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Large Scale Laboratory Testing of Coal

T.P. Medhurst
B.E., M.I.E.Aust.
Rock Mechanics Engineer, CSIRO Division of Exploration and Mining, Australia
E.T. Brown
B.E., M.Eng.Sc., Ph.D., D.Sc. (Eng), F Eng, FTSE, F.I.E.Aust., F.I.M.M., M.I.C.E.
Deputy Vice-Chancellor, The University of Queensland, Australia

Summary A series of triaxial compression tests was carried out on coal samples with the aim of determining strength and deformability properties for coal pillar design. Analysis of the test results shows the effect of scale on coal strength. In association with a characterisation scheme, a peak strength criterion for coal is derived. The criterion uses the parameters σ_c, m and s of the Hoek-Brown empirical strength criterion for rock masses. An experimental technique for investigating the pre- and post-peak deformation properties is also used.

1. INTRODUCTION

Underground coal mining provides one third of Australia's coal production and is being forced to operate in increasingly difficult physical and economical environments as shallow reserves become exhausted and the real price of coal begins to decrease. To liberate the remaining shallow reserves and to access Australia's reserves in thick and multiple seams there remain a large number of significant technical and mine design issues to be resolved. Among these issues, and a key constraint on both mine and equipment design, are suitable methods for predicting the *in situ* mechanical behaviour of coal.

The CSIRO Division of Exploration and Mining is currently undertaking research into the geomechanics of highwall mining under the sponsorship of BHP Australia Coal Pty. Ltd. This mining method reopens significant reserves of coal left abandoned under existing highwalls, increasing the economic viability of Australia's open cut coal mines (Seib, 1989).

To investigate the mechanical behaviour of coal for the purposes of highwall mining pillar design, a program of triaxial testing of 61, 101, 146 and 300mm diameter specimens was carried out. Attention was given to characterising the coal samples to assess the influence of structure on the laboratory test results. The suite of tests was intended to provide data to establish relationships of scale, leading to a method of estimating coal seam properties from standard core tests.

2. BACKGROUND

Only recently have practitioners identified the existence of different strengths for different coal seams (van der Merwe, 1993). The basis for developing a useful strength and deformability model therefore relies on being able to differentiate between coal types. The characterisation scheme used by the authors, shown in Table 1 and discussed previously (Medhurst et al, 1995), aims to capture the compositional and structural features which most influence the mechanical response of a coal seam. Using this approach relationships can be identified which reduce variability in property determination, and provide background to their extension for use in other coal seams.

Table 1. Standard coal categories (AS 2519-1993).

Category	Description	Scale
B (C1)	bright	> 90% bright
Bd (C2)	bright banded	60%-90% bright
DB (C3)	i/banded bright & dull	40%-60% bright
Db (C4)	dull w/minor bright	10%-40% bright
Dmb (C5)	dull banded	1%-10% bright
D (C6)	dull	< 1% bright

2.1 A Strength Model for Coal

The coal used in the study was obtained by core drilling undertaken in the 17DU south highwall mining reserve at BHP Australia Coal's Moura Mine. Data from the initial series of triaxial tests on HQ core (61mm) samples (Medhurst et al, 1995) enabled prediction of the parameters m_i and σ_c in the Hoek-Brown strength criterion for intact rock (Hoek and Brown, 1980),

$$\sigma_1' = \sigma_3' + (m_i\, \sigma_c\, \sigma_3' + s\sigma_c^2)^{0.5} \qquad (1)$$

where σ_1' and σ_3' are the principal effective stresses at peak strength. Results of the analysis gave values of $m_i = 19.5$, $\sigma_c = 25.8$ MPa and $s = 1.0$. The uniaxial compressive strength σ_c is used as a normalisation parameter or scaling factor so that a criterion for estimating *in situ* coal strength can be obtained.

Based upon a combination of back analysis of the known pillar strength formulae (Duncan Fama et al, 1995), large scale *in situ* tests (Bieniawski, 1968) and the HQ core test data, Medhurst et al (1995) extended the approach to obtain a preliminary coal strength criterion defined as

$$\sigma_1' = \sigma_3' + \sigma_c \left(\frac{m\sigma_3'}{\sigma_c} + s \right)^{0.65} \qquad (2)$$

where $m/m_i = 0.15$ and $s = 0.075$. The power term of 0.65 highlights the contrast in behaviour between coal and other rocks.

The parameter m reflects the curvature of the σ_1' vs σ_3' curve and is expected to vary with coal rank, being dependent upon composition and degree of particle interlock. The parameter s controls the vertical positioning of the curve on σ_1' vs σ_3' axes and will depend on coal brightness category, reflecting the extent of structure or cleating present within the coal seam.

2.2 Deformation Behaviour of Coal

The *in situ* experiments on coal pillars by Wagner (1974) and Van Heerden (1975) allowed the complete stress-strain response of pillars to be investigated. This work emphasised the ability of coal pillars to sustain some load beyond their peak strength, and helped to provide evidence for applying a mechanistic approach to pillar strength estimates. Modern stress analysis methods, like that used for the Moura pillar design, can approximate the mechanics of progressive failure or yielding from the edges of a pillar into the coal mass (Duncan Fama et al, 1995). These methods however, require input parameters which describe the post-peak behaviour of coal.

Triaxial tests, with volume change measurement, on core samples provide a valuable means of investigating the deformation behaviour of coal. A technique developed by Elliott and Brown (1985) can be used to determine the irrecoverable components of applied strains. By using unloading cycles, estimates of pre-peak and post-peak moduli, and conditions for describing material flow at the yield state can be made.

More recently, Martin (1995) has shown both in laboratory and *in situ* tests that load-unloading cycles may be used to determine a locus of cumulative permanent or irrecoverable volumetric strain. This locus when defined as a crack damage parameter, was used to track the mobilization of friction and cohesion and incorporated in a strength criterion for predicting the brittle failure of rock.

3. TEST EQUIPMENT AND TECHNIQUE

Two medium pressure triaxial cells were constructed for the smaller samples and a large cell for the 300mm core was obtained for the test work. The large cell consists of an outer pressure cylinder capped at each end by an endplate and separated at both ends by a rubber 'O' ring. The end plates are held in position by 21 tie rods. The axial load is taken by bending in the end plates and tension in the tie rods. The device provides an axial load capacity to 140 tonne, whilst withstanding internal pressures to 4 MPa. Load and displacement measurements are obtained from an array of three LVDT's and a load cell installed internally. A schematic diagram of the large cell is shown in Figure 1. Details of the pressure control system are given by Medhurst et al (1995).

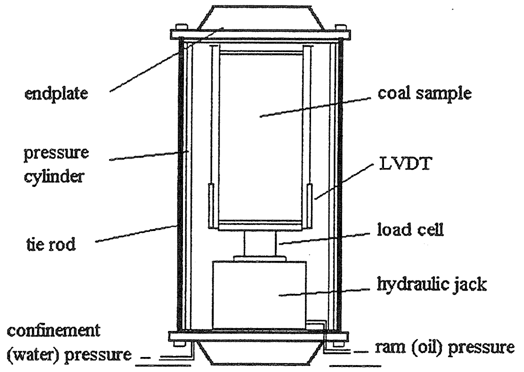

Figure 1. Schematic of the large triaxial cell.

The tests were undertaken generally in accordance with the ISRM Suggested Method for Determining the Strength of Rock in Triaxial Compression (Brown, 1981). The 300mm diameter samples were first loaded isotropically at confining pressures ranging from 0.2 to 0.8 MPa and then loaded axially at rates of between 1% strain/hr and 2% strain/hr. In order to allow efficient handling and testing a specially constructed specimen clamp and jacket applicator were used in conjunction with an overhead crane. The specimens were jacketed with 3mm thick latex rubber sleeves. The 101mm and 146mm diameter samples were tested at confining pressures ranging from 0.2 to 5 MPa. These specimens were jacketed with 0.5mm thick neoprene rubber sleeves.

The complete stress-strain behaviour was obtained for each sample. Relatively large deformations were expected during testing so steel discs were inserted at either end of the specimen, in accordance with a technique developed by Jaeger and Rosengren (1969). As discussed previously (Medhurst et al, 1995), this method helped to maintain a stress field which is very close to uniform throughout the sample until it is near its peak strength.

4. TEST RESULTS

A total of 23 triaxial tests were undertaken on the four sample sizes. Table 2 contains those results used for the analysis. The modulus, E_{av}, is calculated as the average over the linear portion of the axial stress - strain curve. In the first test of each of the three larger sample diameters standard procedures were used, and for the remainder unloading cycles were utilised. The strength measurements obtained from the unloading cycle tests were found to be consistent with those obtained from standard tests.

Table 2. Summary of test results for Moura coal core.

Diam. (mm)	Sample No.	Coal Cat.	σ_3' (MPa)	σ_1' (MPa)	E_{av} (GPa)
61	663T1	C5	0.2	28.92	4.57
	663T3	C3	0.2	24.74	4.41
	663T5	C3/C4	2	46.48	4.72
	599T3	C3	5	61.58	4.73
	600T2	C4	10	84.00	4.84
101	602M1	C4	0.2	26.06	3.18
	594T1	C4	0.2	27.38	3.09
	595M1	C4	2	43.16	2.97
	602T4	C2/C5	5	51.56	3.17
146	601M1	C3	0.2	15.17	1.98
	601T3	C4	0.2	19.37	2.02
	604T1	C4	1	25.66	2.26
	601T1	C5	2	30.90	2.20
	601T2	C3/C4	3	40.28	3.02
	604T2	C5-C3	4	42.23	2.61
300	L1-1	C4/C3	0.2	12.60	2.11
	L1-4	C2	0.2	8.81	1.73
	L1-2	C3/C4	0.4	13.33	2.40
	L2-1	C5/C4	0.8	20.52	2.48

Figure 2 shows deviator stress (σ_1' - σ_3') - axial strain (ε_1) curves for the 300mm diameter samples tested at confining pressures in the range 0.2 - 0.8 MPa. Similar stress - strain behaviour was exhibited for the 101mm and 146mm diameter specimens.

For the mid brightness samples L1-1 and L1-2 axial splitting then shearing was the predominant mechanism. Figure 2 shows a steep drop immediately after the peak stress indicating rapid fracture development in these two samples. Sample L1-4 consisted almost entirely of bright cleated coal which had a marked effect on its response to load. The softer and weaker behaviour observed can be attributed to the larger volume of fractures present in this sample. Such fractures allow relatively large deformations to be mobilised during loading. The duller sample L2-1 was stronger than the C3/C4 coals and tended slightly more towards combined axial/shear failure.

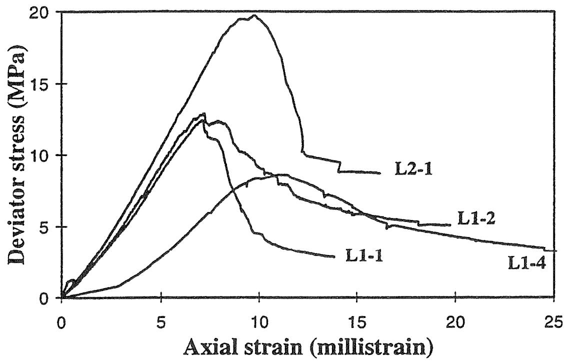

Figure 2. Triaxial test results for 300mm diameter Moura coal core.

The results indicate that different brightness category coals have different strength and deformability characteristics. As expected, the "duller" C5 coals exhibit strong brittle behaviour while the "brighter" coals have a much softer response to loading, reflecting the effect of the discontinuities.

5. SCALE EFFECT ON COAL STRENGTH

The determination of the mechanical properties of coal involves uncertainties, arising mainly from the variability of its composition and the inherent network of discontinuities. Analysis of the test results is therefore undertaken in a manner which aims to separate these features. Criteria are determined upon a basis which aims to provide an easily useable and reproducible method for estimating the mass strength of coal.

Figure 3 shows the results of all the tests plotted with each respective coal strength criterion. Estimates are made using the Generalised Hoek-Brown criterion (Hoek et al, 1994),

$$\sigma_1' = \sigma_3' + \sigma_c\left(\frac{m\sigma_3'}{\sigma_c} + s\right)^a . \tag{3}$$

Each data set is grouped into a general brightness category where possible.

Values of the parameters were obtained by a combination of two techniques. Initially, the simplex method (Nelder and Mead, 1965) was used by choosing a range of values of the power term a then allowing the algorithm to iterate to optimal values of m and s for each data set. Each of the parameters was then plotted against the respective sample size to indicate likely trends in scale. Small adjustments in parameter values were then made which allowed for differences in sample character and grouping. Final estimates were then considered to represent strength properties in both stress range and scale.

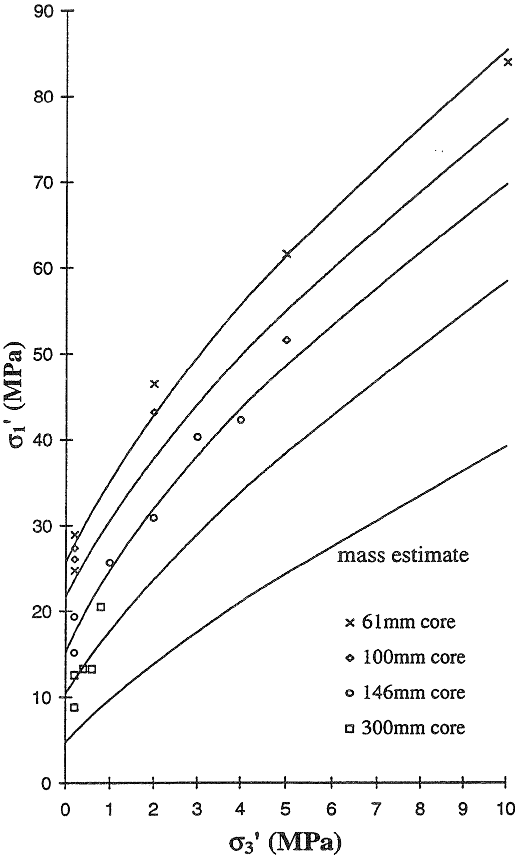

Figure 3. Peak strength criteria for Moura DU coal.

Table 3 shows the values of *m*, *s*, and *a* in the Generalised Hoek-Brown criterion for various sizes and categories of coal.

Table 3. Parameters in peak strength criteria for Moura DU coal.

Diam. (mm)	Coal Cat.	*m*	*s*	*a*
61	C3/C4	19.5	1	0.5
101	C4	15.74	0.71	0.5
146	C4	12.96	0.349	0.5
300	C4	6.81	0.221	0.6
mass	C3/C4	2.93	0.075	0.65

Figure 3 reveals a range of strengths shown by the 300mm diameter samples. These can be explained by variations in coal seam lithology. The upper data point represents the duller C5 sample, and the lowest the bright C2 sample. The vertical spread of data indicates the range likely to exist over the mass size strength for a predominantly dull or bright coal seam.

6. ESTIMATING THE PROPERTIES OF A COAL SEAM

6.1 Coal Strength

According to Australian Standard ranking (AS 2096, 1987) the coal at 17DU south highwall mining reserve was classified as medium rank, bituminous high volatile A (Esterle, 1994). Based on sedimentological studies (Fielding and Esterle, 1992) and numerous brightness logs, Moura DU can be considered as a mid-brightness (C3/C4) coal seam. Such rankings place this coal in the middle of the series for bituminous coals.

The global average cube strength value used in pillar strength formulae has been derived from experience in a large number of coal seams, most likely over the full range of bituminous coals. For geotechnical purposes, based on coal rankings, it is reasonable to assume that the Moura DU coal seam is in fact "average" coal. The results of the large triaxial tests in Figure 3 also indicate that the mid-brightness sample strengths lie centrally between those of the predominantly dull and bright samples. Therefore based on brightness profiles, the results of the 300mm tests provides support for the treatment of Moura DU seam as "average" coal.

Equation (2) was derived on the basis of back analysing data from the pillar strength formulae, results of *in situ* tests and data from the triaxial tests. The results of the 300mm tests suggest that the parameter *s* in equation (2) varies with coal brightness. Values of the parameters in equation (2) are considered to apply to "average" *in situ* strength coal.

6.2 Deformability of Coal

By using the load-unload technique, for each confining pressure, the data from the unloading and reloading cycles were collated in the form of recoverability curves (Elliott and Brown, 1986). For each cycle, the apparent unloading "modulus" of the deviator stress-strain and volumetric-strain curves (E^r and $(1\text{-}2\nu)^r$ respectively) was normalised by dividing by the initial loading "modulus" (E and $1\text{-}2\nu$ respectively) and plotted against the applied axial strain at the start of unloading. As an example the locus obtained, and shown in Figure 4, reflects the degradation of the initial elastic moduli and sample structure as it is strained beyond yield.

Using the recoverability curves, it is possible to construct irrecoverable strain loci on volumetric - axial strain plots for different confining pressures. The construction of the irrecoverable strain locus for sample L1-2 is shown in Figure 5.

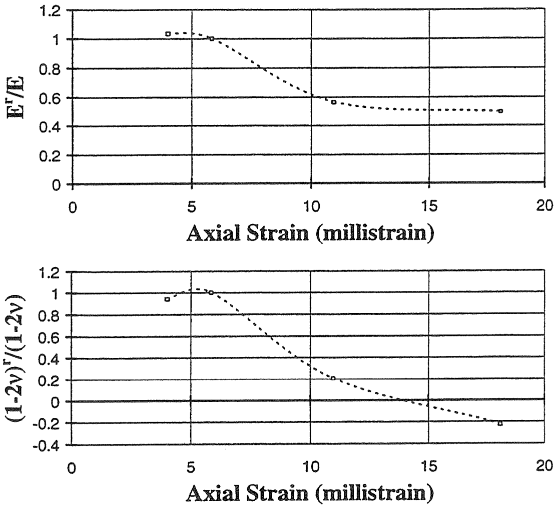

Figure 4. Recoverability curves for sample L1-2.

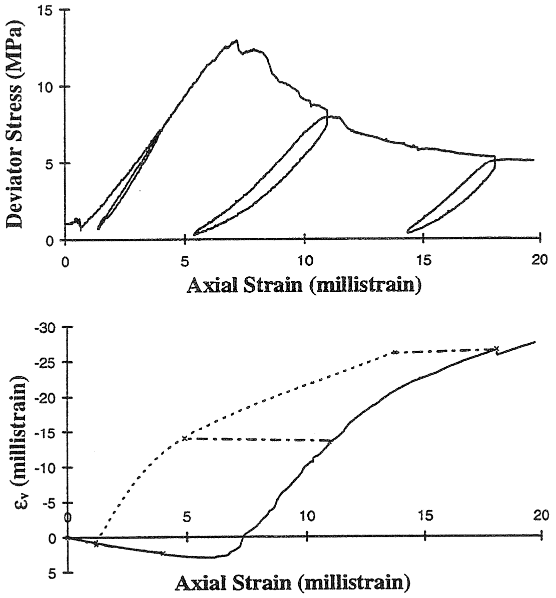

Figure 5. Irrecoverable strain locus for sample L1-2.

The stresses and plastic strain increments at peak strength for the complete series of tests are currently being evaluated (Medhurst, 1996). The results of the triaxial tests provide direct information which allows the determination of the flow rule describing associated or non-associated deformation following yield. This information is needed to describe how coal pillars behave as they are subjected to a process of progressive yielding. Field trials are also underway to assess the performance of coal pillars using these design parameters.

7. CONCLUSIONS

A series of triaxial tests on 61,101,146 and 300mm diameter samples from the Moura DU coal seam have been undertaken. In conjunction with an appropriately selected characterisation scheme, a method to predict properties particular to coal type has been developed. Analysis of the triaxial test data has provided information regarding both the strength and deformation behaviour of the coal seam.

A strength criterion for the DU seam coal is presented. The criterion uses the parameters σ_c, m and s of the Hoek-Brown empirical strength criterion for rock masses. For coal, a power term is included which highlights the contrast in behaviour between it and other rocks. Results of the large scale tests showed that the parameter s varied with coal brightness category reflecting the extent of structure or cleating present within the coal seam. Values of the parameters supplied for the strength criterion are considered to represent "average" *in situ* strength coal.

An experimental technique for investigating the pre-peak and post-peak deformation behaviour of Moura DU coal has been used. Samples tested at each confining pressure were subjected to isolated unloading-reloading cycles during the course of the test. Results of the tests provide direct information which allows the determination of the flow rule describing post-yield deformation behaviour.

8. ACKNOWLEDGMENTS

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