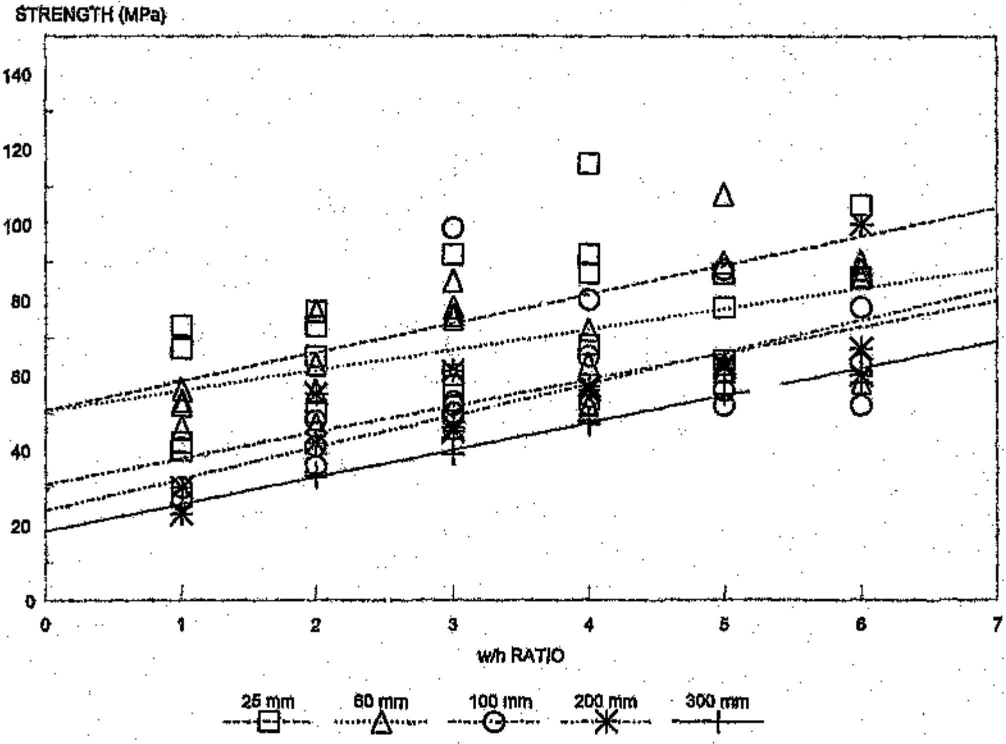

Figure 5.9. Delmas Colliery w/h Ratio Effect Test Results

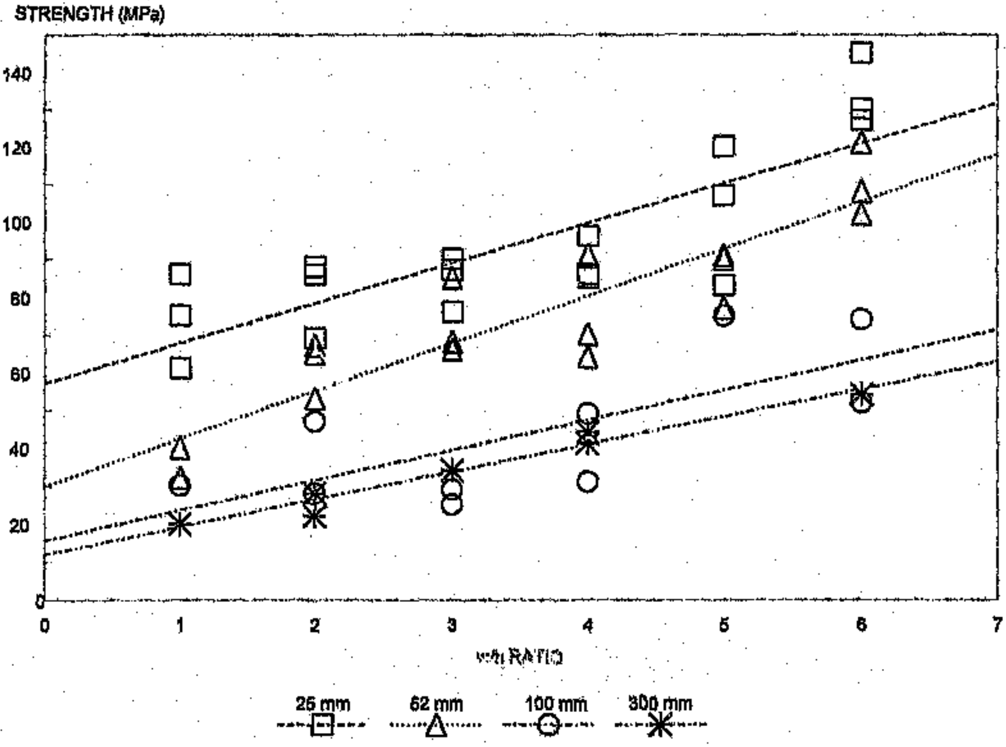

Figure 5.10. Greenside Colliery w/h Ratio Effect Test Results

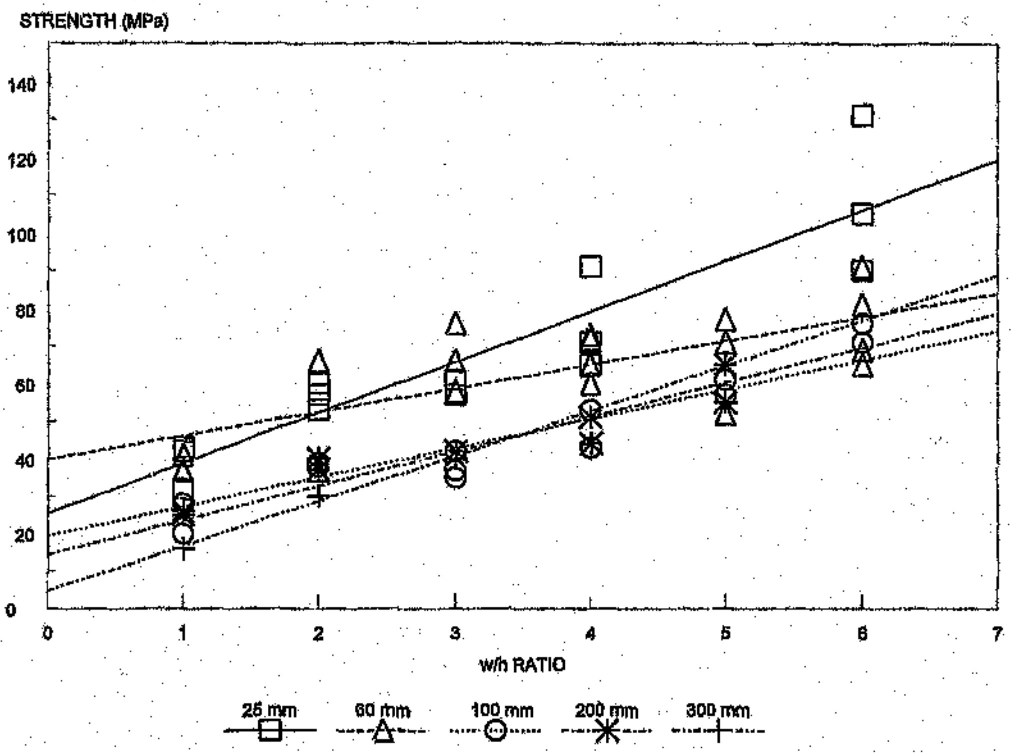

Figure 5.11. Secunda Colliery w/h Ratio Effect Test Results

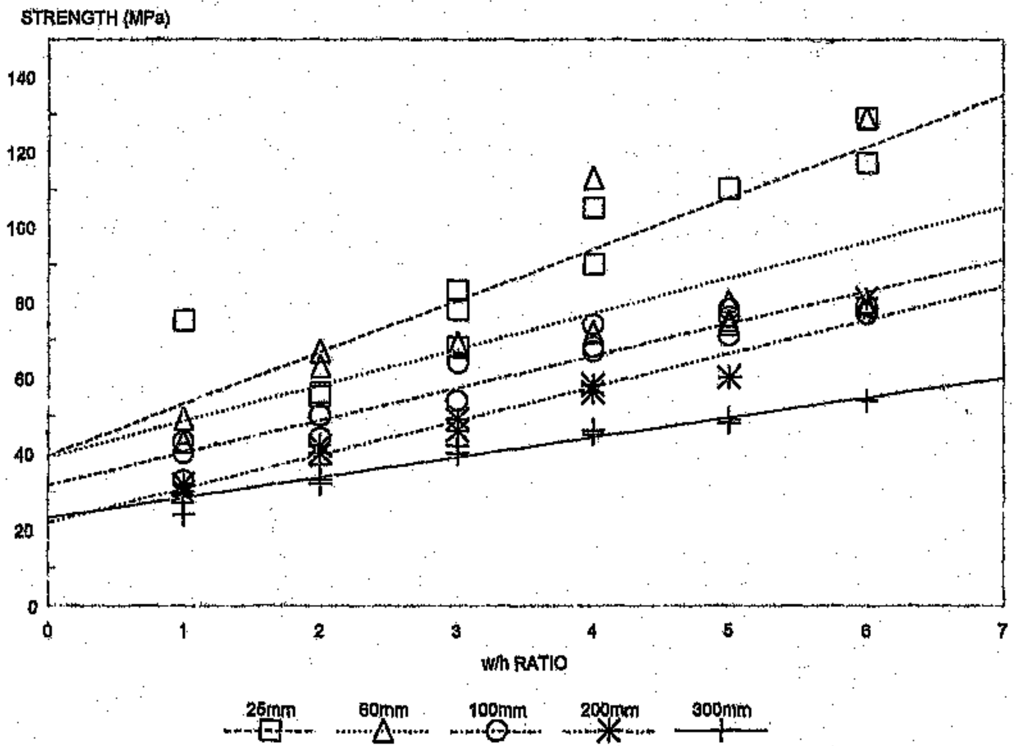

Figure 5.12. Khutala Colliery w/h Ratio Effect Test Results

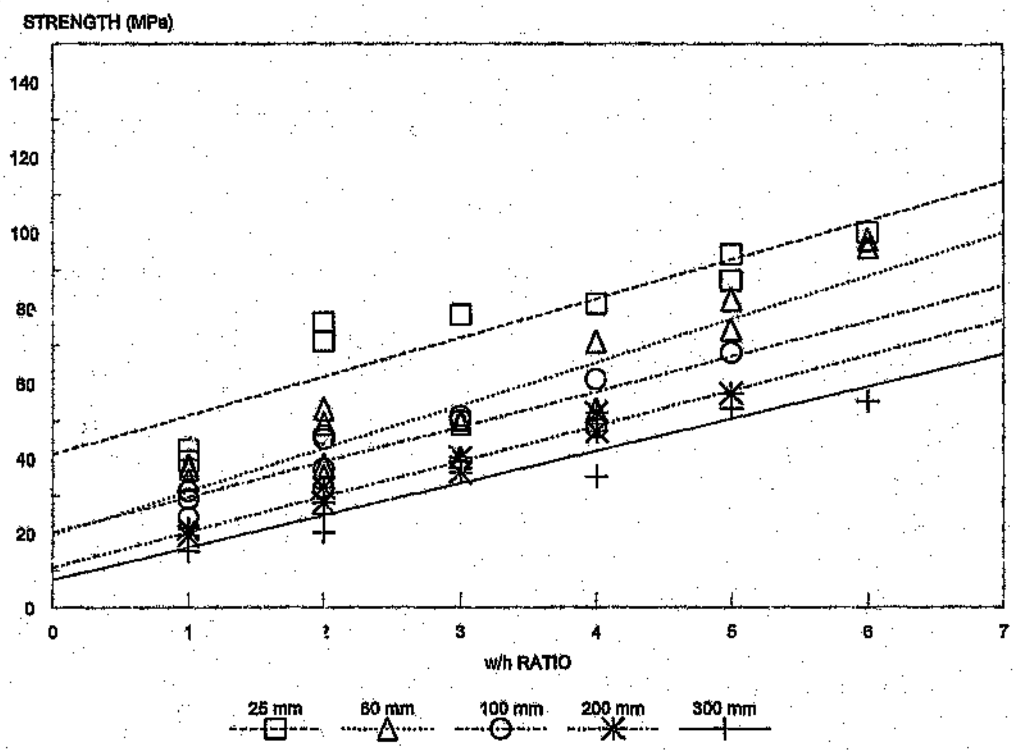

Figure 5.13. Kriel Colliery w/h Ratio Effect Test Results

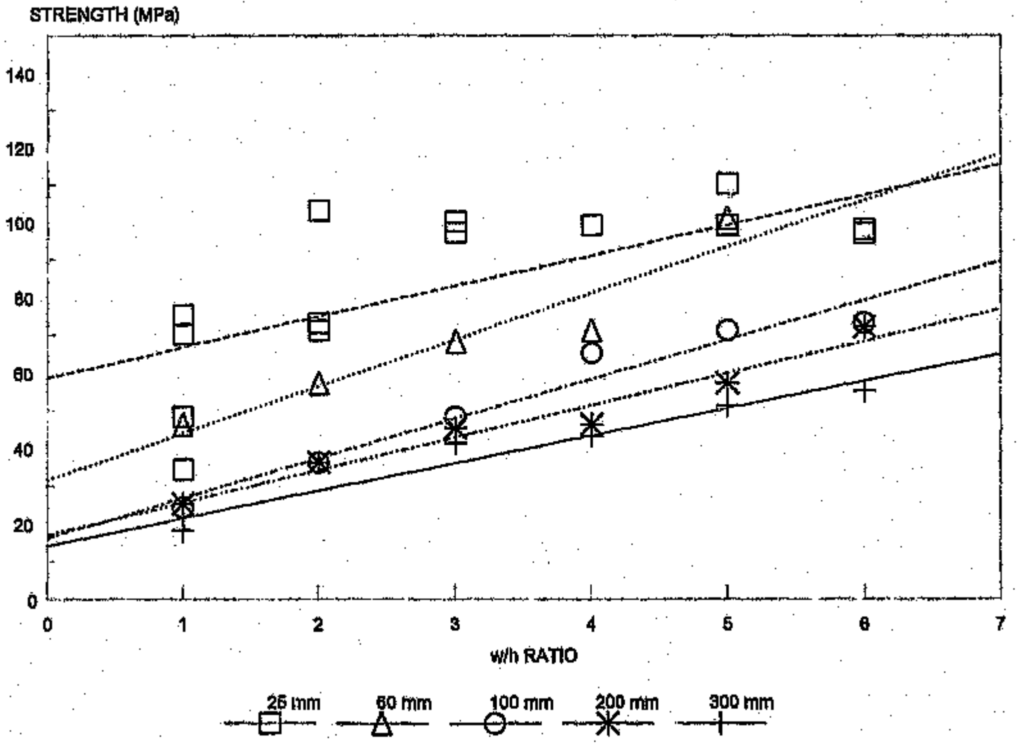

Figure 5.13. Bank Colliery w/h Ratio Effect Test Results

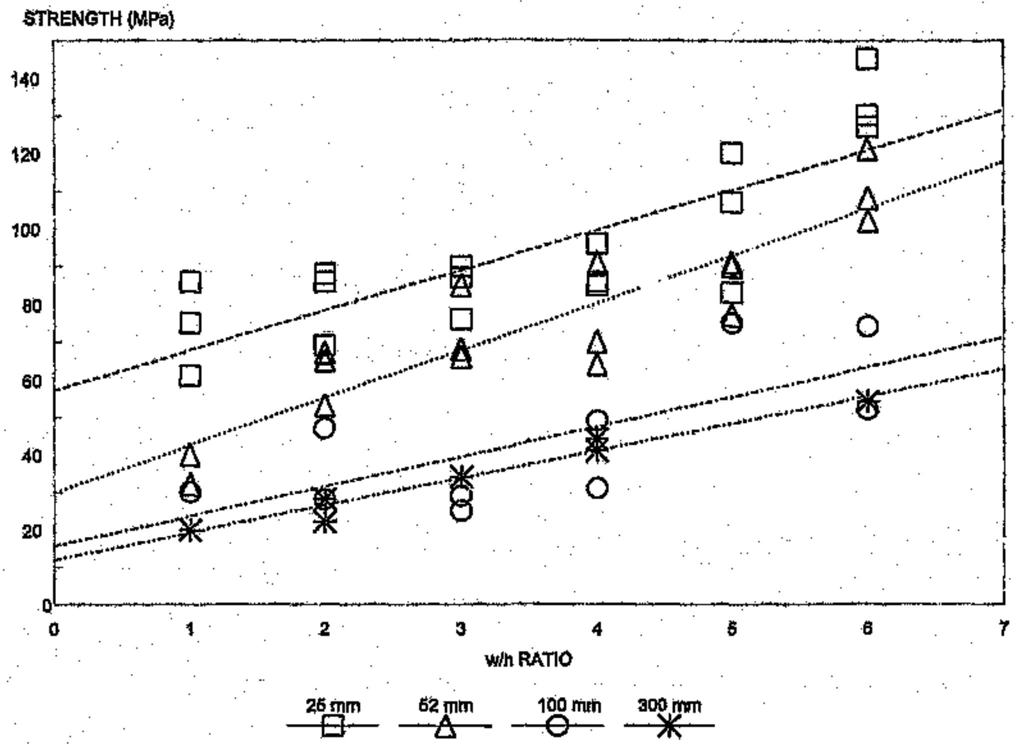

Figure 5.13. Goedehoop Colliery w/h Ratio Effect Test Results

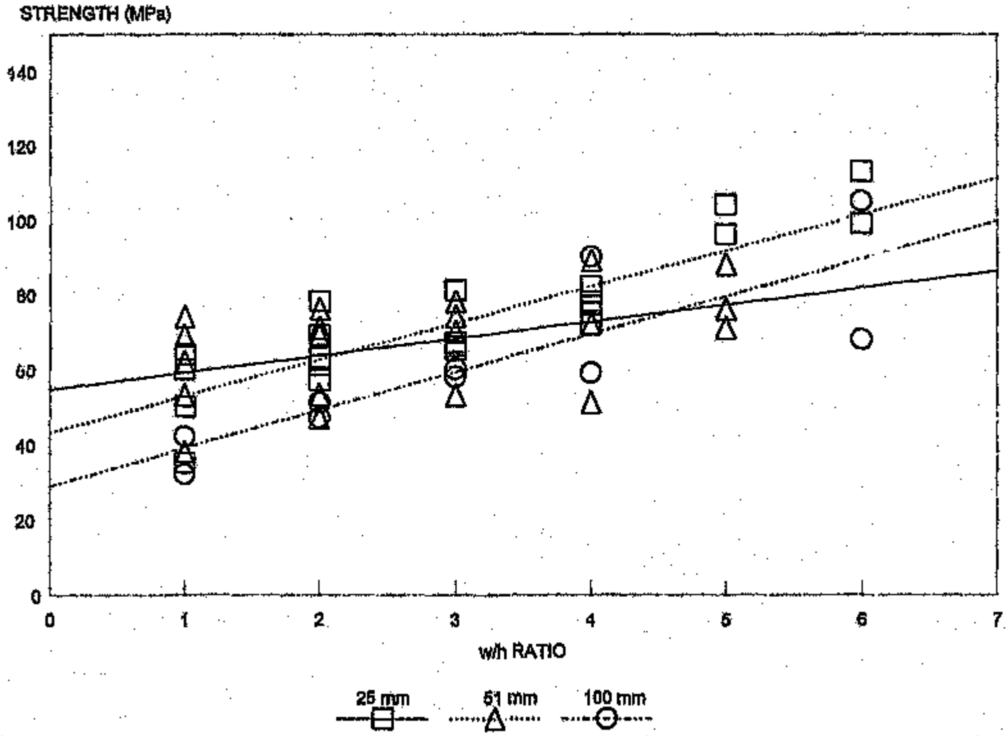

Figure 5.13. Z.A.C. w/h Ratio Effect Test Results

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