Large scale testing of mine spoil

L. R. Bradfield[1,2], S. G. Fityus[2] and J. V. Simmons[2,3].

[1]Thiess Australian Mining, Technical Resources, Brisbane, Queensland
[2]The University of Newcastle, Newcastle, New South Wales
[3]Sherwood Geotechnical and Research Services, Peregian Beach, Queensland

ABSTRACT

This paper presents the results of an experimental study in which a strong Permian mine spoil from the Hunter Valley, Australia was tested under unsaturated and saturated conditions, using a large direct shear machine. The direct shear machine, with a specimen size of 720mm x 720mm x 600mm and a normal stress capacity of 4.5 MPa, was designed and constructed at the University of Newcastle. The spoil material tested is dominated by siltstone with some fine to medium grained sandstone fragments. The large size of the test device allows specimens with particles as large as 100mm to be tested. Tests under unsaturated and saturated conditions recorded considerably different strengths, with peak friction angles of spoil in the unsaturated condition being as much as 6 degrees greater than the same spoil in a saturated state. The reduced strength under saturated conditions is attributed to the effects of reduced matric suction within the rock fragments of the spoil, and the effect this has on the basic rock fragment strength.

Keywords: mine spoil, direct shear, large sample, high stress

1 INTRODUCTION

The Australian open-cut coal mining industry contributes around 80% of the nation's black coal. Safe and economical recovery of deeper reserves requires the resolution of a range of complex geotechnical issues. Design of stable spoil dumps requires prediction of the shear strength as dump heights, and consequences of failure, become proportionately higher.

Currently in Australia there are spoil dump heights in excess of 200m and plans to achieve pit depths of 350m, which potentially translates to dump heights of more than 400m. Shear strength estimation for spoil dumps has been based on limited, very small-scale tests or on published guidelines such as the BMA Coal (BMA) strength framework (Simmons and McManus 2004). The BMA framework strengths are expressed as Mohr-Coulomb linear envelopes which were derived from small-scale testing, and adjusted by backanalyses of failed dumps up to 120m height. For rockfill dam design there is broad acceptance of a curvilinear shear strength envelope (Leps, 1970; Barton and Kjaernsli, 1981), and if this was applicable to coal rock spoil then the BMA approach would potentially overestimate strengths at higher stress levels. Following acknowledgement that current spoil dumping practices are far exceeding the stress limit for which strength has been verified, the coal industry committed funding to research involving testing of the largest possible specimens of spoil to very high stress ranges.

2 BACKGROUND

The BMA strength framework grew out of collaborative research between CSIRO and BHP Engineering over the period 1978-1981, when spoil dumps rarely exceeded 90m in height. Since that time the industry has relied on extrapolation, backed by observations of stable dumps that are currently up to 350m height. Project-specific spoil testing is rare, typically based on samples scalped of oversize to allow direct shear or triaxial testing at a specimen scale of about 100mm, and restricted to effective normal stresses of 1MPa or less that can be achieved using routine equipment.

Scalping of oversize particles to match device scale constraints means that the influence of large particles on shear strength is disregarded. Limited information available (Frossard et al., 2012; Nakao and Fityus, 2008) indicates that scalping of oversize leads to significant strength differences under certain conditions. In addition to this, the effective vertical stress near the base of a 250m dump is likely to be much greater than 1MPa.

To overcome the above limitations, a large-specimen and high-stress direct shear machine has been designed and constructed at the University of Newcastle. The large direct shear machine (LDSM) accommodates specimens with dimensions 720mm-square in the plane of shearing, and 600mm thick. The large specimen volume means that typical spoils can be tested with minimal resort to scalping. The machine can apply a normal stress up to 4.5MPa to the specimen, which is sufficient to simulate field-stress conditions for spoil dumps to at least 400m height, as justified below.

3 DESIGN OF THE LARGE DIRECT SHEAR MACHINE

3.1 Conceptual Design

The approved budget for the project was a limiting factor in determining the largest possible specimen and loading system that could be constructed using the resources available for the project. The first design step was to estimate the expected stress-states for a 400m-high coal-measures spoil dump, based on the shear strength parameters provided by the BMA strength framework. These estimates were made in two ways:

1. Mohr-Circle Analysis. The c-ϕ strength envelopes for the strongest spoils in the BMA framework were extended beyond the framework's implicit normal stress limit of 1.5MPa. Assuming the major principal stress, σ'_1, to be 8MPa, equivalent to 400m of spoil cover, the maximum σ'_n that was likely to act on a failure surface at the base of a 400m-high spoil dump was determined as the tangent point of the Mohr-circles defined by σ'_1 = 8MPa with the extended c-ϕ strength envelope.
2. Limit Equilibrium Analysis. A dump slope height of 400m was assumed, with a steepest-possible single batter angle of 37°, equivalent to the commonly-observed angle of repose for dumped spoil. Stability analyses were carried out in accordance with the BMA framework methodology, from which the maximum normal and shear stresses acting on the slice boundaries of the critical mechanism were determined.

The Mohr Circle analyses indicated that normal and shear stresses at failure were unlikely to exceed 3.5MPa and 2.1MPa respectively; whilst the limit equilibrium analysis indicated that the maximum normal stress could range between 3.1MPa and 3.4MPa, depending on the inclination of the dump foundation. Because both estimation methods were based on the BMA framework strengths, potential envelope curvature meant that the calculated normal and shear stresses might, if anything, overestimate the actual limiting stress conditions applying to 400m high dumps.

Very large forces were required to generate the target stress capacities for the largest practically achievable test specimen. For this reason both the compressive and shear loads were conceived as being applied through a self-supported reaction frame, using commercially available actuators with suitable load capacities and strokes. The finalised LDSM is shown in side view in Figure 1.

3.2 Split Shear Box

Iterative shear box sizing was carried out for different numbers of standard actuators having a minimum safe-load rating of 980kN (100 tonnes). The available budget then guided the choice of a box with shear plane dimensions 720mm-square and a maximum specimen thickness of 600mm. According to relevant test methods, (ASTM D3080-98, and QTMR Q181C-2002), these dimensions allow for maximum particle sizes of 85mm-100mm. During commissioning it was found that specimens with rock fragments up to 150mm in diameter made no significant difference to the measured shear strength. Taking into account the shear plane dimensions, and based on the above-referenced methods, a maximum working shear displacement of 150mm was selected, allowing for a maximum relative shear displacement of 20%.

The upper and lower boxes were each constructed from four pieces of 120mm thick, 250-grade mild steel, and to avoid potential distortion and facilitate maintenance were bolted together rather than welded. Shorter sides were recessed into the longer lengths via a 20mm-deep slot, with the longer sides secured with high-tensile strength threaded rods. To allow for specimen compression of up to 100mm, the upper and lower boxes were 350mm-high, and 250mm-high respectively. Shear displacement is applied to the lower box and the shear stress is transmitted through the specimen to the upper box, which bears on load cells which are reacted by the frame. This maintains suitable reaction line locations for both normal force and shear force application, and it means that any friction at the bottom of the box does not contribute to the measured shear force.

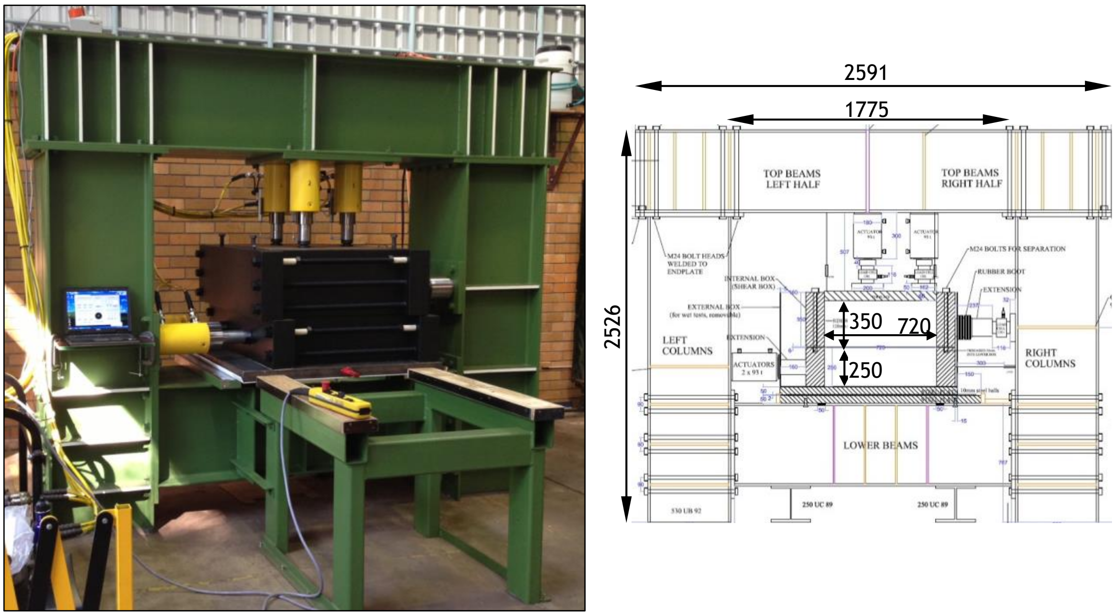

Figure 1. Side view of finalised LDSM showing split shear box and normal and shear load paths

Selection of wall-thickness for the boxes was based on achieving as rigid a structure as possible, to minimise deflection and associated volume changes caused by transfer of forces from the actuators through the specimen to the reaction systems. Two loading conditions and two shear box positions were considered for deflection calculations, as listed in Table 1. Wall thicknesses ranging from 40mm to 120mm were analysed approximately by hand and checked using the Strand7 code. A wall thickness of 120mm was selected to achieve wall deflections of 0.25mm or less at maximum load. The top plate for normal load applications was similarly determined to be 80mm thick using stiffer 350-grade steel.

Table 1: Upper and Lower Bounds of σ'_n based on Available Equipment and Shear Plane Area

		Lower split-box position	
Available Force actuators with nominal 100 tonne safe working load		Start Position, shear plane area = 0.518m^2 (720mm x 720mm)	End Position, shear plane area = 0.410m^2 (720mm x 570mm)
2 actuators	**1960 kN**	σ'_n = 3785 kPa	σ'_n = 4780 kPa
3 actuators	**2940 kN**	σ'_n = 5675 kPa	σ'_n = 7170 kPa

Only two actuators were required to achieve the required normal stress of 3.5MPa across the shear plane at the starting position. However, three actuators were chosen to positively manage loading in the event of rotation of the top plate and to allow for operation at well below maximum capacity.

In addition to nominal separation after initial compression, two thin 'sliders' that are placed between the boxes in the direction of shear. The sliders consist of a strip of lubricated PVC overlying a strip of polished stainless steel. Unloaded tests, and calibration tests on silica sand with known strength parameters, indicate that the sliders generate negligible resistance to the shear loading path.

The assembled box can also be placed within a water-bath to enable specimens to be flooded and tested under saturated conditions. The water-bath consists of a stand-alone watertight external box fabricated from 5mm-thick stainless steel, with elongated rubber grommet seals to accommodate the relative movement between the water bath and the actuators. For work clearance and seal requirements, the shear displacement for inundated tests was restricted to 100mm, equivalent to a relative shear displacement of 14%. For all of the tests performed, the ultimate shear strength was observed to develop at relative shear displacements ranging from 3% to 10%.

3.3 Reaction Frame

The reaction frame was conceived as a self-standing and internally-reacting rectangular enclosure, constructed from 530 UB rolled steel sections, with welded stiffeners and bolted connections. Vertical actuators react against the top of the frame and push the sample against the bottom. Horizontal actuators react against one side of the frame, to push the bottom box, which in turn transmits shear to the upper box which reacts against the other side of the frame (refer to Figure 1). The frame was initially designed using a fixed-end beam configuration then checked using Strand7 and independently reviewed by a structural engineering consulting firm.

3.4 Compressive Loading System

The compressive loading system consists of three 100-tonne double-acting hydraulic actuators mounted to a common base plate on the upper span of the reaction frame. They are positioned so that the centroid of an imaginary equilateral triangle made between the geometric centres of the three cylinders is half-way between the centroids of the shear-plane area at the start position (horizontal displacement = 0mm), and the end position (horizontal displacement = 150mm). Tilt saddles were fitted to the ends of the hydraulic rams to prevent them from exerting any additional shear force that would increase the shear stress applied to the specimen. The tilt saddles are free to rotate in all directions by up to ±15°from the horizontal, but in all tests to date, only tilt angles less than 2° have been observed.

The compressive force exerted by the actuators is transmitted to the specimen by the 80mm thick load cap. The bottom box rests upon a 250-grade, 50mm thick base plate which acts as the bottom of the box. The base plate rests on a fitted PTFE sheet, which is in turn supported by a lower, stationary 50mm bed plate that is fixed to the lower cross members of the reaction frame. The PTFE sheet provides a low-friction sliding interface, and is discussed further in the following section.

3.5 Shear Loading System

Shear displacements are applied to the lower split-box using two 100-tonne double-acting hydraulic actuators mounted to a common steel plate on one side of the reaction frame. The rams contact the lower shear box at mid-height, and are therefore eccentric to the shear plane. Ignoring any frictional losses, the hydraulic system has the capacity to mobilise a shear stress in excess of 3.5MPa at the shear plane.

Shear displacement between the lower box and the frame is accommodated by a 4.5mm-thick, dimpled PTFE sheet, of the type used as a bearing in the incremental launch of concrete bridges. The PFTE sheet is attached to the underside of the bottom plate, and it slides on a 1.5mm-thick sheet of polished stainless steel that is mounted on the top of the bed plate. The PTFE arrangement was selected for ease of fabrication and its very low frictional resistance, with the manufacturer specifications reporting a coefficient of friction, μ, related to normal stress, σ_n (MPa) as:

$$\mu = 1.2 / (10 + \sigma_n) \qquad (1)$$

The coefficient of friction is hence greater for low values of σ_n. For the LDSM, the friction at the PTFE sliding interface translates to an additional 30kN to 300kN load on the actuators for tests performed at 500kPa and 3500kPa respectively.

In tests to date, shear displacement rates between 0.2 and 1.5 mm/min have been used. The shearing rate was initially determined using the provisions of ASTM D3080-98 for the observed time to achieve 50% of specimen compression under applied stress. The calculated displacement rates were then halved to minimise the likelihood of excess pore pressures existing at the observed failure condition.

3.6 Controls and Data Acquisition

The hydraulic system consists of two independent hydraulic circuits powered by a split-flow electric-hydraulic pump, and operated by a hand-held controller. The fluid flow can be set to manual or automatic for both splits, with the automatic flow governed by a manually-operated pressure-flow-control valve located on the pump. The compressive loading system generally operates in a stroke-synchronous mode such that all three rams travel together, however they can also be operated independently of one another. The compressive loading circuit does not have the ability to control pressure, and as such, manual adjustments via the hand-held controller are required to maintain the target test value. Unlike the compressive system, the shearing system does not allow for the hydraulic rams to operate independently of each other.

Compressive loads are measured by three in-line actuator pressure transducers. Shear stresses transmitted to the upper box are measured by two 1800kN load cells, mounted between the upper box and the frame. Based on calibration tests, the pressure transducer accuracy is within ± 1.5%, and the shear load cells within ± 0.5%. Displacement transducers are fitted to each of the hydraulic rams and monitor vertical and horizontal movements to within 0.1mm. The shear displacement rate can be adjusted manually within the range of 0.1mm to 50mm/minute. All data is logged and visually displayed during operation, with real-time monitoring to allow for adjustments to be made manually to any of the load control systems as required.

3.7 Design Implications and Calibration Testing

The LDSM is different from a conventional direct shear apparatus in two potentially significant ways. Because the lower section of the shear box is displaced, a much simpler compressive load path for the large forces is possible. Measurement of the total shear force acting at the specimen shear plane is simplified by the positioning of the shear load cells.

The shear application and reaction lines are not co-planar, implying that a moment is generated at the specimen shear plane. The design of the compression load system allows the rotation of the top plate to be minimised, in effect applying a counteracting moment at the specimen shear plane. This configuration of forces on the nominal shear plane is a significant departure from the conventional direct shear apparatus design, but is considered to be justified because the true stress distribution in any direct shear test is distinctly non-uniform and the intention of any direct shear test is to create a rupture surface along the nominal shear plane with minimal distortion away from the rupture surface.

Inspections of post-test specimens and vertical displacement transducer data have demonstrated that specimen distortion in the compressive load direction is almost negligible for all types of spoil tested under both saturated and unsaturated conditions. A range of measured tilt angles is shown in Figure 2, and significantly lower than top cap tilts and specimen distortions commonly observed in traditional direct shear tests. Because the tilt angles are so small, it is concluded that the LDSM design has reduced internal distortions that are often observed with traditional shear box testing.

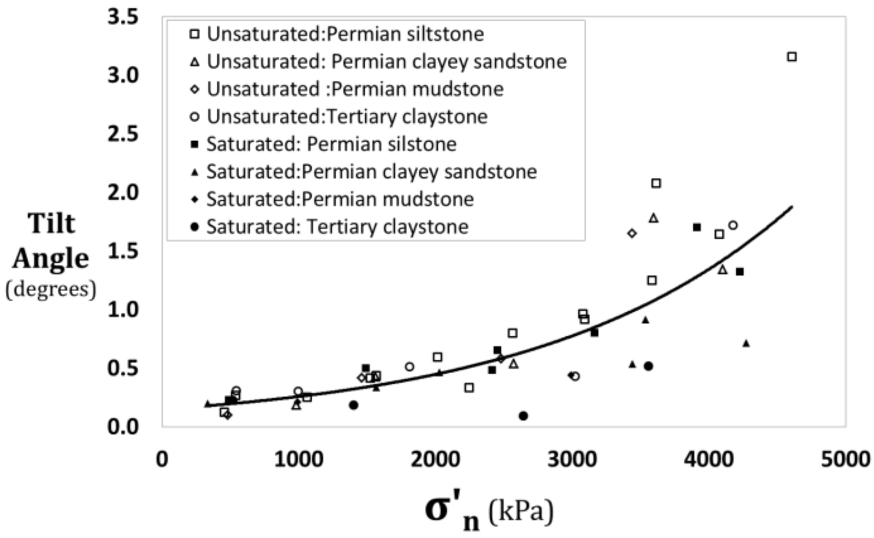

Figure 2. Tilt angle vs. test normal stress for a range of spoils and saturation conditions

Calibration testing was based on a comparison of LDSM and traditional direct shear tests using a locally well-known and consistently graded dry silica sand (Figure 3). LDSM friction angles of 31.4°

and 31.1° were obtained for loose sand over the σ’ₙ ranges 600 - 1200kPa, and 600 - 3400kPa respectively. Friction angles of 29.5° and 31.1° were similarly measured for the same loose sand using commercially accredited 300mm and 60mm equipment respectively. The 300mm tests were performed for the project over the σ’ₙ range 500 - 1100kPa, and separate 60mm tests by Ajalloeian et al. (1996) had previously been performed on similar sand for σ’ₙ of 40 - 380kPa. It was concluded that the LDSM results are comparable with, and as acceptable as, those from traditional apparatuses, and that the 1.6° to 1.9° variation in friction angle between the 300mm box and the other apparatuses is most likely to be a configuration or operational feature of that particular device.

4 MINE SPOIL MOISTURE CONDITIONS FOR TESTING

Mine spoil is created from insitu coal measures rock material by the processes of excavation and dumping. Most insitu rock is initially saturated because it is located below the groundwater table. Formation of a dump occurs incrementally, so that freshly dumped spoil is initially a particulate mass under a low stress state. Under such conditions the particles may be initially saturated but the mass is unsaturated with relatively large void volume. Dump construction increases the stress state, and compression of the mass leads to a reduction in void ratio. Some time-dependent loss of water from the particles may occur by vapour transfer at particle boundaries. Most of the spoil mass within a dump will remain in an effectively unsaturated state, except where the void space becomes filled by water due to some combination of groundwater transport or compression that eliminates gas from the void volume.

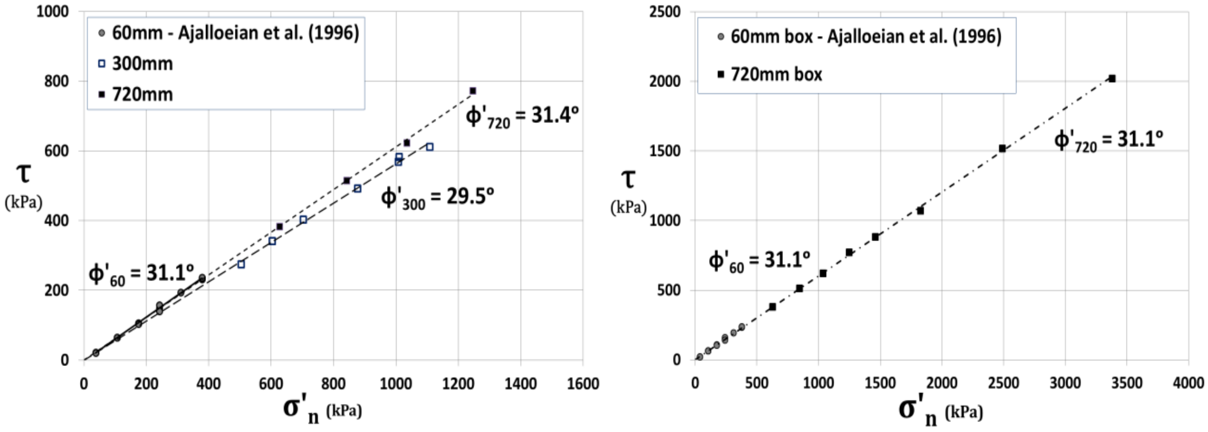

Figure 3. (a) Comparison of measured shear strength for a silica sand in 60mm, 300mm and 720mm shear boxes in the low normal stress range; and (b) Comparison for 60mm and 720mm boxes at low and high ranges of normal stress respectively

Typically, a spoil sample will be therefore be unsaturated but have a characteristic water content that is a function of the conditions at the sampling location. For the research project it was determined that initial air-drying for a period of days at the prevailing naturally ventilated laboratory conditions was unlikely to have any significant effects on the shear strengths measured, while minimising the extent of desiccation damage caused by drying to constant mass at an elevated temperature. Measurements of moisture content before testing indicated that air-drying reduced the initial moisture content by roughly 50% from the as-sampled condition, but not to anywhere near the constant-mass condition of oven drying. The authors believe that this preparation method provided reasonable control of the normal unsaturated condition of mine spoil dumps for testing purposes.

Testing at LDSM-scale involves handling more than 0.5 tonnes of spoil material per test specimen, and the tests reported below were obtained without separating and re-combining particles of different size ranges and lithologies to achieve fully controlled specimen uniformity. For this reason repeat tests were carried out for many compressive stress points to estimate the effects of compositional variability between specimens. Unsaturated specimens were initially air-dried and then loose-placed prior to compression. Saturated specimens were similarly treated until initial compression was complete, and then inundated using the water bath until no further deformation response was observed. This sequence was followed because it is the stress path most likely to occur when a water table develops in an existing spoil dump under actual mining conditions.

5 TESTS ON MINE SPOIL

This paper describes the use of the LDSM to measure the variation in shear strength from the unsaturated to saturated condition for a spoil sample obtained from the Mount Arthur Mine in the Hunter Valley of New South Wales. The spoil was derived from a blocky fresh fine to medium grained Permian sandstone and siltstone sequence of medium and high rock substance strength. It had a small proportion of liberated clay-minerals derived mainly from the cementation of the rock substance. Some scalping was required with particles larger than 100mm being crushed and re-mixed with the bulk sample.

Shear displacement rates were 0.5mm/min and 1mm/min for the saturated and unsaturated tests respectively. Figure 4 shows the data points for the peak strength mobilised in each test. For clarity, strength envelopes are not shown for these data sets, but it is immediately obvious that the saturated test results have an envelope that is significantly lower than for the unsaturated test results, with the individual test secant strength friction angle ϕ_s' (arctan τ/σ'_n) varying by up to 6° between the unsaturated and saturated states.

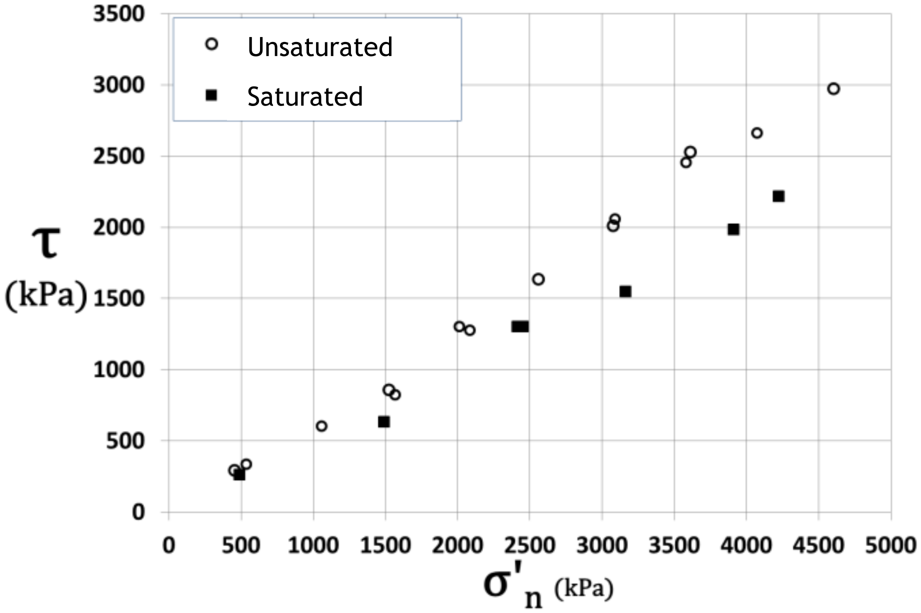

Figure 4. Variation of shear strength results for fresh Permian spoil tested under saturated and unsaturated conditions

Reduced mass shear strength under saturated conditions was attributed to permanent and irreversible alteration of structure that occurs when spoils with water-sensitive mineralogies are saturated. The authors believe that the saturated frictional strength reduction effect is attributable to reductions in the strength of the spoil particles, primarily due to the effects of reduced matric suction at the particle boundaries.

Determination of design shear strength envelopes to the test results shown in Figure 4 is not simple or straightforward and is a matter of judgement that is not discussed in this paper. The fresh Permian spoil envelope appears to be essentially linear, with no obvious reduction in secant friction angle at higher stress levels. Future testing, including consideration of embedded pore pressure sensors, will be undertaken to further evaluate the strength phenomena that have been identified by LDSM testing.

To date, LDSM test results for a wider range of unsaturated coal measures spoils have been generally consistent with the BMA framework parameters. For the Mt Arthur Mine spoil described in this paper, regarded as typical Cat 2, and the subset of Figure 4 test data performed at σ'_n = 500kPa, 1000kPa, and 1500kPa, the linear fit was c'= 54kPa with ϕ'= 27.5°, compared to the framework parameters of c'= 30 (± 15) kPa with ϕ' = 28° (± 3°). The slightly higher c' interpreted from the LDSM data may be explained by a number of factors, including variations in machine stiffness, possible envelope curvature for the σ'_n range used in the LDSM, or the effects of including larger particle sizes that would have been scalped from the small-scale shear box tests results from which the BMAC framework was derived.

Clearly the Figure 4 results are not consistent with the conceptual curvature of the shear strength envelopes that would be expected if the rockfill shear strength model of Barton and Kjaernsli (1981) was applicable. There are many potential factors that contribute to such differences, and these have been the subject of other investigations within the research project that are not reported in this paper.

6 CONCLUSIONS

Shear strength measurement in mine soils and rock fill is a difficult task because of the size of the sample needed to give results that are representative of the true grading of the material. It is made more difficult in the situation where the stresses become very large. The large direct shear machine described in this paper allows for direct measurement to obtain meaningful data.

Shear strength data obtained to date and described above are closely consistent with some but not all of the BMAC strength framework. The reduction in friction angle by around 6 degrees between saturated and unsaturated conditions is consistent with the BMA framework of Simmons and McManus (2004). Evidence has been presented above that the curvilinear strength envelope concept of Barton and Kjaernsli (1981) may not be applicable to spoil derived from coal measures rocks. Separate investigations within the project are suggesting that concepts of unsaturated soil mechanics may be applied to unsaturated spoil materials because of the dominating role of interparticle contact shear behaviour within essentially granular masses.

7 ACKNOWLEDGEMENTS

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