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Shear strength characterisation for very-high coal mine spoil dumps: Applicability of an industry-accepted framework

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ABSTRACT: Selection of appropriate shear strength parameters for mine spoil slope stability analysis and design is difficult because it requires prohibitively large laboratory equipment to test characteristic spoil samples under meaningful stresses. A convenient alternative to estimate mine spoil shear strength is to adopt published guidelines that have been tried-and-tested in practice. For more than two decades, the Australian coal mining industry has adopted a linear shear strength framework derived from small-scale test data and verified in practice by slope performance of dragline-scale spoil dumps up to 120m in height, and to date this framework has appeared reliable. However, in the field of rockfill dam design there is a broad acceptance of a curvilinear shear strength envelope, and if this is applicable to coal mine spoils, then this industry-accepted framework may overestimate the strength and stability of dumps at higher stress levels. This is particularly relevant in modern times where dump heights (>350m) often exceed the scale (≤120m) for which the framework was developed. This paper explores the applicability of this framework for high-dump situations for a range of coal mine spoils. This is achieved by comparing their framework-assigned strength envelopes with direct measurements of their strength obtained from a custom-built large direct shear machine (LDSM). The machine can test at a much larger scale, in terms of combined specimen size (720mm x 720mm x 600mm) and stress (σ'_n up to 4600kPa) than has ever been achieved using a direct shear machine for geotechnical testing of rockfill. A critical outcome is that the LDSM data highlights several non-compliant mine spoils, and stress-dependent shearing behaviour, for which correct application of the published framework will not provide reliable shear strength parameters for design.

1. INTRODUCTION

Selection of appropriate shear strength parameters for mine spoil for slope stability assessment and design is a challenging task. There are limited options available to precisely determine shear strength parameters for mine spoil materials. Direct measurement of shear strength requires prohibitively large laboratory equipment that can test characteristic (large) spoil samples under meaningful stresses. An alternative is to indirectly determine shear strength parameters from back-analysis, but this requires specific conditions and data to be available.

A convenient approach is to adopt published guidelines such as the BMA Coal (BMAC) shear strength framework (Simmons and McManus, 2004), which assigns typical shear strength parameters for coal mine spoils, according to their categorisation based on qualitative visual-tactile attributes. The BMAC framework has been used by the Australian coal mining industry for more than two decades, and mostly appears to be reliable. However, because the BMAC framework was developed for spoil dump heights ≤120m typical of dragline strip mines throughout the 1970's and '80's, the applicability or potential limitations of the framework for modern dump heights (commonly >350m) with correspondingly larger stresses is unknown.

This paper explores the applicability of the BMAC framework to high-dump situations that exceed the stress limits for which the BMAC framework was originally developed. Theoretical limitations of the BMAC framework are also considered.

This is achieved by comparing BMAC framework strengths for a range of Australian Permian black coal mine spoils with direct measurements of their shear strength obtained using a purpose-built large direct shear machine (LDSM). The machine can test a much larger scale, in terms of combined specimen size (720mm x 720mm x 600mm) and stress (up to 4600kPa), than has ever previously been achieved using a direct shear machine for geotechnical testing of rockfill.

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2. BACKGROUND

Over the period 1978-1981, when spoil dumps rarely exceeded 90m in height, BHP Engineering and CSIRO conjointly investigated the stability of dragline-scale spoil dumps in the Bowen Basin. The intent was to develop a shear strength framework for a range of spoil types which could be used in the absence of acquiring laboratory data, because there was rarely an opportunity to perform spoil-specific testing. The result was subsequently published as the BMA Coal (BMAC) spoil shear strength framework (Simmons and McManus, 2004), summarized in Tables 1-2 and Fig. 1., which provides guidelines for classifying coal mine spoils into one of four categories (CAT 1, CAT 2, CAT 3, or CAT 4), and for each it provides shear strength parameters c' and ϕ' for three strength mobilisation modes, corresponding to unsaturated (U), saturated (S) and remoulded (R) conditions.

Table 1. Spoil Categories and Attributes, after Simmons and McManus (2004)

Spoil Category		1	2	3	4
Description Attributes	Weight (*excl. Age)*	Fine-grained clay-rich high plasticity	Fine-grained low plasticity with larger clasts	Larger clasts with fine matrix, low plasticity	Large blocks, minor fines, minor slaking
Predominant Particle Size	9.7% *(11.6%)*	Clay	Sand	Gravel	Cobbles
Consistency: cohesive cohesionless	22.6% *(26.9%)*	Soft to Firm Loose	Stiff Med. Dense	Hard Dense	XLS+ rock Very Dense
Structure	22.6% *(26.9%)*	Matrix only	Matrix Supported	Framework Supported	Framework only
Liquid Limit	29% *(34.6%)*	High (>50)	Intermediate (35-50)	Low (20-35)	Not Plastic (<20)
Age	16.1%	0-2y	2-10y	10-30y	>30y
Note: XLS+ refers to rock of extremely low strength, or higher					

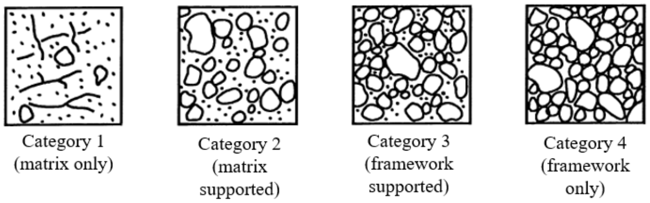
Category 1 (matrix only)
Category 2 (matrix supported)
Category 3 (framework supported)
Category 4 (framework only)

Fig. 1. Spoil structure control ranking (use with Table 1). Source: Simmons and McManus, 2004

The strengths are expressed as linear Mohr-Coulomb failure envelopes (Eq.1) and are based on small-medium scale laboratory shear strength tests with empirical adjustments using back-analyses of spoil dump failures of comparable stress.

$$\tau = \sigma'_n \tan \phi' + c' \qquad (1)$$

The framework is intended to be used with confidence for spoil dumps 30-120m in height, assuming the spoil is categorised correctly, as the stresses in dumps of this height correspond to those for which the framework was calibrated.

Table 2. Shear strength parameters for spoil categories and mobilisation modes per the BMA framework, after Simmons and McManus (2004)

Spoil Category	Unsaturated			Saturated			Remoulded c' = 0kPa
	γ' kN/m^3	c' kPa	ϕ' deg	γ' kN/m^3	c' kPa	ϕ' deg	ϕ' deg
1	18 *(1)*	20 *(10)*	25 *(2.5)*	20 *(1)*	0 *(0)*	18 *(3)*	18 *(1.5)*
2	18 *(1)*	30 *(15)*	28 *(3)*	20 *(1)*	15 *(7.5)*	23 *(2.5)*	18 *(1.5)*
3	18 *(1)*	50 *(15)*	30 *(2)*	20 *(1)*	20 *(10)*	25 *(2.5)*	18 *(1.5)*
4	18 *(1)*	50 *(15)*	35 *(2.5)*	20 *(1)*	0 *(0)*	30 *(1.5)*	28 *(2)*
Parameter standard deviations in italicised parentheses							

3. THEORETICAL LIMITATIONS OF THE STRENGTH FRAMEWORK FOR HIGH DUMP SITUATIONS

In current practice, spoil-specific shear strength testing is seldom performed 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 BMAC framework continues to be adopted in the absence of, or more commonly in preference to, obtaining laboratory data. However, despite proving a reliable tool for shear strength estimation for decades, soil mechanics theory suggests it has limitations, particularly for shear strength estimation of high dumps that are much higher than those by which the framework was developed and calibrated.

These limitations are presented below and investigated in the sections that follow.

3.1. Scale Effects: Size and Stress

The scale effects on shear strength suggests that there will be a minimum test specimen size, and a minimum test normal stress, that can be considered technically acceptable for simulating a shear surface within a high dump constructed of mine spoil.

The BMAC framework strengths were derived from laboratory tests performed on small samples scalped of oversize particles to allow for shear strength testing at a specimen scale of 100mm-300mm and restricted to an effective normal stress of around 1000kPa. The shear strength data was then adjusted empirically, based on back-analysis data from spoil dump failures for similar stresses, to account for scale effects. Limited information available (Brown and Gonano, 1976; Barton and

Kjaernsli, 1981; Barton, 2008; Frossard et al., 2012; Nakao and Fityus, 2008) indicates that scalping of oversized particles to match device constraints leads to significant strength differences under certain conditions, because the influence of large particles on shear strength is disregarded.

For rockfill dam design there is broad acceptance of a curvilinear shear strength envelope (Marsal, 1967; Leps, 1970; Barton, 1976; Barton and Choubey, 1977; Hoek and Brown, 1980; Barton and Kjaernsli, 1981; Barton and Bandis, 1982; Charles and Soares, 1984), and if this was applicable to coal mine spoil then the BMAC framework approach, which provides linear shear strength envelopes, would potentially overestimate strengths at higher stress levels if true failure envelopes are curved in a concave-down manner, as shown in Fig. 2.

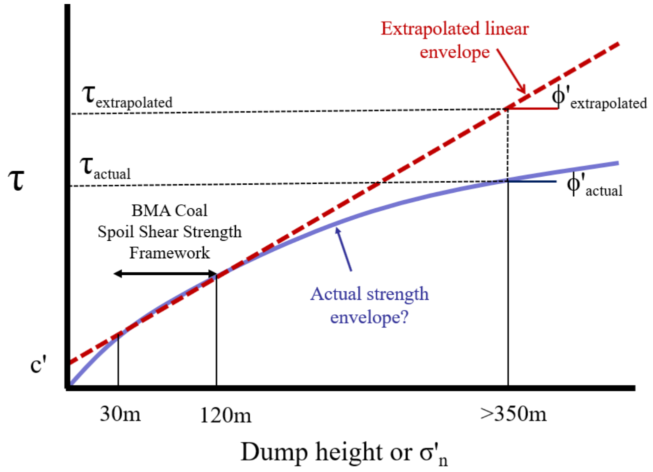

Fig. 2. Mohr Diagram showing the potential overestimation of shear strength when extrapolated BMAC framework strengths are used to define an envelope that in reality may be curved in a concave-down manner.

3.2. Bulk unit weight

The framework uses a constant value for bulk unit weight, which is unlikely to be realistic for spoil at all depths within a dump. The significance of this is that for very high dumps, the framework may underestimate bulk unit weight at depth, which in turn may underestimate the stress-states at failure.

3.3. Slake Potential

There is no specific provision for slake-prone spoils within the BMA framework. The "remoulded" condition is adopted to describe the strength of saturated, strongly-slaking spoil, although it also used to describe other modes (such as the residual strength in a failed spoil mass, or water-sensitive clays with mineralogy disposed to swelling and dispersion on saturation). The framework includes the liquid limit as a categorisation criterion, however, this is relevant only to the fine-fraction of spoil in its as-sampled condition. The literature (Gamble, 1971; Taylor and Spears, 1981; Ergular and Ulusay, 2009; Gautum and Shakoor, 2013) reports an association between slaking behaviour and the liquid limit of fine-grained soils. However, this association is relevant only to the extent that the fine-fraction is representative of the lithotypes that make up the coarse fraction.

3.4. Particle (Clast) Strength

Consistent with the terminology used by Simmons and McManus, 2004, the term "clast" is used in this paper to describe coarse "rock-like" fragments, and the term "matrix" is used to described fine "soil-like" particles in mine spoil.

Clast strength has little contribution to shear strength at low stress where shearing is achieved by dilation or repacking, however it does determine the stress level at which particle repacking ceases, and particle breakage commences.

The literature reports an association between particle strength and shear strength of rockfill material (e.g. Leps, 1970; Barton and Kjaernsli, 1981; Barton, 2008, 2012), however the BMAC framework does not directly reference particle (or clast) strength.

4. APPROACH AND METHODS

The applicability of the BMAC framework for high-dump situations was investigated for five different Australian Permian black coal mine spoils. Each of the mine spoils were first categorised using the BMAC framework (Simmons and McManus, 2004). Laboratory testing to characterise the basic engineering properties for each of the spoil types was also conducted.

Comparisons were then made between the assigned BMAC framework shear strength envelopes for each of the spoil types with direct measurements of their shear strength obtained using a purpose-built large direct shear machine (LDSM), both within the intended stress range for which the BMAC framework was developed, and when extrapolated to higher stresses.

Evaluations were made over the wide normal stress range offered by the LDSM of ~325-4600kPa, noting that the applicable stress range of the BMAC Framework for a typical Category 2 spoil material is ~270 – 1080kPa (Bradfield et al., 2014).

4.1. Test Materials

The quantities of spoil material required for the large-scale laboratory testing provided some significant challenges. Of primary importance was to obtain sufficient quantities of a wide variety of spoils that would be representative of those typically encountered in Australian Permian black coal mines. Expressed in terms of the BMAC framework, Category 2 or Category 3 spoils were the priority for bulk sampling as these are the most common of the Permian spoil materials. Category 1 spoil was also important because it represents the weakest and ‘worst’ material for dump stability. Category 4 spoil was low priority in terms of reliability for design because it is strongest coal mine spoil.

Five spoil types (Fig. 3) were bulk sampled from coal mines in the Bowen Basin and Hunter Coalfields of Eastern Australia. At least 20 x 200L drums of material was required for each spoil type to produce enough shear strength data. In total, more than 120 drums of spoil were collected and for testing, representing BMAC Category 1, 2 and 3 materials.

4.1.1. Description of Spoil Types

The discussion that follows includes references to geotechnical index properties (described in Section 4.2.2 and summarized in Table 5) for each of the spoil types.

Spoil Type 1 was derived from rocks of Late Permian in age in the Hunter Coalfields, and lithology was predominantly siltstone and fine to medium grained sandstone, with small amounts of claystone, shale, tuff, laminite and conglomerate. The samples were obtained from freshly exposed interburden debris and from a spoil dump aged 2 years, but upon close inspection, were essentially the same material. The fines had low plasticity, and the clasts demonstrated low slake and swell properties.

Spoil Types 2, 3 and 4 were also fresh spoils derived from rocks of Late Permian age, but with varied lithologies.

Spoil Type 2 from the Hunter Coalfields was a low strength carbonaceous mudstone spoil that had variable, but generally low slake and swell potentials.

Spoil Types 3 and 4 were Bowen Basin spoils, obtained from the same pit, geological sequence and mining horizon. They derived from the same interburden sequence and were therefore operationally handled in the same way. Despite this their geotechnical properties differed considerably. Spoil Type 3 derived from an interbedded sequence of clayey siltstone and clayey sandstone and contained low-medium strength clasts, and had low to moderate slake potential and low dispersion potential. Spoil Type 4 derived from a massive clayey sandstone unit and consisted of very low strength clasts, and had very high slake and high dispersion potential. The lower slake and dispersion potential of Spoil Type 3 was attributed to its higher organic matter content (within the carbonaceous siltstones) than Spoil Type 4.

Spoil Type 5 was a Neogene claystone soil produced from weathered volcanic extrusives. It was sampled from a prestrip horizon in a Bowen Basin coal mine. The sample was extensively degraded, occurring mostly as lumps of clay with little or no recognizable rock structure. This spoil had extremely low strength clasts, the fines exhibited high plasticity, and the soil fragments exhibited very-high slake and swell potentials.

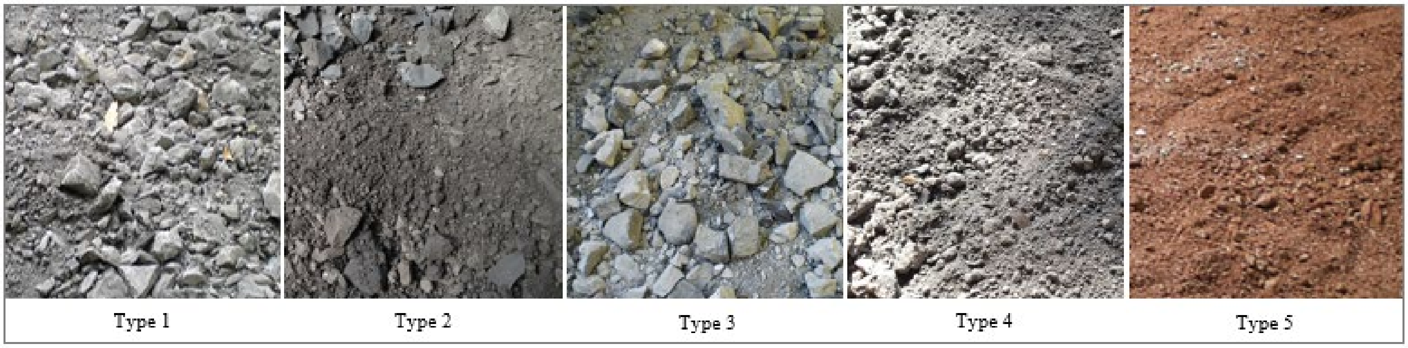
Type 1 Type 2 Type 3 Type 4 Type 5

Fig. 3. Photographs of the five spoil types considered in this study

4.3. *Characterisation of Mine Spoil*

4.3.1. BMA Coal Spoil Shear Strength Framework

Each of the spoil types were categorised according to the BMA Coal (BMAC) Shear Strength Framework (Simmons and McManus, 2004) (Table 3). The categorisation is based on the likelihood (expressed as a percentage) that a spoil applies to a particular category, based on five geological attributes. The resultant spoil category is that which has the highest likelihood (majority weighting); for example, a spoil that has an 84% likelihood of being a Category 2, and a 16% likelihood of being a Category 1 receives the Category 2 classification (CAT2). However, industry practitioners occasionally adopt shear strength parameters that are intermediate between two spoil categories (e.g.CAT1.5, CAT2.5, CAT3.5) if slope performance and/or back-analysis provides sufficient basis to do so. Consistent with this practice, the spoil types were also categorised by likelihood, but noting that this is not the method prescribed in the spoil categorisation process.

Table 3. Shear strength parameters for spoil categories and mobilisation modes per the BMA Coal strength framework, after Simmons and McManus, 2004

	Spoil Type				
	1	2	3	4	5
Likelihood (%)					
CAT 1	0	10	16	44	100
CAT 2	71	74	84	56	0
CAT 3	29	16	0	0	0
CAT 4	0	0	0	0	0
Spoil Category by Majority Weighting					
	CAT2	CAT2	CAT2	CAT2	CAT1
Spoil Category by Likelihood					
	CAT2.5	CAT2	CAT2	CAT1.5	CAT1

From Table 3, by majority weighting, Spoil Types 1, 2, 3 and 4 are all CAT2 spoils, whilst Spoil Type 5 is a CAT1 spoil. If the spoils are categorised by likelihood, however, Spoil Type 1 becomes a CAT2.5 spoil, and Spoil Type 4 becomes a CAT1.5 material.

4.3.2. Geotechnical Properties

Laboratory testing to characterize additional engineering properties of the spoil included: evaluation of moisture content, clast strength, spoil fabric composition, Atterberg limits, and slake, swell and dispersion potentials. The results of these engineering properties are summarized in Table 5.

Moisture Content

Gravimetric moisture content, *w* (%), was measured for each of the spoil samples in accordance with AS1289.2.1.1-2005. Operational constraints meant that bulk spoil samples could not be prepared to identical moisture contents; and instead, representative samples were prepared in similar ways to simulate "unsaturated (air-dried)" and "saturated" moisture conditions, consistent with the strength mobilisation modes described by Simmons and McManus, 2004. Hence, the objective became to identify 'typical' moisture contents for each spoil type in its unsaturated (air-dry) condition, and in its saturated condition.

For the unsaturated "air-dried" moisture condition, bulk samples (500-600kg) were placed onto a 3-m x 3 m square tarpaulin on the floor, raked to a uniform thickness, and left to dry-back by evaporation for 12–24 hours prior to testing. For the "saturated" moisture condition, samples for moisture content testing were collected after the saturated direct shear tests were performed.

Clast strength

Clast strength was estimated using the descriptions provided by CoalLog (Larkin and Green, 2012), as shown in Table 4.

Table 4. CoalLog rock strength descriptions (Larkin and Green, 2012)

Estimated Rock Strength	Code	Description
Extremely low strength rock	R1	UCS < 1 MPa; may be broken by hand and remoulded (with the addition of water if necessary) to a material with soil properties.
Very low strength rock	R2	UCS 1 - 5 MPa; crumbles under a single firm hammer blow, can be peeled with a knife.
Low strength rock	R3	UCS 5 - 10 MPa; breaks under a single firm hammer blow, scored but not peeled with a knife
Medium strength rock	R4	UCS 10 - 25 MPa; breaks under 1 to 3 hammer blows, can be scratched but not scored with a knife
High strength rock	R5	UCS 25 - 50 MPa; breaks under 3 to 5 hammer blows, hard to scratch with a knife, can be scratched with tungsten-tipped tool, hard sound when struck with hammer
Very high strength rock	R6	UCS 50 - 100 MPa; breaks under 1 hammer if resting on solid surface, cannot be scratched by knife, scratched with difficulty by a tungsten-tipped tool, dull ringing sound when struck with hammer.
Extremely high strength rock	R7	UCS > 100 MPa; difficult to break with hammer even if resting on solid surface, bright ringing sound when struck with hammer

Spoil fabric

Mine spoils are highly variable materials that can consist of both fine and coarse fractions in any relative proportions, depending on parent rock lithology, mine handling processes, and exposure to air and water. The relative proportions of fine and coarse particles can vary strongly between samples obtained from the same location and more broadly within the dump, which reduces the meaningfulness of precise particle size distribution of small samples and makes classification according to particle size distribution problematic. Rigorous particle size distribution assessment was not performed on the spoil samples, primarily for this reason.

Instead of performing particle size analysis, the relative proportions of fine "matrix" and coarse "framework" material was qualitatively described for each spoil type consistent with the "spoil structure control ranking" (Simmons and McManus, 2004).

Atterberg Limits and Classification

Atterberg limits were determined according to AS1289.3.3.1-2009, AS1289.3.2.1-2009 and AS1289.3.1.1-2009. Preparation for Atterberg Limits testing involved sieving air-dried spoil samples to sub 425 µm. Because the mineralogical composition of the spoil samples was not known, potentially destructive processes such as oven-drying and mechanical crushing (mortar and pestle) were avoided to preserve mineralogy and soil structure. The liquid limit and plasticity index for the fine-grained fraction of the spoil samples were plotted on the AS1726-1993 plasticity chart (Fig.4). Classifications of the fine-fraction were conducted in accordance with the AS1726-1993 soil groups. Classification of the bulk samples, which contained varying amounts of coarse-grained material, was guided by the method set out in AS1726-1993, however it is noted that the results may be of limited value because exact particle size analysis was not performed.

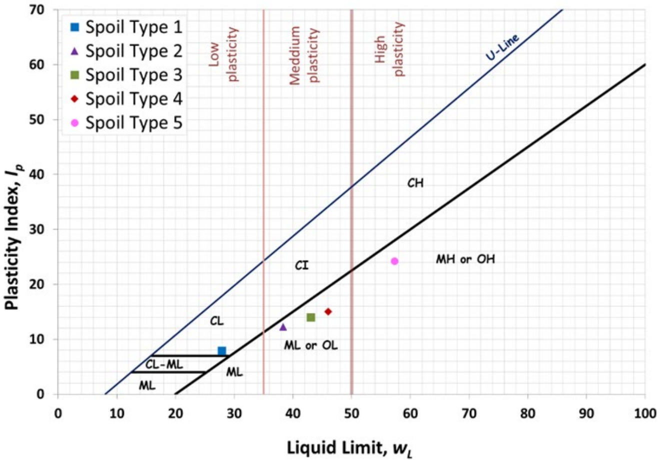

Fig. 4. Plasticity chart showing Atterberg limit test results

Slaking and Dispersion Potentials

There are several durability test standards available for various rock types and engineering applications. The in-house test method developed by Coffey and Partners *"Static Test for Field Determination of Slaking and Dispersion Potentials"* (unpublished), was used for this investigation. The method involved placing rock fragments of 30-40mm size into a glass container, filling the container with distilled water to provide 20mm of water cover, and making visual assessments of the specimen condition at elapsed times of 1 min, 10 min, 1 hour, 5 hours and 24 hours (Fig. 5).

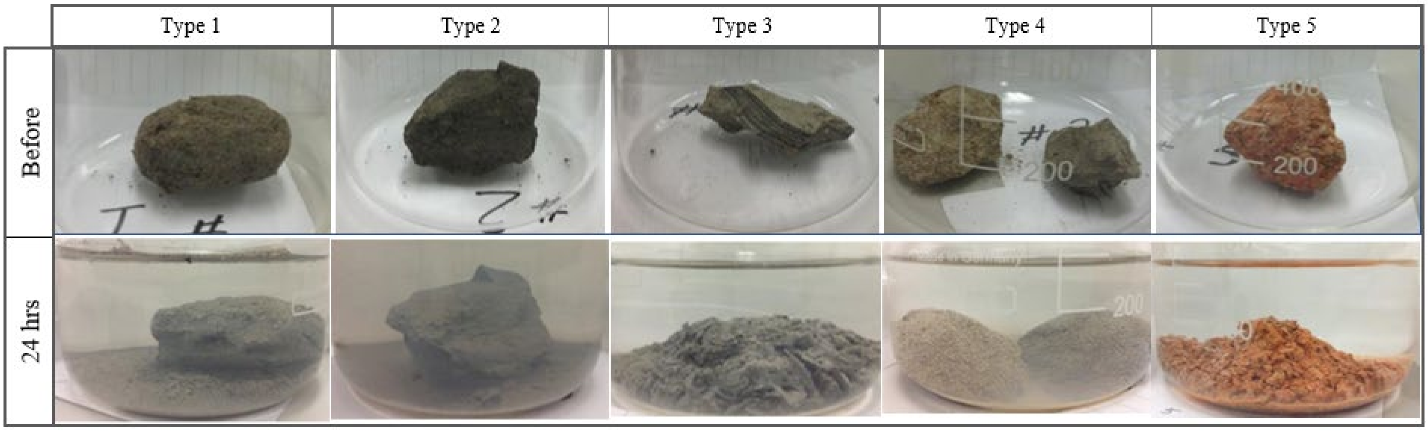

Fig. 5. Photographs of spoil specimens before and after 24hrs of immersion

Table 5. Summary of geotechnical characteristics of spoil samples

Spoil Type	**Type 1**	**Type 2**	**Type 3**	**Type 4**	**Type 5**
Sample Description					
Parent rock lithology	Fine to medium grained sandstone and siltstone (some carbonaceous), minor claystone, conglomerate, laminate and tuff	Carbonaceous mudstone, minor claystone and fissile shale	Interbedded sediments (clayey siltstone and clayey fine to medium grained sandstone)	Clayey silty fine to medium grained sandstone, minor siltstone, mudstone, claystone and shale.	Residual soil derived from weathering of tuffaceous claystone
Age at sampling	< 1month to 2yrs	>10yrs	<1 week	<1 week	< 1 month
Weathering	Fresh	Fresh	Fresh	Fresh	Weathered
Degradation	Slight to moderate.	Extensive	Extensive	Extensive	Extensive
Rock-like or Soil-like	Rock-like	Rock-like	Rock-like	Rock-like	Soil-like
Fabric Structure Control Ranking (BMA Coal Framework)	Matrix-supported	Matrix-supported	Matrix-supported	Matrix-only to matrix-supported	Matrix-only
BMA Spoil Category					
By majority	CAT 2	CAT 2	CAT 2	CAT 2	CAT 1
By likelihood	CAT 2.5	CAT 2	CAT 2	CAT 1.5	CAT 1
Clast strength					
CoalLog rock strength	R3-R5 Low to high	R3 Low	R3-R4 Low to medium	R2 Very low	R1 Extremely low
Corresponding UCS range	*5MPa to 50MPa*	*5MPa to 10MPa*	*5MPa to 25MPa*	*1MPa to 5MPa*	*0MPa to 1MPa*
Atterberg Limits and Soil Classification					
Plasticity of fines	Low	Medium	Medium	Medium	High
Liquid Limit (%)	28	38	43	46	57
Plastic Limit (%)	20	26	29	31	33
Plasticity Index (%)	8	12	14	15	24
Fine Fraction	CL	ML	ML	ML	MH
Bulk Sample	SC	ML	SM	SM	MH
Durability Potentials					
Slaking	Low	Low to moderate	Low to moderate	Very high	Very High
Swell	Low	Low	Moderate	Very high	Very high
Dispersion	Moderate	Low	Moderate	High	Very Low
Average Moisture Content (%)					
Air-dried / Saturated	7.3/13.6	12.5/20.1	10.7/14.0	11.9/16.7	12.9/24.9

4.4. Large-Scale Shear Strength Testing

The terminology used in this section refers to data for "unsaturated" spoil from the tests on spoil prepared to air-dried conditions, and data for "saturated" spoil from the tests on spoil prepared by inundating the test specimens in a water bath prior to shearing. The soil mechanics literature regards soils as being saturated when the degree of saturation, Sr = 1.0, where all void spaces are completely filled with water. Given the highly variable nature of spoil, both in terms of lithology and grading, it is likely that some or all of the so-called "saturated" test specimens may not in fact be truly saturated. However, these tests were performed to provide data on very wet spoils (the saturated materials of the BMAC framework of Simmons and McManus, 2004), hence, the tests on inundated specimens will be referred to as saturated tests, with their results considered to adequately represent materials under saturated conditions.

4.4.1. Large Direct Shear Machine

The large direct shear machine (LDSM) used for this study was custom-built specifically to handle characteristically-large samples of mine spoil and test them under representative stresses.

The LDSM (Fig. 6) consists of a split-shear box with 120mm-thick solid steel walls, mounted to a large self-reacting steel frame. The LDSM was designed to test saturated and unsaturated specimens with dimensions 720mm x 720mm x 600mm (L x W x H) over a wide normal stress range; of up to 4600kPa. The large specimen volume allowed the mine spoil samples to be tested with minimal requirement for scalping. The 4600kPa normal stress capacity is sufficient to simulate field-stress conditions for spoil dumps of up to 400m in height (Bradfield et al., 2014).

Fig. 6. Photograph of large direct shear machine (LDSM)

4.4.2. Sample Preparation and Test Conditions

Direct shear tests for this investigation generally followed the procedures outlined in ASTM D 3080M-11 and QTMR Q181C-2002. However, some aspects of sample preparation and testing were changed to reflect the conditions specific to the nature of coal-measures spoil dumps.

Sample preparation involved placing the materials onto a tarpaulin, raking samples to a uniform thickness and allowing them to dry-back by evaporation for 12-24 hours before testing. ASTM D 3080M-11 provides instructions for preparing soil specimens to a nominal density, compacted in layers of a specified thickness. This preparation method was not adopted as it does not effectively simulate the relatively loose condition of spoil emplaced by dragline or end-dumping by haul truck. Samples were instead raised above, and poured into the split boxes to closely replicate the mechanisms of spoil emplacement in the field.

Specimens were precompressed to the normal stress chosen for the test. For saturated tests, specimens were flooded after the preloading stage and left to soak until there was no further water uptake.

Tests were conducted under constant normal effective stress (σ'_n) and constant rate of horizontal displacement (d). Rates of displacement were applied so as not to generate excess pore pressures by undrained shear response. These were calculated according to ASTM D 3080M-11 and based on the time for the specimen to achieve 50% consolidation under the relevant test σ'_n. Peak shear strength (τ_p) was interpreted as the maximum recorded shear stress value.

A total of 49 tests were performed for the five spoil types (Table 6) for σ'_n ranging from 300-4600kPa. Fewer tests were performed on Spoil Types 2, 3 and 4 than were performed on Spoil Types 1 and 5. This was primarily due to the sample quantity available for each of the spoil types.

Table 6. Number of LDSM tests performed and corresponding test normal stress range for each of the spoil types

Spoil Type	Number of Unsaturated Tests and	(*σ'ₙ range in kPa*)	Number of Saturated Tests and	(*σ'ₙ range in kPa*)
Type 1	14	*(453-4605)*	9	*(490-4224)*
Type 2	4	*(474-3574)*	2	*(965-3049)*
Type 3	3	*(1544-3596)*	2	*(2030-3574)*
Type 4	2	*(996-4027)*	4	*(325-4273)*
Type 5	5	*(542-4174)*	4	*(1399-3555)*

5. RESULTS

5.1. *Shear Strength*

Plots of peak shear strength (τ_p) vs. normal effective stress (σ'_n) were developed for each of the spoil types for saturated and unsaturated conditions, noting their BMAC framework categorisation (Table 3.) This data was then compared to the linear shear strength envelopes for the four BMAC framework spoil categories, both within the BMAC framework applicable stress range (σ'_n ~270kPa-1080kPa), and for the wider stress range offered by the LDSM (σ'_n up to 4600kPa).

Figures 7-10 compare the LDSM shear strength data for the five spoil types with the linear shear strength envelopes for the four BMAC spoil categories. Fig. 7 and Fig.8 show the unsaturated test data over normal stress ranges applicable to the BMAC framework, and the wider LDSM stress range, respectively. Fig.9 and Fig.10 are the equivalent figures for the saturated test data. Note that there is no test data for Spoil Type 3 within the BMAC σ'_n range for either unsaturated or saturated moisture conditions.

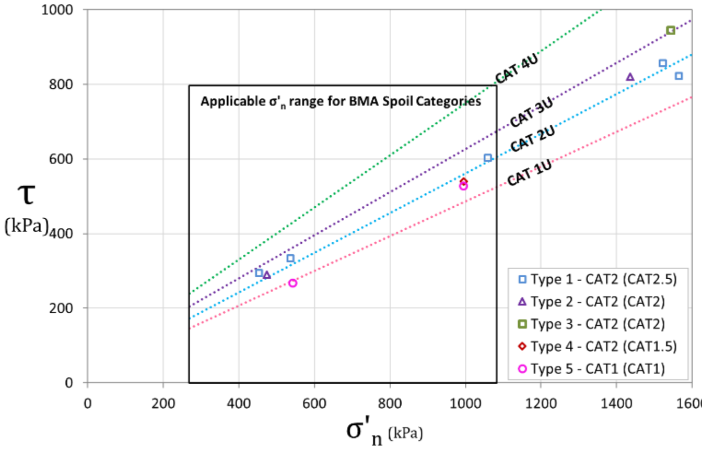

Fig. 7. Comparison between unsaturated LDSM test data of intermediate spoil types and shear strength envelopes for BMAC framework unsaturated spoil categories. Spoil types are annotated by the assigned BMAC Coal category by majority weighting, with the category by likelihood shown in brackets.

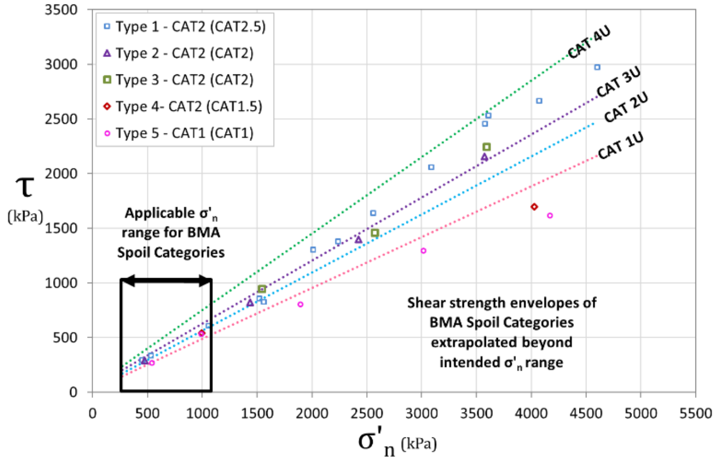

Fig. 8. Comparison between unsaturated LDSM test data of intermediate spoil types and extrapolated shear strength envelopes for BMAC framework unsaturated spoil categories.

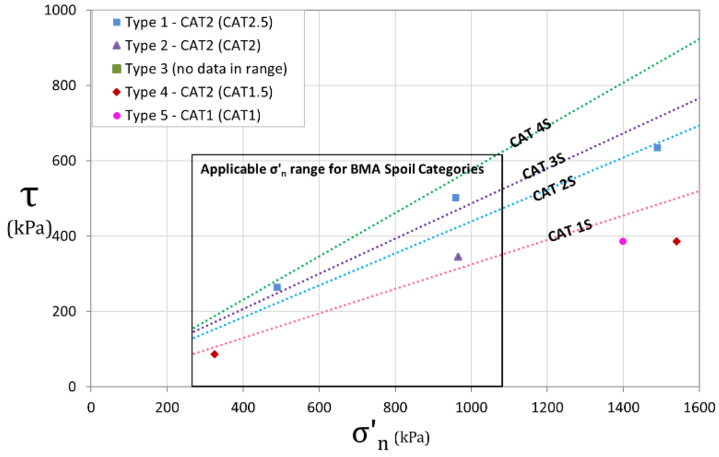

Fig. 9. Comparison between saturated LDSM test data of intermediate spoil types and shear strength envelopes for BMAC framework saturated spoil categories.

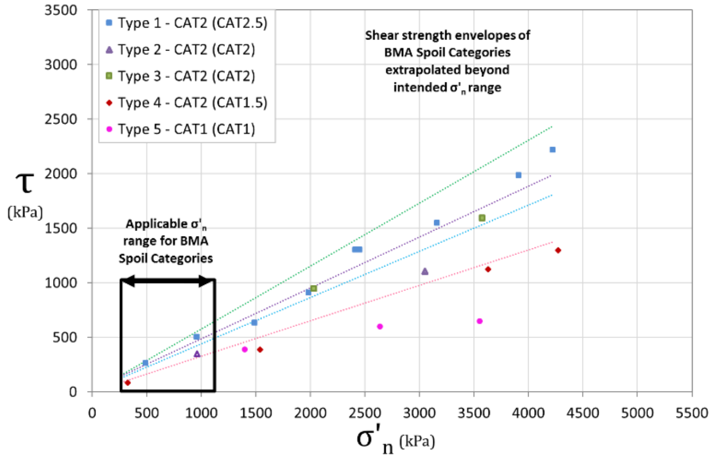

Fig. 10. Comparison between saturated LDSM test data of intermediate spoil types and extrapolated shear strength envelopes for BMAC framework saturated spoil categories.

Spoil Type 1

By majority weighting, Spoil Type 1 is a CAT 2 spoil (Table 3). It receives Category 2 scores for four attributes (material particle size, relative density, structural control ranking, and age), and a Category 3 score for one attribute (plasticity of fines, expressed as Liquid Limit). By likelihood, there is a 71% chance that Type 1 is classed as a CAT 2 material, and a 29% likelihood of being classed as a CAT 3 material solely based on its low-plasticity fines. An interpretation of this classification is that Spoil Type 1 may exhibit a shear strength slightly above Category 2 spoil when unsaturated. However, when saturated, because the fines are of low-plasticity, the shear strength may resemble that expected for a less water-sensitive Category 3 spoil.

As shown in Fig.7, the unsaturated LDSM test data is located between the strength envelopes for the Category 2 and 3 spoils for the BMAC σ'_n range. By comparison, Fig.9 for the saturated condition shows that LDSM data straddles the Category 3 spoil shear strength envelope.

The data demonstrates that plasticity (of the fine fraction) influences shear strength to the extent that Spoil Type 1 adopts a different spoil categorisation when saturated. Spoil Type 1 demonstrated a 29% likelihood of being a Category 3 spoil based on its plasticity value. For the BMAC σ'_n range, and based on a limited data set, these results suggest that the plasticity attribute should receive a higher weighting score for spoils when in a saturated condition. More data is required to support this assertion.

Fig. 8 and Fig. 10 compare the LDSM test data for with extrapolated BMAC framework strengths for the LDSM stress range (σ'_n up to 4600kPa) for unsaturated and saturated moisture conditions, respectively. For both moisture conditions, with increasing σ'_n above the BMAC stress range, the LDSM data migrate from the CAT 2 envelope towards the CAT3 envelope, and approach the CAT4 envelope at very-high stress. Contrary to traditional soil mechanics principles, these results suggest that extrapolation of failure envelopes for this type of material to higher stress ranges may in fact provide a conservative estimate of shear strength, rather than overestimate it.

Spoil Type 2

Spoil Type 2 is classed as a CAT2 material (both by majority weighting and likelihood), has low to moderate slake potential, medium plasticity (of the fine fraction) and low-strength clasts (R3). The data for unsaturated tests is located on the CAT2U shear strength envelope within the BMAC σ'_n range, and up to approximately $\sigma'_n \sim 1500$kPa (Fig.7). With increasing normal stress, and if the BMAC framework strength envelopes are extrapolated beyond their intended stress range, as shown by Fig.10, the test data for unsaturated Spoil Type 2 lies near or on the BMAC CAT3U extrapolated failure envelope, and even exceeds it at very high stress ($\sigma'_n \sim 3600$kPa).

From Fig.9 and Fig.10, the shear strength data for saturated Spoil Type 2 is intermediate between a CAT1S and CAT2S spoil envelopes, both within the BMAC σ'_n range, and when compared to the extrapolated CAT1S failure envelope. This means that when saturated, Spoil Type 2 no longer conforms to the failure envelope expected for a CAT2 material. The results are attributed to its moisture-sensitivity, as well as its clast strength (R3). Of the five attributes used in the BMAC categorisation process, the ‘liquid limit’ is one which is used to characterise the moisture-sensitivity of a spoil. There is no direct provision for slaking, although the literature reports a link between strongly slaking materials and high liquid limits. The shift in shear strength for Spoil Type 2 from a CAT2 when unsaturated, to a CAT1.5 when saturated, suggests either that a higher weighting score should be assigned to the ‘liquid limit’ attribute in the categorisation process, or that other measures of moisture sensitivity should be included in the categorisation process.

Furthermore, when compared with the test data for saturated Spoil Type 3 (discussed in the paragraphs which follow), it is evident that clast strength has far greater influence over the saturated shear strength, than the liquid limit of the fine fraction, at medium-very high normal stresses (~1500kPa+). Spoil Type 3 is also classified as a CAT2 spoil and has similar slaking and plasticity properties as Spoil Type 2, but has stronger clasts (R3-R4). From Fig.8 and Fig.10, which compare the LDSM shear strength data with the extrapolated BMAC framework failure envelopes, with increasing normal stress, Spoil Type 3 does not undergo a shear strength loss sufficient for it to adopt a different spoil category when saturated.

The results suggest that the addition of a ‘clast strength’ attribute to the BMAC categorisation process could be useful for determining whether a spoil with intermediate plasticity (of the fine fraction) behaves more like a CAT2 material or a CAT1 material, when saturated. Furthermore, although the moisture-sensitivity is explained by the ‘liquid limit’ attribute, which is performed on the fine-fraction, a ‘slaking’ attribute would be useful for evaluating the moisture-sensitivity of the clasts (which potentially may contain different lithotypes to the fine fraction).

Spoil Type 3

Spoil Type 3 is classed as a CAT2 material (both by majority weighting and likelihood), has low to moderate slake potential, medium plasticity (of the fine fraction) and low to medium strength clasts (R3-R4). There is no test data (for unsaturated or saturated moisture conditions) within the BMAC σ'_n range. However, when compared to the extrapolated BMAC framework shear strength envelopes (Fig.8 and Fig.10), the data for both moisture conditions plot on or adjacent to the CAT3 failure envelope; i.e. there is no obvious shift in shear strength data that would imply a change of spoil category when saturated.

It is interesting to note that the shear strength data for Spoil Type 3, as well as the shear strength data for the baseline spoil, Spoil Type 1, both plot closer to the CAT3 failure envelopes than the CAT2 failure envelopes, despite being categorised as CAT2 materials. Furthermore, with increasing normal stress, the Spoil Type 1 data approaches the CAT4 failure envelope for both moisture conditions.

Furthermore, the shear strength data appears to be differentiated by clast strength at low stress (which for these spoils is asserted to be within the pre-crushing stress range) as well as at high stress. For example, Spoil Type 1 has low to high strength clasts (R3-R5), Spoil Type 3 has low to medium strength clasts (R3-R4), and Spoil Type 2 has low strength clasts (R3). Within the BMAC σ'_n range for the unsaturated data, Spoil Type 2 is the only material which records a shear strength consistent with a CAT2 failure envelope. This suggests that CAT2 materials could be assigned a R3-strength clast attribute in the categorisation process. Similarly, R4-strength clasts could be aligned with the CAT3 failure envelope, and R5-strength clasts could be associated with the CAT4 failure envelope. The shear strength data of spoils containing clasts of various strengths would be intermediate between the corresponding failure envelopes, as is evident in the Spoil Type 1 and Spoil Type 3 data (Fig.11). With increasing normal stress, the shear strength data still appears to be differentiated by clast strength, however, in the case of the spoils containing a range of clast strengths, the shear strength data approaches the failure envelope that corresponds to the strongest clasts at very-high stress.

For example, Spoil Type 1 which contains R3-R5 clasts, approaches the CAT4 failure envelope at very-high stress, whilst Spoil Type 3 which contains R3-R4 clasts, exceeds the CAT3 failure envelope at very-high stress. Fig.11 shows the BMAC framework extrapolated failure envelopes, together with the LDSM unsaturated test data. The coloured areas denote ranges of notional shear strength envelopes on the basis of clast strength. Failure envelopes for materials containing clasts of R3-strength or higher deviate from linearity at approximately σ'_n~3500kPa suggesting widescale particle crushing at high stress; failure envelopes are sigmoidal-linear for materials comprising R2-strength clasts and appear curved for spoils with majority R1-strength clasts.

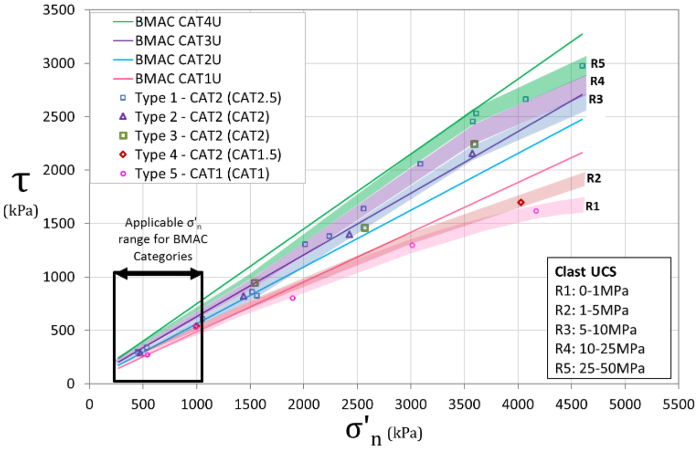

Fig. 11. Unsaturated LDSM test data together with extrapolated BMAC strength envelopes. Coloured areas are notional shear strength envelopes developed on the basis of clast strength.

Spoil Type 4

Spoil Type 4 is classed as a BMAC CAT2 material by majority, and a CAT1.5 material by likelihood. It has very high slake potential, high plasticity (of the fine fraction) and very low strength clasts (R2). There is one unsaturated test data point for the BMAC σ'_n range, and it is located between the CAT1U and CAT2U strength envelopes (Fig.7). The data point for the other unsaturated test, located at $\sigma'_n \sim$ 4000kPa, is significantly lower than the extrapolated CAT1U shear strength envelope (Fig.8).

The saturated test data plot just below the CAT1S shear strength envelope, both within (Fig.9), and beyond (Fig. 10) the BMAC σ'_n range. The distance between the data points and the CAT1S failure envelope does not increase with increasing normal stress, which implies that a linear trend is appropriate for this data. This is attributed primarily to the very low clast strength of Spoil Type 4 such the frictional resistance associated sliding shear at low stress is similar to the particle breakage that occurs at high stress.

It is interesting to note that the shear strength of Spoil Type 4 is similar to that of Spoil Type 5 (a clay-rich soil), at low stress, and is only slightly stronger than Spoil Type 5 at very high stress.

If shear strength associations are made based on clast strength, the extremely low strength clasts (R1) of Spoil Type 5, correspond to the CAT1U failure envelope; and, the very low strength clasts (R2) of Spoil Type 4 lie between the CAT1U and CAT2U failure envelopes (notional CAT1.5U failure envelope). This complements the earlier discussion which suggested that the CAT2U failure envelope corresponds to R3 clasts, CAT3U to R4 clasts, and CAT4U to R5 clasts within the low to medium stress ranges. However, with increasing normal stress, the shear strength data for the spoils containing R1 clasts do not correspond to the CAT1U failure envelope, and a similar observation is noted for the R2 clasts. The reasons for this are as follows:

- **(i)** The BMAC σ'_n range (270-1080kPa) is sufficient to cause widespread clast-crushing of the spoils containing R1 clasts (and to some extent for R2 clasts);
- **(ii)** The slope of the failure envelope corresponding to the clast breakage zone is not as steep for R2 clast spoils as it is for stronger spoils (R3 clasts or higher); and
- **(iii)** the stresses at which particle breakage occurs for weaker spoils (R1 and R2 clasts) occur at lower stress levels than for the stronger spoils

Spoil Type 5

Spoil Type 5 is a BMAC framework Category 1 spoil. It is apparent from Fig.7 that below $\sigma'_n = 1500$kPa, the shear strength data for the unsaturated tests are closely consistent with those set out in the BMAC framework. However, extrapolation of the framework beyond this stress range results in an overestimation of shear strength (Fig.8). The overestimation of shear strength by extrapolating the BMAC framework is even greater for the case of the saturated specimens, as shown in Fig.10.

Consistent with soil mechanics principles, these results suggest that extrapolation of failure envelopes to higher stress ranges for clay-mineral rich spoils will overestimate the true available shear strength, but additional test data at low stresses is needed to increase the certainty in this conclusion.

5.2. Bulk Unit Weight

Figures 12 and 13 are plots of bulk unit weight, γ, of the spoil specimens with respect to the test normal effective stress, σ'_n for the unsaturated LDSM tests, and for the saturated LDSM tests, respectively.

The BMAC strength framework assumes constant values for γ, irrespective of the dump height, or equivalently, the magnitude of σ'_n. For all spoil categories in the unsaturated moisture condition this is 18kN/m^3, and for all spoil categories in the saturated condition, this is 20kN/m^3.

However, it is evident from the data that for all spoil types tested, and for both moisture conditions, bulk unit weight is stress-dependent, and depth-based equations are more appropriate for estimating the unit weight profile. The data also demonstrates that bulk unit weight is material-type dependent.

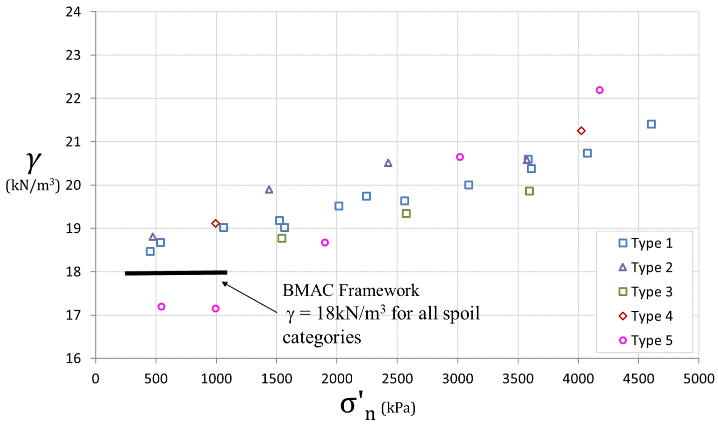

Fig. 12. Bulk unit weight vs. normal effective stress for all spoil types prepared to unsaturated conditions. The BMAC framework bulk unit weight is shown for comparison.

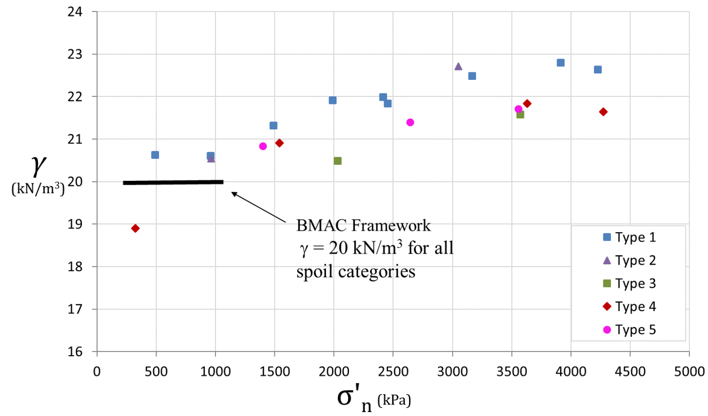

Fig. 13. Bulk unit weight vs. normal effective stress for all spoil types prepared to saturated conditions. The BMAC framework bulk unit weight is shown for comparison.

6. APPLICABILITY OF THE BMA COAL SHEAR STRENGTH FRAMEWORK FOR HIGH DUMPS

6.1. Unsaturated Moisture Conditions

It has been asserted that the BMAC framework strengths can be relied upon to provide conservative estimates of shear strength for CAT2, 3 or 4 spoils prepared to unsaturated conditions for spoil dumps with height-equivalent σ'_n ranges of ~1500 to ~4600kPa, provided that these materials contain majority proportions of R3-strength clasts, with or without lesser quantities of R4 or R5-strength clasts.

Spoils which are classed as CAT2 materials, but which consist of majority proportions of R2 (very-low strength) clasts, may exhibit CAT2 framework strengths within the BMAC framework applicable stress range (σ'_n: 270kPa-1080kPa), however they should not be relied upon for spoil dumps with height-equivalent stress ranges of ~1080kPa or more.

Spoils which are classed as CAT1 materials, will consist of either R1 and/or R2-strength clasts. The BMAC framework strengths can only be relied upon in the applicable stress range (σ'_n: 270kPa – 1080kPa), because extrapolation of CAT1 failure envelopes (σ'_n> 1080kPa) will overestimate the available shear strength.

CAT1 spoils are rarely subjected to high material loads, because mining best-practice requires selective placement of these materials; usually within the upper lift(s) of a spoil dump (i.e. near surface). Therefore, the shear strength of this sort of material subjected to high or very-high normal stresses would only need to be known if poor mining practice led to in-pit dump placement, or if the material was deliberately encapsulated by stronger material within a spoil dump.

6.2. Saturated Moisture Conditions

A review of the shear strength data for all spoil types considered in this study (Spoil Types 1-5) indicates that the BMAC framework strengths will overestimate the shear strength of CAT1 and CAT2 spoils prepared to saturated moisture conditions, both within the BMAC framework applicable stress range, and when extrapolated to very-high normal stresses, if the following conditions are met:

(i) They contain majority proportions of R3-strength clasts or weaker (R1 or R2); and

(ii) They have 'intermediate' or 'high' liquid limits (BMAC framework attribute); or they contain clasts with moderate, high or very-high slake potential

For spoils that are classed as CAT2 materials and contain blends of clasts of R3-strength or stronger (e.g. R3-R4, or R3-R4-R5 blends), the CAT2S failure envelope will underestimate the true available shear strength, both within the BMAC σ'_n range, and when extrapolated to very-high normal stresses. Therefore, the BMAC framework strengths could be used to provide a conservative estimate of saturated shear strength for CAT2, R3+ blended spoils.

Perhaps counterintuitively, the data indicates that clast strength has a far greater influence over the saturated shear strength than the moisture sensitivity of a spoil (as defined by liquid limit or slake potential) within the medium to very-high stress range (σ'_n: ~1500kPa – 4600kPa). It is possible that the same is true within the BMAC σ'_n range, however more data is required to support this assertion.

6.3. Bulk Unit Weight

The BMAC framework assumes a constant value for bulk unit weight, irrespective of the spoil category and the dump height (or equivalently, the magnitude of σ'_n) presumably as no representative data on the extent of compression under very high loads was available when the framework was originally conceived. The LDSM data suggests that linear depth-based equations are more appropriate for estimating the unit weight profile for spoils exposed to increasing depths of burial. The data also demonstrates that bulk unit weight is material-type dependent.

7. SUMMARY

The differences between the BMAC framework strengths (both within the intended stress range and when extrapolated to higher stresses) and the LDSM shear strengths for several spoil types, particularly when saturated, is a key finding because it identifies several non-compliant spoils for which correct application of the BMAC framework categorisation process will not provide reliable shear strength parameters.

The problem is associated with the categorisation process itself, rather than with the assigned shear strengths. That is, the categorisation process does not sufficiently account for spoils derived from low-strength rocks that have strong slaking and dispersion properties.

The data suggests that the BMAC framework can be used for reliable estimation of shear strength for spoil dumps of current and planned heights (i.e. up to 400m), under the following conditions:

(i) CAT2 or CAT3 spoils contain clasts with UCS ≥ 5MPa

(ii) The fine fraction of the spoil has a liquid limit ≤ 35%

(iii) The clasts have low slake and swell potentials, and low or moderate dispersion potential

(iv) CAT1 strengths are only reliable within the BMAC intended stress range (i.e. dumps up to 120m in height)

(v) Consideration is made for a stress-dependent bulk unit weight profile, particularly for very-high dumps

To update the BMAC framework categorisation process would require considerations for clast strength, fines that have medium to high plasticity, and slake, swell and dispersion potentials that are moderate to very-high. Pending such a comprehensive study, shear strength of non-compliant spoils requires material-specific shear strength testing, ideally using a large-scale-high-stress apparatus such as the LDSM.

8. REFERENCES

1. AS (1993). AS 1726-1993. Geotechnical site investigations. *Standards Australia*
2. AS (2005). AS 1289.2.1.1-2005. Methods of testing soils for engineering purposes Soil moisture content tests - Determination of the moisture content of a soil - Oven drying method (standard method). *Standards Australia.*
3. AS (2009). AS 1289.3.1.1-2009. Methods of testing soils for engineering purposes Soil classification tests - Determination of the liquid limit of a soil - Four-point Casagrande method. *Standards Australia*
4. AS (2009). AS1289.3.2.1-2009. Method of testing soils for engineering purposes. Soil classification tests – determination of the plastic limit of a soil – Standard Method. *Standards Australia.*
5. AS (2009). AS 1289.3.3.1-2009. Methods of testing soils for engineering purposes Soil classification tests - Calculation of the plasticity index of a soil. *Standards Australia*
6. ASTM (2010, 2014). D4318-10, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. *American Society for Testing and Materials.*
7. ASTM (2011). D3080/3080M-11, Standard test method for direct shear testing of soils under consolidated drained conditions. *American Society for Testing and Materials.*
8. ASTM (2011). D2487-11, Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *American Society for Testing and Materials.*
9. Barton, N. 1976. The shear strength of rock and rock joints. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts Rock Mechanics Review,* 13: 255-79.
10. Barton, N. 2008. Shear strength of rockfill, interfaces and rock joints, and their points of contact in rock dump design. *Keynote lecture, proceedings, Rock Dumps 2008, Perth.*
11. Barton, N. 2012. Shear strength criteria for rock, rock joints, rock fill and rock masses: problems and some solutions. *Journal of Rock Mechanics and Geotechnical Engineering,* 5: 249–261.
12. Barton, N. and Bandis, S. 1982. Effect of block size on the shear behaviour of jointed rock. *Proceedings of the 23rd US Symposium on Rock Mechanics*, Berkeley, pp. 739-60.
13. Barton, N., Choubrey, V. 1977. The shear strength of rock joints in theory and practice. *Rock Mechanics,* 10:1-54.
14. Barton, N., and Kjaernsli, B., 1981. Shear strength of rockfill. *Journal of the Geotechnical Engineering Division,* 107 :873-891.
15. Bradfield, L.R., 2018. Reliable shear strength estimation for very-high spoil dumps. *Doctoral dissertation, University of Newcastle, Newcastle, Australia,* 463p.
16. Bradfield, L., Simmons, J., Fityus, S., 2013. Issues related to stability design of very high spoil dumps, *Proceedings of the 13th Coal Operators' Conference,* Woollongong: 376-386.
17. Bradfield, L., Koosmen, K., Fityus, S., Simmons, J., (2014). Practical considerations for direct shear testing of mine spoils. *Proceedings, 10YGPC: The 10th ANZ Young Geotechnical Professional's Conference.* Queensland, pp. 123-130.
18. Bradfield, L.R, Fityus, S.G., Simmons, J.V., 2015.a. Large scale testing of mine spoil. *Proceedings of the 12th Australia New Zealand Conference on Geomechanics*, Wellington, New Zealand, 22-25 February 2015.
19. Bradfield, L.R, Fityus, S.G., Simmons, J.V., 2015.b. A trilinear shear strength envelope for coal mine spoil. *Proceedings of the International Symposium on Slope Stability in Open Pit Mining and Civil Engineering, South African Institute of Mining and Metallurgy*, Cape Town, 12-14 October 2015.
20. Brown, E.T., and Gonano, L.P. 1975. An analysis of size effect behaviour in brittle rock. *Proceedings, 2nd Australia-New Zealand Conference on Geomechanics, Brisbane:* 139-143.
21. Charles, J.A. and Soares, M.M. 1984. Stability of compacted rockfill slopes. *Géotechnique,* vol. 34. no. 1. pp. 61-70.
22. Coffee and Partners report (undated). Static Test for Field Determination of Slaking and Dispersion Potentials. *Unpublished.*
23. Ergular, Z.A., and Ulusay, R., (2009). Assessment of physical disintegration characteristics of clay-bearing rocks: Disintegration index test and a new durability classification chart. *Engineering Geology*, vol. pp. 11-19.
24. Gamble, J.C., (1971). Durability-plasticity classification of shales and other argillaceous rocks. *Ph.D. dissertation,* University of Illinois.
25. Gautam, T.P., and Shakoor, A. (2013). Slaking behaviour of clay-bearing rocks during a one-year exposure to natural climatic conditions. *Engineering Geology* vol. 166, pp. 17-25.
26. Fakhimi, A. and Hosseinpour, H. 2011. Experimental and Numerical Study of the Effect of an Oversize Particle on the Shear Strength of Mined-Rock Pile Material. *Geotechnical Testing Journal*, Vol. 34, No. 2
27. Frossard, E., Hu, W., Dano, C., Hicher, P.Y. (2012). Rockfill shear strength evaluation: a rational method based on size effects. *Géotechnique* vol. 62, pp. 415-427.
28. Hoek, E. and Brown, E.T. 1980. Empirical strength criterion for rock masses. *Journal of Geotechnical Engineering,* vol. 106. no. 9. pp. 1013-1035.

29. Jewell, R.A., and Wroth, C.P. (1987). Direct shear tests on reinforced sand. *Géotechnique,* 37, No.1, 53-67.

30. Larkin, B.J., and Green, D.R., (2012). Borehole Data Standard for the Australian Coal Industry: CoalLog Manual Version 1.1, *ACARP Project C21003. Australian Coal Association Research Program (ACARP),* 128p.

31. Leps, T. M., 1970. Review of Shearing Strength of Rockfill. *Journal of the Soil Mechanics and Foundations Division,* 96:1159-1170.

32. Marsal, R.J. 1967. Large-scale testing of rockfills materials. *Journal of the Soil Mechanics and Foundations Division,* 93: 27-44.

33. Nakao, T. and Fityus, S. (2008). Direct shear testing of a marginal material using a Large Shear Box. *ASTM Geotechnical Testing Journal,* 31 (5), 393-403.

34. QTMR. (2002). Q181C, Effective angle of internal friction at constant volume conditions for granular materi-als. *Queensland Transport and Main Roads, Materials Testing Method.*

35. Simmons, J.V., and McManus, D.A. 2004. Shear Strength Framework for Design of Dumped Spoil Slopes for Open Pit Coal Mines. *Proceedings, Advances in Geotechnical Engineering: The Skempton Conference,* 2: 981-991.

36. Taylor, R.K., and Spears, D.A. (1981). Laboratory investigation of mudrock. *Quarterly Journal of Engineering Geology,* vol. 14, pp. 291–309.

37. Wang, J. and Gutierrez, M. (2010). Discrete element simulations of direct shear specimen scale effects. *Géotechnique* 60, No. 5, 395–409