DETERMINING COAL DIRECTIONAL MECHANICAL PROPERTIES USING TRUE TRIAXIAL TESTING FACILITY

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ABSTRACT: Knowledge of coal mechanical properties and strength is critical in modelling and understanding pillar stability, gateroads stability, gas drainage borehole integrity as well as coal responses to hydraulic fracturing stimulation. However, due to the complexity of coal structures and difficulties in obtaining decent coal specimens, measurements of coal mechanical properties have been limited to the application of traditional triaxial and UCS tests, which in turn has shown adverse influence on the design confidence and reliability in practice. In addition, coal is an anisotropic material and such conventional testing techniques are clearly not capable of directly capturing coal anisotropic features. In this work, a true tri-axial testing facility was used to quantify coal strength and its anisotropic characteristics. Eight 50 mm side cube coal blocks were prepared and three types of tests were implemented. The proposed testing procedure measured successfully the mean values of coal young's moduli in three different x, y and z (vertical) directions as 1,025 MPa, 1,887 MPa, and 2,543 MPa, respectively, which gives the ratio of 1.00: 1.84: 2.48. The mean Poisson's ratio is also measured as 0.098, 0.038, and 0.091 in x, y and z directions. Coal strength follows the Hoek-Brown criterion reasonably well, and the m value is found to be 23.9. These findings suggest that the implementation of true-triaxial testing techniques for coal mechanical properties can effectively capture its anisotropic characteristics, which could enhance analysis confidence for future designs.

INTRODUCTION

Underground coal mining operations are subjected to a diverse range of tectonic and mine-induced stresses throughout their lifetime (M. Li et al., 2016). Therefore, proper understanding of coal strength over time is critical for the reliable geotechnical design of pillar size, roof and rib support, and gateroads short-term and long-term stability (Bieniawski, 1968; Liu et al., 2019). Coal is characterized as a heterogeneous, anisotropic and porous medium repletes with discontinuities, cracks, cleats, bedding plates and faulty zones that control its microstructure (Figure 1). These complex microstructures (mainly with various properties in different directions) determine coal static and time-dependent properties and its ultimate response to stress and excavations (Hudson and Harrison, 1997).

Despite proven and well-known directionally dependent properties in coal, relatively limited efforts have been carried out in the literature to investigate the influence of material heterogeneity on stress-strain redistribution and its impact on coal failure behaviour under uniaxial compressive loading (Zhao et al., 2014). The compressive strength and deformation characteristics of coal have therefore been mainly limited to the application of conventional triaxial apparatus (Barla, Barla, and Debernardi, 2010; Perera, Ranjith, and Choi, 2013; Ranjith and Perera, 2011; Somerton, Söylemezoğlu, and Dudley, 1975), but with a few recent exemption studies (Dexing et al., 2018; Li, et al., 2019). In addition, due to the anisotropic nature of the coal, the traditional triaxial and UCS testing methods are no longer capable of directly capturing the mechanical parameters of coal. Moreover, the effect of the intermediate principal stress on the coal deformational analysis is ignored under the conventional triaxial apparatus. With

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these motivations in mind, this study aims to symmetrically quantify coal triaxial strength and its directional mechanical properties using true triaxial testing procedures.

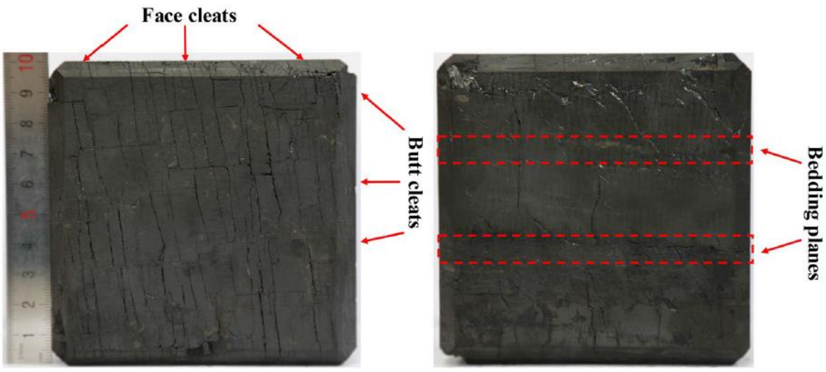


Figure 1: Cleats and bedding plates in coal (After Yubing et al, 2019)

EXPERIMENTAL DESIGN AND SETUP

Experimental design

For this work, eight coal cubed samples were prepared using high-quality bituminous coal samples collected from Dongda Coal Mine, Ordos basin in China (Figure 2). Three types of laboratory measurements were designed: Uniaxial Compressive Strength (UCS), step-compression (SC), and true triaxial strength (TTS) tests. The step-compression tests, in particular, were designed to gain coal directional mechanical properties (i.e., Young's modulus and Poisson's ratio) as described below in detail. The UCS and true triaxial strength measurements were further aimed to obtain coal triaxial strength data. The numbering of each sample and the corresponding type of measurement are summarized in Table 1. It is to be noted that Sample 3 was not tested due to the existence of extensive visable cleats/fractures presented in the sample, which were expected to reduce the sample strength significantly and thus unable to provide comparable results.

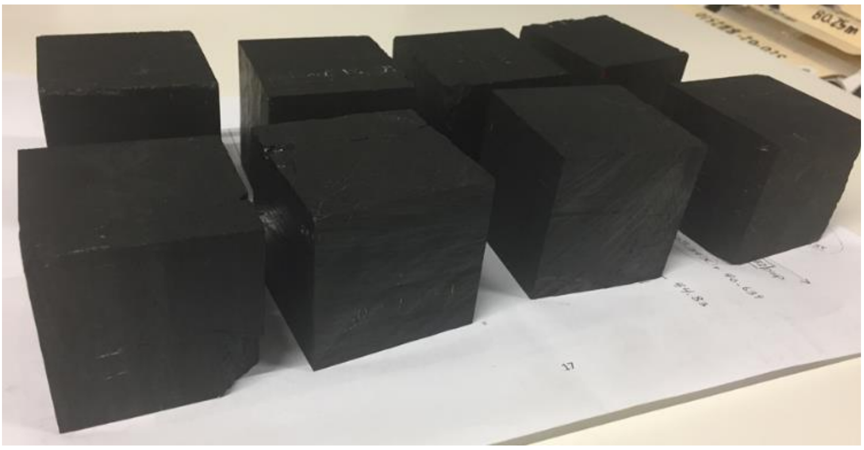


Figure 2: Coal cubic samples

Table 1: Sample specification and the corresponding testing

Sample Label	Proposed Testing	Sample Dimension (mm)		
		L1 direction	L2 direction	L3 direction
S1	UCS	50.75	49.20	49.31
S2	UCS	49.26	48.31	48.51
S3	Not tested due to major cracks	49.04	49.29	49.47
S4	SC TTS	49.64	47.11	49.35
S5	SC TTS	49.26	49.98	48.15
S6	SC TTS	49.38	49.96	50.62
S7	SC TTS	49.98	50.23	48.19
S8	SC TTS	49.36	49.50	47.44

For the step-compression measurements, each sample is tested following the sequence below:

1. Step loading: Nine loading steps, starting from 2 MPa in all three directions, and gradually increasing the stress in different orders (as illustrated in Table 2) until reaching 8 MPa in all three directions.
2. Unloading the sample to 2 MPa; and then
3. Conducting true-triaxial strength testing: the two horizontal principal stresses are loaded to the designed value, and then the vertical load increases gradually until failure.

Table 2: Loading sequence for the true triaxial testing

Loading Step	Sigma x (MPa)	Sigma y (MPa)	Sigma z (veritical) (MPa)
1	2	4	2
2	2	4	4
3	4	4	4
4	4	4	6
5	6	4	6
6	6	6	6
7	8	6	6
8	8	8	6
9	8	8	8
True-triaxial Strength Testing			
Sample 5	2	2	To fail
Samples 4 and 7	4	4	To fail
Sample 6	6	6	To fail
Sample 8	8	8	To fail

True Triaxial Testing Facility

The True Triaxial Testing system used in this study is located at the Geotechnical Engineering Centre (GEC) within the School of Civil Engineering at the University of Queensland (UQ). The GEC is equipped with a number of cutting-edge rock testing facilities, unique in Australia, such as True Triaxial Testing System and a Biaxial Testing System, supported by a stereo (3D) ultra-high-speed and high-resolution camera system capable of running at up to 1,000,000 frames per second, a Stereo Digital Image Correlation (DIC) software platform, and Hoek triaxial cells of various diameters, as well as rock preparation equipment including coring, cutting and grinding machines. The true triaxial testing rig at the UQ Civil is capable of applying up to 340 MPa on 50 mm cubed specimens in three orthogonal directions (or up to 21 MPa stress on 200 mm cubic specimens). It is equipped with temperature (up to 100^{o} C) and relative humidity control, has the capability for testing under saturated and unsaturated conditions (see Figure 3 below). The system is also capable of performing hydraulic fracturing at up to 51 MPa injection pressure and rock permeability tests at water pressure up to 10 MPa.

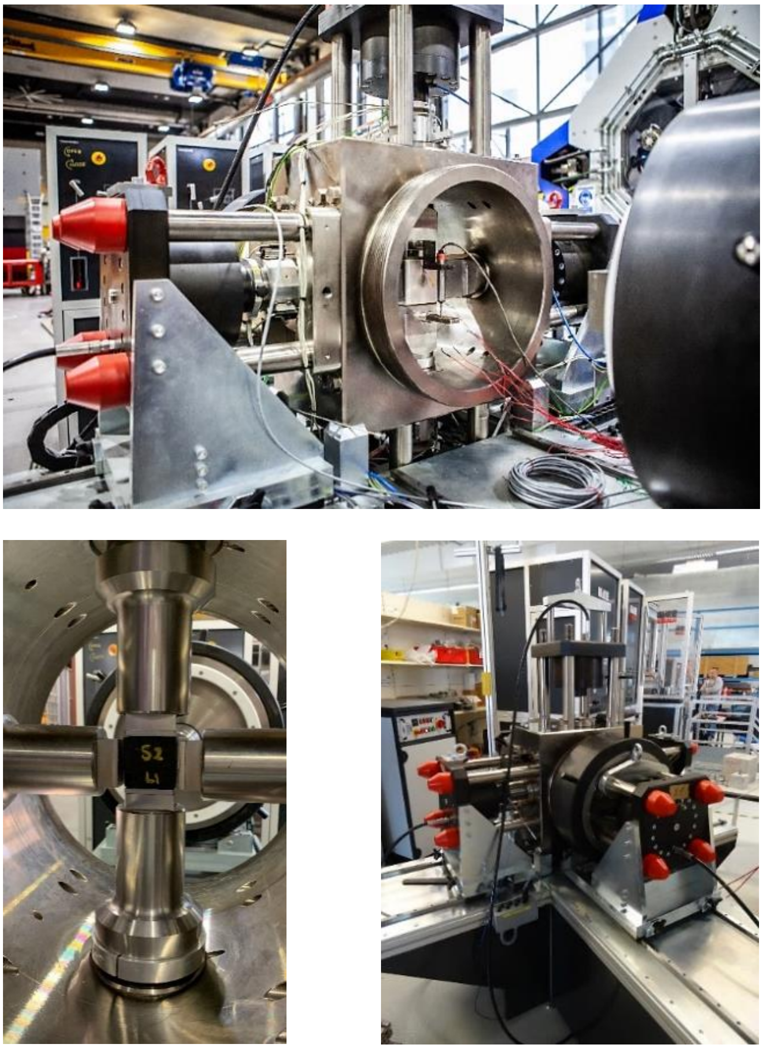


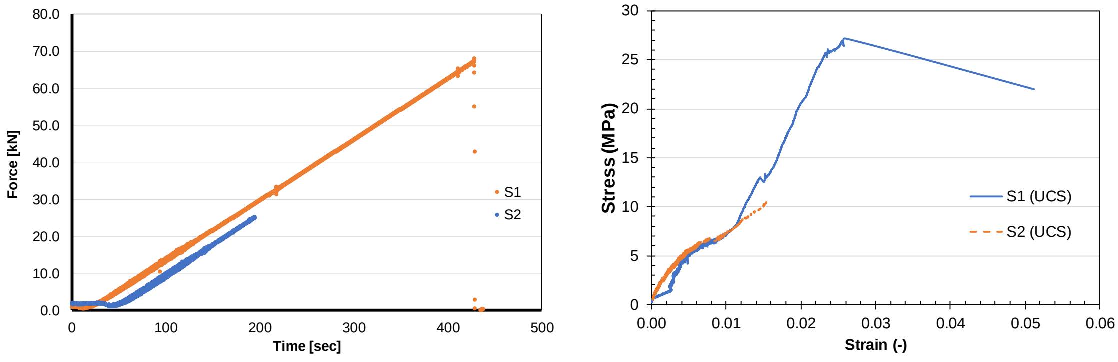
Figure 3: The true triaxial testing facility at UQ Geotechnical Engineering Centre

RESULTS AND ANALYSIS

UCS and true triaxial strength measurements

A loading rate of 10 kN/ min was applied to satisfy the ISRM standard recommendations. The time taken for S1 and S2 to fail is 437 s and 195 s, respectively. The maximum compressive strains at failure for two samples are 2.59% and 0.927%, respectively. As the samples are cubes rather than cylinders, the comparison with traditional UCS measurements was not conducted, but based on the existing literature (CAPRARO and MEDEIROS, 2019), the difference is generally within the range of 20%, with greater values from cubic samples.

The UCS values for samples 1 and 2 are 26.77 MPa and 10.57 MPa. The calculated E values are 1,404 MPa and 611 MPa, respectively. The result for Sample 2 is apparently not presentive due to the existence of fractures. The measured values are consistent with existing work done on cylindrical samples from the same basin, which show an average of E and UCS values of 2,171 MPa and 26.71 MPa (Cao, Kang and Deng, 2019). It is worth mentioning that the displacement data from the rig does not subtract the contribution of the loading cell to the total deformation, which means that the actual deformation should be less and thus the E values are expected to be slightly higher.



(a) (b)

Figure 4: Loading path (a) and stress-strain curves (b) for S1 and S2 samples

Step-compression testing

Coal is generally more anisotropic than most other types of rocks. For an anisotropic material, in general, its compliances/stiffness matrix can have 36 different properties, but the number reduces to 21 independent constants due to symmetry. In this work, we do not aim to determine all these independent constants, instead, we assume that the properties are the same in three orthogonal planes of microstructural symmetry (i.e. coal samples are treated as an orthotropic body with properties that differ along three mutually-orthogonal axes of rotational symmetry at a particular point). The number of properties, therefore, reduces to 9 accordingly which includes 3 Young's moduli and 6 Poisson's ratios. To directly calculate each of the mechanical properties, the loading step was particularly designed as illustrated in Table 2.

The stress-strain relationship under 3D stress conditions can be represented through the compliance matrix as shown in Equation 1:

$$\begin{cases} \varepsilon_x = \dfrac{1}{E_x}\sigma_x - \dfrac{\upsilon_{yx}}{E_y}\sigma_y - \dfrac{\upsilon_{zx}}{E_z}\sigma_z \\ \varepsilon_y = \dfrac{1}{E_y}\sigma_y - \dfrac{\upsilon_{xy}}{E_x}\sigma_x - \dfrac{\upsilon_{zy}}{E_z}\sigma_z \\ \varepsilon_z = \dfrac{1}{E_z}\sigma_z - \dfrac{\upsilon_{xz}}{E_x}\sigma_x - \dfrac{\upsilon_{yz}}{E_y}\sigma_y \end{cases} \tag{1}$$

When only σ_x changes during the test, e.g., increasing from σ_{x2} to σ_{x1}, Equation 1 can be re-arranged into:

$$\begin{cases} \Delta\varepsilon_x = \varepsilon_{x2} - \varepsilon_{x1} = \dfrac{1}{E_x}(\sigma_{x2} - \sigma_{x1}) = \dfrac{1}{E_x}\Delta\sigma_x \\ \Delta\varepsilon_y = \varepsilon_{y2} - \varepsilon_{y1} = -\dfrac{\upsilon_{xy}}{E_x}\Delta\sigma_x \\ \Delta\varepsilon_z = \varepsilon_{z2} - \varepsilon_{z1} = -\dfrac{\upsilon_{xz}}{E_x}\Delta\sigma_x \end{cases} \tag{2}$$

Therefore, the following three properties can be determined from the stress-strain data in the three principal directions.

$$\begin{cases} E_x = \frac{\Delta\sigma_x}{\Delta\varepsilon_x} \\ \upsilon_{xy} = -\frac{\Delta\varepsilon_y}{\Delta\sigma_x} \times E_x \\ \upsilon_{xz} = -\frac{\Delta\varepsilon_z}{\Delta\sigma_x} \times E_x \end{cases} \quad (3)$$

Similarly, when varying σ_y and σ_z, the following correlations stay true.

$$\begin{cases} E_y = \frac{\Delta\sigma_y}{\Delta\varepsilon_y} \\ \upsilon_{yx} = -\frac{\Delta\varepsilon_x}{\Delta\sigma_y} \times E_y \\ \upsilon_{yz} = -\frac{\Delta\varepsilon_z}{\Delta\sigma_y} \times E_y \end{cases} \quad (4)$$

$$\begin{cases} E_z = \frac{\Delta\sigma_z}{\Delta\varepsilon_z} \\ \upsilon_{xy} = -\frac{\Delta\varepsilon_y}{\Delta\sigma_z} \times E_z \\ \upsilon_{xz} = -\frac{\Delta\varepsilon_z}{\Delta\sigma_z} \times E_z \end{cases} \quad (5)$$

In this work, Equations 3-5 are combined to determine the nominated 9 properties shown in Equation 1. Theoretically, they can be determined by changing the loading of each direction once, but to minimize data uncertainty the 9 steps (3 steps in each direction) in total are implemented.

There is a large amount of data recorded during the tests. Due to space limitations, only the data for sample 5 was presented in detail here as an example. The loading history and the calculated results of the sample are plotted in Figure 5 and Equation 6, respectively.

Figure 6 summarizes the results of the directional E of the four samples (S5-S8). A significant difference in E values along different orientations was observed. The mean E values in x, y and z directions are 1,025 MPa, 1,887 MPa, and 2,543 MPa, which gives the ratio of 1.00: 1.84: 2.48. The difference in E values is considerable. The prediction of gateroads deformation could be quite different when different E values are used, and this uncertainty should be beard in mind when conducting a geotechnical analysis.

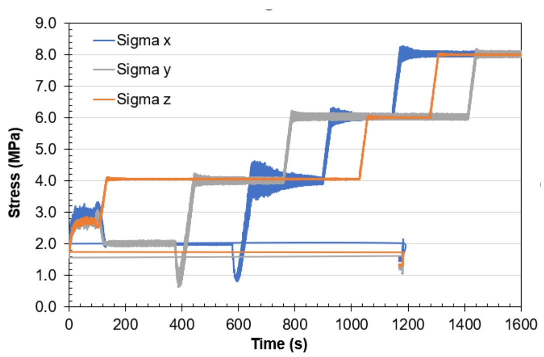


Figure 5: Loading history of Sample 5

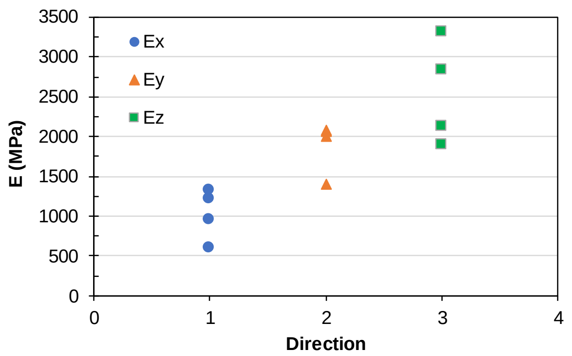


Figure 6: Results of directional Young's moduli

The results of Poisson's ratio are a bit messy as illustrated in Figure 7, and do not show a particular trend. The mean Poisson's ratio values are 0.098, 0.038, and 0.091 respectively (x, y and z directions), which gives the ratio of 1.00: 0.38: 0.93. The majority are significantly smaller than representative values for coal, which varies from 0.26 to 0.43 (Szabo, 1981).

A good potential reason could be associated with the stiffness of the loading plates of the true triaxial rig. TThe stiffness of coal is typically one or two orders of magnitude lower than hard rocks (e.g., 1.5 GPa for coal vs 10 GPa for sandstone vs 30 GPa for granite). This means that during coal compression testing, the Poisson's effect will not generate adequate forces in the two orthogonal directions to push the loading plates away to maintain designed constant pressure. Essentially the loading condition of coal changes from stress-controlled by design to uniaxial strain equivalent conditions. This could result in minimal detection of coal lateral deformation, thus obtain much smaller values of Poisson's ratio from the calculation.

$$\begin{bmatrix} E_x & \upsilon_{xy} & \upsilon_{xz} \\ \upsilon_{yx} & E_y & \upsilon_{yz} \\ \upsilon_{zx} & \upsilon_{zy} & E_z \end{bmatrix} = \begin{bmatrix} 1{,}210 & 0.04 & 0.05 \\ 0.20 & 2{,}068 & 0.16 \\ 0.10 & 0.02 & 2{,}841 \end{bmatrix} \quad (6)$$

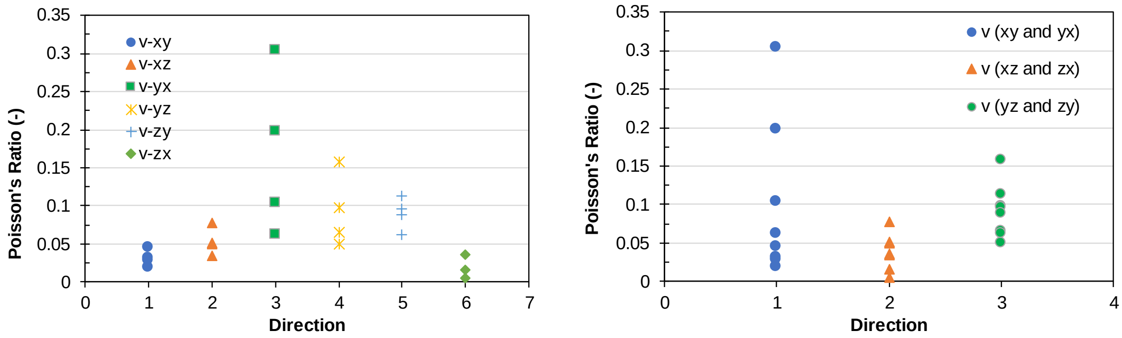


Figure 7: Result of directional Poisson's ratio

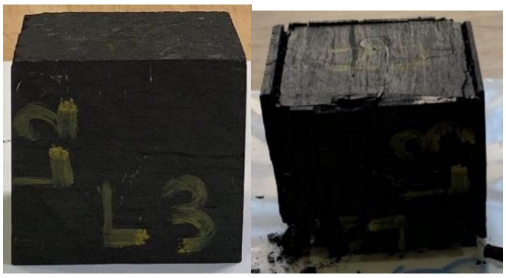
Coal triaxial strength

Samples 5-8 were used for conducting step-compression and the subsequent strength measurements, and the failure modes are provided in Figure 8. No noticeable difference in failure modes is observed for the four samples and it is consistently seen that the shear surface occurs along the gaps between loading plates.

Sample 5

Sample 6

Sample 7



Sample 8

Figure 8: Coal samples before and after true triaxial tests

To calculate coal triaxial strength, two probably most widely used criteria can be applied: Mohr-Coulomb and Hoek-Brown. The latter is used for this work due to its more suitable feature for rock-like materials. The expression of Hoek-Brown criterion can be defined as (Eberhardt, 2012):

$$\boldsymbol{\sigma_1' = \sigma_3' + \sigma_{ci}\left(m\frac{\sigma_3'}{\sigma_{ci}} + s\right)^{0.5}} \quad (7)$$

where σ_1' and σ_3' are the major and minor principal effective stresses at failure, *m* and *s* are constants for the target material (*s* is normally taken as 1.0 for intact samples), and σ_{ci} is the UCS strength of intact coals. The experimental results of triaxial compression tests are plotted in Figure 9. The data point in red is from sample S4, and seems a bit off the trend. The m value is 23.9 for all data and m = 22.3 if the red dot point is excluded in the fitting. The difference seems minimal for coal mining at shallow depth (e.g. < 500m).

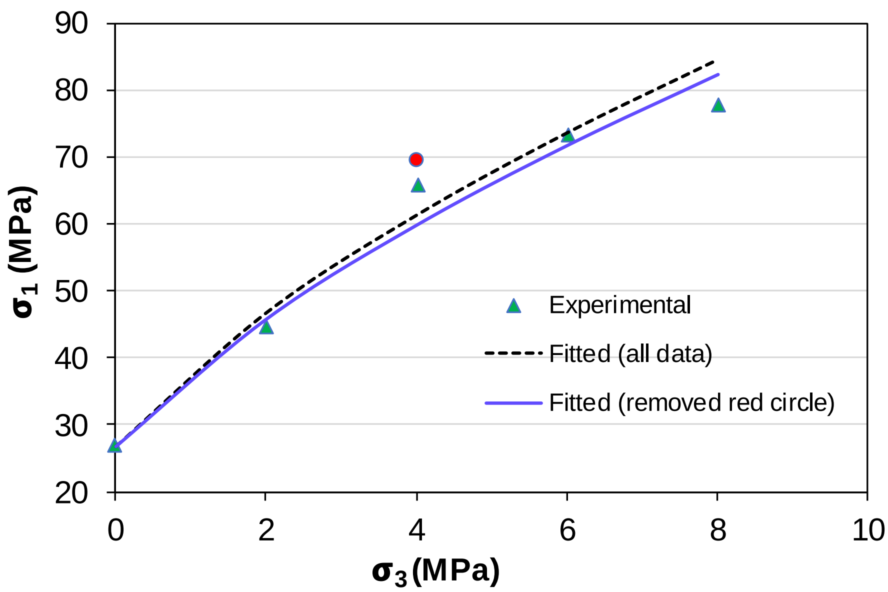


Figure 9: Coal Strength Based on Hoek-Brown Criterion

CONCLUSIONS

In this work, a series of tests were conducted to determine coal strength and directional mechanical properties using a true triaxial testing rig. Three types of tests were designed on seven coal samples. The key findings from this work are:

- E values along different orientations are quite different. The mean E values in x, y and z directions are 1,025 MPa, 1,887 MPa, and 2,543 MPa, which gives the ratio of 1.00: 1.84: 2.48.
- The results of Poisson's ratio do not show obvious trend in different directions. The mean Poisson's ratio values are 0.098, 0.038, and 0.091 respectively (x, y and z directions), which gives the ratio of 1.00: 0.38: 0.93.
- Coal strength follows the Hoek-Brown criterion reasonably well. The m value is 23.9 for all data and m = 22.3 if the red dot point is excluded in the fitting from Figure 9.

The results show that coal anisotropic feature is quite strong, and should be considered when conducting the relevant geotechnical analysis. Coal mechanical properties need to be probably tested and used to enhance analysis confidence.

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