Measurement of pore water pressure properties of unsaturated brown coal using triaxial test

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ABSTRACT: Skempton's B parameter characterises the effect of fluid compressibility on the time dependent deformation of materials during isotropic loading. The Skempton B-parameter has been determined for a sample of Victorian brown coal for a range of confining pressures, corresponding to the range of conditions which the coal experiences below the ground water table. The relationship between the change in the B-parameter with respect to time and pressure has also been examined. It has been found that a high back pressure (more than 400 kPa) is required in the material to achieve a degree of saturation close to 100%. The set of data from these tests is able to provide important evidence of the depth and stress dependent behaviour of the coal.

1 INTRODUCTION

The geological sequence centred on the Latrobe Valley, Victoria, Australia hosts 23% of the world's brown coal reserves, the largest brown coal deposit in the world (Australia Mineral Resource, 2011). More than 80% of Victoria's 430 billion tonnes of brown coal is located in the Latrobe Valley, 160km south-east of Melbourne (DPI, 2012). Three open-pit mines are operated in this region and supply coal to four power stations, which produce most of Victoria's electricity. The readily accessible reserves can be mined for at least 500 years at the 2008 production level

Borehole measurements have confirmed that brown coal reach depths up to 250 metres below ground level. Depressurising of the groundwater in the underlying aquifers and the coal adjacent to the mine walls is required to maintain the stability of the mines. Groundwater abstractions are also required for process and fire prevention supplies. These abstractions impact on the degree of saturation of the upper coal sequences close to the mines. Initial investigations suggest that gas other than air may exist in the coal.

Skempton's B-parameter can be used to describe the change in degree of saturation with respect to the depth below the water table. This may be useful in determining the depth below the water table where it is reasonable to assume the coal is approaching saturation.

2 LITERATURE REVIEW

2.1 *Skempton's B-parameter*

The B pore pressure parameter was first proposed by Skempton in 1954. The pore pressure coefficients were developed out of the need to know the change in pore pressure associated with various changes in total stress, for problems involving the undrained shear strength of soils.

Skempton used the B-parameter (see Equation 1) to represent the degree of saturation of a material, such that,

B → 0, when the degree of saturation = 0 and,
B → 1, when the degree of saturation = 1

$$\Delta u = B[\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)] \qquad (1)$$

where, Δu is change in pore water pressure, A and B are pore-pressure coefficients, and σ_3 and σ_1 are minor and major principal stresses.

These correlations show that degree of saturation is related to the ratio of the compressibility of voids in a soil sample to the compressibility of the soil structure.

Since water is largely incompressible, compressibility of the voids is smallest when filled with water, and therefore the ratio of void compressibility to soil structure compressibility would be lowest for water filled voids.

The B-parameter is defined as the change in pore water pressure divided by the change in confining cell pressure applied to a soil or rock specimen (Skempton, 1954). The cell pressure increment is the increase in confining pressure, which is compared to the increase in pore water pressure during a triaxial saturation to derive a B value.

Following Skempton's paper, Bishop (1954) discussed the practical applications of pore-pressure coefficients including use in design of foundations of structures, stressing of compacted impervious fill of earth dams, rapid draw-down of earth dams, as well as applications in formation of slopes and cuttings as is intended for the results of this project.

More recently Fredlund and Rahardjo (1993) noted that the changes in both pore-air and pore-water pressures directly affected the mechanical behaviour of unsaturated soils. Based on this, they set out to account for both the compressibility of air and compressibility of water in determining the pore pressure parameters for unsaturated soils. If the tests on the brown coal show that if the material is not fully saturated until some depth below the water table, techniques such as those set out by Fredlund and Rahardjo may have to be employed in slope stability calculations for slopes or batters in coal.

2.2 *Determination of saturation*

The procedure used to achieve and test for saturation is derived from the Australian Standards. Methods that can be used in the determination of the degree of saturation for materials using the triaxial testing apparatus can be found in a number of standards publications, such as: the Australian Standard (1998) method for testing soils for engineering purposes, the British Standard (2002) Methods for testing soils, and the American Society for Testing and Materials (1990) Standard Test Method for consolidated undrained triaxial compression test for cohesive soils.

The Australian Standard (1998) Method 6.4.2 for Soil strength and consolidation tests includes a procedure for back pressure saturation. A specimen is prepared and mounted in the triaxial system, and a cell pressure is applied to the specimen, simulating the initial conditions of the sample. The standard then suggests application of pressure increments of 50kPa to the cell pressure and back pressure systems simultaneously. The pore pressure is then monitored at the opposite end of the specimen, where the back pressure is applied, to ensure the drainage lines in the specimen are saturated.

Once the pore pressure equals the back pressure and becomes stable, a new pressure increment may be applied to the back pressure and cell pressure systems. The increment size should increase as pressures are applied to the specimen. To monitor the progress of the saturation, all drainage should be closed off, and a small increment should be applied to the cell pressure, with the resulting change in pore pressure measured. The Australian Standards suggests that the resulting B-parameter should not be less than 0.95 when saturation is reached.

2.3 *Effect of degree of saturation on soil properties*

Tests on samples that are not saturated may result in inaccurate measurements of soil properties. Effects on the material may include:

Suction effect due to unsaturation, which may result in a higher apparent cohesion if the degree of saturation is low, as shown by Fredlund et al (1978):

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_w - u_a) \tan \phi_b \qquad (2)$$

where τ is the shear stress on the failure plane at failure, c' is the intercept of the extended Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero (effective cohesion), σ_n is the net normal stress state on the failure plane at failure, u_a the pore-air pressure on the failure plane at failure, ϕ' is the angle of internal friction associated with the net normal stress state variable, (u_w-u_a) is the matric suction on the failure plane at failure, and ϕ_b is the angle indicating the rate of increase in shear strength relative to the matric suction.

For nearly saturated conditions, the effect of any gas present is hard to measure during undrained shear, since the gases may be far more compressible than the soil structure and any water. Reducing the specimen to two phases allows the stress on the soil structure to be more easily determined, providing an assumption is made that the water present is largely incompressible.

If there are gases present in the sample in the drained test it may become difficult to determine the change in volume, since it is possible for both gas and water to be leaving the specimen.

3 METHODOLOGY

3.1 *Material description*

The coal samples were taken from Loy Yang open-cut coal mine in the Latrobe Valley, Australia. Latrobe Valley brown coal is classified as lignite, and naturally contains both water and gas. The coal is a light organic material with a unit weight of 11.5kN/m^3, low permeability (around 10^{-10} m/sec), void ratio of 1.5 and dry basis water content up to 200%.

3.2 *Equipment*

In addition to the coal samples, the triaxial testing setup included the triaxial system hardware and software , a computer connected to triaxial data accusation box, water supply, mains pressure, pressure booster, specimen membranes, porous stones, and O-rings. Moisture content tests were also conducted in an oven, using ceramic dishes, heat proof gloves and scales.

The employed triaxial system in this project is the IPC Global Universal Cyclic Triaxial System (see Figure 1) which comprises; 2 column Load Frame, PC controlled with 20 bit IMACS & 13 channels, 10kN actuator with 50mm stroke and air receiver. The system has closed loop control of axial load, cell pressure and back pressure. The laboratory where the tests were conducted was temperature controlled at 21°C throughout testing, to ensure the rate of saturation would not be affected by fluctuations in temperature.

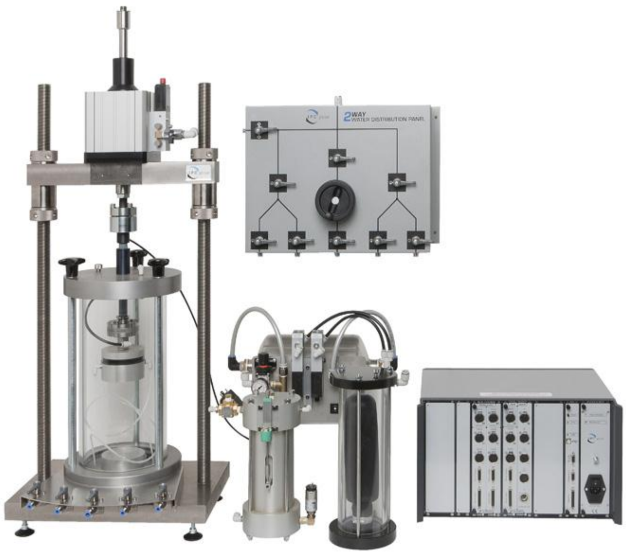

Figure 1. IPC Global Universal Cyclic Triaxial System

3.3 *Test procedure*

The following procedure for saturation was derived from the Australian Standards.

Cylindrical test specimens with 48mm diameter and 50mm length were cut from the Loy Yang coal block sample using an electric core drill. The specimens were submerged in water for a month to aid in the initial saturation of the drainage lines. Before the start of each test, the dimensions and weight of the specimen were recorded.

The triaxial system was supplied with de-aired tap water by a reservoir tank, and the system de-aired. The specimen was placed in a membrane, mounted in the confining cell with porous stones on the top and bottom, and sealed with O-rings. The confining cell was put in place and filled with de-aired water.

Through the triaxial system software, the axial actuator was set in contact with the specimen to record any variation in height and the test was defined in the software, by entering the specimen dimensions, initial cell pressure and back pressure conditions, differential pressure between cell and back pressure and target back pressures using continuous pressure ramp loading.

At the start of each test the cell and back pressures were increased simultaneously and the software recorded pore water, cell and back pressures values at 10 second increments. Once a steady pore water pressure close to the back pressure was observed, the first check on the B parameter was done by increasing the cell pressure and observing the change in pore pressure. During each check the pore pressure, cell pressure, and volume change were recorded. For each test, four more B-parameter checks were conducted at approximately 3 to 4 hour intervals. Each test consisted of five stages, each applying a 200kPa increment to the specimen.

Following saturation and consolidation, the moisture content of each of the specimens was measured to provide some indication of the variation in the structure of the coal in each specimen. Three to four samples weighing approximately 20 grams each were taken from each specimen, and the moisture content was determined.

3.4 *Test results*

The most important result the tests provided was a relationship between the B-parameter and back pressure for the samples of Loy Yang coal, the plot of which is shown in Figure 2. This plot shows the maximum B-value recorded for each stage of each test and the target back pressure for each stage.

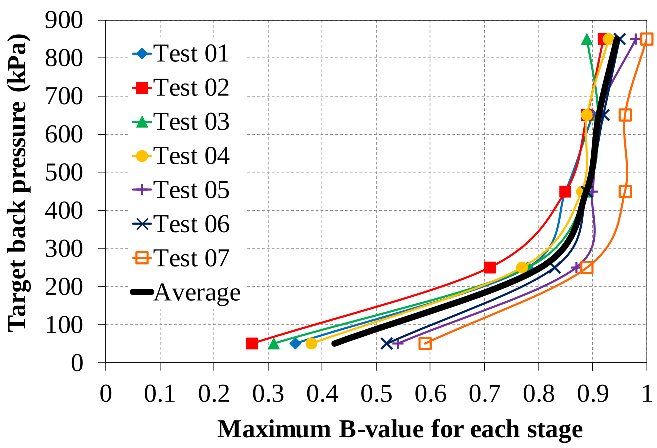

Figure 2. Plot of B-value versus target back pressure

A significant change in trend can be seen once the back pressure reaches about 300kPa. At this point the rate at which the B-value increases with respect to back pressure slows down significantly. This change in trend also marks the point where the specimens began to reach B-values above 0.85, which indicates that the specimens are approaching full saturation condition.

Although some differences were seen in the behaviour of each of the specimens, particularly those that appeared to be more dense and woody, the plots all follow the same trend. These plots may also be interpreted as a rough representation of the relationship between the B-parameter and depth below the water table, as shown in Figure 3.

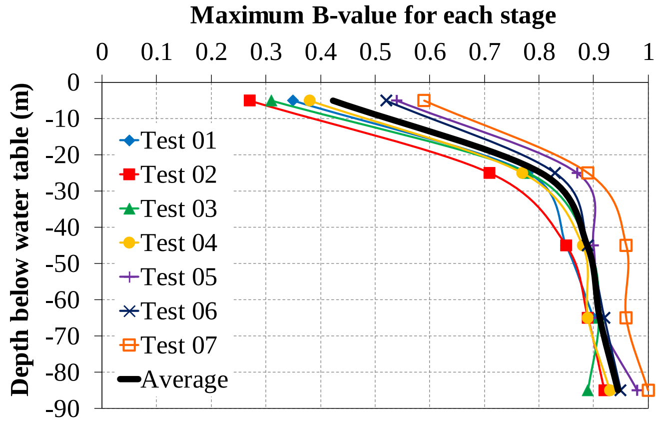

Figure 3. Plot of B-value versus depth below water table

Figure 3 provides a more convenient relationship than Figure 2 because it shows an approximate depth below the water table where the samples may be considered fully saturated if hydrostatic conditions are assumed. The depth where saturation may occur is approximately 40 metres below the ground water table, however depending on the nature of the coal it may occur at depths as shallow as 30 metres. If the pressure distribution in the water is not hydrostatic but dependent on vertical dewatering, then depths at which saturation occurs may be significantly greater.

In the Latrobe Valley open cuts mines, an assumption that the coal is fully saturated below the water table has been adopted. These results however, suggest this assumption is not necessarily true. This may mean that coal seams below the water table behave differently to what has been expected and that calculations of undrained shear strength should account for the material being unsaturated.

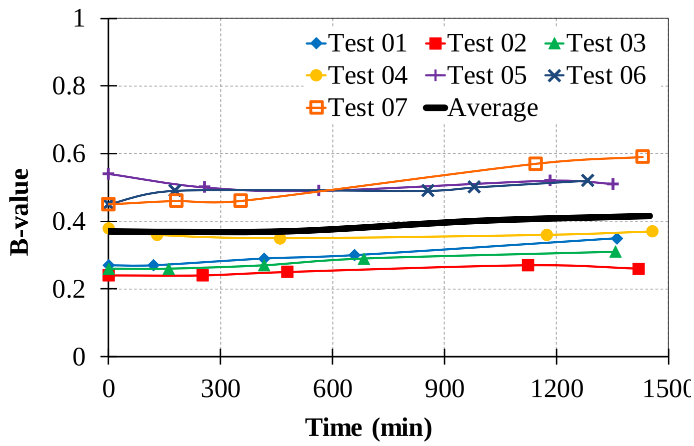

Figure 4. B-value versus time for Stage 1 in all seven tests (Back Pressure=50kPa)

From Figure 2 it appeared that most of the change in the B-parameter was induced by the change in back pressure. To investigate the time factor, the possible relationship between time and B-parameter in a constant back pressure regime was measured. Figure 4 shows the B-parameter values versus time in Stage 1 of all performed seven tests in which the back pressure has been kept constant at 50 kPa. In this figure it is clear that the B-parameter does not change with time.

The relationship between the B-parameter and volume change was also investigated, however the plots provided no clear relationship. An example plot of B parameter versus volume change is shown in Figure 5 which represents the B-parameter values versus time in Stage 1 of all performed seven tests in which the back pressure has been kept constant at 50 kPa

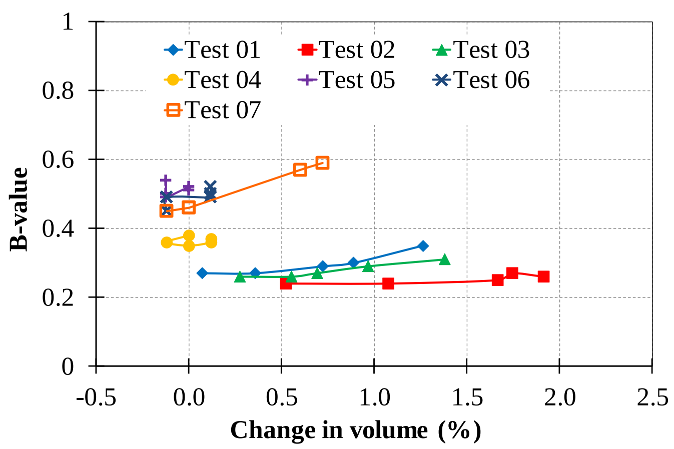

Figure 5 B-value versus volume change for Stage 1 in all seven tests (Back Pressure=50kPa)

Although it appears there may be some relationship in the early tests, the data set as a whole clearly shows that the change in B-parameter and the volume change occurred independently of each other.

4 RESULTS AND DISCUSSION

The research suggests that Latrobe Valley brown coal will not be fully saturated immediately below the water table. The results indicate that approximately 40 metres below the water table the brown coal approaches saturation. In addition to this, the rate at which brown coal approaches saturation significantly slows once pressures in excess of 250kPa are reached.

This research also suggests that in the short term, increase in pressure has a greater influence on degree of saturation of brown coal than the length of time the pressure is applied. However, it can also be assumed that if a constant lower pressure is applied to a specimen for a long period, the B-parameter will continue to increase but very marginally.

Finally, it appears that some chemical constituents in the water may have reacted with the specimens during the tests, even though de-aired water was used as suggested by the referenced standards. Without further testing, few conclusions may be drawn about the actual effect on the specimens due to reactions with the de-aired water supply used. The rust and deterioration observed in the equipment in such short time periods suggest some chemical reactions were present. In future tests the use of an equivalent groundwater may be beneficial. Otherwise, a representative sample of groundwater from the coal sampling site may be used.

5 CONCLUSION AND RECOMMENDATIONS

Latrobe Valley brown coal was found to be not fully saturated in the stress level just below the water table, and it doesn't approach saturation unless it is approximately 40 meters below the water table.

This research will contribute to improvements in the current understanding of coal movements during and following open-cut mining. The findings will be used in the development of a new consolidation theory for coal and effective stress analysis and inform slope stability modelling in open-cut coal mines.

Further analysis could be done to develop more representative B-values by include testing samples from a larger range of sampling sites, both on a mine scale and a regional scale. Testing could also be conducted on larger samples of coal to see if this has any influence on the results.

Investigation into the geochemical make-up of the brown coal, including determining what gases are present and the behaviour of the brown coal structure under pressure are also required.

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