Laboratory Testing of Cemented Rock Fill for Open Stope Support

M Cordova[1], H Saw[2] and E Villaescusa[3]

ABSTRACT

Cemented rock fill (CRF) is often used to support open stope voids. This allows for the full recovery of ore while achieving global mine stability. In such cases, the exposed CRF masses require adequate compressive strength and stiffness to resist the forces and limit the displacement associated with movements in the rock mass surrounding the excavations. The CRF material preparation often involves the use of large particles, either from crushed rock or development mining waste. This means that conventional laboratory samples cannot be readily used to determine the laboratory strength. Consequently, a research project was undertaken to determine the influence of sample size on uniaxial compressive strength. This paper presents the results from CRF samples that were prepared using the same mix design and then cast into moulds with diameters of 150, 240, 300 and 400 mm. The laboratory testing also allowed a better understanding of the effect of particle size distribution upon the overall strength of a rock fill mass. The laboratory results were compared to a database of large-scale results from the testing of fill masses from a number of mine sites.

INTRODUCTION

Sample preparation and testing was carried out by the Western Australia School of Mines (WASM) on samples from Xstrata's Cosmos nickel mine. The Cosmos mine is located about 500 km north of Kalgoorlie, Western Australia and uses cemented rock fill (CRF) to fill the mining voids (Saw, Prentice and Villaescusa, 2011). The main functions of CRF are to:

- provide regional stability to a surrounding rock mass
- allow for the undercutting of sill stoping levels once the bottom-up sequence reaches the top of an extraction panel
- retain unconsolidated waste rock in the back half of a stope in longitudinal benching
- allow for a free-standing face and facilitate the removal of an adjacent stope
- enable resilience to slot-firing activities within close proximity to a cemented fill mass.

Finding the most suitable sample size for CRF to obtain the uniaxial compressive strength (UCS) was a focus of this investigation due to the adverse cost effects of sample transportation from the mine site to the WASM facility and difficulties in handling large samples. The objective of this research was to determine the variability of the UCS results as a function of sample size while maintaining the same mix design. The crushed aggregate from the mine site and other materials were characterised by their particle size distribution.

Previous research indicated that the sample diameter should be at least four times the maximum particle size. Furthermore, the use of smaller diameters can lead to poor-quality samples due to large particles obstructing the flow of the CRF material. Casting is also important when filling the samples due to the selection of the mix used in the samples. Sometimes the mix is not even and there can be a high concentration of large particles on one side of the mix, while in other cases there can be high concentration of fines.

The CRF was cast into moulds of 150 × 300 mm, 240 × 480 mm, 300 × 600 mm and 400 × 800 mm (diameter × length). The UCS of the samples was determined using the WASM large-scale static testing machine, which has a capacity of 250 t (Morton *et al*, 2007).

CEMENTED ROCK FILL DESIGN OPTIMISATION

The main objective of the CRF design optimisation was to reduce the cost of mine fill at the Cosmos mine. The procedure for the optimisation included the determination of the minimum strength required to fulfil a performance criteria, optimisation of the mix variables to produce the required minimum strength for the lowest cement usage and implementation of quality control procedures and monitoring of the fill performance on a periodic basis to ensure compliance with design.

Cemented rock fill strength

The required mine fill strength is a function of the mining method, geometry of the orebody and stope and possible failure modes. Mitchell and Roettger (1989) described the potential failure modes of cemented mine fill used to support uncemented mine fill in steeply dipping ore zones. Failure modes include sliding, crushing, flexing and caving. Sliding occurs due to low frictional resistance between the mine fill and a rock wall. Crushing occurs when the induced stress exceeds the UCS of a fill mass. Flexural failure occurs when

1. Research Engineer, Western Australian School of Mines, CRC Mining, Kalgoorlie WA 6430. Email: m.cordova@curtin.edu.au

2. Senior Research Fellow, Western Australian School of Mines, CRC Mining, Kalgoorlie WA 6430. Email: h.saw@curtin.edu.au

3. Chair Rock Mechanics, Western Australian School of Mines, CRC Mining, Kalgoorlie WA 6430. Email: e.villaescusa@curtin.edu.au

a fill mass has a low tensile strength, while caving can be due to arching and rotational failure as a result of low shearing resistance at a rock wall. When mine fill is considered as a roof slab, the analysis methods developed by Evans (1941) and later modified by Beer and Meek (1982) can be applied. Such methods for roof design procedures that consider plane strain is described in Brady and Brown (1993).

The minimum strength requirements at the Cosmos nickel mine were established based on the numerical modelling conducted by AMC Consultants (2009) and stability charts suggested by Stone (1993). Stone developed the stability charts using the pseudo-3D formulations of Mitchell and Roettger (1989). A safety factor of two was considered due to the effects of segregation and the potential for occasional improper mixing by underground operators. A summary of minimum required UCS for different loading mechanisms is shown in Table 1.

Material characterisation

Waste rock

Three containers full of material (1 m^3 each) were sourced from the Cosmos nickel mine. Tests such as specific gravity (SG), bulk density and particle size distribution (PSD) were conducted to characterise the material. Figure 1 shows the PSD curves for the waste rock.

The Cosmos mine aggregate used in this project was compared using Talbot grading. The materials include waste rock A (90 mm), waste rock B (100 mm) and waste rock C (120 mm), which were previously used for testing at Cosmos. The results show that the distribution is similar to the Talbot grading. Talbot and Richart (1923) proposed a general equation for combined (fine and coarse) regularly graded aggregate. Swan (1985) suggested that the Talbot grading equation can be used to make an optimal grading of waste rock for CRF design. The Cosmos nickel mine

TABLE 1

Summary of minimum required uniaxial compressive strength.

Loading mechanism	Minimum required uniaxial compressive strength (safety factor: 2) (MPa)	Design method
Free-standing vertical exposure	0.52	Mitchell and Roettger empirical method
Undercut sill	2.34	
Pillar to retain uncemented rock fill	2.25	

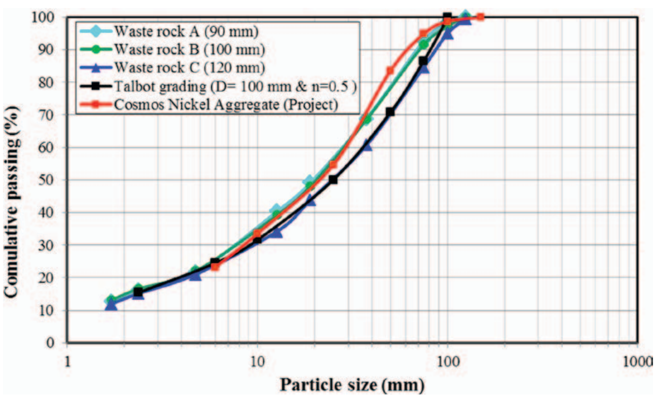

FIG 1 – Particle size distribution comparison.

aggregate curve fits on the Talbot grading equation with a variable exponent (n) of 0.5.

The Talbot grading equation is:

$$p = 100(d/D)n$$

where:

p is the percentage of aggregate passing given sieves having openings of width d

D is the maximum particle size of the given aggregate

n is a variable exponent

A large-scale device was designed to screen the aggregate. Particles were separated using meshes of 150, 100, 75, 50, 25, 10 and 6 mm.

In general, for a CRF application, a particle size greater than 10 mm is classified as a coarse aggregate, while a particle size of less than 10 mm is defined as a fine aggregate. Figure 1 illustrates the PSD curve for the Cosmos nickel mine, suggesting that the actual material consists of 33.6 per cent of fine aggregate and 66.4 of coarse aggregate. No particle was retained in the 150 mm sieve, and 10.4 per cent passed the smallest 6 mm sieve.

The SG and bulk density ranged from 2.77 to 3.02 and 2.00 to 2.16 g/cm^3 respectively. The water content and water absorption conducted on coarse aggregate prior to mixing was 0.05 per cent and 0.14 per cent respectively. The coarse aggregate was mostly composed of felsic volcanic rock. The UCS of felsic volcanic rock at the Cosmos nickel mine ranged from 135 to 252 MPa according to a test conducted at WASM by Machuca, Cordova and Villaescusa (2010).

Binders

Binders such as cement or natural pozzolans are the main components for strength development in any type of mine fill and are the most expensive component of the mix. The choice of binders depends on the strength and durability requirements of a particular mine fill operation. The most widely used cement is normal or ordinary Portland cement, which is also known as general purpose cement. It is primarily manufactured as a blend of cement clinker and calcium sulfate (usually gypsum). The cement clinker is a partially fused product that results from the burning of calcareous minerals (limestone) and other argillaceous materials. The cement comprises a fine powder that reacts with water to bind particles together as aggregate by hardening from a flowable plastic to a solid mass. In this research, general purpose cement produced by Swan Cement was used for the CRF mixing.

Mixing water

The mixing water has three main functions:

1. it reacts with the cement powder, thus producing hydration
2. it acts as a lubricant, contributing to the workability of a fresh mixture
3. it secures the necessary space in the cement paste for the development of hydration products.

Research conducted by Lawrence (1992); Wang and Villaescusa (2001); Coxon *et al* (2003); Benzaazoua, Belem and Bussiére (2002) and Benzaazoua, Fall and Belem (2004) showed that impurities in the mixing water can reduce strength in any type of mine fill. The impurities can either be dissolved or suspended in the water. The amount of strength reduction can change with the type of tailings and the binder dosage used. In certain cases, contaminated water can be used for mine fill purposes by mixing it with fresh water. However, it is important to determine whether the impurities may lead to a strength reduction. In this optimisation work, Kalgoorlie tap water was used for CRF mixing.

MOULDS PREPARATION, MIXING, SAMPLE CASTING AND TESTING PROGRAM

The CRF was cast into moulds with dimensions of 150 × 300 mm, 240 × 4580 mm, 300 × 600 mm and 400 × 800 mm (diameter × length). The 150, 240 and 300 mm diameter moulds were prepared using PVC, while the 400 × 800 mm mould was previously made for commercial backfill testing at WASM.

Mixing was undertaken with a reversing drum concrete mixer with a capacity of 0.5 m^3. The aggregate and cement were weighed and placed in a concrete machine to mix them dry first. Water was also measured and placed into the concrete mixer continuously until the batch was completely homogeneous.

The mix design was calculated based on the SG, waste rock, bulk density, cement percentage and water:cement ratio. The Cosmos nickel mine uses three per cent of cement by volume. This represents 5.06 per cent by weight using a bulk density of 2.03 t/m^3. Consequently, based on the aggregate properties and the mixer capacity of 0.5 m^3, four mixes were required to obtain 48 samples. The research required 12 samples from each mix, with nine samples for each size. Table 2 presents the mix design of five per cent of cement by weight with a water:cement ratio of 1.5 prepared for each mix of 0.60 m^3. For each mix, 1218 kg of aggregate, 60.90 kg of cement and 91.35 kg of water were required.

Casting was made using a forklift and a purpose-built water container. After casting, all of the samples were kept in the WASM curing chamber, which was set to a temperature of 30°C at 90 per cent humidity. Figure 2 shows the CRF mixing, sample casting and curing in the WASM curing chamber.

The testing program was mainly controlled by the laboratory testing capability per day, the capacity of the chambers and the mixer capacity. Mix 1 was prepared on the first day, mix 2 on the fifth day, mix 3 on the 13th day and mix 4 on the 35th day. From each mix, a total of 12 samples were obtained, with three samples each of 150 mm, 240 mm, 300 mm and 400 mm diameter. The samples of each size were tested at 7, 14 and 28 days.

UNIAXIAL COMPRESSIVE STRENGTH TESTING

At the start of the testing program, the UCS of the 150 × 300 mm (diameter × length) samples were determined using a 50 t capacity Avery universal testing machine. The 240 × 480 mm, 300 × 600 mm and 400 × 800 mm samples were tested using the WASM large-scale static test machine (Morton *et al*, 2007). Later, all the samples were tested using the WASM large-scale static testing machine because the Avery machine did not provide accurate displacements. The loading rate was approximately 2 mm/min. The axial displacement was measured with four potentiometers, which were attached to the base plate of each specimen. The test machine automatically acquires load and displacement using a SignalExpress data-logging system. Specimen top caps were prepared using Boral dental plaster. This ensured that the load was evenly applied during testing. The large-scale WASM static test machine set-up for a UCS test is shown in Figure 3.

TABLE 2

Required mix components for each mix.

Mix number	Cemented rock fill quantity (m^3)	Waste rock (kg)	Cement (kg)	Water (kg)
1	0.60	1218	60.90	91.35
2	0.60	1218	60.90	91.35
3	0.60	1218	60.90	91.35
4	0.60	1218	60.90	91.35

FIG 2 – Concrete mixer, sample casting and curing in the Western Australian School of Mines curing chamber.

Uniaxial compressive strength testing results and discussion

Figures 4, 5, 6 and 7 show the results from mixes 1–4 respectively. Mix 1 showed a slight increase in strength with time for all the sample sizes. Strength exceeded 1.5 MPa in all cases.

Mix 2 (Figure 5) represents samples with a higher water: cement ratio, which created some segregation (Figure 8) that resulted in a low strength for this mix. In general, all of the samples exceeded 1 MPa. Overall, little strength development with time was experienced with this mix.

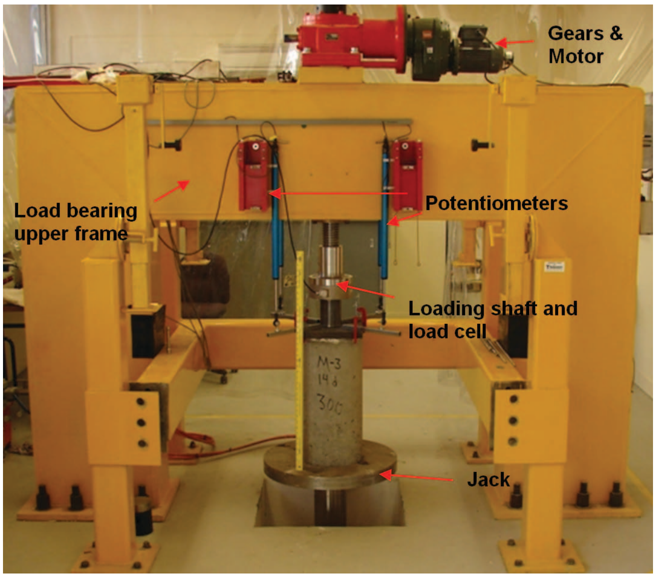

FIG 3 – Western Australian School of Mines large-scale static testing machine set-up for uniaxial compressive strength testing.

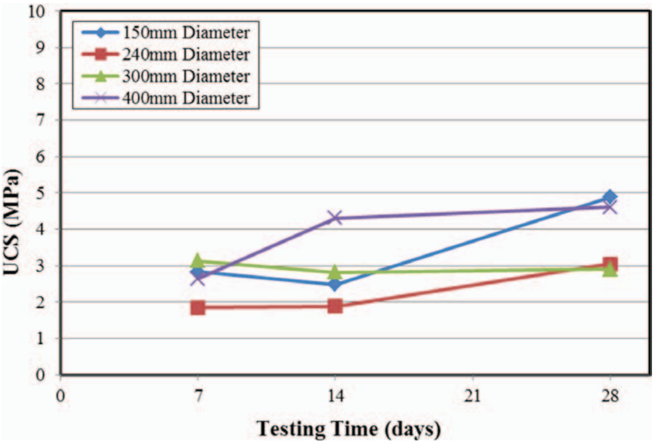

FIG 4 – Uniaxial compressive strength results for mix 1 at seven, 14 and 28 days for the different sample sizes.

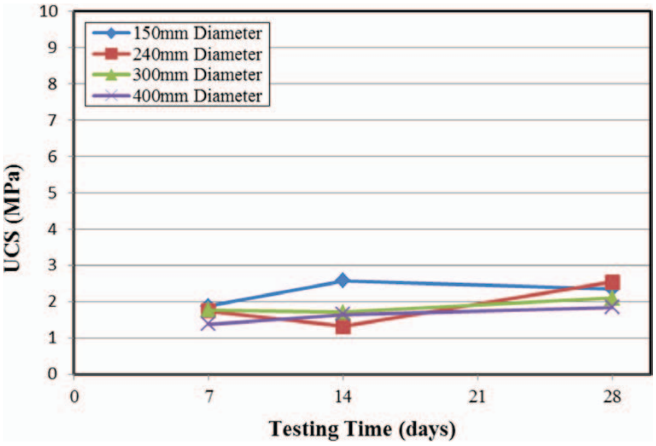

FIG 5 – Uniaxial compressive strength results for mix 2 at seven, 14 and 28 days for the different sample sizes.

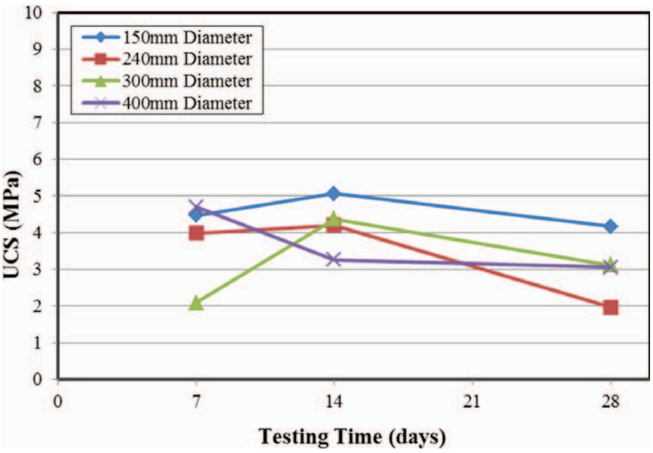

FIG 6 – Uniaxial compressive strength results for mix 3 at seven, 14 and 28 days for the 150, 240, 300 and 400 mm sample sizes.

The results for mix 3 (Figure 6) at 28 days were lower than at 14 days because the samples tested at 14 days were very well compacted and had a high fines content, as observed in Figure 9. In addition, the results show that the 150 mm diameter specimens were stronger than the rest of the samples. The samples at 28 days showed a strength decrease. However, all samples exceeded 2 MPa.

Observation of the 28-day samples show that they had low fines content and large particle concentration, which made

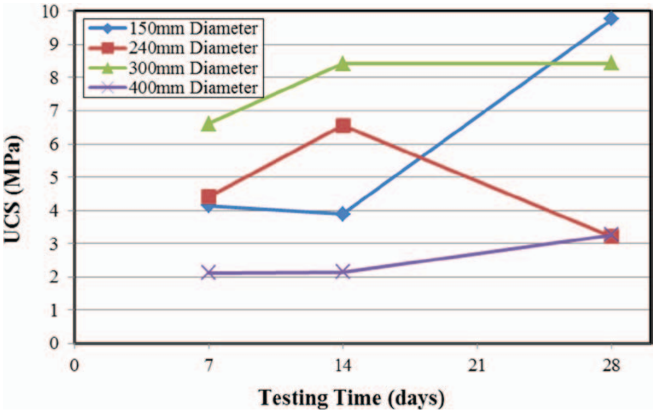

FIG 7 – Uniaxial compressive strength results for mix 4 at seven, 14 and 28 days for the 150, 240, 300 and 400 mm sample sizes.

FIG 8 – Segregation in mix 2, thereby resulting in low strength.

FIG 9 – Seven- and 14-day samples with high fines content.

rock contact possible and produced a weak zone of failure (Figure 10; M3–28d 300 mm sample). Therefore, a large particle size concentration can sometimes reduce the strength of a sample.

The purpose of mix 4 was to replace mix 2, which showed segregation in all the samples due to high water content. The results for mix 4 (Figure 8) show that the 400 mm diameter samples had lower strength. Figure 11 shows that a 400 mm sample tested at seven days with low fines content and poor contact between the particles produced low strength samples. In general, the results for mix 4 show a significant increase in UCS compared with the earlier three mixes.

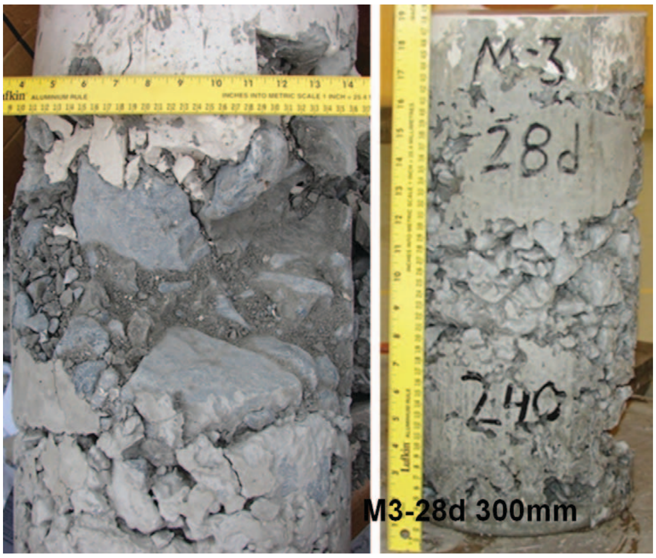

FIG 10 – Large particles and low fines content reduce sample strength.

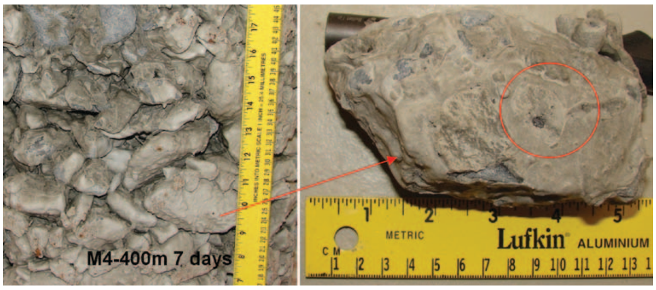

FIG 11 – Poor contact between the particles significantly reduces the cemented rock fill strength.

Influence of sample size on cemented rock fill uniaxial compressive strength results

Uniaxial compressive strength results and sample size

Figure 12 shows a slight decrease in strength as sample size increases. Exceptions were the 240 mm sample from mix 4 tested at 14 days and all the 300 mm samples from mix 4. These samples were very compacted (Figures 13 and 14). It is believed that the high density of these samples resulted in them having higher strength.

It was difficult to get good representative samples of some of the 150 mm samples because their maximum particle size was large (up to 100 mm). In addition, there was a low concentration of fines in other samples, as can be seen in Figure 15.

Average uniaxial compressive strength

Average UCS for each sample size and testing day was calculated to find out a relationship between strength and size. Mix 2 was excluded from the calculations. Figure 16 shows that the 150 and 300 mm samples (7, 14 and 28 days) had a higher strength than the 400 mm samples. In all cases, the average strength exceeded 3 MPa.

Standard deviation uniaxial compressive strength

The standard deviation was calculated for each sample size and testing day to see the strength variance between sample sizes. As shown in Figure 17, there was less UCS variation

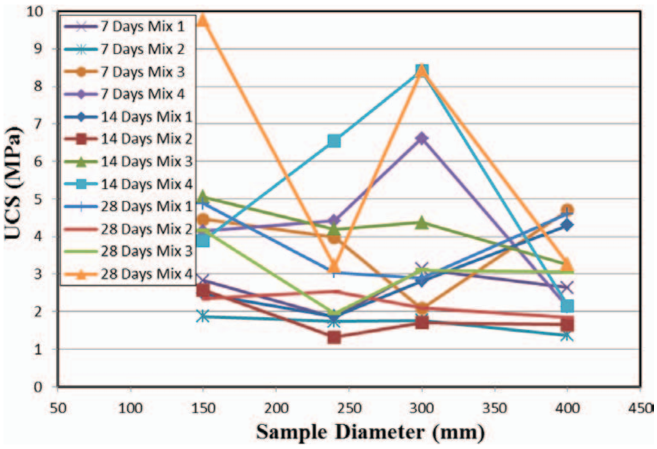

FIG 12 – Summary results from the four mixes.

FIG 13 – Very high strength samples due to them being very well compacted and having low porosity and a high fines content.

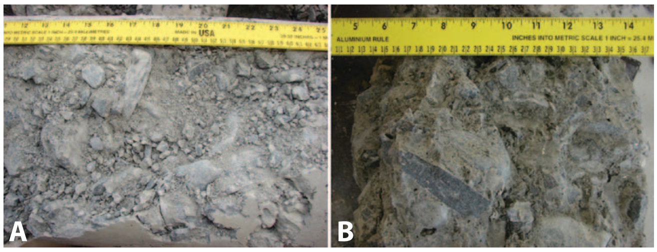

FIG 14 – Internal view showing high fines content and low porosity of (A) the 300 mm sample form mix 4 tested at seven days and (B) the 300 mm sample from the same mix tested at 14 days.

for the 400 mm diameter samples. The research shows that they provide a better representation of the mix. In general, the standard deviation increases with time for all the samples except those with 400 mm diameters. There is less deviation in the 400 mm samples, which is probably due to the fact that when the sample is larger there is better representation of the mix.

Strength and sample density

A good relationship between sample density and strength was found. As shown in Figure 18, the denser the sample, the higher the strength. Many factors can influence the density of the samples, such as the concentration of fines and different compaction achieved during casting. Again, the samples with a diameter of 150 mm showed more variability.

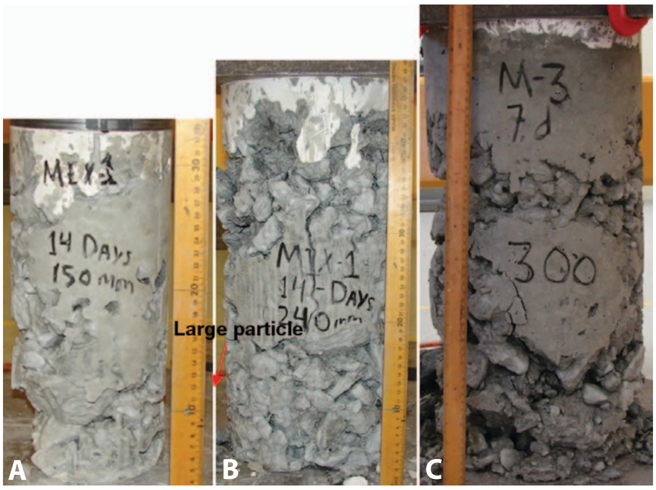

FIG 15 – (A) 150 mm sample with a large particle on the bottom that obstructed the pass of the cemented rock fill. (B) and (C) Low concentration of fines.

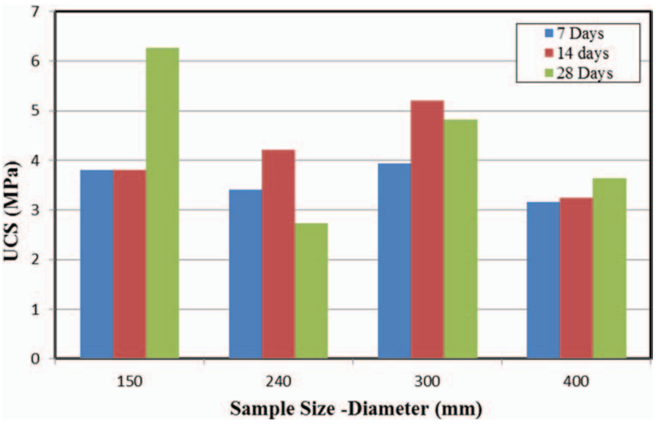

FIG 16 – Average uniaxial compressive strength form mix 1, 3 and 4 at seven, 14 and 28 days.

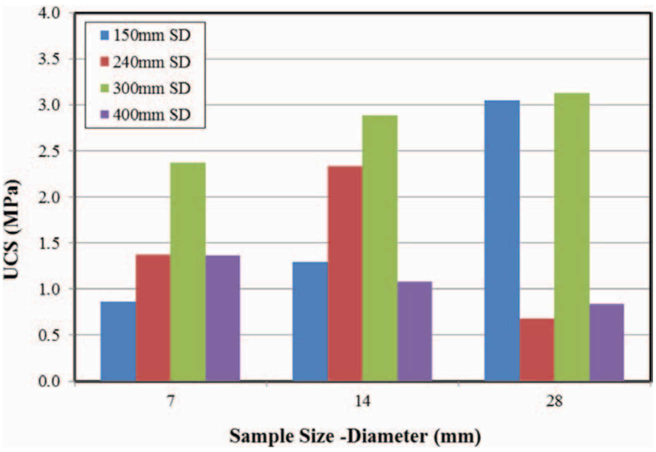

FIG 17 – Standard deviation for each sample size at seven, 14 and 28 days.

Comparison between research project results and Cosmos nickel samples

Over a two-year period, WASM conducted a testing program on large backfill samples for the Cosmos nickel mine. The size of the samples tested were 500 × 1000 mm (diameter × length). Cosmos has been using different mix designs during this time. Figure 19 compares the 500 mm Cosmos samples (three per cent cement by volume) with the 150, 240, 300

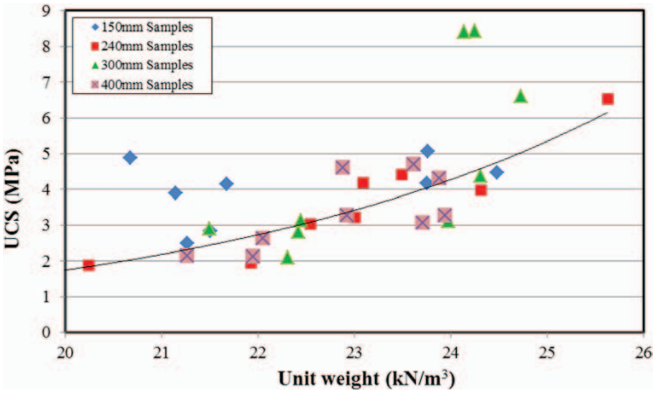

FIG 18 – Fill sample strength versus sample density.

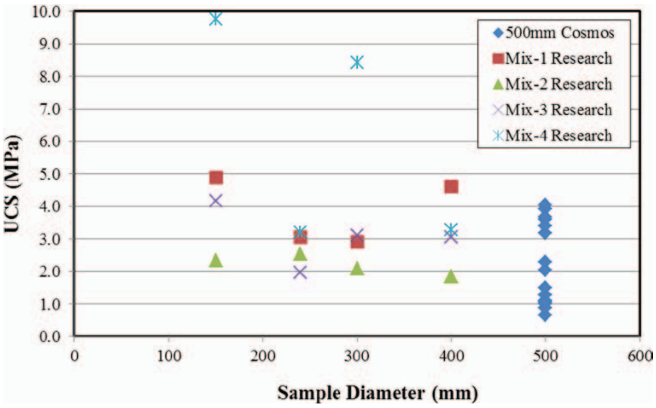

FIG 19 – Comparison between research project and Cosmos nickel samples of three per cent cement content by volume at 28 days.

and 400 mm samples from the research project. In general, it shows that the strength of the samples prepared at the mine site vary from 0.5 to 4.0 MPa. The combined database shows a decrease in strength as sample size increases.

Axial stress and strain

Four linear variable differential transformers (LVDT) were used to measure the axial strain on the samples. The LVDTs are a type of electrical transformer used to measure linear displacement.

Axial displacement graphs of the samples tested at 28 days for mixes 1, 3 and 4 are presented in Figures 20, 21 and 22 respectively. Most of the samples deformed between 2 mm (2000 microstrain) and 5 mm (5000 microstrain). Furthermore, around 12 mm (12 000 microstrain) displacement can be achieved at a post peak of around 1 MPa. Mix 3 showed more displacement but less strength, while mix 4 showed more strength and displacement.

Elastic properties test results

The Young's modulus was determined for mixes 1, 3 and 4 cured for 28 days. The results were derived from the stress-strain curves. The stress-strain curves were calculated from load displacement measured with the WASM large-scale static testing machine.

The calculated stress-strain relationship curves are shown in Figures 20, 21 and 22. A summary of tangent Young's modulus (Et_{50}), secant Young's modulus (E_s) and average Young's modulus (E_a) are shown in Table 3. The elastic modulus for all the mixes and samples were between 531 and 2621 MPa.

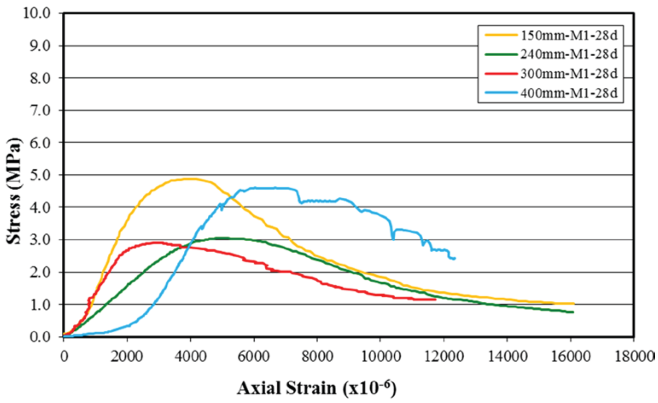

FIG 20 – Stress–axial strain curves for mix 1, 28 days.

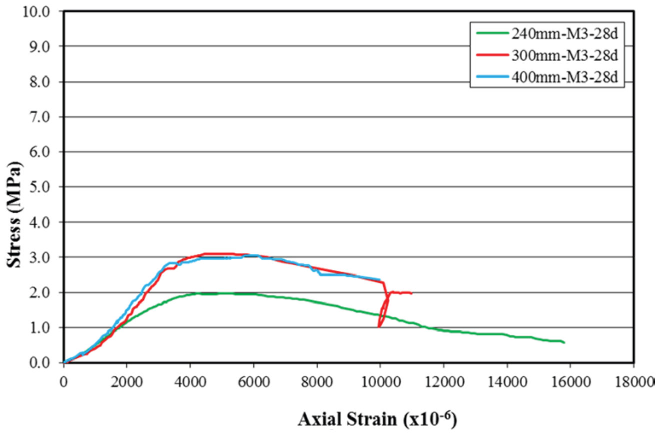

FIG 21 – Stress–axial strain curves for mix 3, 28 days.

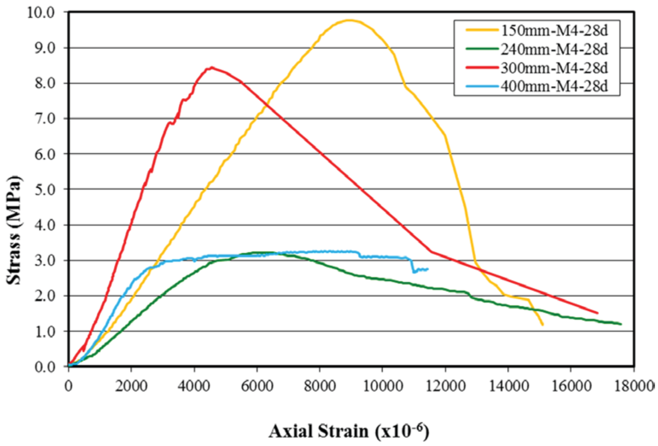

FIG 22 – Stress–axial strain curves for mix 4, 28 days.

UNDERGROUND MIXING AND FILLING PROCESS

According to the laboratory testing conducted at WASM, the minimum required strength of CRF for the Cosmos nickel mine can be achieved by adding two to three per cent cement by volume. The main steps for the underground CRF filling process are the construction of waste rock bund and bogger stop, batch up cement slurry, tram waste rock and cement slurry, mix CRF with bogger and fill into the stope. The mixing and filling of CRF samples with bogger at an underground stockpile is shown in Figure 23. A schematic of cemented and uncemented rock filled stope is shown Figure 24.

TABLE 3
Elastic modulus.

Mix and sample ID	Elastic properties (MPa)		
	E_{t50}	E_s	E_a
150 mm-M1-28d	1695	1786	1675
240 mm-M1-28d	808	769	808
300 mm-M1-28d	1631	1319	1631
400 mm-M1-28d	1500	625	1500
150 mm-M3-28d	-	-	-
240 mm-M3-28d	531	566	530
300 mm-M3-28d	1017	710	1012
400 mm-M3-28d	1102	755	1100
150 mm-M4-28d	1395	1130	1390
240 mm-M4-28d	767	644	765
300 mm-M4-28d	2621	2038	2617
400 mm-M4-28d	1456	1106	1431

FIG 23 – Mixing and filling cemented rock fill samples for quality assurance/quality control test at Cosmos nickel mine.

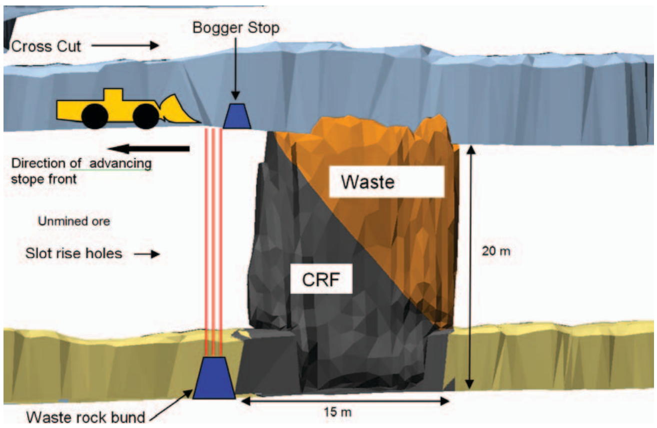

FIG 24 – Schematic diagram of cemented and uncemented rock filled stope (after Van Der Merwe, 2009).

CONCLUSIONS

The testing results showed a slight decrease in UCS as the sample size increased. In addition, this research shows that a 400 mm diameter sample size provides the most representative mix for the PSD tested. Therefore, the standard deviation decreases when the sample size is increased.

Samples that were very well compacted and had a higher content of fines had higher strength. On the other hand, samples with low fines content and a large particle concentration that made rock contact possible produced a weak zone of failure. Therefore, a large particle size concentration can sometimes reduce the strength of a fill mass.

A good relationship was found between sample strength and sample density. This means that as sample density increases, so too does the strength. Finally, there were several examples of failure at low strength where segregation was evident.

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