Properties of cemented rockfill used in an open pit mine

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ABSTRACT
This paper examines the physical properties of cemented rockfill that is being used to form a crown pillar between future underground mining and the existing open pit at the Diavik Diamond mine in Canada. This is a unique application of cemented rockfill in mining. The preparation and placement procedures and quality control measures used for the cemented rockfill are presented. The insitu density is a key quality control parameter. Measurements of density and moisture content were made with a Troxler nuclear gauge. For quality control purposes, moisture content and grain size analysis of the aggregate, and specific gravity and water to cement ratio of the cement slurry were routinely measured. In addition, the density, moisture content, compressive strength, and stiffness of cemented rockfill cylinders were measured. The predicted as-placed field properties for the cemented rockfill are presented.

RÉSUMÉ
Ce document examine les propriétés physiques du rockfill cimenté qui est employé pour former un pilier de couronne entre la future mine souterraine et le puits ouvert existant à la mine de diamant de Diavik au Canada. C'est une application unique de rockfill cimenté dans l'exploitation. Les procédures de préparation et de placement et des mesures de contrôle de qualité utilisées pour le rockfill cimenté sont présentées. La densité in-situ est un paramètre principal de contrôle de qualité. Des mesures de la densité et de la teneur en eau ont été faites avec une mesure nucléaire de Troxler. Pour le contrôle de qualité, l'analyse de grosseur du grain de l'agrégat de pierres concassées, et la densité et l'eau de cimenter le rapport de la boue de ciment ont été par habitude mesurées. En outre, la densité, la teneur en eau, la résistance à la pression, et la rigidité des cylindres cimentés de rockfill ont été mesurées. Les propriétés comme-placées prévues de champ pour le rockfill cimenté sont présentées.

1 INTRODUCTION

Diavik Diamond Mine (DDM) is located 300 km northeast of Yellowknife, Northwest Territories. A portion of the A154 N kimberlite pipe, one of three pipes currently being mined, is exposed on the northeast wall of the A154 pit. This pipe has been mined from surface and the pit floor is being covered with a cemented rockfill (CRF) cap in a series of layers not more than 1 m thick to form a crown pillar between future underground mining and the existing open pit. The CRF along with a buttress of waste rock placed on top of the CRF also serves to stabilize a steep highwall. This is a unique application of CRF in mining and contrasts a typical use of CRF in underground mines to fill mined-out stopes.

This paper examines the properties of CRF used at DDM and discusses the techniques used to prepare and place the CRF as well as the field and laboratory tests conducted for quality control (QC) and quality assurance (QA) purposes to measure the physical properties of the CRF. The in situ CRF density and the unconfined compressive strength (UCS) of cast CRF cylinders are the key QC parameters included in this study. The locations of the aggregate stockpile, mixing bay, batch plant, QC laboratory and CRF placement area are shown in Figure 1.

2 PREPARATION AND PLACEMENT OF CRF

2.1 Preparation of Cemented Rockfill

The CRF design specifications include the physical properties of the materials used to prepare the CRF, the mixing and placement procedures, and quality control and quality assurance measures required to ensure that the design specifications are met. The CRF design specifications were given in reports by Golder Associates (2007a, b). The CRF was prepared at DDM by mixing crushed granite comprised of <50 mm aggregate with cement slurry to create a zero slump concrete similar to that used for rolled compacted concrete.

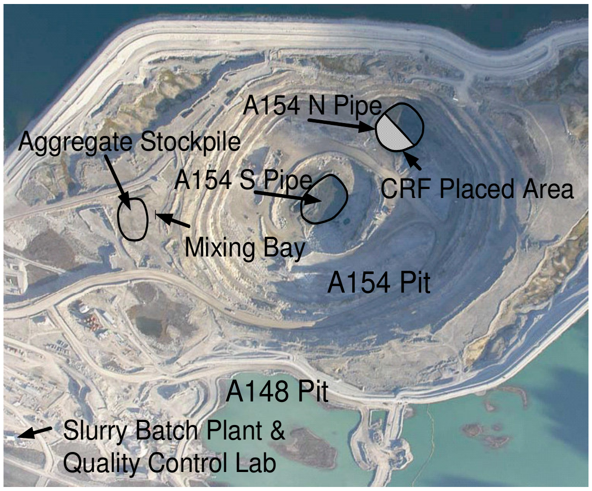

Figure 1. Location of CRF placement area at A154 pit (after DDMI, 2005)

A stockpile of aggregate was produced in 2006 by crushing non-sulphide bearing waste granite rock originating from the A154 open pit. The aggregate was manufactured to fall within specified gradation limits (Figure 2). Grain-size analyses and moisture content measurements were obtained at least once per shift during the production of the aggregate in 2006.

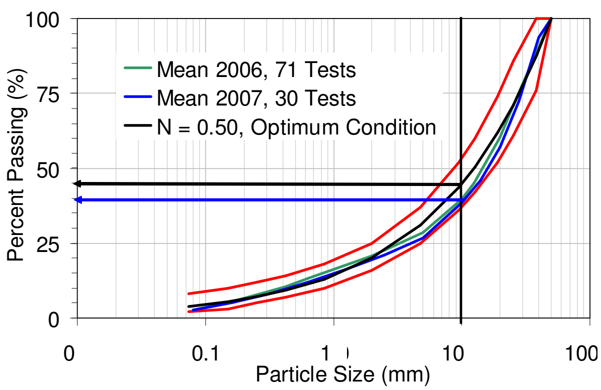

Figure 2. Aggregate gradation in 2006 and 2007 compared to specified upper & lower bounds (in red)

Batches of cement slurry (6 m^3) were prepared in a batch plant using GU Type 10 Portland cement and untreated lake water at specified mass ratios. The cement content was selected to be 5.5% or 6% of the mass of the aggregate. The batch plant included a cement-weighing hopper, a water metering system, and a truck load-out facility. The cement slurry was transported from the batch plant in a concrete truck.

A mixing bay used to mix the cement slurry with the aggregate was constructed near the aggregate stockpile (Figure 1). The mixing bay (Figure 3) consisted of vertical steel plates on both ends, inclined concrete faces along its length, and a flat concrete bottom. The mixing bay had a volume of 96 m^3 (12 m long, 2 m deep and width from 8 m at the top to 2 m at the bottom).

Aggregate was hauled from the stockpile and placed into the mixing bay by a Caterpillar 988G loader. The mass of aggregate placed in the mixing bay was estimated based on bucket counts. A full bucket of aggregate (6 m^3) had an approximate mass of 10.14 tonnes (aggregate bulk density of 1.69 t/m^3). The cement slurry was poured into the mixing bay from a concrete truck and mixing was performed by a Caterpillar 385B excavator (Figure 3). The excavator mixed the CRF for about 10 to 15 minutes before loading the material into a Caterpillar 777 haul truck for delivery to the open pit.

Figure 3. Pouring and mixing cement slurry

2.2 Placement of Cemented Rockfill

The CRF placement started after the exposed kimberlite in the pit floor was covered with a 150 mm thick layer of clean gravel. The CRF was dumped by the haul truck and then spread and compacted by a Caterpillar D5M LGP dozer. The process of placing, spreading, and compacting the CRF was repeated until a 1 m thick lift was completed. In the corner and periphery areas, a Caterpillar 345C excavator and a Caterpillar CS 563D roller compactor were sometimes used for spreading and compaction (Figure 4).

Three lifts of CRF were placed on the top of the kimberlite in two stages in 28 days with 16 days of site preparation and 12 days of continuous placement. Additional CRF was also placed on the highwall slope.

Figure 4. Spreading and roller compaction

3 QUALITY CONTROL AND TESTING

3.1 Field Measurements

In situ wet and dry densities and moisture contents were measured by using a Troxler nuclear gauge (model 3430, Troxler, 2006) in the direct transmission mode (ASTM D2922-91 and ASTM D3017-88). The void ratio e and porosity η were also calculated based on the assumed specific gravity of the aggregate G_a, the measured dry density γ_d of the CRF, and the density of water γ_w using:

$$e = \frac{G_a \cdot \gamma_w - \gamma_d}{\gamma_d} \qquad \eta = \frac{e}{1+e} \times 100$$

In situ measurements of density and moisture content were conducted two to five times per shift, covering the area of each lift as it progressed.

3.2 Aggregate Testing

Typically, an aggregate sample was collected once per shift for grain-size analysis and moisture content measurement. An aggregate sampling pad was prepared by placing a full loader bucket of aggregate from the stockpile onto flat ground and levelling it. A 20 kg sample was collected in a plastic bucket by digging from different locations with a shovel.

Grain-size analyses were carried out based on ASTM C136-05. The sample was sieved using a Gibson vibratory sieve (model TS1) with 40, 28, 20, 14, 10, and 5 mm sieves. The sample was vibrated for about 15 minutes. The total mass of the aggregate retained on each sieve was measured with a precision of 0.1 g. The <5 mm size fraction retained in the pan of the Gibson vibrator was further processed. A 0.5 to 1 kg sample of the <5 mm aggregate was washed over a 0.08 mm sized screen, oven-dried and placed in an ATM Arrow shaker for about 15 minutes. This sample was then sieved with screen sizes of 5, 2.5, 1.25, 0.63, 0.315, 0.16, and 0.08 mm. The gradation curve was obtained by plotting the weight percent passing each size screen.

The moisture content present in a 0.75 to 1 kg sample of the <5 mm aggregate was measured according to ASTM 2216-05. The original aggregate's moisture content was corrected based on ASTM D4718-87.

3.3 Cement Slurry Testing

Typically, a sample of the cement slurry from the batch plant was collected twice each shift from the chute of the concrete truck while it was being poured into the mixing bay. At the laboratory, the cement slurry sample was thoroughly mixed by using a steel rod. The specific gravity of the cement slurry was measured by using a Fann Instrument Company mud balance (Model 140) with a precision of 0.01.

3.4 Cemented Rockfill Testing

A sample of CRF was collected at least twice per shift near Troxler nuclear gauge test locations to determine the moisture content and to cast cylinders for UCS tests. The CRF samples were tested to verify the in situ moisture content measurements made by using the Troxler nuclear gauge. About 1 kg of CRF was placed in a pan and oven-dried at 110 ± 5°C until a constant weight was reached to determine the moisture content based on ASTM D4959-00.

The laboratory-measured values of the moisture content were compared with in situ measurements. Based on the laboratory moisture content, the in situ bulk density measured by using the Troxler nuclear gauge was adjusted. The in situ dry density γ_d based on the Troxler bulk density γ_b adjusted using the lab moisture content w of the CRF is calculated using:

$$\gamma_d = \frac{\gamma_b}{1+w}$$

Cast cylinders of CRF were prepared for UCS tests. For 100 mm diameter cylinders, only the <25 mm sized fraction was used and it was placed into a cylindrical mould in 3 layers. A standard proctor hammer was used to pound each layer 20 times. For 150 mm diameter cylinders, unscreened CRF was used to cast cylinders in a steel mould in five layers, with each layer being pounded 20 times. The number of blows from the Proctor hammer per layer was found through trial and error to obtain a desired dry density close to 2150 kg/m^3. The dry density of the cylinders was calculated based on the volume of the mould, the weight of the cylinders, and the moisture content present in the CRF (no 'rock correction' was used).

The CRF cylinders were cured at room temperature (23 ± 3°C). The CRF cylinders were wrapped inside a moist jute cloth that was periodically moistened to prevent the cylinders from drying. After curing to a specified age, the cylinders were capped with a sulphur compound prior to testing.

Unconfined compressive strength tests were conducted after 3, 7, and 28 days of curing using a

Matest test machine. The vertical deformation of some of the test cylinders was measured by using a dial gauge with a precision of 0.01 mm. The stress was applied at a rate of 50 kPa/s. Stress-strain curves were obtained by simultaneously reading the applied stress from the machine's display unit and the corresponding dial gauge displacement.

4 RESULTS AND DISCUSSION

4.1 Aggregate

Literature reviews indicated that the aggregate strength, gradation, and moisture content are relevant aggregate properties when designing CRF. In UCS tests carried out in 1998, Nishi-Khon/SNC-Lavalin (2004) reported that the average UCS for granite, from which the aggregate was produced, was 98.2 MPa with a minimum value of 72.6 MPa.

The average grain-size distribution curves for 71 tests of the aggregate measured during its production in 2006 and 30 tests during preparation of the CRF in 2007 lie within the design specification (Figure 2). The specified gradation follows the Talbot & Richard (1923) curve, with N ranging from 0.44 to 0.55; ideal or optimum grading being $N = 0.5$ as per O'Toole (2004).

The average proportion of coarse aggregate (>10 mm) is slightly more than 60%. The relative proportion of coarse and fine aggregate is close to the value specified by Brechtel et al. (1989) to obtain the optimum CRF strength. The average *Cu* values were 3.64 and 3.33 respectively, during aggregate production (2006) and CRF preparation (2007). These values are well within the limits (1.44 to 6.54) suggested by Annor (1999). However, the average values of *Cc* are 5.04 and 5.14, and are lower than the limits (9.15 to 59.7) specified by Annor (1999).

The aggregate moisture content measured in 2006 ranges from 0 to 6.4% with an average of 1.85% from 71 tests, and 0.5 to 2.1% with an average of 1.1% from 30 tests in 2007. The average moisture content of the aggregate was close to the typical values of 2 to 3%, reported by Stone (2007) for dry aggregate in general.

4.2 Cement Slurry

The w:c ratio for the cement slurry was almost constant from the batch plant. For each batch of slurry, the quantity of water was 4504 kg, whereas the cement content ranged from 4092 to 4575 kg reflecting differences between the 5.5 and 6% mix designs. The w:c ratio typically fell between 0.98 and 1.10. The quality of the water obtained from the lake and used to prepare the slurry is close to that of distilled water.

Generally, the specific gravity of the cement slurry was measured twice per shift to assess the slurry quality. The w:c ratio was also recorded at the same time from the tickets of the slurry delivery truck. The variation of the specific gravity with the w:c ratio is presented in Figure 5. The average specific gravity of cement slurry G_s can be calculated based on the average w:c ratio and the specific gravity of the cement G_c. The theoretical specific gravity of cement slurry for a given w:c ratio is calculated using:

$$G_s = \frac{G_c + (w:c) \cdot G_c}{1 + (w:c) \cdot G_c}$$

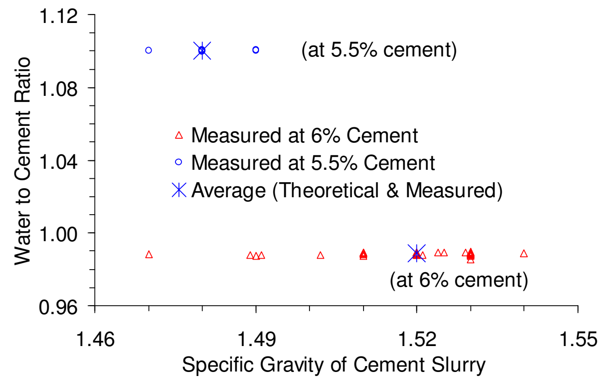

Figure 5. Water to cement ratio versus specific gravity of cement slurry

Type 10 Portland cement typically has a G_c of 3.15 (Lehigh, 2002). The calculated theoretical value of the G_s for 6% and 5.5% cement slurry is 1.52 and 1.48, respectively, which matches with the corresponding measured average value from 54 tests (Figure 5).

4.3 Cement Rockfill

The key to producing effective CRF is to coat all of the aggregate with the cement slurry (Yu, 1989; Farsangi, 1996). Therefore, the cement slurry quality and its proper mixing with the aggregate play a vital role in creating the CRF strength. The cement content for the CRF mix design was either 5.5% to 6% by weight of aggregate, which is within the usual 5 to 7% range of values reported in the literature.

During preparation of the CRF, the weight of the aggregate placed in the mixing bay was estimated by simply counting the number of loader buckets. Using this technique, some variation in the aggregate quantity is expected and thus the cement content varies accordingly. The mixing is done solely based on visual observations and operator experience. The presence of different cement and moisture content at different locations of the placed CRF indicated that some variability occurred in the preparation process.

The quality of the mixing process was better than it would have been by simply spraying the cement slurry onto aggregate in a haul truck or while the aggregate left a conveyor belt. Tesarik et al. (2003) and Young et al. (2007) reported a procedure for mixing and placing CRF at the Buick Mine that is similar to that used at DDM. The in situ deformation modulus values reported by Tesarik et al. (2003) are twice those for methods where the slurry is simply poured over the aggregate in a truck box and then driven and dumped into a stope.

4.4 Densities and Moisture Contents

The measured in situ dry density of CRF from 95 tests ranges from 1924 to 2253 kg/m^3 with an average of 2117 kg/m^3. The in situ moisture content ranges from 3.4 to 12.4% with an average of 7.2%. The variation of dry density with moisture content for a given compaction effort of the dozer, shown in Figure 6 indicates that a moisture content between 5 to 8% gives a higher density, and that a moisture content of around 7% provides optimum compaction.

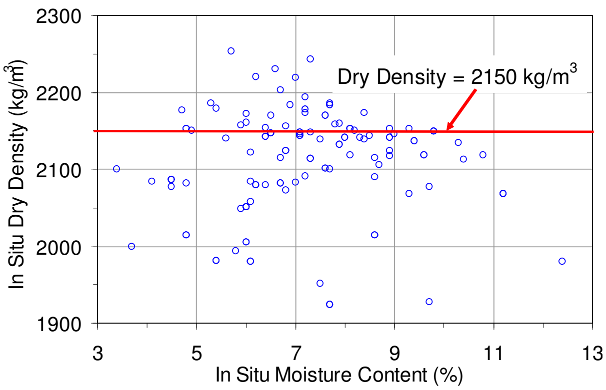

Figure 6. In situ dry density versus moisture content

CRF collected near the Troxler test locations (86 samples) had moisture contents ranging from 4.5 to 9.2% with an average of 6.8%. The in situ dry density ranged from 1916 to 2253 kg/m^3 with an average of 2125 kg/m^3. The in situ dry density measured using a Troxler nuclear gauge is essentially the same as the corresponding laboratory moisture content corrected values. This result supports the use of the Troxler nuclear gauge for measuring the in situ dry density.

The in situ bulk density of cored CRF samples studied by Hedley (1995) ranged from 1835 to 2161 kg/m^3 with an average of 2000 kg/m^3. Therefore, at DDM the measured densities are higher than but still close to Hedley's (1995) values. Tesarik et al. (2003) used a value of 2146 kg/m^3 in their numerical modeling of the Turquoise Ridge Mine, although they calculated this value from laboratory samples.

The calculated void ratio varies from 0.20 to 0.40 with an average of 0.28, and the porosity ranges from 17 to 29% with an average of 22%. The void ratio is lower than the value of 0.51 reported by Yu (1990) and Farsangi (1996), and 0.37 reported by Nokken et al. (2007). The porosity is lower than values of 33% to 45% reported by Hassani and Archibald (1998) and 0.27% reported by Nokken et al. (2007). The higher density and lower void ratio and porosity of the CRF at DDM may have resulted from the use of a excavator and dozer to compact the CRF lifts.

The overall bulk density of the tested cylinders varied from 2197 to 2477 kg/m^3 with an average of 2343 kg/m^3 and the dry density varied from 1953 to 2316 kg/m^3 with an average of 2154 kg/m^3. The moisture content ranged from 4.9 to 12.5% with an average of 8.9%. Annor (1999) and Kockler (2007) reported bulk densities of CRF cylinders ranging from 1790 to 2430 kg/m^3 and from 2114 to 2163 kg/m^3.

4.5 Unconfined Compressive Strength

The UCS test results from 178 cylinders are shown in Figure 7. The targeted 28-day design strength was 2.5 MPa (Dimitroff, 2007). The UCS increased with the curing time, as expected and easily exceeded the design value.

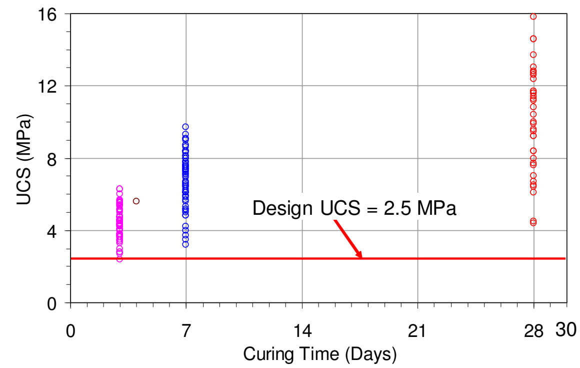

Figure 7. UCS versus curing time

The UCS is poorly correlated with the moisture content or the density of the cylinders (Figure 8) although cylinders with moisture content higher than 11% tended to give lower UCS. The poor correlation with density was possibly related to the variability in other factors such as the cement content, mixing, cylinder preparation, and curing.

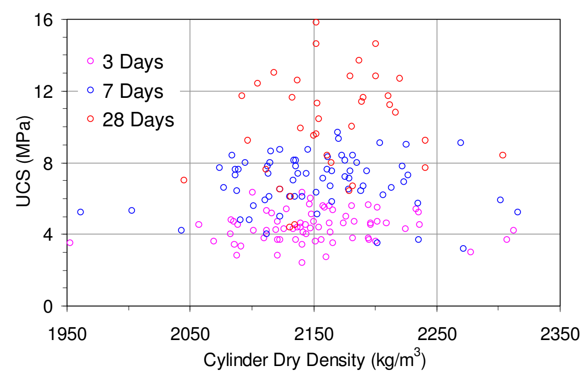

Figure 8. UCS versus dry density of cylinders

The cement content in the CRF mix design changed from 6% to 5.5% and the influence of this change on the UCS can be seen in Figure 9. The 6% cement content resulted in an average 28-day UCS of 11.5 MPa versus 8 MPa for 5.5% (100 mm diameter cylinders). The 28-day UCS from the larger 150 mm diameter cylinders is about 86% of the strength of the 100 mm diameter cylinders.

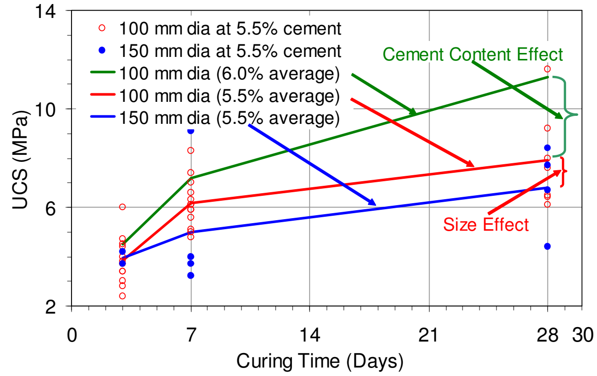

Figure 9. UCS of different CRF-cylinder sizes & cement content versus curing time

Figure 10 compares the CRF strength with various published results for CRF that is used underground (4 to 7.8% cement and w:c ratio ranging from 0.42 to 1). The UCS is typically higher than the published values. However, a direct comparison is difficult due to variability in the mix design, sample size, preparation method, and curing.

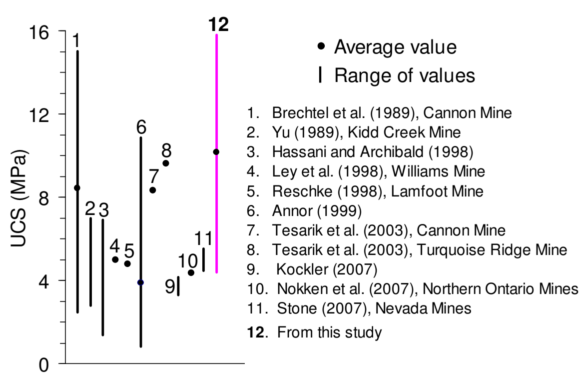

Figure 10. Laboratory UCS of (5.5 & 6% cement) CRF from this study compared with reported values

4.6 Relationship between Strength and Modulus

For some UCS tests, the vertical deformation was measured using a dial gauge, and the corresponding stress value was obtained directly from the display unit of the UCS testing machine at a typical interval of 5 seconds during each UCS test. Stress-strain curves were obtained from 26 tests conducted on 100 mm diameter cylinders with a curing time from 3, 7, and 28 days. The Young's modulus E was calculated as the slope of a tangent to the stress-strain curve taken at 50% of the UCS. A plot of the UCS versus the Young's modulus is shown in Figure 11. The following two empirical equations provide a good correlation to the test data:

$$E = 0.4615 \cdot (UCS)^{1.0408} \quad \text{or} \quad E = 501 \cdot (UCS)$$

This figure also shows empirical relationships reported by Swan (1985), Annor (1999) and Kockler (2007). The relationships from Swan (1985) and Annor (1999) are similar to that for the DDM data.

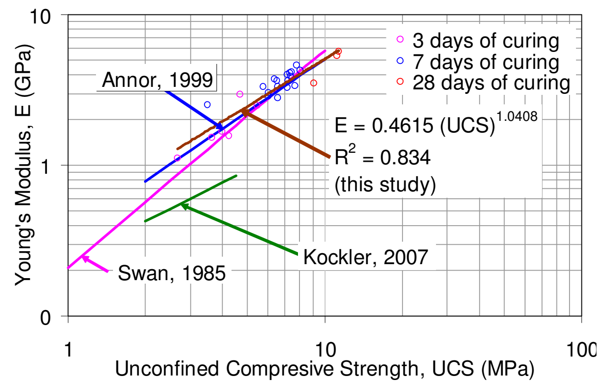

Figure 11. UCS versus Young's modulus

5 DISCUSSION AND RECOMMENDATIONS

5.1 CRF Preparation

The quantity of the aggregate used to prepare each batch of the CRF was not accurately known because it was simply based on counting the number of buckets dumped into the mixing bay. A more accurate system that involves weighing the aggregate would improve the consistency of the CRF.

The grain size distribution of the aggregate used to make CRF at DDM is close to the recommended distributions found in literature but has a tendency to be slightly coarser than optimum. The aggregate may be improved by adding up to 5% sand. Rather than adding the sand directly to the aggregate, the best option to ensure thorough mixing is to add the sand to the cement when the cement slurry is prepared.

The moisture content of the aggregate was within a narrow range of 1 to 2%. Therefore, the preparation of the cement slurry by adding a constant amount of water provides a consistent w:c ratio for the CRF and this practice should be continued. The mixed CRF had a moisture content of approximately 7%.

5.2 CRF Placement

Plots of in situ density versus moisture content suggest that the maximum dry density is achieved at moisture contents close to 7%. This moisture content matches the CRF mix design.

The specified target in situ dry density of the CRF was 2150 kg/m^3. This density typically could not be achieved at DDM by using a dozer and excavator to spread and compact the CRF in lifts that were one metre thick. The average in situ dry density was 2117 kg/m^3. This suggests that the design specification for density was too conservative and should be reduced slightly.

5.3 CRF Testing and Quality Control

In order to obtain more representative laboratory specimens of the CRF, the CRF sample should be taken from the mixing bay as the CRF is being loaded into the haul truck. This would substantially reduce the time elapsed between CRF preparation and casting of laboratory cylinders. Obtaining samples of CRF from the compacted lifts in the field is not recommended.

A proper curing chamber or a moist room at a constant temperature is recommended to minimize the variability in the measured CRF strength caused by different curing temperatures and humidity.

5.4 Predicted In Situ CRF Properties

The 28-day UCS of the 100 mm diameter cylinders from the DDM site varies from 4.5 to 15.8 MPa with an average of 10.6 MPa, and ranges from 4.4 to 8.4 MPa with an average of 6.9 MPa for the 150 mm diameter cylinders. The laboratory UCS of CRF reported in the literature usually ranges from slightly more than 1 MPa to nearly 7 MPa. Thus, the strength of the CRF tested at the DDM site tends to exceed many of the values reported elsewhere, as Figure 10 has already shown. The higher strength and lower void ratio is possibly achieved because of the better mixing by the excavator, compaction effort by the dozer, and implementation of good QC/QA practices at DDM.

The UCS is typically size-dependent, with larger specimens having a lower strength. This phenomenon extends to the prediction of the in situ UCS for CRF (Yu and Counter, 1983; Reschke, 1993). These researchers assumed that the in situ UCS is about 2/3 of the strength measured from 150 mm diameter specimens. At DDM, the UCS from 150 mm diameter cylinders is about 86% of the UCS of 100 mm diameter cylinders. Therefore, the in situ UCS is predicted to be about 60% of the strength measured from the 100 mm diameter cylinders. The lower bound of the in situ UCS of the CRF at DDM is predicted to be about 4 MPa. None of the test results measured a strength lower than 4 MPa. The upper bound of the in situ UCS is conservatively predicted to be around 7 MPa, which is less than the average measured strength from the 150 and 100 mm diameter samples.

Figure 12 compares the predicted in situ strength of the CRF at DDM with other published in situ strengths. The predicted UCS at the DDM site is slightly higher than most reported in situ values. The UCS of the CRF at the DDM site was designed to be 2.5 MPa after 28 days (Dimitroff, 2007) which was easily achieved at the DDM site, even when using the lower bound on the size-adjusted in situ strength.

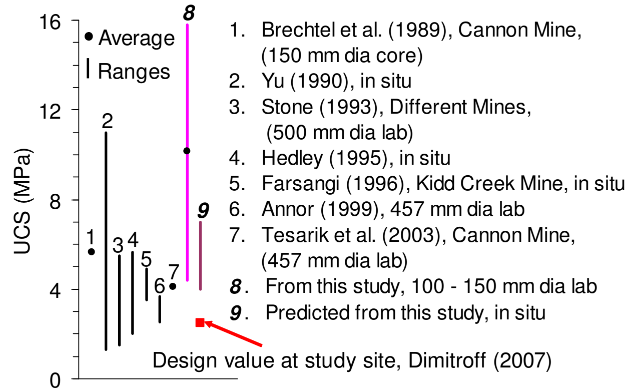

Figure 12. Predicted in situ UCS compared with reported values

The in situ CRF Young's modulus was estimated based on correlations with UCS and ranges from 2 to 3.5 GPa. Figure 13 compares the predicted in situ modulus with reported values from large-scale laboratory and in situ cored samples. This figure also presents reported design values. The predicted in situ modulus of the CRF at DDM is slightly higher than most estimated and design values published elsewhere. However, the modulus lies within the measured in situ-modulus range obtained at the Buick Mine. The Buick Mine used similar placement and compaction practices to those used at DDM.

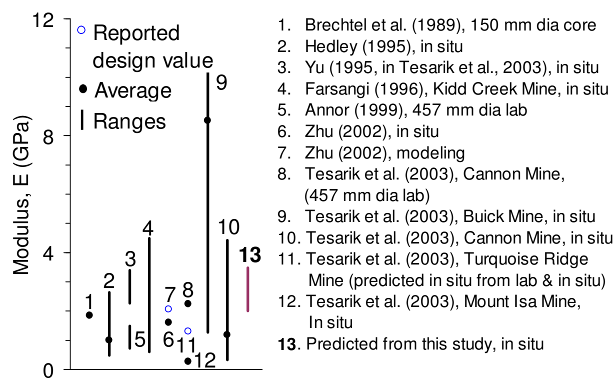

Figure 13. Predicted in situ Young's modulus compared with reported values

The predicted in situ CRF properties at the DDM site are summarized in Table 1. These values provide a useful starting point for conducting strength or deformation analysis of the CRF as the underground mining proceeds and undercuts the cap or crown pillar of the CRF.

Table 1 Predicted in situ CRF properties at DDM

Parameters	Range		Remarks
UCS, σ_c (MPa)	4.0	7.0	Predicted from measured values
Modulus, *E* (GPa)	2.0	3.5	
Dry density, γ_d (kg/m^3)	2070	2140	
Friction angle, ϕ	35º	40º	Estimated from UCS & literature review
Cohesion, *c* (MPa)	0.8	1.7	
Poisson ratio, ν	0.2	0.3	
Void ratio, *e*	0.2	0.4	Calculated
Porosity, η (%)	17	29	

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