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A critical look at uniaxial test procedures applied in the backfill industry

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Abstract

Uniaxial/unconfined compressive (UCS) strength testing and triaxial testing are two of the most commonly used test procedures to assess the shear strength of backfill today. Some of the backfill test procedures currently in use were originally developed by other engineering disciplines and modified to meet the requirements of the mining industry. For example, UCS tests are performed by geotechnical, concrete and rock engineers.

When using procedures developed for other engineering disciplines it is important to think critically about the intended purpose behind specifications and requirements and the applicability of these related to backfill.

This paper compares the most commonly used UCS test procedures. The paper will then investigate the effect of the most important parameters influencing test results, such as specimen shape, size and aspect ratios, by presenting laboratory test results for a specifically designed test campaign.

A graphical model is presented demonstrating the relationship between strength, water content and parameters influencing backfill pumpability.

1 Introduction

There are few test procedures directly applicable to backfill. UCS testing and triaxial testing are two of the most commonly used procedures to assess the shear strength of backfill today. The strength is typically estimated by casting smaller specimens from a proposed mix design and crushing them in a laboratory while measuring displacement and load.

UCS test procedures and standards were originally developed by geotechnical, concrete and rock engineers. The UCS test procedures developed by these engineering disciplines were modified to meet the requirements of the mining industry.

The standards for concrete compression testing vary from country to country (Gongkang & Elwell 1995). One of the significant differences between these standards is the shape of specimens used. Countries like the United States, Canada and Australia typically use cylindrical specimens 150 mm in diameter by 300 mm in height, while South Africa and most European countries use either 100 or 150 mm cube specimens.

The effects of shape influence testing procedure and specimen preparation. Cylindrical specimens need to be planed or capped in order to provide parallel surfaces that can mate with testing machine platens. Cubes do not require such preparation as they are cast in rigid moulds that provide two sets of parallel moulded surfaces.

Rock engineers perform compressive strength testing on drilled cores. Cylindrical specimens are preferably not less than the NX core size which is approximately 54 mm in diameter with a 2.5 to 3.0 height to diameter (h:d) ratio. The use of capping materials or end surface treatments other than machining is not permitted (Bieniawski et al. 2007).

Geotechnical UCS test procedures are based on cylindrical specimens where the test is strain controlled as opposed to load controlled and includes strain adjustments when calculating shear strength.

A quick assessment of the above presents several problems. Firstly compressive strength test procedures vary greatly between disciplines and even within disciplines. Furthermore compressive strength test procedures were developed for specific technical fields that are not directly relatable to backfill. Therefore testing procedures and specifications need to be questioned critically to establish the applicability to backfill test work.

Well-known UCS test standards are compared in order to demonstrate variations between standards, followed by a literature review of important parameters and considerations when applied to backfill. A carefully designed test campaign investigating the parameters identified is then presented.

2 Literature review

2.1 Standards

The following standards and test procedures were considered as part of the study:

- 'Suggested methods for determining the uniaxial compressive strength and deformability of rock materials' (Bieniawski et al. 2007).
- ASTM D1633-00 (reapproved 2007) 'Standard test method for compressive strength of moulded soil-cement cylinders' (ASTM International 2000a).
- ASTM D2166-00 'Standard Test Method for Unconfined Compressive Strength of Cohesive Soil' (ASTM International 2000b).
- ASTM D4832-02 'Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders' (ASTM International 2002).
- SANS 5860: 2006 'Concrete tests — Dimensions, tolerances and uses of cast test specimens' (The South African Bureau of Standards 2006a).
- SANS 5861-3: 2006 'Concrete tests – Making and curing of test specimens' (The South African Bureau of Standards 2006b).
- SANS 5863: 2006 'Concrete tests – Compressive strength of hardened concrete' (The South African Bureau of Standards 2006c).

The following aspects of the test standards are compared in Table 1:

- Intended purpose of the standard.
- Specimen geometry which includes the shape, dimensions, height to diameter ratios and constraints on mould sizes.
- Curing conditions.
- Edge preparations and tolerances.
- Loading rates.
- Methods to assess the precision and bias of tests.
- Other differences not covered under the headings listed above.

Table 1 Standards comparison

Property	Bieniawski et al. (2007)	ASTM D1633 (ASTM International 2000a)	ASTM D2166 (ASTM International 2000b)	ASTM D4832 (ASTM International 2002)	SANS 5860/1/3 (The South African Bureau of Standards 2006a)
Intended purpose	Testing of rockdrill cores	Moulded soil cement. Two methods Method A – only if 30% or less material retained on 19 mm sieve Method B applicable to materials passing 4.75 mm sieve	Cohesive soil (no bleed water during loading) clays and cemented soils	Controlled low strength material	Testing of hardened concrete
Specimen shape	Cylindrical drill core	Cylindrical specimens	Cylindrical specimens	Cylindrical specimens	Cubes, cylinders or rectangular prisms
Height to diameter ratio	2.5-3.0	Method A: 1.15 Method B: 2.0	2.0-2.5	2.0	Cylinders: 2.0 Rectangular prisms: varies
Specimen size	Minimum NX drill core 54 mm Ø	Method A 101.4 mm Ø by 116.6 mm H Method B 71.1 mm Ø by 142.2 mm H	Minimum size 30 mm Ø Other diameters permitted	Preferred size 150 mm Ø by 300 mm H Other diameters permitted	Cubes and cylinders: 100 and 150 mm preferred 200-300 mm also permitted
Mould size constraint (diameter to largest grain size)	10:1	See intended purpose	30 mm Ø 10:1 72 mm Ø 6:1	Nothing specified	Nothing specified
Curing conditions	Specimen stored no longer than 30 days in a way to preserve the natural moisture content	Moist cure specimens, immerse in water for 4 h at end of moist cure period. Remove from water and test ASAP	Humidity controlled room. Prevent change in moisture content	Water bath, damp sand, fog room	Directly after casting 90% humidity room for 24 h then demould in water bath until testing

Property	**Bieniawski et al. (2007)**	**ASTM D1633 (ASTM International 2000a)**	**ASTM D2166 (ASTM International 2000b)**	**ASTM D4832 (ASTM International 2002)**	**SANS 5860/1/3 (The South African Bureau of Standards 2006a)**
Curing temperature	N/A	See ASTM D1632	N/A	16-27° C	22-5° C
Edge capping	Edge capping not permitted Only machining of edges permitted	Check smoothness of faces with straightedge. If necessary cap the faces to meet requirements of ASTM D1632	Edge carving or trimming permitted. Fill voids (as a result of trimming) with remoulded soil or cap with plaster of Paris or hydrostone	Edge capping permitted using sulphur mortar, gypsum plaster or elastomeric pads	Edge capping or machining and grinding permitted Keep in water for 48 h before testing
Edge conditions	Flat to 0.02 mm and perpendicular to 0.05 mm in 50 mm	Ensure uniform seating is obtained	Ends perpendicular to longitudinal axis	No further specifications	Flat to 0.5 mm/m of edge length
Loading rate	Failure to occur within 5-10 min of loading, alternatively stress rate to be within limits of 0.5-1.0 MPa/s	Screw power machine 1 mm/min Hydraulic machines (140 ± 70 kPa)/s	Strain control. Apply load to produce an axial strain at a rate of ½-2%/min. Failure within 15 min	Apply load (constant rate) such that cylinder will fail in not less than 2 min	Uniform loading rate of 0.3 ± 0.1 MPa/s
Precision and bias	No method provided to confirm precision and bias	122 sets of data used to determine average (8.1%) and median (6.2%) difference on duplicate specimens	Precision included, bias excluded	No method provided to confirm precision and bias	No method provided to confirm precision and bias Three specimens to be tested
Other	–	Multiply strength of Method B with 1.10 to convert strength for an h:d of 2.0 to that of 1.15	UCS = maximum load attained per unit area or the load per unit area at 15% axial strain Strain adjustments included in strength calculation	Only two samples (use 0.03 m^3 per two cylinders) Strength <8,400 kPa Typical 350-700 kPa	–

It is clear from the comparison in Table 1 that parameters such as specimen geometry, loading conditions or h:d vary depending on the standard. One can argue that any of the above standards may be applied to backfill testing depending on the type of fill, fill composition and target strength.

Specimen geometry is probably the single biggest difference between the standards compared in Table 1 and the literature review focussed on the impact that this difference has on UCS test results as well as important considerations for backfill.

2.2 Specimen geometry

It is well known that different results are obtained when comparing strength results obtained from cubes and cylinders. Research conducted in the concrete industry to assess the relationship between compressive strength of cylinders and cube specimens has identified several factors that affect the cylinder/cube strength ratio which include target strength, direction of loading and machine characteristics, aggregate grading, specimen geometry as well as casting and test procedures. Specimen geometry includes cross–section shape, h:d and diameter (Gongkang & Elwell 1995).

True uniaxial stress distribution throughout the specimen during testing is not possible due to frictional effects between the specimen and platens of the load frame. The frictional effects produce lateral stresses which results in a multiaxial state of stress that tends to increase the strength exhibited by test specimens. Lateral stresses affect the specimen stress state in a cone shaped region to a depth of about $\left(\frac{\sqrt{3}}{2}\right) \times d = 0.866d$ at each end (Gongkang & Elwell 1995).

Cylinders with a h:d ratio larger than approximately 1.7 will therefore have a region not affected by multiaxial stresses, while cubes will always be affected by these stresses. Due to friction between specimen ends and platens higher strengths are expected from cubes than that of cylinders. The stress distributions that can be expected in cylinders and cubes are presented in Figure 1.

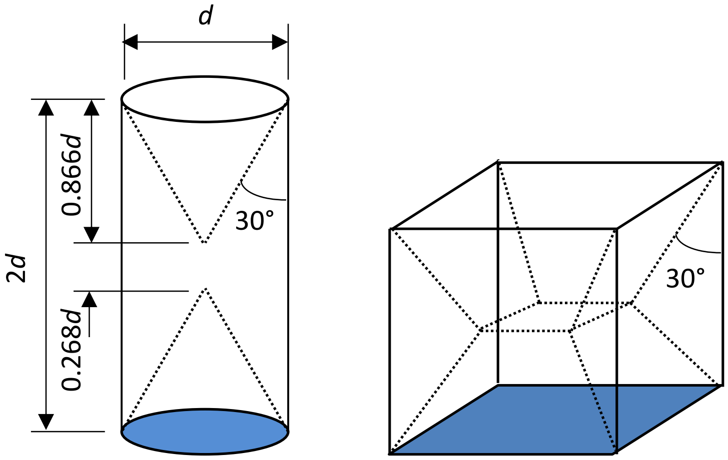


Figure 1 Stress distribution in cylindrical and cubical specimens (Gongkang & Elwell 1995)

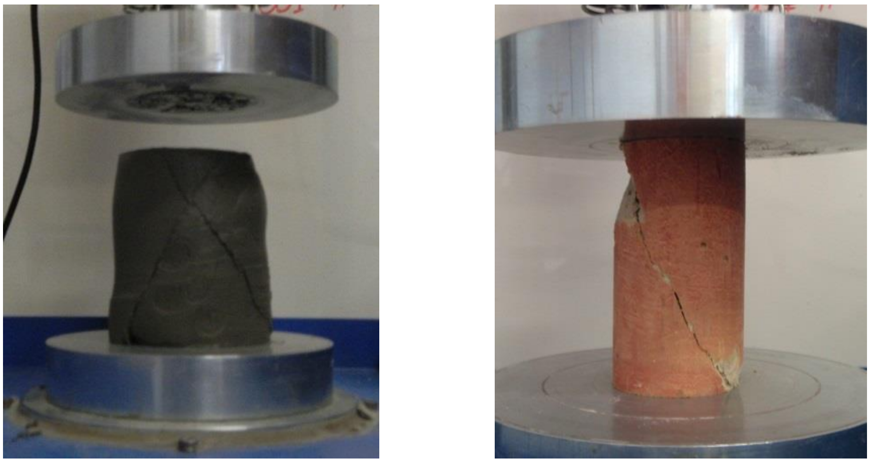
The test program presented in this paper focussed on evaluating the effect of different h:d as well as specimen size on unconfined compressive strength.

2.3 Types of failure

Of importance to UCS tests is the different types of failure modes that can be expected when doing UCS tests. Concrete technology assumes brittle failure of specimens. However in backfill technology a combination of brittle and plastic failure is possible. Three types of failure are recognised (Head & Epps 2011), namely:

1. Plastic failure in which the specimen bulges laterally into a barrel shape as presented in Figure 2(a).

2. Brittle failure in which the specimen shears along one or more well defined surfaces as defined in Figure 2(b).
3. Failure in manner between 1 and 2.



(a) (b)

Figure 2 Modes of failure in compression test specimens; (a) plastic failure ('barrelling'); (b) brittle failure (shear plane)

When considering the two examples presented in Figure 2, it is clear that the test procedure and data analysis for the two cases cannot be the same.

The only standard presented in Table 1 that employs strain control as opposed to load control is ASTM D2166 (ASTM International 2000b). This is also the only standard that defines failure as a percentage of axial deformation and indicates that the change in area should be considered when calculating the stress at failure.

The cemented platinum tailings presented in Figure 2(a) exhibits plastic behaviour when tested 4 h after mixing. One of the primary criteria for this support medium is to be self-supporting after 4 h. The mining and fill cycles are such that blasting will take place approximately 4 h after a filling cycle stops, by which time the backfill must have developed sufficient strength to support itself.

The area correction that should be applied when testing samples exhibiting plastic behaviour is briefly presented below.

2.4 Area correction

During a UCS test, a cylindrical specimen experiences a decrease in length (x) under the axially applied load (F) (Head & Epps 2011). If it is assumed that the specimen is fully saturated and both the water and backfill material particles are incompressible, the volume of the specimen remains unaltered. The decrease in volume lost in the length must appear as an increase in diameter and the specimen shape outline will have a 'barrelling' effect as presented in Figure 3.

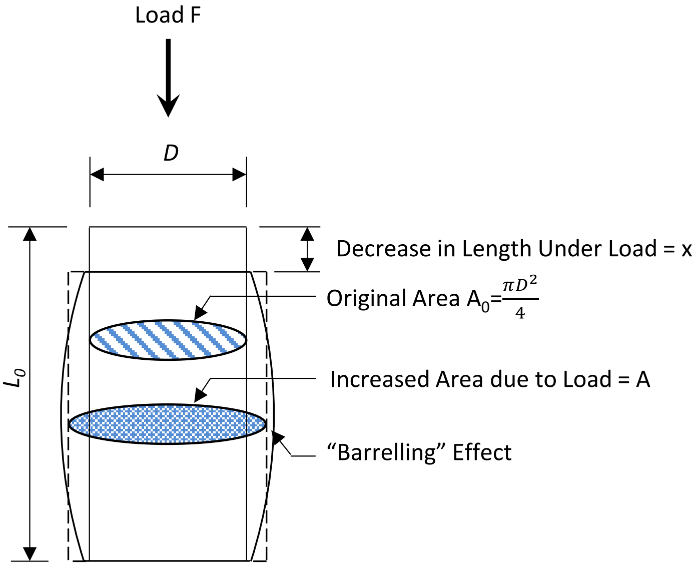


Figure 3 UCS test specimen deformation under load (‘barrelling’)

The increased diameter causes an increase in cross-sectional area of the specimen and the induced vertical stresses will be less than those calculated with the original unloaded cross sectional area. An area correction should be applied to the measured stress in order to determine the actual induced stress in the specimen. The stress induced in the specimen should be calculated with Equation (1) to account for the increase in cross-sectional area of the specimen under load.

$$\sigma_{\text{induced}} = \frac{F(1-\varepsilon)}{A_0} \tag{1}$$

Where:

ε = the strain under load and is calculated with Equation (2).

$$\varepsilon = \frac{x}{L_0} \tag{2}$$

The UCS test campaign, developed for the study, focussed on the impact of specimen geometry. The test campaign was limited to 28 day strength tests as the strength gain over time for cemented backfill is well documented in the literature.

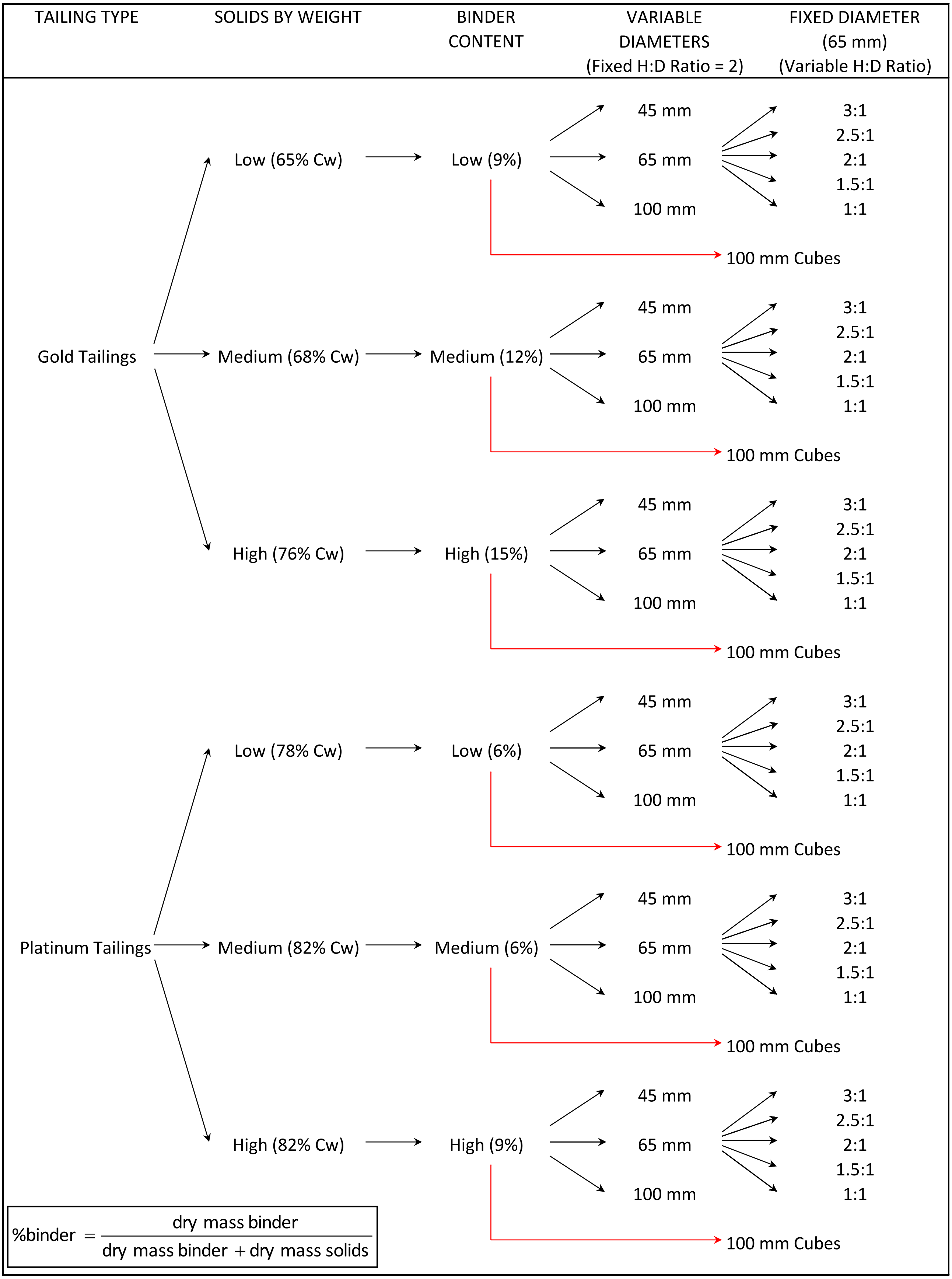
3 Test program

The test matrix for this study is presented in Figure 4. There are four main factors that contribute to produce the test matrix, namely: tailings type, solids by weight, binder content and specimen geometry.

3.1 Specimen geometry

The specimen geometry is divided into the following areas:

- Different cylinder diameters were considered while maintaining a constant height to diameter ratio of 2.
- The diameter was kept constant while varying the height to diameter ratio between 1 and 3.
- 100 mm cubes were considered for comparison with the cylindrical specimens.



$$\%binder = \frac{\text{dry mass binder}}{\text{dry mass binder} + \text{dry mass solids}}$$

Figure 4 Test matrix

3.2 Tailings material properties

The material properties of platinum and gold tailings samples used during the study are presented in Table 2.

Table 2 Material properties

Material property	Platinum tailings	Gold tailings
Solids density	3,560 kg/m^3	2,800 kg/m^3
d_{90} particle size	150 µm	250 µm
d_{50} particle size	68 µm	94 µm
d_{10} particle size	12 µm	6 µm
Freely settled bed packing concentration, Cb_{free}	77.9% m or 49.8% v	66.1% m or 41.8% v
Maximum settled bed packing concentration, Cb_{max}	82.1% m or 56.4% v	75.6% m or 53.2% v
Coefficient of uniformity $= (d_{60}/d_{10})$	6.17	18.92
Coefficient of curvature $= (d_{30})^2/(d_{60} \times d_{10})$	1.75	2.05

The particle size distribution of the two tailings samples is graphically presented in Figure 5.

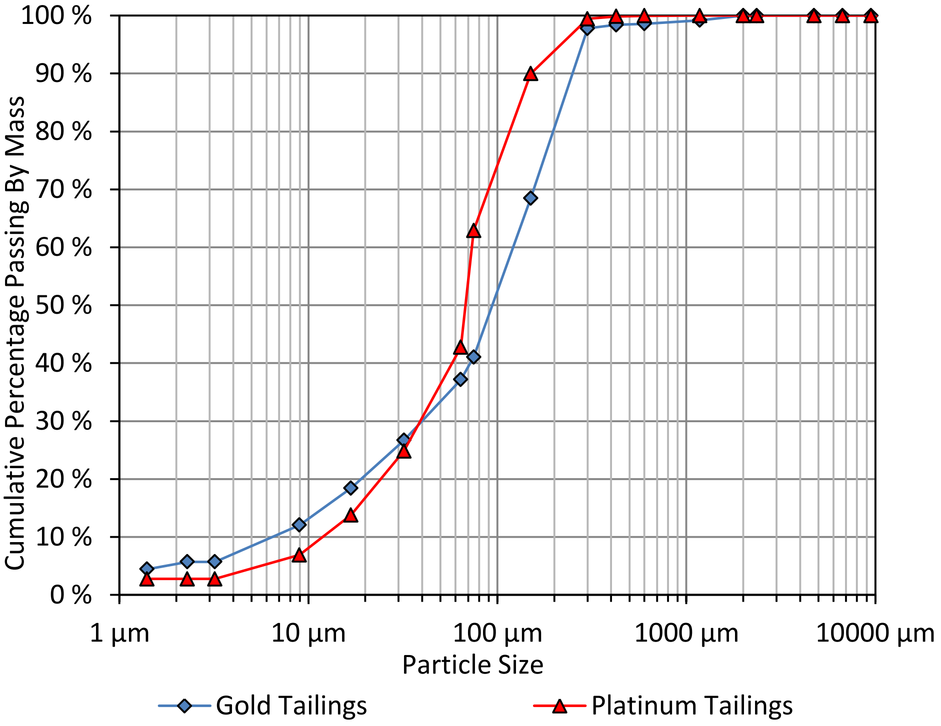
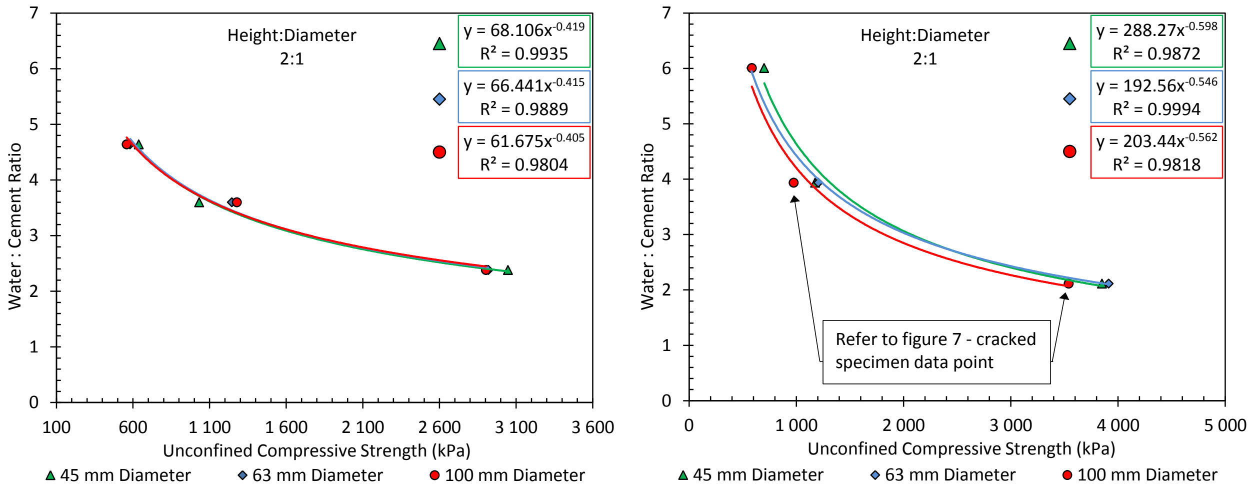


Figure 5 Particle size distributions

4 Test results

4.1 Variable diameters and fixed h:d

The influence of variable cylinder diameters with a fixed h:d (2:1) on strength was investigated using cylinder diameters of 45, 63 and 100 mm (Figure 6) at the various solids by weight and binder content listed in the test matrix (Figure 4). The backfill strength increased with a decrease in water:cement ratio in all cases for both tailings types. The small difference in backfill strength correlations obtained with the various cylinder diameters demonstrates that variations in cylinder diameter do not influence strength. This is expected due to the small nature of the tailings which provides for a more homogeneous matrix on a smaller scale as compared with concrete technology.



Refer to figure 7 - cracked specimen data point

(a) (b)

Figure 6 Strength comparison between variable cylinder diameters with a constant h:d; (a) platinum tailings; (b) gold tailings

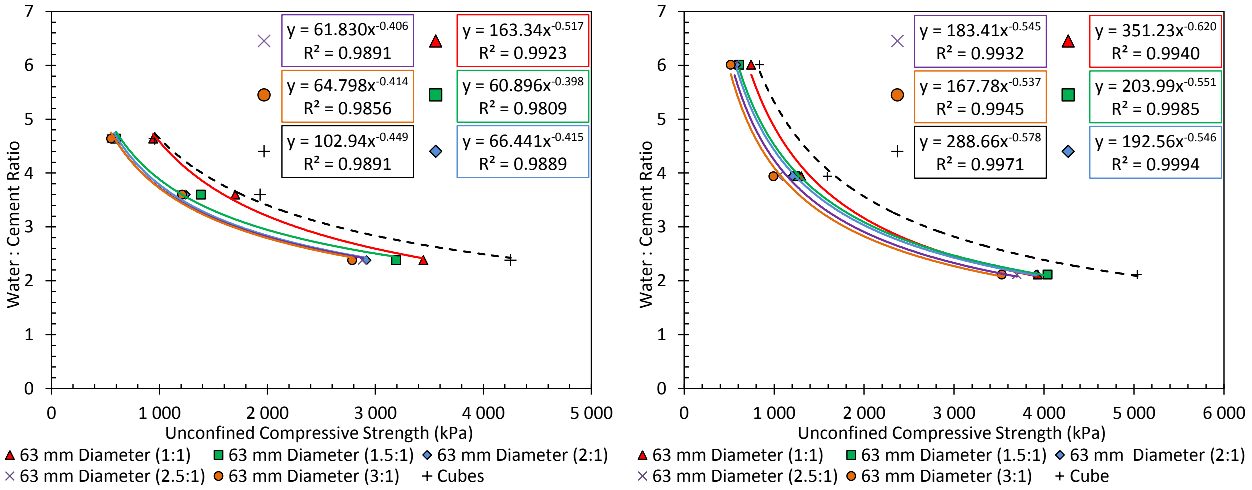
Shrinkage cracks developed at the mould joints for the 100 mm diameter gold tailings cylinders as indicated in Figure 7. The results obtained from these specimens display lower strengths. It was decided to include the measured data and to indicate the affected data sets as indicated in Figure 6(b). A closer correlation is therefore expected.

Figure 7 Shrinkage crack development on one gold tailings test set influencing the final results

4.2 Variable h:d and fixed diameter

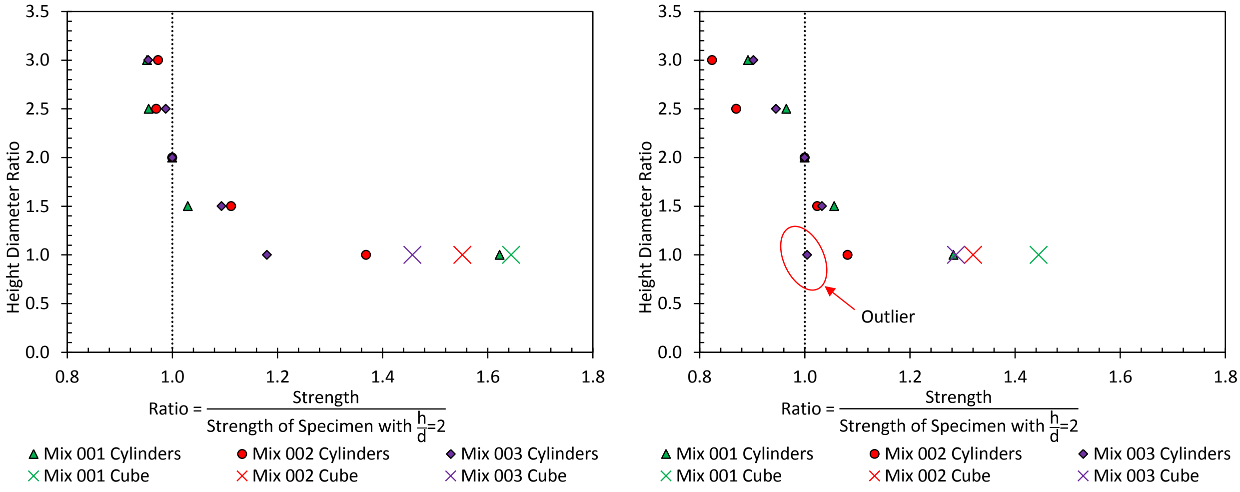
The influence of variable h:d with a fixed cylinder diameter (63 mm) on strength was investigated using a h:d of 1:1, 1.5:1, 2:1, 2.5:1, and 3:1 (Figure 8) at the various solids by weight and binder content listed in the test matrix (Figure 4). 100 mm cubes were investigated for the same discrete mix designs. An increase in h:d results in reduced strength for a specific water:cement ratio. The test work confirmed that a variation in h:d influences the UCS test results for a specific mix design.

The strength of cylinders with various h:d was compared to the strength of a cylinder with a h:d of 2 (Figure 9). Cylinders with h:d larger than 2 reduce in strength when compared to cylinders casted from the same mix design with a h:d of 2. Comparatively cylinders with a h:d ≤1.7 show a significant increase in strength.



(a) (b)

Figure 8 Strength comparison between variable h:d with a constant cylinder diameter; (a) platinum tailings; (b) gold tailings



(a) (b)

Figure 9 Strength comparison between variable cylinder diameters compared to a constant h:d of 2; (a) platinum tailings; (b) gold tailings

5 Graphical model

A graphical model developed by Paterson & Cooke is shown to demonstrate the effects of varying diameters as well as varying h:d on final binder content selection in backfill design.

It can be seen that varying diameters (with constant h:d) will provide a similar prediction while varying height to diameter ratios can have a large effect on the predicted binder content required.

Figure 10 presents the model for the gold tailings which formed part of the UCS test campaign. The model is explained with the following example.

5.1 Requirements

Backfill strength: A UCS strength of 1,000 kPa after 28 days.

Pumping system: The yield stress of the backfill mixture in the pipeline should not exceed 60 Pa.

5.2 Procedure

Step 1 – The required water:cement ratio is determined by plotting the required backfill strength on the unconfined compressive strength versus water:cement ratio graph in the upper right corner.

Step 2 – The determined water:cement ratio is plotted across the range of binder concentrations anticipated in the upper left hand corner.

Step 3 – The required mass concentration is determined by plotting the allowable yield stress in the pipeline on the yield stress versus Cm graph in the lower left corner. This mass concentration should be between the Cb_{free} and Cb_{max} range of the material shown on the model.

Step 4 – The determined mass concentration is plotted across the range of binder concentrations anticipated in the upper left hand corner graph.

The intersection point for the two lines represents the optimal binder concentration. For example, the optimal binder concentration to achieve a backfill strength of 1,000 kPa after 28 days while keeping the backfill yield stress at 60 Pa is 10%.

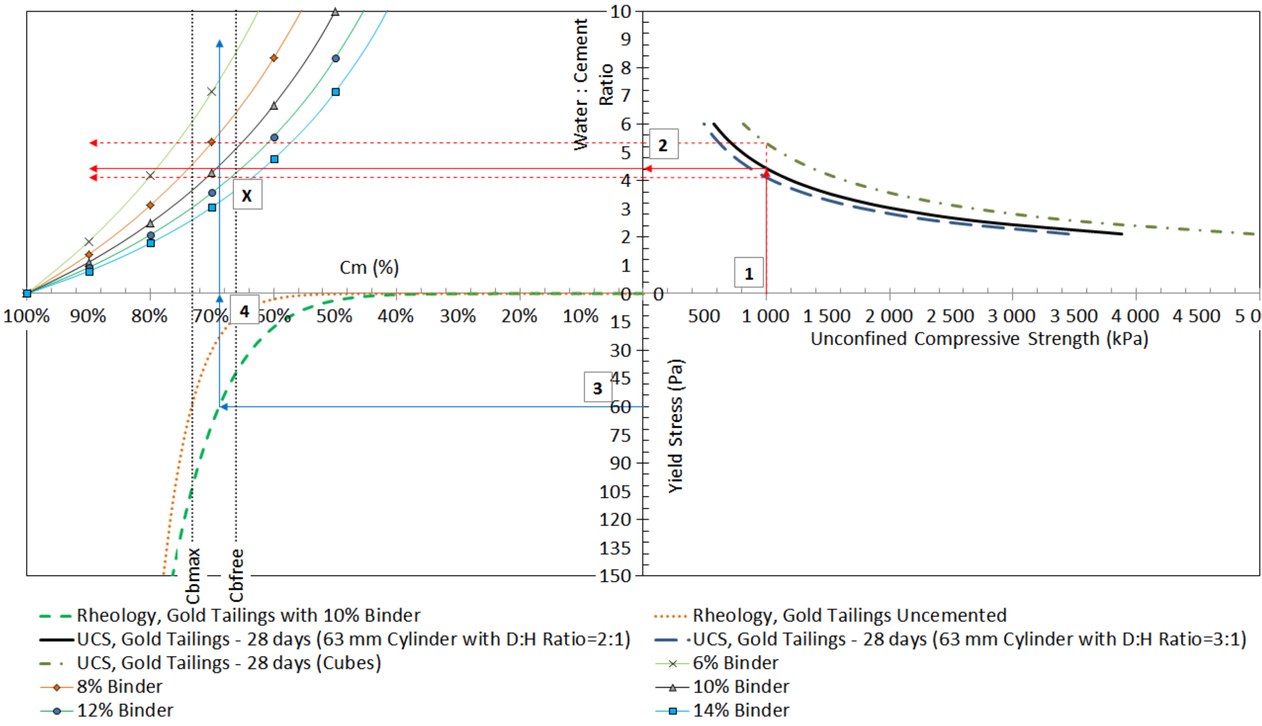


Figure 10 Graphical relationship model

6 Conclusions

This paper presents a summary of a number of standards for unconfined compressive strength tests. The variations between standards indicated in this paper can have a significant impact on UCS test results. Careful judgement should be exercised when selecting a standard to comply with.

The differences between cylinders and cubes and its influence on UCS test results are discussed and confirmed through test work.

The results from the test campaign indicated that the diameter of the specimen does not affect the overall strength provided a constant h:d is maintained. This is expected due to the small nature of the tailings which provides for a more homogeneous matrix on a smaller scale as compared with concrete technology. One of the major factors affecting concrete strength, the interfacial transition zone between aggregate and paste, is not present in backfill as the whole mix is considered to be a paste. The large specimen size required in concrete to account for the effects of the interfacial transition zone is therefore not applicable to backfill as supported by the test results.

The test work confirmed that a variation in height to diameter ratio influences the UCS test results for a specific mix design. Cylinders with a height to diameter ratio larger than 2 reduce in strength when compared to the same mix design with a height to diameter ratio of 2. Comparatively cylinders with a height to diameter ratio ≤1.7 show a significant increase in strength.

A model is presented which indicates a direct relation between UCS tests, water cement ratio, binder content and pumpability.

Selection of specimen shape and h:d will have a large impact on UCS strength results. Understanding of the main mechanisms of strength gain, testing and failure is critical in the interpretation of test results. While cemented backfill is a combination of concrete, cement, geotechnical and rock engineering, it is imperative to understand their differences in the application of UCS standards.

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