International Journal of Rock Mechanics & Mining Sciences 63 (2013) 62–71

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A numerical study of the scale effect in coal strength

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ARTICLE INFO

Article history:
Received 8 November 2012
Received in revised form
15 April 2013
Accepted 11 June 2013
Available online 17 July 2013

Keywords:
Coal strength
Scale effect
Coal scale effect
Bonded particle model
Coal mass strength

ABSTRACT

A reduction in peak strength with increasing volume has been observed in laboratory tests of coal and attributed to an increase in the total number of cleats and defects in the sample. It is also observed that with increasing coal sample volume an asymptotic strength is reached and the variability in this characteristic strength is remarkably low. In this paper we develop a numerical Bonded Particle Model (BPM) which exhibits the stiffness and strength properties of coal. A scale effect is introduced to the BPM by introduction of a random distribution of defects. After calibrating this model to laboratory sized test samples of 61, 101, 146 and 300 mm diameter we simulate the compression-testing (or loading) of a mass size sample representative of the *in situ* strength of coal. It is observed that the failure mode of the mass scale sample is by tensile failure from mid-sample height resulting in a final “hour-glass” shape at ultimate strength. From testing at a mass scale samples whose UCS varies by 400% at the laboratory scale, it is noted that, in absolute terms, the tensile strength variation is much smaller than the variation in compressive strength and it is observed that the variation in mass strength is likewise minimal. These observations lead to an explanation for the coal strength paradox; why a wide variation is commonly observed in the laboratory compressive strength of coal yet the mass strength is remarkably uniform between coal producing basins and even between continents.

1. Introduction

A decrease in rock strength recorded with an increase in sample size is a well-known phenomenon in rock mechanics and is attributed to an increase in total defects with the increase in sample volume [1–4]. In rock these defects include joints, micro-cracks, foliation and faults that in isolation may have zero tensile strength or tensile strength an order of magnitude less than that of the rock continuum [5] which may be 10–50% of the compressive strength [6,7]. It has been observed that this strength reduction is asymptotic to a characteristic strength at a volume referred to as (rock) mass size, where the average number of defects per characteristic volume is assumed to remain constant [2–4].

In coal, cleats and micro-defects play a similar role in reducing coal strength [8,9]. Most coal seams consist of “bright” and “dull” bands of coal possibly with bands of sedimentary rock or tuff. Coal cleats are formed during coalification and typically organised into face and orthogonal butt cleats. Face cleats are considered persistent extensional discontinuities oriented to the major compressive stress applied during coalification. Butt cleats are non-persistent discontinuities oriented perpendicular to face cleats. Cleating is generally of greater density in the bright, vitrain rich, bands where defects may be counted at the millimetre scale while in dull, durain rich coal, cleats and defects typically occur at the decimetre scale [10].

In rock mechanics the role of fractures in reducing rock strength with increase in sample volume is well recognised and inherent in the Hoek–Brown failure criterion [3,4,11]. Medhurst and Brown [12] conclude that in coal, cleating plays the same role, and that the Hoek–Brown criteria can also be used to estimate coal strength. In coal it was found that Hoek–Brown criterion parameters σ_c and m were functions of rank, and s was an estimate of cleat density determined from the brightness profile [12].

During the 1990s in Queensland, Australia, the Australian Governments research agency the CSIRO undertook a carefully controlled laboratory programme of coal strength testing for highwall mining pillar design [12,13]. Significant effort went into the consistent treatment of the coal samples from drilling, sample preparation to testing. All coal was obtained from localities within one mine and tested with confining stress in a triaxial test rig. To investigate the scale effect in coal, samples of height twice diameter were tested at diameters of 61, 101, 146 and 300 mm. Results from the test programme produced a significant range of strengths; for the 61 mm samples at 0.2 MPa confining stress, strengths ranged from 11.6 MPa to 40.0 MPa.

From this laboratory study the authors concluded there was no statistical similarity in coal strength between samples from the same locality. What was observed as statistically significant was

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http://dx.doi.org/10.1016/j.ijrmms.2013.06.006

a correlation between coal strength and brightness as an indirect measurement of cleat intensity. Mean strengths of the 61 mm samples with a high percentage of brights ranged from 12.7 to 19.4 MPa, strengths of samples of mostly dull coal ranged from 26.1 to 34.0 MPa at 0.2 MPa confining stress.

This variability in coal strength at a small size was also noted in a review of laboratory coal UCS tests encompassing more than 3200 samples [14]. Mark and Barton [14] claim the variability and uncertainty in the measured strength reduced the test usefulness in predicting coal pillar strength to the point where an average strength was statistically more accurate [14,15]. The authors did not claim coal strength is everywhere the same but identify (1) a high variability in strength within a seam, (2) sensitivity to and variability in standard sampling and testing techniques and (3) variation in size and shape scaling relationships [14].

Meanwhile the asymptotic coal strength is estimated by both direct and indirect methods; it has been measured directly in large-scale physical tests and indirectly from the performance of coal pillars left to support and provide stability to the mine roof [16].

Large-scale physical tests are expensive and have been found to present many challenges. Since no standard exists for such tests, a variability in method and boundary conditions is reported. In South Africa, Bieniawski and Van Heerden [9] reported 69 tests from 0.3 to 2 m in size that have determined mass strengths from 4.5 to 14.5 MPa.

The indirect estimation of coal mass strength benefits from a much larger database of production coal pillars that covers a greater range of underground conditions, mining seams, mining methods and localities. Databases of failed and stable coal pillars have been statistically analysed in South Africa, Australia and America and the asymptotic strength estimated to range between 5.4 and 7.4 MPa [14].

The aim of this paper is to address this apparent contradiction between the coal strength at a small and large sample size and to see if, by accounting for discontinuities in the coal matrix and with appropriate boundary conditions, a wide variation in the coal strength at laboratory scale results in a relatively small perturbation in the mass strength.

For this purpose the Discrete Element method is utilised to create a Bonded Particle Model (BPM) of coal [17–19]. Particle models of cohesive frictional materials are not common in rock engineering due to computational overheads and the lack of relationships between macro-properties and inter-particle stiffnesses and strengths. However, the method has several attractions for this study.

In BPM complex macro-scale responses evolve from the relatively simple interaction of a dense packing of many circular or spherical particles. These evolved responses include stiffness, strength, strain softening/hardening, the strength envelope, failure modes *etc.* For example it is observed that fractures between particles initiate then coalesce such that the resultant strength envelope is an outcome of the model [17]. Failure modes at the laboratory scale may be (most probably will be) different to those of the mass sample but these should be self-generating in a BPM, given appropriate boundary conditions, as the model scale varies.

This paper is organised as follows: in the next section data from the laboratory test programme as reported in Refs. [12,13] is presented together with a summary of the stiffness and strength properties as recorded or inferred by the program RocLab [20] by RocScience. This is the data used to calibrate the numerical model. Coal tensile strength estimation, strength estimation from *in situ* tests and strength estimation of coal pillars is also discussed in the next section. Following this the BPM is introduced with a simple introduction to the contact laws. After calibration, the inter-particle and resultant macro-properties of the coal BPM are summarised. Finally a model of a mass sized coal sample is created and the plane strain assumptions are discussed and addressed for this model. The model, with inter-particle properties based on the smaller laboratory scaled samples, is calibrated to 6.4 MPa by the introduction of defects. This model is then analysed with two additional property sets whose UCS vary from 10 to 40 MPa, results are discussed.

2. Strength of coal as measured in the laboratory, *in situ* and indirectly by empirical methods

2.1. Laboratory estimation of coal strength

The numerical model constructed for this paper will be designed and calibrated to a database of 57 coal test undertaken by Medhurst and reported in Refs. [12,13]. As reported in Refs. [12,13], in a carefully controlled laboratory study on coal from the Moura mine in Queensland, Australia, cylindrical coal samples were tested at 61, 101, 146 and 300 mm diameter with height twice diameter. As reported in Ref. [12], coal moisture levels were typically observed between 3% and 6% and tests were conducted generally in accordance with the ISRM suggested method for determining the strength of rock in triaxial compression [12]. The purpose of the study was to estimate the strength of coal pillars left to provide support during highwall mining operations [12,13] and for that purpose it was important to study the scale effect in coal strength to estimate the mass and pillar strength.

Coal samples were tested in a triaxial test cell to address the variability inherent in UCS testing. In all, 40 tests were undertaken of 61 mm samples, 4 tests of 101 mm, 9 tests of 146 mm and 4 tests of 300 mm samples. Peak confining stresses for the four sample sizes are 10, 5, 4 and 0.8 MPa and minimum confining stress is 0.2 MPa in all cases (Fig. 1).

By consideration of the full dataset for each sample size the measured and inferred properties are summarised in Table 1. For each sample size the equivalent Mohr–Coulomb friction angle is determined from a fitted Hoek–Brown strength envelope fitted by the software RocLab. Inferred UCS in Table 1 refers to the extrapolation of the fitted strength envelope to the equivalent unconfined strength.

As observed in Fig. 1, measured strengths of the standard test size of 61 mm diameter at all confining stresses was highly variable and for 0.2 MPa the strength ranged from 11.6 MPa to 40.0 MPa. When analysed by seam the authors conclude there is no statistically significant characteristic strength at the 61 mm sample size.

For this study of "average" coal whose properties are generic, the average stiffness properties and strength based on the Hoek–Brown strength curve fitted to the full dataset will be used to calibrate the numerical model. Based on the fitted Hoek Brown failure envelope from the total dataset of 61 mm samples, the TS to UCS ratio is approximately 5%.

Direct measurement of the tensile strength (TS) of coal is notoriously difficult [21,22] and indirect methods are often preferred. Pomeroy and Morgans [21] report compressive strength for four coal seams from the United Kingdom and estimate indirectly the tensile strength calculated by bending thin rectangular samples of coal and relating the maximum bending moment to tensile strength from the simple beam theory. Whilst highlighting the variability in results from test samples, Pomeroy and Morgans conclude the tensile to compressive strength ratio is approximately 10%.

The more common indirect test for tensile strength estimation is the Brazilian test in which circular disks of the test material are compressed between platens [22,23]. Compared with the direct