SME Annual Meeting
Feb. 25 - 28, 2018, Minneapolis, MN

Preprint 18-031

ESTIMATING THE UNCONFINED COMPRESSIVE STRENGTH (UCS) OF EMPLACED CEMENTED ROCKFILL (CRF) FROM QA/QC CYLINDER STRENGTHS

S. N. Warren, NIOSH, Spokane, WA
M. J. Raffaldi, NIOSH, Spokane, WA
K. K. Dehn, NIOSH, Spokane, WA
J. B. Seymour, NIOSH, Spokane, WA
L. A. Sandbak, Barrick Gold Corp., Winnimuca, NV
J. Armstrong, Barrick Gold Corp., Crescent Valley, NV

ABSTRACT

Confidence in the design and stability of an undercut cemented rockfill (CRF) span requires a thorough understanding of its emplaced material properties. The unconfined compressive strength (UCS) of cast 6×12-inch QA/QC cylinders is typically used as an index test to track the performance of a backfill plant. However, these strengths need to be adjusted for oversize aggregate removal and sample size effects if used to estimate the emplaced UCS.

UCS testing of 6×12, 12×24, and 18×36-inch cast CRF cylinders was used to quantify the relationship between readily available 6×12-inch QA/QC strength data and the emplaced UCS. Test results indicate that the UCS of 18×36-inch cylinders is roughly 40% of the 6×12-inch UCS for similarly compacted samples.

Mine QA/QC data indicate that the UCS of CRF is highly dependent on the degree of compaction as measured by bulk density. Based on these results, knowledge of the emplaced CRF density compared to 6×12-inch QA/QC density is also necessary to estimate the emplaced UCS.

The scale effect reported in this study is more pronounced, compared to current understanding of backfill properties discussed in the literature, and underscores the need for further site-specific testing.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) Spokane Mining Research Division (SRMD), in cooperation with Barrick Gold Corporation, is conducting research with the goal of determining a relationship between 6-inch QA/QC cylinder strengths and the in-place strength of cemented rockfill (CRF). CRF cylinders with dimensions (diameter × length) of 6×12, 12×24, and 18×36 inches were cast onsite at the Turquoise Ridge Joint Venture (TRJV) and Cortez Hills Underground (CHUG) mines using CRF mixed at the mines' respective batch plants. UCS tests were performed after 28 days of curing to estimate the size correction factor for each mine's CRF. This paper presents an overview of the mix designs, sample collections, testing methods, test results, and an estimate of the UCS size correction factor for CRF at these mines.

BACKGROUND

Underhand cut and fill mining methods utilizing cemented backfill are common in underground metal mines in the United States. These methods are advantageous for controlling weak or highly stressed rock mass conditions by creating an engineered material that can be placed in openings, forming a beam that provides a safe, stable back for the next undercut. Increased use of underhand methods in the last 30 years has greatly improved safety in many cut-and-fill mines. However, with the continual push for more efficient and cost effective mining, there is a need to thoroughly understand the geotechnical properties of cemented backfill to assist in designing safe, stable openings while optimizing costs and production schedules.

To design safe undercut spans, engineers must ensure that the emplaced strength of the backfill exceeds the strength required to support its own weight and resist applied loads from the surrounding rock mass. Strength requirements are typically determined through a combination of analytical formulae (Mitchell, 1991), empirical design (Pakalnis, et al., 2005), and numerical modeling. The final CRF mix (water content, cement content, aggregate grading, etc.) is generally created using traditional concrete guidelines, and available aggregate materials, to create a product with a desired workability while meeting the design strength requirements.

A quality assurance and control program (QA/QC) is usually initiated during the commission of the CRF batch plant. The unconfined compressive strength (UCS) test is the most common measure of backfill strength and is the most common QA/QC test in mines. The tests are usually performed on 6×12-in cast cylinders of CRF, following the ASTM C31/C31M concrete standard as closely as possible. This typically requires the removal of aggregate greater than 1/3 the diameter of the cylinder (2 inch), known as wet sieving. This process effectively changes the mix by increasing the cement/aggregate ratio (Neville, 1995) and could inflate the apparent CRF strength.

The strength results from 6-inch QA/QC cylinders are very useful as an index value for tracking performance of the batch plant, as long as sample preparation is consistent. This also provides a readily available database that can be used to estimate emplaced properties of the CRF. However, the UCS values from the 6-inch cylinders likely overestimate emplaced strength and should be corrected accordingly (Stone, 1993 and O'Toole 2005). The appropriate strength correction is the topic of this paper.

Strength size effects associated with cylinder diameter have been well documented for concrete tested in tension, flexure, and compression (Neville, 1995). Figure 1 shows the typical relative reduction in UCS with increasing sample size for concrete.

The strength levels off when the cylinder diameter exceeds about 20 inches, indicating that placed concrete has a UCS that is only 85% of the 6-inch test cylinders (Blanks and McNamara, 1935). The trend of this curve has been found valid for numerous concrete mixes and variations in top aggregate size up to 9 inches.

Various correction factors for estimating the emplaced CRF strength from UCS tests on 6-inch cylinders are mentioned in the available literature, but with scant documentation. The strength reduction estimates for CRF are much more drastic compared to concrete and are shown above in Table 1. This size effect, if not accounted for and where large cylinder test data are not available, could have implications for safety when there is an operational inquiry to potentially enlarge the maximum span of openings under CRF or to optimize the CRF mix design.

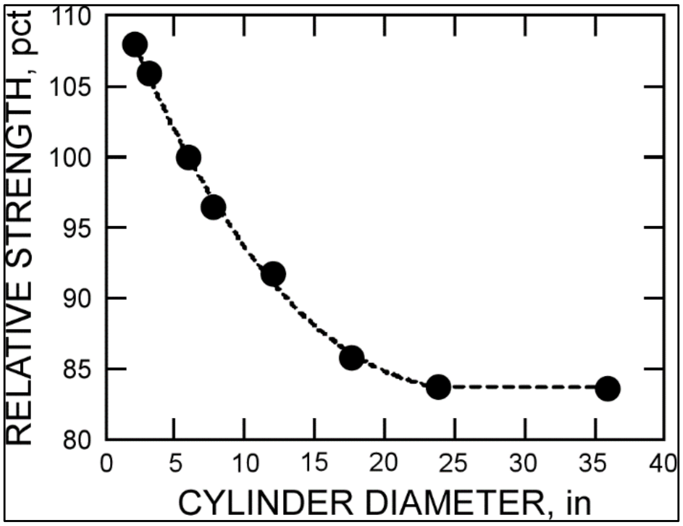

Figure 1. Typical compressive strength size effect for concrete (after Blanks & McNamara, 1935).

Table 1. Reported size correction factors for CRF and concrete compressive strength.

Source	Cylinder Diameter Min.	Cylinder Diameter Max.	Correction Factor	Agg Top Size
Stone 1993	6 in	20 in	0.65[a]	N/A
Barrett et al. 1983	6 in	17.7 in	0.60[a]	4 in
O'Toole 2005	6 in	20 in	0.66[a]	N/A
Blanks & McNamara 1935	6 in	24 in	0.85[b]	3 to 9 in

(a) Cemented Rockfill (CRF)
(b) Concrete with aggregate top size of 3 to 9 inches

GEOLOGY AND GEOTECHNICAL CONDITIONS

Both mine sites are located in Northeastern Nevada, USA. TRJV mine is a Carlin-style deposit hosted by Cambro-Ordovician mudstone and lesser carbonate with interbedded basalt. The area has undergone very complex structural disruption, both before and after gold mineralization was deposited. Cryptic metamorphism in the area is likely related to the intrusion of the Cretaceous Osgood granodiorite stock. Alteration associated with gold is characterized by the remobilization of carbon, decarbonatization of limestone beds, and argillization of basalt and dacite units (Jackson, 2017).

CHUG is a breccia-related Carlin-type ore deposit located in the Devonian Wenban and Silurian Roberts Mountain carbonate units, cross cut by a Jurassic quartz monzonite/granodiorite stock and Tertiary quartz porphyry dikes. Although less complexly faulted than TRJV, the CHUG orebody is controlled and cut by both high and low angle faults. The local host rock carbonates have undergone some calc-silicate metamorphism related to the intrusion of Mesozoic or Eocene rocks (Jackson, et al. 2010).

Production zones within the ore bodies are typically composed of highly altered and intensely fractured rock with Rock Mass Ratings (RMR) (Bieniawski, 1976) of less than 45 (Sandbak and Rai, 2013; Sun and Chen, 2013). Access drifts and infrastructure often intersect faults and altered material of varying thickness and geotechnical quality ranging from blocky competent rock to saturated soil-like material (Warren et al., 2016).

UNDERHAND CUT-AND-FILL WITH CRF

TRJV and CHUG utilize an underhand cut-and-fill mining method, which results in the replacement of the weak rock mass with engineered cemented backfill (CRF). Initially, topcuts are mined in parallel, with roughly 15×15-ft panels. Upon completion of a mined heading, CRF is dumped at the heading and jammed into place using a modified LHD equipped with a steel boom called a "jammer." The jammer pushes and jams the CRF tight to the heading back, resulting in high density compacted CRF. A schematic of this process is shown below in Figure 2.

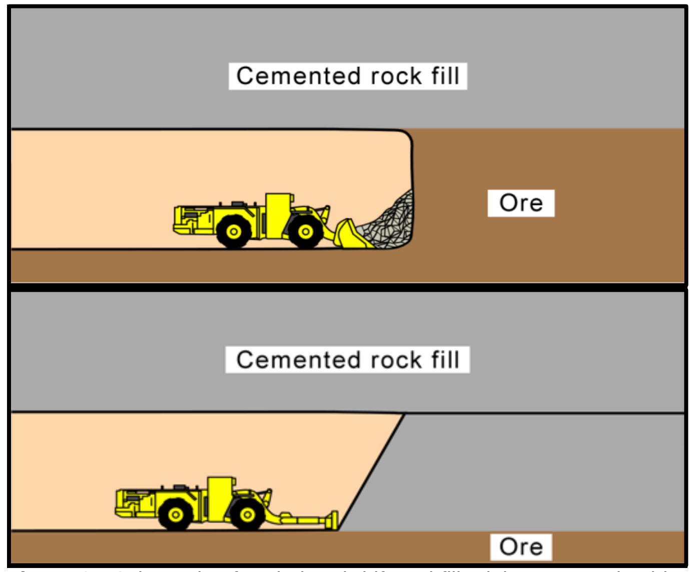

Figure 2. Schematic of underhand drift-and-fill mining as practiced in Northern Nevada gold mines.

A series of parallel topcuts are mined and backfilled forming a CRF sill across the entire ore body. This sill provides a stable backfill beam to work beneath for subsequent undercuts. The process of undercutting and backfilling continues for each subsequent level until the ore body is mined out. A simplified mining sequence is shown in Figure 3.

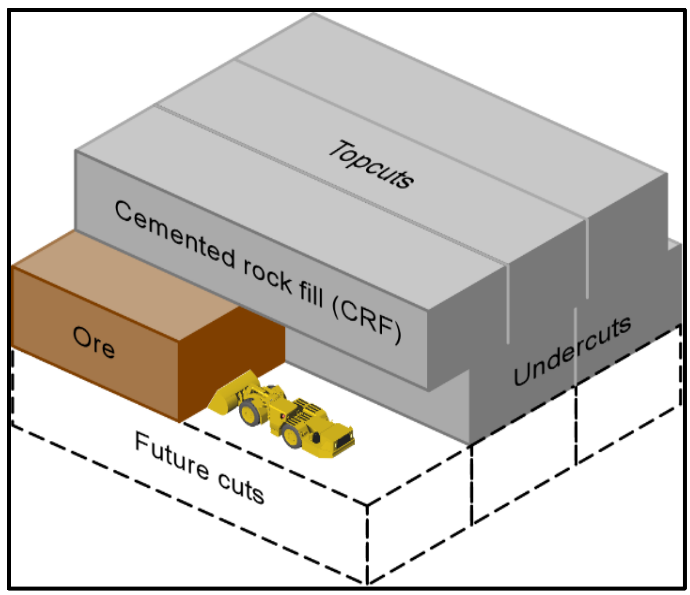

Figure 3. Schematic cross section through a top and bottom cut showing offset drifts.

CEMENTED ROCKFILL COMPOSITION

The following subsections provide information regarding the CRF mix design, aggregate source, and aggregate gradations. The composition of the CRF is important with respect to understanding the empirical test results in this study and their applicability to CRF mixes used at other mines.

The defining characteristics of CRF are a larger aggregate top size of 2 to 6 inches depending on the operation, inclusion of fines from the crushing process, and a less than 1 inch slump which is essential for creating self-standing faces when jamming the material.

Mix Designs

A CRF mix used for underhand cut-and-fill mining was chosen from each mine for casting the test cylinders. The mix designs for both mines are listed in Table 2.

Table 2. Tested cemented rockfill mix designs.

CRF Formula	Water/Cement Ratio	Binder, wt%	Admix[(a)], oz/lbs Water	Design UCS, psi
TRJV	0.73	5.3	0.10	600[(b)]
CHUG	0.96	7.3	0.06	700[(c)]

(a) water-reducing admixture
(b) Barnard and Sandbak (2017)
(c) CHUG 2017

Aggregate Source

TRJV obtains aggregate from an on-site surface quarry; the aggregate is primarily composed of micritic limestone with interlayered siltstone, both units having minimal alteration. Quarried rock is crushed and screened to 3-inch minus.

The Cortez Hills Underground Mine (CHUG) obtains aggregate from the overlying Cortez Hills Open Pit (CHOP) waste rock that is crushed and screened to 2-inch minus. CHOP waste rock is a mixture of limestone, marble, quartz monzonite and rhyolitic intrusive dike, and some quartzite. The aggregate sources for TRJV and CHUG are summarized below in Table 3.

Table 3. Summary of TRJV and CHUG Aggregate Sources.

Mine	Source	Lithology	Top Size
TRJV	Local quarry	Micritic limestone with interbedded siltstone	3 inch
CHUG	CHOP[(a)] Waste rock	Limestone, Marble, Dike, Quartzite	2 inch

(a) Cortez Hills Open Pit

Figure 4. Aggregate on belt at TRJV underground batch plant.

At TRJV the aggregate must be transported from a surface stockpile and down a borehole to one of two underground batch plants. At CHUG the CRF is mixed at a surface batch plant, and the aggregate is stockpiled nearby. Figure 4 above shows a photo of TRJV aggregate on the belt at the underground batch plant. Figure 5 shows the aggregate stockpile at the CHUG surface batch plant. Both mines perform routine sieve analyses for QA/QC of the aggregate size distribution.

Aggregate Size Distribution

Aggregate gradation controls the density of the CRF and, therefore, has a significant impact on CRF strength (Stone, 2007). The Talbot and Richard (1923) gradation equation, shown below, was originally developed for concrete design and represents the optimal gradation curve to minimize void space when N = 0.5 (Stone, 1993). However, a coarser gradation, with N ranging from 0.55 to 0.45, is desirable for jammed stopes so that the CRF has a lower slump and will stand at a steep angle prior to curing. A finer aggregate gradation, with N ranging from 0.35 to 0.45, performs better in end-dumped longhole stopes (Stone, 2007).

$$P = 100\left(\frac{u}{U_{max}}\right)^{N} \qquad (1)$$

where,

P = percent passing
u = particle size
U_{max} = maximum particle size
N = distribution constant

Figure 5. Aggregate stockpile at CHUG surface batch plant.

Figures 6 and 7 present typical gradation curves obtained from sieve analyses at TRJV and CHUG, respectively. They show that the aggregate used at both TRJV and CHUG are on the coarser side, suitable for jam-filling underhand cut-and-fill stopes. The sieve samples were taken after sending the aggregate down the chute (where applicable) and just before CRF batching. Table 4 summarizes the backfill sieve data from TRJV and CHUG.

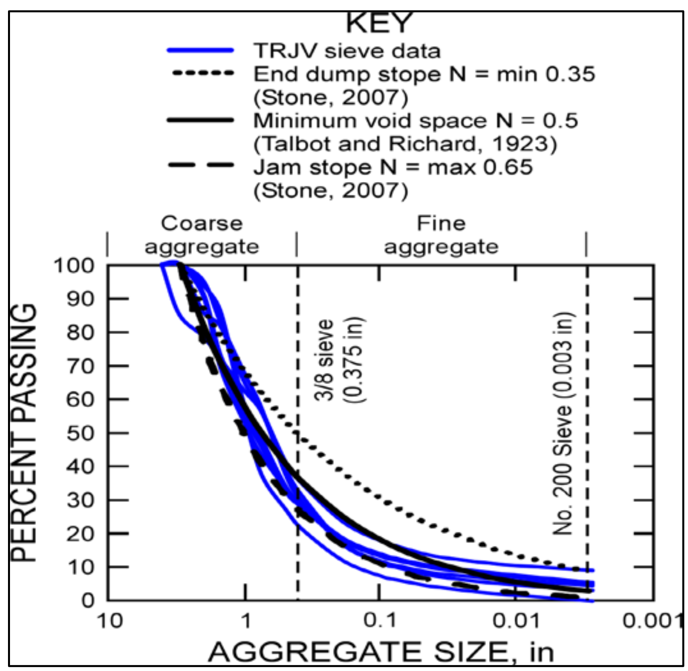

Figure 6. TRJV backfill QC/QA sieve analyses from Jan 2017 to May 2017. Note that samples were taken from the belt at the underground batch plant.

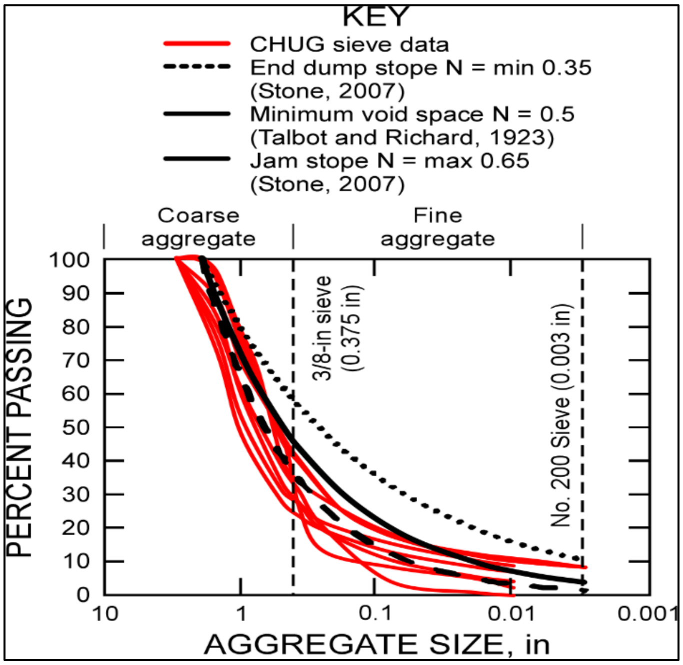

Figure 7. CHUG backfill QC/QA sieve analyses from Oct 2016 to May 2017. Sieve samples were taken from the stockpile at the surface batch plant.

Table 4. Summary of TRJV and CHUG Average Aggregate Gradations.

Mine	% coarse rock >10mm (0.375 in)	% fine rock 0.075 – 10 mm (0.375 – 200 sieve)	% fines <0.075 mm (200 sieve)
TRJV	68%	26.7%	5.3%
CHUG	70%	21.8%	8.2%

Both mine sites have a slightly higher content of fines passing 0.075 mm than desired due to the aggregate not being washed after crushing. Fines in concrete mix design are typically limited to 5 percent depending on its intended use [ASTM C33]. This higher fines content does improve the workability of the CRF for jamming and making a “sticky” material that compacts well, but has a detrimental effect on strength (Stone, 2007).

CYLINDER CASTING AND HANDLING

During the study, an effort was made to cast test samples using a consistent methodology at both mine sites. This section describes the methodology that was used and points out the differences in sample collection and handling between the cylinders collected at the two mines.

Cylinder Casting

Backfill samples were cast in typical concrete cylinder forms in three different sizes (diameter × length): 6×12, 12×24, and 18×36 inch. The 6×12-inch cylinders were cast in standard plastic molds and prepared according to procedures similar to those used at the mines, which follow, as closely as possible, to ASTM C31/C31M. Oversize aggregate greater than about one-third of the cylinder diameter (2 inches) was removed by hand while making the cylinders.

Due to the low-slump nature of CRF, strict adherence to the ASTM C31 standard is difficult. Consistency of sample density between cylinders, and ideally in comparison to the in-place density underground, is the goal. Table 5 lists the number of each size of cylinders cast for UCS testing.

Wax-coated cardboard concrete forms were used for molds for the 12×24 and 18×36-inch cylinders. The ASTM C31/C31M standards only cover preparation of cylinders up to 9 inches in diameter. Preparation of the 12×24-inch and 18×36-inch cylinders followed ASTM standards as practical and appropriate. The 12×24 and 18×36-inch cylinders were cast in lifts of approximately 6-inch sequences. Each lift was tamped approximately 50 times with an inflatable rock bolt used as a tamp rod. Cylinders were completed within roughly 45 minutes to one hour after mixing at the batch plant in an effort to not exceed the working time of the CRF.

Table 5. Quantity of each size CRF cylinder cast.

Mine	6 × 12[(a)] (inches)	12 × 24[(a)] (inches)	18 × 36[(a)] (inches)
TRJV	8	3	4
CHUG	8	4	4

(a) diameter × length

At TRJV, the test samples were prepared from four separately mixed batches. For each cylinder size, a quarter of the total quantity of cylinders were cast from each batch. A small front loader was used to take a scoop of CRF from a loaded truck and to then dump it nearby for sampling. Each batch required about one hour for two people to cast the cylinders. Figure 8 shows the completed TRJV 12×24-inch cylinders.

Figure 8. Completed 12×24-inch cylinders at the TRJV underground casting site before covering.

At CHUG, the cylinders were cast on surface, and a much larger work force could be assembled. This allowed all cylinders to be cast from a single batch of CRF. Figure 9 shows the CHUG backfill being delivered to the surface casting site. Cylinders were cast on surface during a typical Nevada summer morning (ambient temperature around 90 degrees Fahrenheit and a low relative humidity).

Figure 9. CRF batch used to cast cylinders at CHUG being dumped at the casting site on the surface.

Cylinder Handling and Storage

The TRJV samples were stored underground at the casting location for 24 hours before being moved to the underground QA/QC laboratory. After approximately three weeks curing underground, the samples were transported to Spokane, WA for 28-day strength testing.

The CHUG cylinders were left on the surface at the casting site for 24 hours and then moved to a surface laydown and stored for a week before they were picked up and transported to Spokane. In Spokane, the cylinders were stored in a fog room until 28-day strength testing was completed. The samples were handled with care and not exposed to any extreme weather conditions or impacts during transport.

SAMPLE PREPARATION AND TESTING

Samples were tested to determine the unconfined compressive strength (UCS) of the three sizes of CRF cylinders. The following subsections describe sample preparation and test.

Sample Preparation

Prior to testing, both ends of the 6×12-inch cylinders were capped with a sulfur capping compound to meet ASTM C39/C39M end-parallelism requirements. The 12×24 and 18×36-inch cylinders were capped on the top surface with Hydro-Stone®, a self-leveling, rapid curing gypsum cement product that can achieve a compressive strength of 4,000 psi after one hour. The bottoms were not capped because they were already flat from casting in the form. Figure 10 shows the four 18×36-inch cylinders, cast from the CHUG CRF mix, capped and ready to be tested.

Figure 10. 18×36-inch cylinders of CRF, cast at CHUG, and prior to testing at SMRD.

Test Procedures

Test procedures followed ASTM C39/C39M as closely as possible. An axial compressive load was applied to the test cylinders at a specified loading or displacement rate so that failure generally occurred within two to five minutes. The compressive strength of the test specimen was calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen.

Depending on the size of the cylinder, two different test machines were used to conduct the tests. The 6×12-inch cylinders were tested using a 200-kip, servo-controlled, electro-mechanical, stiff frame test machine. The 12×24 and 18×36-inch cylinders were tested using a 600-kip, manual-hydraulic controlled, stiff-frame test machine, shown in Figure 11.

TEST RESULTS

Observed Failure Mechanisms

The samples typically developed either a Type 1 (shear cones) or Type 4 (diagonal shear fracture) ASTM C39/C39M fracture pattern. Both fracture patterns occurred in all cylinder sizes and samples. Figure 12 below shows post-test photographs of an 18×36-inch CRF cylinder from both TRJV and CHUG. The formation of a shear fracture plane is clearly visible on the TRJV sample, while the CHUG sample has developed shear cones and an hourglass failure pattern is observed.

Figure 11. Unconfined compression testing of an 18×36-inch CRF cylinder.

Figure 12. Example post-test photographs of 18×36-inch CRF cylinders from (left) TRJV and (right) CHUG, both showing well-defined ASTM C39 Types 1 and 4 shear fracture patterns.

After testing, the larger test samples were broken apart with sledge hammers to examine the shear fractures. Figures 13 and 14 below show well-developed shear fracture patterns for both the TRJV and CHUG samples. The TRJV samples tended to fail by shearing through intact aggregate, while the CHUG samples tended to fail by shear fracturing of the cement bonds between the individual aggregate particles.

Figure 13. Photograph showing well-developed shear cone in an 18×36-inch CRF cylinder from TRJV.

Figure 14. Photograph showing well-defined shear fracture in an 18×36-inch CRF cylinder from CHUG.

Unconfined Compressive Strength (UCS)

Tables 6 and 7 provide the average UCS and standard deviation of the TRJV and CHUG test samples, respectively. The complete test data for TRJV and CHUG are provided graphically in Figure 15. The TRJV samples were much stronger than the CHUG samples for all cylinder sizes, but both sets of tests exhibited a clear decrease in strength with increasing cylinder size.

Table 6. Average UCS Results for TRJV CRF Cylinders.

Cylinder Size (in)	Sample Quantity	Density (pcf)	UCS (psi)	Std Dev (psi)
6 × 12	8	139.8	2907	403
12 × 24	3	139.5	1582	685
18 × 36	4	136.5	962	164

Table 7. Average UCS Results for CHUG CRF Cylinders.

Cylinder Size (in)	Sample Quantity	Density (pcf)	UCS (psi)	Std Dev (psi)
6 × 12	7	133.9	811	135
12 × 24	4	146.9	707	57
18 × 36	4	142.2	498	90

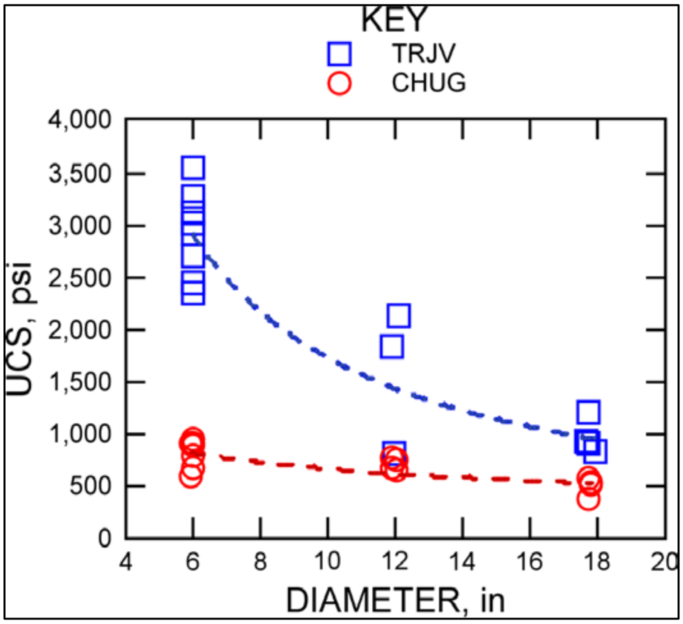

Figure 15. Unconfined compressive strength in the various sized cylinder diameters for TRJV and CHUG.

The UCS of CRF is directly related to the bulk density of the samples (Stone, 2007), and a clear tendency for samples with higher bulk densities to have higher UCS values has been observed in the QA/QC data at both mines, as shown in Figure 16. This relationship is intuitive, as higher density CRF has a decreased void ratio and likely improved aggregate interlocking.

Bulk Density Effect on UCS

In the authors' experience, cylinder preparation methods can significantly affect the density of cast CRF test cylinders. Despite efforts to maintain consistency of bulk density between test cylinders, some variability within a given cylinder size is unavoidable. However, the main objective when casting was to maintain a consistent average density across all cylinder sizes so that strengths could be directly compared.

Figure 17 provides a plot of the densities of both the TRJV and CHUG test samples for all cylinder sizes. The average densities for each size are provided in Tables 6 and 7.

The average density of the TRJV 18-inch cylinders (136.5 pcf) was slightly less than that of the 6 and 12-inch cylinders at 139.8 and 139.5 pcf respectively. Good consistency was maintained between the 12 and 18-inch CHUG samples, at 146.9 and 142.2 pcf; however, the 6-inch densities were around 10 pcf lighter (133.9 pcf). Typical bulk densities for 6-inch samples measured in the CHUG lab were between 138 and 142 pcf with higher densities in the 140-145 pcf range. A sample with a bulk density as low as 134 would not normally reach the target strength of 700 psi. This difference in density is substantial and the data set likely underestimates the true strength of the 6-inch cylinders with respect to the 12 and 18-inch cylinders if densities were consistent.

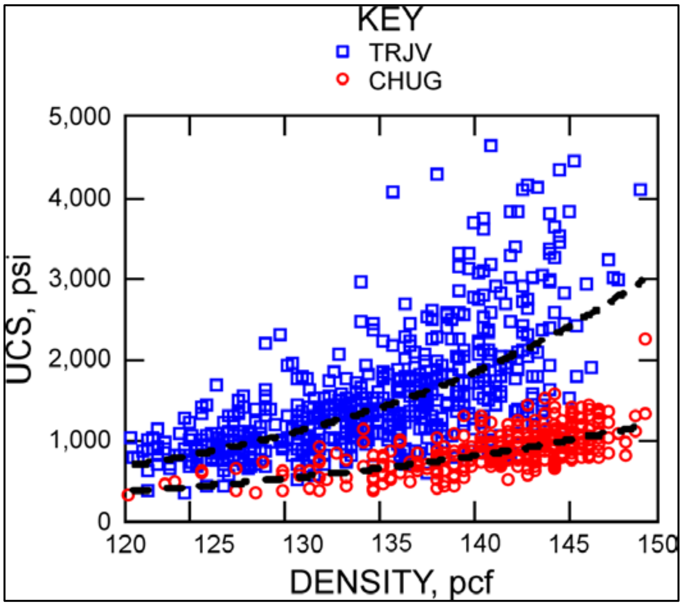

Figure 16. TRJV and CHUG QC/QA CRF strength data, showing clear relationship between UCS and bulk density.

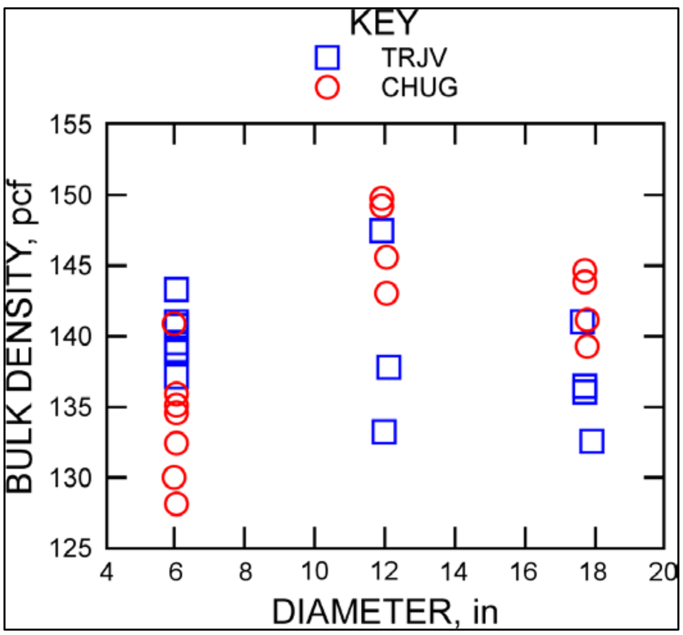

Figure 17. Bulk density of 6×12, 12×24, and 18×36-inch CRF cylinders from TRJV and CHUG.

CORRECTING UCS FOR DENSITY

Figure 16 indicates that sample density has a significant effect on UCS. To estimate the relationship between UCS and density, trend lines were individually fit to the 28-day QA/QC data from TRJV and CHUG (Figure 16). Each trend line was normalized to the UCS at a reference density of 140 pcf so that the strength is on a relative rather than absolute scale. In this way, a strength of 1 is assigned to 140 pcf, and the strength at lower and higher densities is provided as a fraction of this strength.

Table 8 lists the relative strength of the 6-inch QA/QC samples with 140 pcf as the reference density. The 140 pcf reference density is somewhat arbitrary, but it was chosen based on the estimated in-place density.

This relationship was used to scale the individual UCS values measured in this laboratory study, based on the densities of the samples. The density-adjusted UCS values are plotted in Figure 18. Note that the average CHUG 6×12-inch cylinders moved up to around 1,100 psi compared to the measured 811 psi on Figure 15 and Table 7. These values will be referred to as “density-adjusted values” to distinguish them from the measured UCS values during testing.

Table 8. Approximate relationship between average bulk density and average UCS in a 6×12-inch cylinder for CRF based on QA/QC data from TRJV and CHUG (Fig 16).

Bulk Density (pcf)	Predicted Strength (psi)		Relative Strength	
	TRJV	CHUG	TRJV	CHUG
125	880	452	0.49	0.51
130	1125	552	0.62	0.64
135	1438	674	0.79	0.80
140	1839	822	1.00	1.00
145	2351	1004	1.27	1.25
150	3005	1226	1.62	1.57

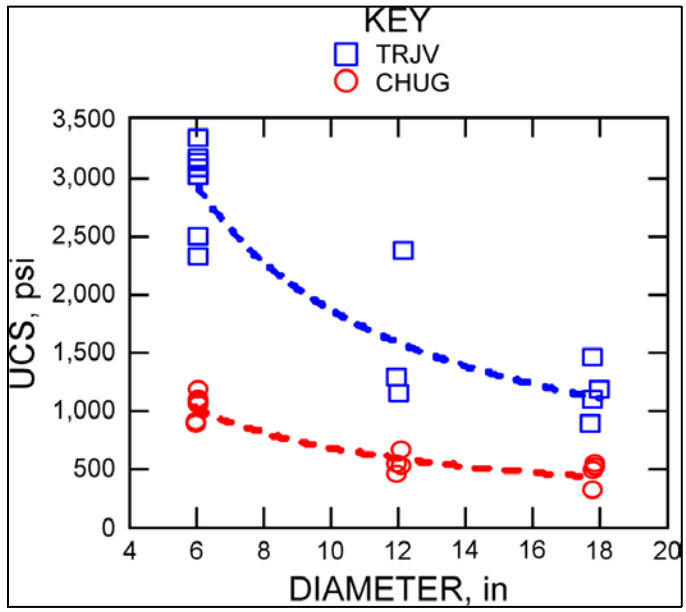

Figure 18. Density-adjusted UCS test values.

EMPLACED STRENGTH CORRECTION FACTOR

A plot of the measured UCS values as a percentage of their corresponding average 6-inch UCS is shown in Figure 19. The black dashed line is the generalized concrete size effect curve presented previously in Figure 1. The measured size reduction factors to convert the strength of the 6-inch cylinders to 18-inch for TRJV and CHUG CRF are roughly 0.33 and 0.61, respectively.

The variations in average density between different sized cylinders, as discussed previously, may exaggerate or underestimate the true size effect. To account for density differences in the samples, the density-adjusted UCS data, shown in Figure 18, were used to create a new density-adjusted size effect plot as shown in Figure 20.

Figure 20 shows that the size effect for both the TRJV and CHUG samples, when adjusted for differences in density, is approximately the same (0.4).

The measured and density-adjusted UCS size correction factors are provided in Table 9. The density-adjusted correction factors represent the best estimate of the true size effect.

SUMMARY AND CONCLUSIONS

The purpose of this study was to relate the strength of 6×12-inch QA/QC cylinders to the emplaced CRF strengths in the mine. This information is relevant to increase the confidence of CRF undercut span design and optimize CRF mix designs. The strength of 6×12-inch cast CRF cylinders was compared to 12×24 and 18×36-inch cylinders to quantify the scale effect, and predict emplaced CRF UCS, using readily available QA/QC cylinder data.

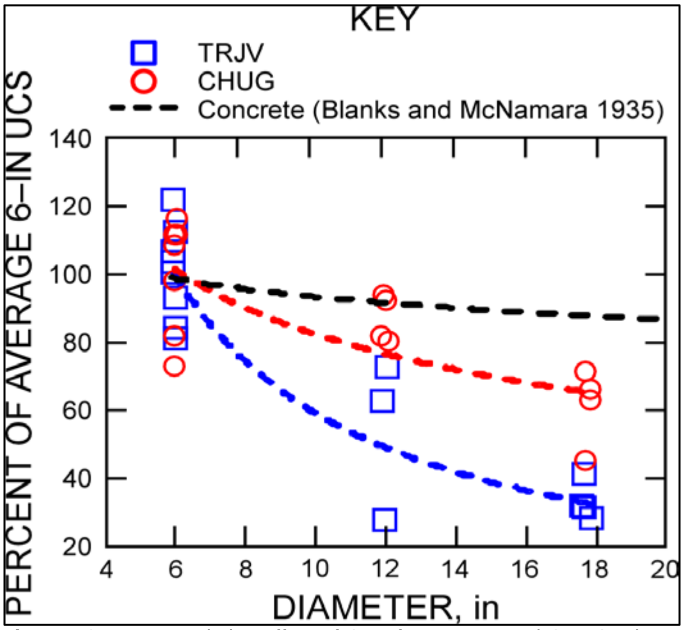

Figure 19. Measured size effect of CRF from TRJV and CHUG mines compared with that of concrete.

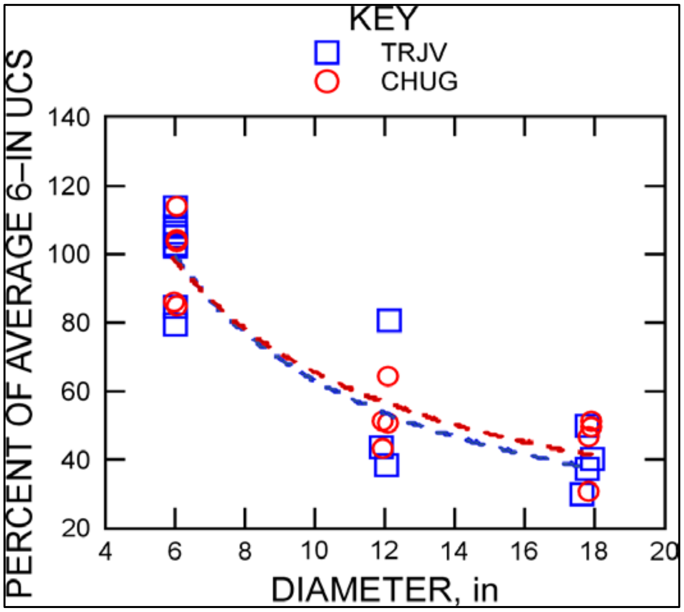

Figure 20. Density-adjusted size effect of CRF from TRJV and CHUG mines.

Table 9. Density-adjusted size correction factors for 18×36-inch (approximately in-place) CRF compressive strength.

Mine	Measured Correction Factor	Density- adjusted Correction Factor	Aggregate Top Size
TRJV	0.33	0.39	3”
CHUG	0.61	0.45	2”

Results indicate that the measured scale effect from 6×12 to 18×36 can range from 0.33 to 0.66. The higher end of this range is consistent with previously published values; however, only a few studies have been published and results from these studies are generally only descriptive.

Mine QA/QC test data indicate that compaction, as measured by density, has a significant effect on the unconfined compressive strength (UCS). For example, an increase in density from 130 pcf to 140 pcf results in a roughly 60% increase in UCS. This underscores the importance of obtaining a reasonable estimate of the in-place CRF density compared to the 6×12-inch QA/QC cylinder density.

When sample strengths are adjusted for differences in density, the scale effect from 6×12 to 18×36-inch cylinders is much more constrained to 0.39 to 0.45 and is considered to be the best estimate of the true scale effect. Effectively, this means that the emplaced backfill strength is roughly 40% of the 6×12 cylinder strength for similarly compacted materials.

This scale effect is most likely a combination of at least two major factors, including: 1) the removal of oversize aggregate from the smaller cylinders, and 2) sample cylinder size effect. The removal of oversize aggregate (+ 2 inches) from the smaller 6×12-inch sample effectively changes the mix design and increases the cement/aggregate ratio (Neville, 1995). This typically results in a relative increase in the 6×12-inch cylinder strength compared to the emplaced strength. A reduction in UCS strength with increasing sample size is a well-documented phenomenon in concrete and rock samples. These effects cannot be quantified individually because aggregate size screening practices are different for different sample sizes. Therefore, the aggregate removal and sample size effect can only be expressed as an overall scale effect.

20×40-inch cylinders are generally accepted as representative of emplaced concrete strength; however, this relationship has not been investigated for CRF. Data from this investigation indicate that the size effect curves generally level out around 18 inches; however, the true cylinder size that represents emplaced CRF strength is not actually known.

Testing results presented in this paper indicate that a much larger variation in scale effect is possible compared to the current understanding of backfill properties discussed in the literature. Therefore, the strength correction factor may be more complicated than a simple sample size correction and underscores the need for site-specific scale correction factor testing.

ACKNOWLEDGEMENTS

The authors thank Barrick Gold N.A. for collaborating in this research. In particular, thanks to Chase Barnard and Patrick Braden for coordinating support and transport of the cylinders at TRJV, along with the backfill plant operators for their patience. From Cortez Hills, the authors wish to thank Kaitlynn Hrenko, Mariah McCormick, and Jeremiah Larocque for coordinating support and handling of the cylinders, along with the CHUG 2017 summer interns for helping expedite the casting of the cylinders. We also gracefully acknowledge the following NIOSH personnel: Mike Stepan and Habte Abraham for fabricating the test cylinder transport frames and conducting the UCS testing, along with Jerry Richardson and Seth Powers.

DISCLAIMER

The findings and conclusions in this paper are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

ASTM C31/C31M-10, 2010, Standard Practice for Making and Curing Concrete Test Specimens in the Field. ASTM International, West Conshohocken, PA.

ASTM C33/C33M-93, 1993, Standard Specification for Concrete Aggregates. ASTM International, West Conshohocken, PA.

ASTM C39/C39M-15, 2015, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA.

Barnard, C. and Sandbak, L. 2017. "Practical geotechnical design in backfill at the Turquoise Ridge Mine, Nevada," Proceedings *of the 12th International Symposium on Mining with Backfill* (Minefill 2017), Denver, CO.

Barrett, J.R., Stewart, J.E., and Brock, J.G., 1983, "Cemented gravel for a small underground mine," *Proceedings of the International Symposium on Mining with Backfill*, Lulea, Sweden, pp. 69–78.

Bieniawski, Z., 1976, "Rock mass classifications in rock engineering," *Exploration for Rock Engineering*, A.A. Balkema, Cape Town, South Africa, pp. 97–106.

Blanks, R.F. and McNamara, C.C., 1935, "Mass concrete tests in large cylinders", Journal of the American Concrete Institute, Vol. 31, pp. 280–303.

CHUG 2017. Cortez Hill Underground, Ground control management plan. Internal mine document.

Jackson, J., Arbonies, D., Creel, K., 2010, "Architecture of the Cortez Hills Breccia Body," Great Basin Evolution and Metallogeny, *Geological Society of Nevada, 2010 Symposium*, pp 97–123.

Jackson, J., 2017, Personal communication regarding the geology of Carlin-type gold deposits in Northeastern Nevada.

Mitchell, R.J., 1991, "Sill mat evaluation using centrifuge models," *Mining Science and Technology*, Elsevier Science Publisher B.V., 13: pp. 301–313.

Neville, A.M., 1995, Properties of concrete (Vol. 4). London: Longman Group.

O'Toole, D., 2005, "A review of some important aspects of cemented aggregate fill", Handbook on Mine Fill, Chapter 8, Section 8.8, p.136.

Pakalnis, R., Caceres, C., Clapp, K., Morin, M., Brady, T., Williams, T., Blake, B., MacLaughlin, M., 2005, "Design spans – Underhand cut and fill mining. *Proceedings from the 107th CIM-AGM*, Toronto, Canada.

Sandbak, L. and A. Rai., 2013, "Ground support strategies at the Turquoise Ridge joint venture," *Rock Mechanics and Rock Engineering,* 46: pp. 437–454.

Stone, D.M.R., 1993, "The optimization of mix design for cemented rockfill," *Proceedings of MINEFILL 1993*, Johannesburg, published by SAIMM, 1993, pp. 249–253.

Stone, D.M.R., 2007, "Factors that affect cemented rockfill quality in Nevada mines," *Proceedings of MINEFILL 2007*. Denver, Colorado.

Sun, C. and Chen, J., 2013. "Ground control practices at Leeville Underground Mine," *Proceedings of the 32nd International Conference on Ground Control in Mining*, 2013, Morgantown, WV, Pp. 156–163.

Talbot, A.N., Richard, F.E., 1923, "The strength of concrete, its relation to the cement aggregates and water," Bulletin No. 137, University of Illinois Engineering Experiment Station, Urbana, Illinois, pp. 24–27.

Warren, S.N., Kallu, R.R., and Barnard, C.K., 2016, "Correlation of the Rock Mass Rating (RMR) System with the Unified Soil Classification System (USCS): Introduction of the Weak Rock Mass Rating System (W-RMR)," *Rock Mechanics and Rock Engineering*, Vol. 49, No. 11, pp. 4507–4518.