Effect of Sample Size on CRF Strength Properties

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Abstract
Cemented rockfill (CRF) is commonly used in conjunction with underhand cut-and-fill mining methods to provide ground support in weak rock conditions, particularly in the underground gold mines in Nevada. Because miners work directly beneath the backfill at these operations, a thorough understanding of the material properties of the in-place CRF is needed in order to design safe undercut spans beneath the fill. To assess the quality and strength of the backfill, unconfined compression tests are typically conducted with standard-sized samples of CRF as 6 × 12 in (15 × 30 cm) cylinders. However, depending on the preparation and testing of the CRF sample, the resultant unconfined compressive strength (UCS) may not be representative of the in-stope fill. To address this issue, the National Institute for Occupational Safety and Health (NIOSH) has been conducting research in cooperation with several underground mines in the United States to develop a better means of relating the material properties of in-stope CRF to test results obtained from standard-sized samples.

This paper presents the results of tests conducted with CRF samples from Nevada Gold Mines' Goldstrike Operations near Carlin, NV, and compares these findings with similar tests conducted with CRF samples from other mines. Strength and elastic properties are reported for tests conducted with CRF samples ranging in size from 6 ×12 in (15 × 30 cm) to 18 × 36 in (46 × 91 cm). The effects of sample size, density, and maximum aggregate screen-size are discussed along with the consequences of unintended changes in mix design during sampling. Developing better methods of relating the strength of CRF samples to the properties of the in-stope material should lead to more clearly defined target strengths, more appropriate factors of safety, and, thus, safer backfill mine designs.

Key words: cemented rockfill, density, aggregate screen-size, *in situ* strength

Introduction
The Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health (NIOSH) has been conducting research in cooperation with several underground metal mines in the Western United States to determine the strength properties and *in situ* performance of cemented backfill. Cemented rockfill (CRF) is commonly used in conjunction with underhand cut-and-fill mining methods to provide ground support. The CRF supports the overlying material in the mine roof and confines the surfaces of rock pillars and abutments, thereby enhancing their ground support capabilities (Seymour et al., 2019). CRF is a zero or low slump, coarse aggregate, concrete-like engineered material used for backfilling mined-out openings (Bourgeois et al., 2023). It is typically weaker and drier than concrete, and its mix constituents are not as closely controlled. Compared to concrete, CRF usually has a lower cement content, a higher water-to-cement ratio (but a drier consistency), and a more variable aggregate gradation, containing larger aggregate with the maximum size of coarse aggregate ranging from 2–6 inches (5–15 cm) and including more fines from the crushing process. As noted by Stone (2007), aggregate gradation controls the density of CRF and significantly impacts its strength. Although CRF is commonly used with

backfill mining methods throughout the world, a better understanding is needed of the engineered properties of this material to ensure the safety of miners working underground near backfilled entries.

As part of a mine's quality assurance and quality control (QA/QC) program, freshly batched CRF is routinely sampled in 6 ×12 in (15 × 30 cm) cylinders, and then unconfined compressive strength (UCS) tests are conducted with these samples to track the performance of the batch plant and to estimate the *in situ* strength of the in-stope CRF. However, depending on the physical characteristics of the backfill mix constituents and the consistency of the batching, sampling, and testing procedures, the UCS test results may not always accurately represent the strength of the in-stope backfill. To address these issues, NIOSH is conducting research to develop improved methods for sampling and testing CRF. As part of this research effort, SMRD researchers collaborated with the Nevada Gold Mines' Goldstrike Operation, an underground gold mine near Carlin, NV, to measure the strength and elastic properties of one of their backfill mixes and to determine if the properties obtained from standard 6 × 12 in (15 × 30 cm) QA/QC samples reflect the bulk properties of larger CRF samples and, thus, the *in situ* properties of the in-stope backfill. The results of this study are presented below and compared with results from similar tests conducted with CRF samples from other mines.

Sample Size Effect

Many materials, including rock (Hoek and Brown, 2003), exhibit a general decrease in strength with increasing sample size. The influence of sample size on strength properties has been well documented for concrete (Blanks and McNamara 1935, U.S. Bureau of Reclamation 1981) (Figure 1). As the size of a concrete cylinder increases, the UCS of the sample decreases. This reduction in compressive strength diminishes when the diameter of sample approaches 18–20 in (46–51 cm), eventually leveling off to reflect the bulk strength of the in-place concrete. The UCS of these larger diameter samples is about 83% of the UCS for standard 6 × 12 in (15 × 30 cm) cylinders, or about a 17% reduction in compressive strength (Neville 1973).

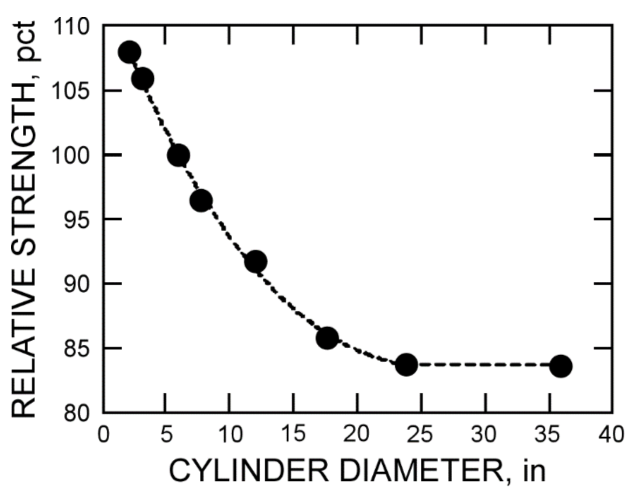

Figure 1. Relative compressive strength of concrete versus cylinder size (Blanks and McNamara, 1935).

As discussed by Warren et al. (2018b), various scale factors or size effect ratios for estimating the *in situ* strength of in-stope CRF from UCS tests with 6 × 12 in (15 × 30 cm) cylinders have been suggested by others, most notably Barrett et al. (1983), O'Toole (2005), and Stone (1993). Although only limited details have been provided regarding the testing and development of these values, they appear to range from about 0.60–0.66 of the UCS for standard 6 × 12 in (15 × 30 cm) samples, indicating that CRF has a larger size effect (ie, a greater reduction in UCS) as compared to concrete. Prior to the research with Goldstrike reported in this paper, NIOSH collaborated with three underhand cut-and-fill metal mines in the Western United States to determine the strength and elastic properties of CRF samples ranging in size from 6 × 12 in (15 × 30 cm) to 18 × 36 in (46 × 91 cm). These tests indicated that depending on the CRF mix, the UCS of the larger 18 × 36 in (46 × 91 cm) samples can range from about 22–61% of the UCS for a standard 6 × 12 in (15 × 30 cm) sample, a substantially larger decrease in strength. Because many factors contribute to this CRF sample-size effect, the site-specific testing of large cylinders is the best means of assessing the magnitude of this strength reduction.

CRF Mix Design

All CRF test samples for this study were prepared using the same backfill mix design. Four separate batches of the same CRF mix were prepared at the Meikle underground batch plant, a well-designed, completely automated system capable of producing consistent well-mixed CRF to meet design specifications.

Aggregate

Aggregate for the CRF mix came from open-pit waste rock which was crushed to a maximum aggregate screen-size of 3 in (7.6 cm). The aggregate consisted mostly of black to dark-grey, fine-grained micrite and limestone, with varying degrees of low-grade metamorphism and remobilized carbon. A significant amount of fines (material passing a 200 mesh) was contained in the aggregate, some of which was undoubtedly caused by inherent remobilization of carbon and further comminution of the aggregate during its delivery down a borehole from the surface. Because of the laminated nature of the sedimentary host rock, much of the aggregate was lenticular, with length-to-width ratios > 2:1.

Cement

A 5% binder, consisting of straight Portland Type II cement, was used for the CRF mix. As reported by the mine, this particular backfill mix is typically used in overhand bench stoping areas where underhand mining is not expected.

Water-to-cement ratio

At the batch plant, fresh (non-potable) mine water was added directly into the paddle mixer to prevent potentially detrimental chemical reactions from processed or recycled drill water. During casting of the CRF cylinders for this study, the workability of the backfill material resembled that of a mix having a 0.7 water-to-cement ratio (sticky, zero-slump consistency). The aggregate more than likely had a high moisture content due to the wet weather conditions on the surface and the hot, humid atmosphere underground when the CRF samples were prepared. Based on the underground atmospheric conditions, evaporation of water from the mixed backfill material was not an apparent problem.

Sample Collection and Handling

Goldstrike and NIOSH personnel cast all CRF test samples for this study on May 22, 2019, at the entrance of an unused stoping area located near the Meikle batch plant on the 1075 level of the mine. Freshly mixed CRF from the batch plant was transported to the sampling location using a 6 yd^3 (4.6 m^3) load, haul, dump machine (LHD). A total of 32 cylinders were cast from four separate batches of the same CRF mix. From each batch, eight samples were cast: six 6 × 12 in (15 × 30 cm) cylinders, one 12 ×2 4 in (30 × 61 cm) cylinder, and one 18 × 36 in (46 × 91 cm) cylinder. All CRF samples had a 2:1 length-to-diameter ratio. An example of the three sizes of cylinders that were cast from each batch is shown in Figure 2, and the number and size of the cylinders cast for each type of laboratory test are listed in Table 1. The CRF cylinders were cast from four separate batches so that all of the samples from each batch could be prepared within one hour of mixing and, thus, avoid exceeding the working time of the cement. With four people, it took approx 45 mins to fill one set of cylinders for each batch.

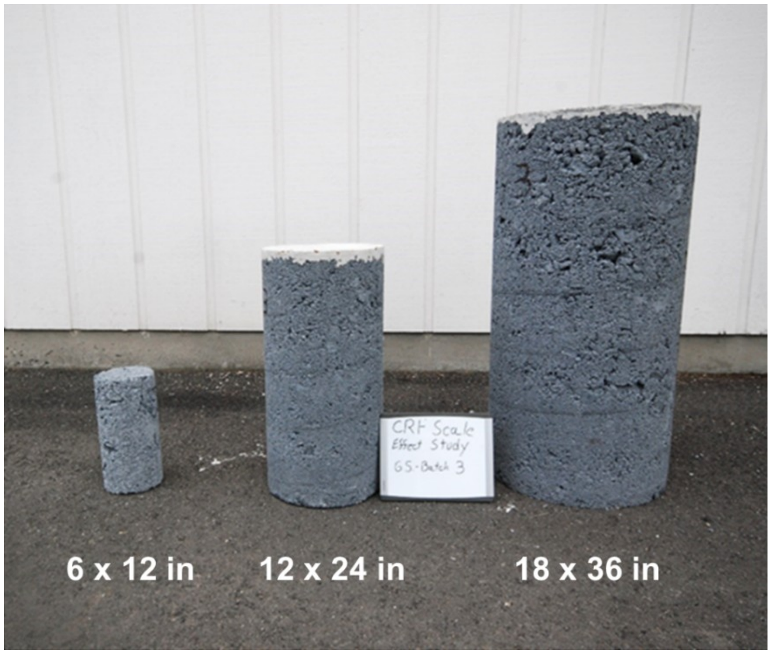

Figure 2. Example of the three sizes of backfill cylinders tested from Batch 3.

Table 1. Quantity of samples cast for each test method.

Type of Test	Cylinder Dimensions (in)	Number of Samples
UCS[1]	6 × 12	12
UCS	12 × 24	4
UCS	18 × 36	4
STS[2]	6 × 12	8
Archive[3]	6 × 12	4

[1]Unconfined compressive strength
[2]Splitting tensile strength
[3]Samples retained for testing after long-term curing

Application of ASTM C31
Twenty-four 6 × 12 in (15 × 30 cm) CRF samples were cast in standard plastic cylinder molds and prepared, following as closely as practical the procedures specified in ASTM C31/C31M (2022): Standard Practice for Making and Curing Concrete Test Specimens in the Field. As shown by the slump test for Batch 1 (Figure 3), CRF is typically a dry, low-slump, concrete-like material. Although ASTM C31 is not recommended for dry, zero-slump concrete, its procedures are still the most practical options available for casting CRF samples. However, due to the low-slump nature of CRF, strict adherence to ASTM Standards is difficult.

ASTM C31 only covers the preparation of cylinders up to 9 in (23 cm) in diameter, so the 12 in (30 cm) and 18 in (46 cm) diameter cylinders were prepared following as closely as appropriate the recommended procedures. Four 12 × 24 in (30 × 61 cm) samples and four 18 × 36 in (46 × 91 cm) samples were cast in wax-coated cardboard concrete forms, which were reinforced and restrained in wooden frames. The large cylinder forms were filled and compacted in roughly 6 in (15 cm) high lifts, with each lift tamped about 50 times using an uninflated Swellex rockbolt (28 mm diameter) or a Split-Set rockbolt (39 mm diameter).

Because the density of a sample significantly affects its strength, all 32 CRF samples were compacted in a similar manner regardless of cylinder size to achieve bulk densities that were consistent with visual inspections of CRF jammed in underhand cut-and-fill entries.

Figure 3. Slump test with CRF mix from Batch 1.

Removal of oversized aggregate

According to ASTM C31, the diameter of a concrete cylinder should be at least three times the nominal maximum size of the coarse aggregate; therefore, when the coarse aggregate > 2 in (5 cm), the concrete mix should be treated by wet sieving through a 2 in (50 mm) sieve before casting 6 in (15 cm) diameter cylinders. Because the nominal maximum size of the Goldstrike aggregate was 3 in (7.6 cm), the CRF mix was wet screened to remove coarse aggregate having an edge length longer than 2 in (5 cm) before the 6 × 12 in (15 × 30 cm) samples were cast. Coarse aggregate > 4 in (10 cm) was visually identified in the CRF mix and manually removed from the 12 × 24 in (30 × 61 cm) samples. No coarse aggregate was removed from the 18 × 36 in (46 × 91 cm) cylinders.

Curing of CRF cylinders

Once the forms were filled, the CRF samples were sealed with standard plastic lids for the 6 × 12 in (15 × 30 cm) cylinders or with tight-fitting wooden lids for the 12 × 24 in (30 × 61 cm) and 18 × 36 in (46 × 91 cm) cylinders. The samples were allowed to remain stationary and undisturbed for at least 24 hours, and then they were moved to a nearby storage bay for additional curing. After curing 21 days underground, the cylinders were transported to the surface where they were loaded on a flatbed truck and driven to the NIOSH Spokane Research Laboratory (SRL) for testing. During their transport, the CRF samples were handled carefully and not subjected to extreme weather or impacts. Upon their arrival at SRL, four of the 6 × 12 in (15 × 30 cm) cylinders were stored in their molds in a climate-controlled curing room to allow them to cure for an extended period of time before being tested. The remaining 28 samples were prepared for UCS or splitting tensile strength (STS) tests.

Cemented Rockfill Testing

Sample preparation

After the CRF samples were stripped from their forms, the final dimensions of each cylinder were measured to identify differences from their nominal diameter and length. Each cylinder was also weighed to account for variations in density and the presence of voids. Prior to conducting UCS tests, both ends of the 6 × 12 in (15 × 30 cm) cylinders were sulfur capped to meet the end-parallelism requirements cited in ASTM C39/C39M (2021).. The uneven tops of the 12 × 24 in (30 × 61 cm) and 18 × 36 in (46 × 91 cm) cylinders were leveled using a mixture of hydrostone gypsum cement and water. All capping procedures followed as closely as practical those mentioned in ASTM C617/617M (2015). No end preparation procedures were required for the 6 × 12 in (15 × 30 cm) cylinders used for the STS tests.

Unconfined compressive strength tests

To determine the compressive strength of the CRF, 20 UCS tests were conducted with the following samples: twelve 6 × 12 in (15 × 30 cm) cylinders, three samples from each batch; four 12 × 24 in (30 × 61 cm) cylinders, one sample from each batch; and four 18 × 36 in (46 × 91 cm) cylinders, one sample from each batch. Depending on the size of the CRF sample, two different test machines were used to conduct the tests (Figure 4). After 28 days of curing, the 6 × 12 in (15 × 30 cm) samples were tested using a servo-controlled hydraulic, stiff-frame test machine having a 200,000 lbf (1,000 kN) capacity (Tinius Olsen 1000SL). The next day, the 12×24 in (30×61 cm) and 18 × 36 in (46 × 91 cm) samples were tested using a manual-controlled hydraulic, stiff-frame test machine with a 400,000 lbf (2,000 kN) capacity and a loading frame capable of accommodating large bulk samples (Tinius Olsen Super L). The UCS tests were performed following as closely as practical the procedures outlined in ASTM C39. To improve the consistency of the test results, the displacement rates for the tests were varied so that the samples would fail within 2–3 mins. Depending on the size and strength of the samples, the displacement rate varied from 0.020–0.050 in/min (0.5–1.3 mm/min), and the test duration ranged from about 1–9 min.

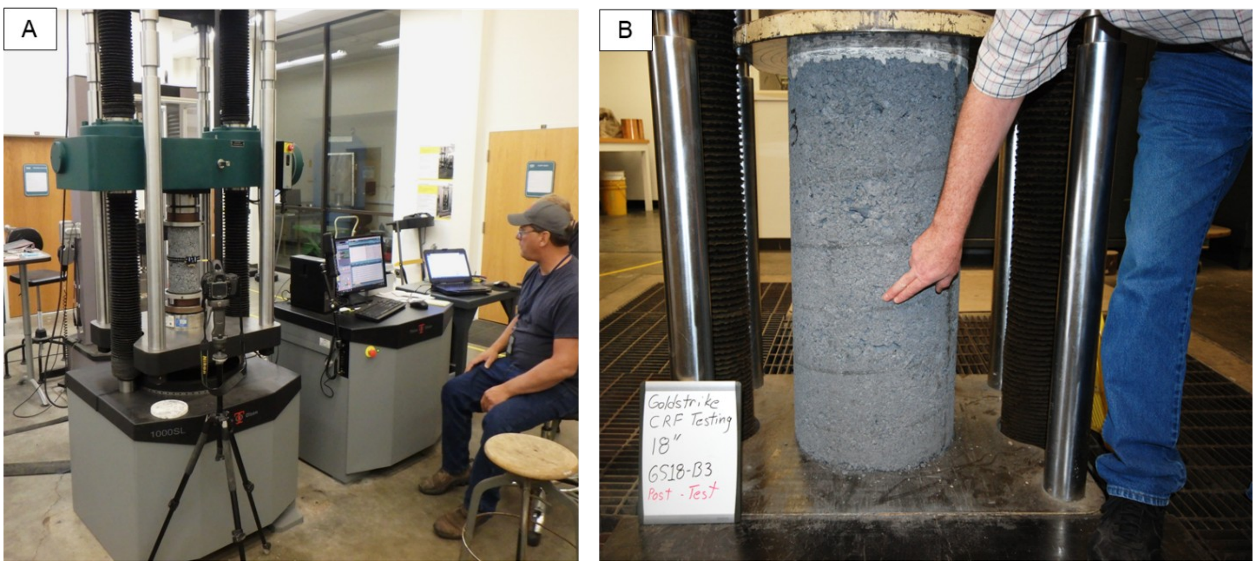

Figure 4. UCS tests with CRF samples: (a) 6×12 in cylinder and (b) 18×36 in cylinder.

During UCS tests with the 6 × 12 in (15 × 30 cm) cylinders, a custom-made compressometer device was used to measure the axial and radial deformation of the samples following ASTM C469/C469M (2014). As shown in Figure 5A, the compressometer consisted of two linear variable differential transformer (LVDT) position sensors for measuring axial deformation, and a radial chain device from GCTS Testing Systems for measuring transverse or circumferential deformation. During UCS tests with the larger diameter samples, two linear potentiometers positioned on opposite sides of the sample were used to measure convergence of the loading platens, and a custom-made linear potentiometer device was used to measure transverse or circumferential deformation of the sample (Figure 5B).

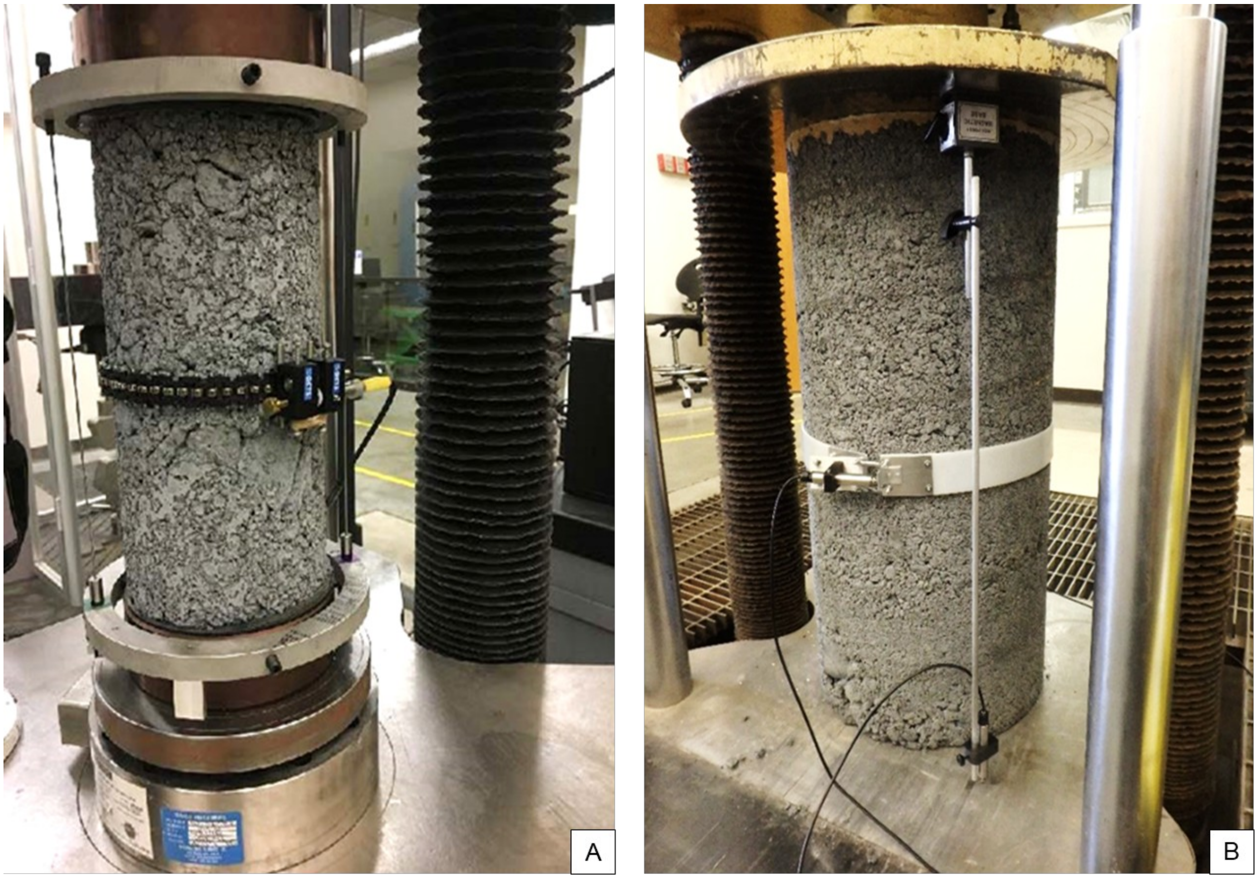

Figure 5. UCS tests with instrumented CRF samples: (a) 6×12 in cylinder and (b) 12×24 in cylinder.

Splitting tensile strength tests

After the samples had cured for 28 days, eight STS tests were conducted with two 6 × 12 in (15 × 30 cm) cylinders from each batch. The STS tests were performed using a Tinius Olsen 1000SL test machine and the test procedures outlined in ASTM C496/C496M (2017). The configuration for an STS test with a 6 × 12 in (15 × 30 cm) CRF sample positioned in a custom-designed test fixture is shown in Figure 6. For consistency, the STS tests were conducted at a constant displacement rate of 0.050 in/min (1.3 mm/min), which caused the CRF samples to fail in ~ 2–3 min.

Figure 6. Splitting tensile strength test with a 6×12 in CRF sample.

Test Results

Bulk density

Prior to destructive testing, the CRF samples were measured to determine their average dimensions (diameter and length), and they were weighed in order to calculate their bulk density. The density of a CRF sample directly affects its strength with more dense samples typically having higher UCS and STS values than less dense but similarly sized samples (Stone, 2007; Warren et al., 2018a, 2018b; Bourgeois et al., 2023). The density of the Goldstrike CRF samples ranged from about 127–143 pcf (2,028–2,291 kg/m^3); although the same CRF mix design was used for all four batches, there was a noticeable difference in bulk density depending on the batch number and cylinder size (Figure 7).

The average bulk density of the samples was 133 pcf (2135 kg/m^3), but it varied by batch number from 128.6 pcf (2059 kg/m^3) for Batch 1 to 137.4 pcf (2201 kg/m^3) for Batch 2. Nevertheless, the average densities of the CRF samples were fairly consistent in terms of sample size, as indicated by the statistical summary in Table 2. Any noticeable voids and low-density layers within the CRF samples were usually associated with the presence of a higher percentage of large aggregate.

Table 2. Average bulk density of CRF samples

Cylinder Dimensions[1] (in)	Average Bulk Density (pcf)[2]	Standard Deviation (pcf)	Coefficient of Variation (%)
6 × 12	133.4	3.9	2.9
12 × 24	136.1	5.2	3.8
18 × 36	129.9	3.5	2.7

[1]Average values for the 6×12-in cylinders include both UCS and STS samples.
[2]Pounds per cubic foot

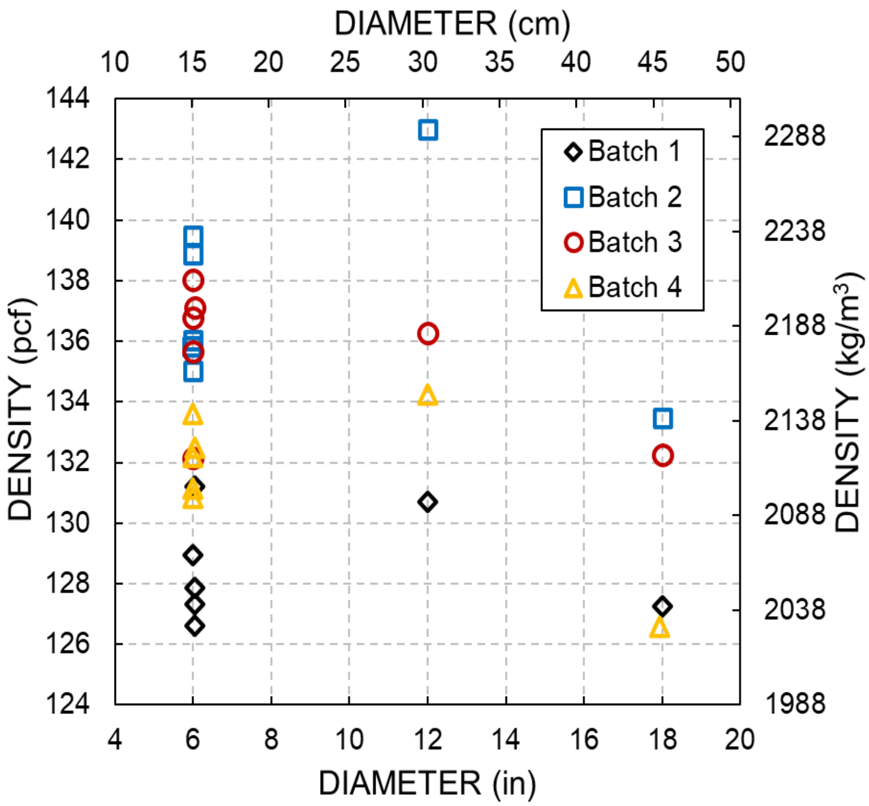

Figure 7. Bulk density of CRF samples by cylinder size and batch number.

Unconfined compressive strength

Individual results of the UCS tests are plotted versus cylinder diameter according to batch number (Figure 8). Although the test results vary somewhat depending on the specific batch, the trend lines for the individual batches indicate a noticeable decrease in compressive strength with increasing sample size. If the UCS values for the different batches and cylinder sizes are normalized in terms of the average UCS for all twelve of the 6 × 12 in (15 × 30 cm) cylinders, then this decrease in strength with increasing sample size is more apparent and less confusing (Figure 9).

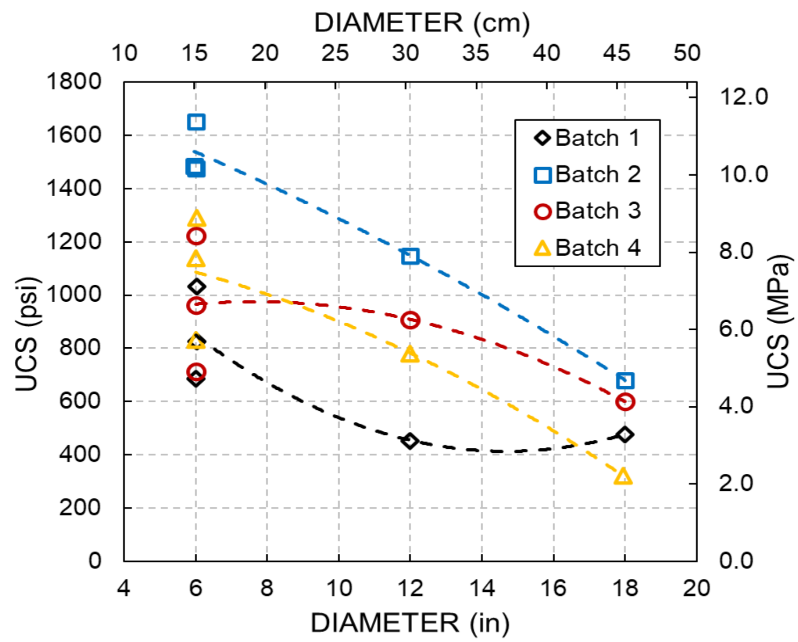

Figure 8. 28 day UCS versus cylinder diameter for CRF samples.

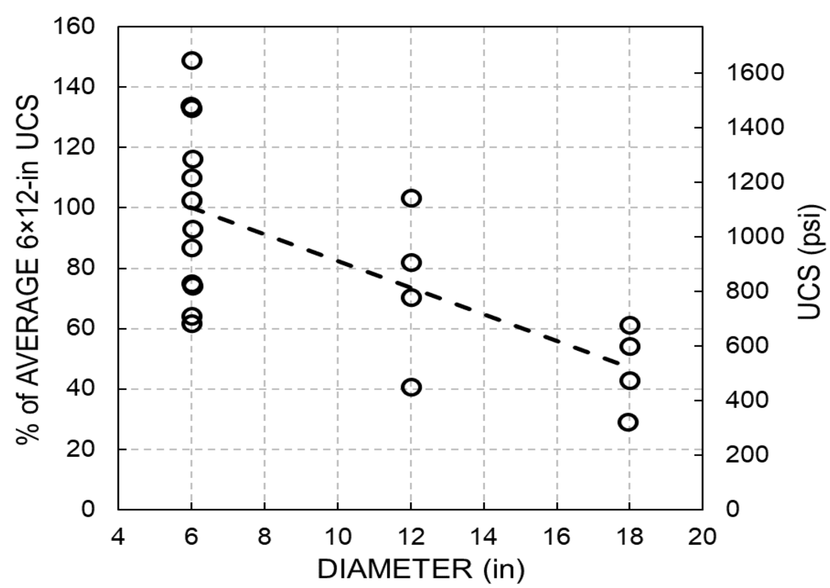

Figure 9. Compressive strength size effect for CRF samples

A summary of the average UCS test results by cylinder size is provided in Table 3, again indicating a substantial decrease in compressive strength with increasing sample size. The average UCS of the 12 × 24 in (30 × 61 cm) samples was about 74% of the average UCS for the 6 × 12 in (15 × 30 cm) samples, whereas the average UCS for the 18 × 36 in (46×91 cm) samples was only about 47% of that of the 6 × 12 in (15 × 30 cm) samples. Although efforts were made to prepare and test the UCS samples in a consistent manner, there were still significant differences in the test results as shown by the variation in compressive strengths for the different batches (Figure 8) and the high coefficient of variation values listed in Table 3.

Table 3. Summary of results from UCS tests with CRF samples

Cylinder Dimensions (in)	Samples Tested	Average Bulk Density (pcf)	Average UCS[1] (psi)	Standard Deviation (psi)	Coefficient of Variation (%)	Percent of Average 6×12-in UCS (%)
6 × 12	12	133.6	1110	322	29	100.0
12 × 24	4	136.1	822	290	35	74.1
18 × 36	4	129.9	520	156	30	46.9

[1]Unconfined compressive strength after 28 days of curing for 6×12-in samples and after 29 days of curing for 12×24 in and 18×36 in samples

Elastic properties

During the UCS tests, the axial and circumferential deformations of the CRF samples were measured so that the modulus of elasticity and Poisson's ratio could be determined. The modulus values were computed following as reasonably as possible the practices outlined in ASTM C469, where the elastic range is defined by the section of the stress-strain curve between 50 microstrains and the strain corresponding to 40% of the sample's ultimate compressive strength or UCS. For ASTM C469, the test specimen is normally loaded and unloaded through several cycles within the elastic response range of the material to determine the modulus and Poisson's ratio. However, due to the relatively low strength and variability of the CRF samples, the UCS test specimens were loaded to failure in one cycle, thus requiring the modulus and Poisson's ratio to be determined from this single loading cycle. The compressometer device that was used for the 6 × 12 in (15 × 30 cm) cylinders seemed to provide reasonable and reliable measurements. However, the instrument measurements for the larger diameter samples were suspect, particularly the circumferential deformation measurements from the custom-made linear potentiometer device. Nevertheless, the average modulus of elasticity that was calculated for each cylinder size is provided in Table 4 along with the average Poisson's ratio for the 6 × 12 in (15 × 30 cm) samples.

Table 4. Summary of average elastic properties for CRF samples

Cylinder Dimensions (in)	Average Modulus of Elasticity (10^3 psi)	Percent of Avg. 6×12-in Modulus (%)	Average Poisson's Ratio
6 × 12	551	100.0	0.08
12 × 24	232	42.1	NA[1]
18 × 36	225	40.8	NA[1]

[1]Data not available due to instrumentation problems

According to the American Concrete Institute, ACI 318-19.2.2 (2023), for a cylindrical sample of normal-weight concrete having a density of 145 pcf (2323 kg/m^3), the modulus of elasticity is proportional to the square root of the compressive strength (Neville, 2009; Wight and MacGregor, 2009). As noted by Warren et al. (2018b), a similar form of this equation also reasonably represents the relationship between the modulus of elasticity and UCS for cylindrical samples of CRF. Because the modulus of elasticity is directly related to the compressive strength of a sample, the average modulus of elasticity of the Goldstrike CRF also decreased with increasing sample size (Table 4). The average modulus of elasticity of the 18 × 36 in (46 × 91 cm) samples was only about 41% of the average modulus computed for the 6 × 12 in (15 × 30 cm) samples.

Splitting tensile strength

The individual results of the STS tests are shown below in Figure 10, and a summary of the overall results is provided in Table 5. The average indirect tensile strength of the CRF was 190 psi (1.31 MPa), which is approximately 17% or 1/6 of the average UCS for the mix, 1,110 psi (7.65 MPa). This STS value is higher than the 10% or 1/10 value that is commonly used to estimate the tensile strength of CRF. Although the STS tests were performed in a consistent manner (identical displacement rates and similar test durations), there were some discrepancies in the test results as evidenced by the noticeably different tensile strengths for the Batch 2 samples (Figure 10) and the high coefficient of variation listed in Table 5.

Table 5. Summary of results from STS tests with CRF samples

Cylinder Dimensions (in)	Number of Samples	Average STS[1] (psi)	Standard Deviation (psi)	Coefficient of Variation (%)	STS/UCS[2] Ratio (%)
6 × 12	8	190	54	28	17

[1]Splitting tensile strength after 28 days of curing
[2]Unconfined compressive strength after 28 days of curing

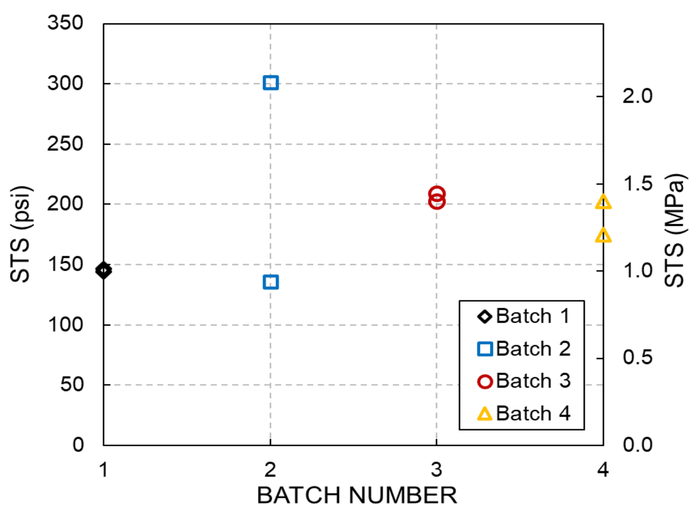

Figure 10. 28 day STS of 6×12 in CRF samples by batch number.

Discussion

As noted by Stone et al. (2019), there are currently no established standards for preparing and testing cemented backfill samples. As a result, standards for other materials such as concrete are loosely applied to backfill. For this study, the CRF sampling methods and testing procedures followed as reasonably as possible the guidelines developed for concrete by the American Society for Testing and Materials (ASTM) and the American Concrete Institute (ACI).

Bulk density

As mentioned earlier, the CRF samples for this study were cast using four batches of the same backfill mix. Even though the same mix was used for all samples, the density of the CRF samples still varied depending on the batch number and cylinder size. The differences in density can undoubtedly be attributed to relative changes in mix constituents and processes at the batch plant, and inconsistent screening and rodding procedures by the sampling crew members. This illustrates the difficulty of producing CRF samples at a consistent density using current batching and sampling methods. Nonetheless, the density of a

CRF sample typically has a significant effect on its strength. This relationship is clearly shown by the UCS and STS test results that are plotted in Figures 11 and 12, respectively, in terms of the density of the CRF samples. Regardless of batch number, the denser CRF samples generally exhibited higher UCS and STS values than the less dense samples. The low UCS values for each batch shown in Figure 11 usually resulted from tests with larger diameter samples.

Because density is such an important factor, industry guidelines recommend documenting the bulk density of QA/QC backfill cylinders as a part of a mine's regular QA/QC practices (Stone, 2007). However, maintaining consistent compaction with CRF samples is difficult given the dry, coarse nature of the backfill material and the manual procedures required to cast the cylinders and to wet screen the oversized aggregate. Ideally, the amount of compaction that is used to cast a 6 × 12 in (15 × 30 cm) QA/QC cylinder should produce a density that realistically represents the *in situ* density of the in-stope CRF. On the other hand, the in-place density of CRF is often difficult to determine because it requires coring of the in-stope backfill or retrieval of large blocks of CRF for bulk density testing.

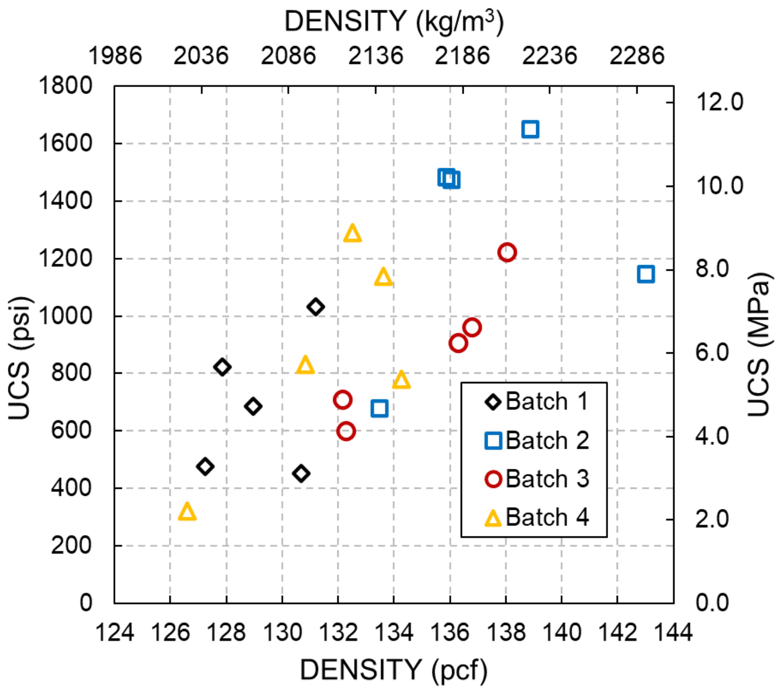

Figure 11. UCS versus density for CRF samples.

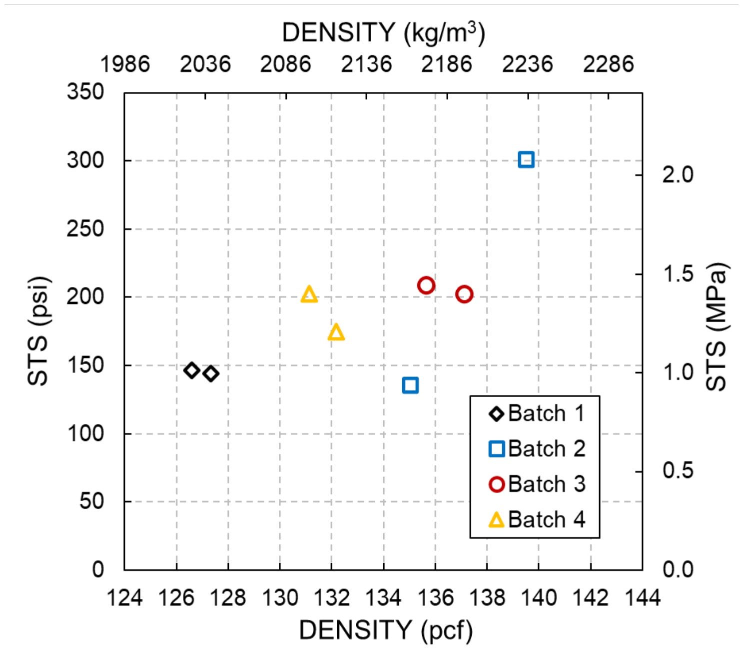

Figure 12. STS versus density for CRF samples.

To reduce the variability in UCS test results caused by differences in the density or compaction of CRF samples, NIOSH researchers are developing custom-made tamping tools and modifying ASTM tamping procedures. Furthermore, NIOSH is also investigating the use of a rotary impact hammer equipped with a tamping plate to compact CRF samples, following the procedures mentioned in ASTM C1435/C1435M (2020). Results of initial compaction tests with CRF samples from the Eagle Mine, an underground nickel/copper mine located in the Upper Peninsula of Michigan, indicate that this method produces a more consistent density and, thus, less variable UCS test results for standard 6 × 12 in (15 × 30 cm) cylinders (Bourgeois et al., 2023). Further research is needed to develop appropriate methods for relating the strength of CRF samples to the properties of in-stope material.

Unconfined compressive strength

UCS tests with Goldstrike CRF samples demonstrated a substantial decrease in compressive strength with increasing sample size. Using the same backfill mix, the average UCS for 18 × 36 in (46 × 91 cm) samples was only about 47% of the average UCS for 6 × 12 in (15 × 30 cm) samples. As shown in Figure 13, these test results are comparable to previous NIOSH test results with similarly sized CRF samples from several other mines (Stone et al., 2019; Warren et al., 2018a, 2018b) and also with test results published by other researchers (Sainsbury et al., 2021). Although the backfill mix (cement content, water/cement ratio, type of aggregate, gradation, etc.) varied somewhat from one mine to another, all of the CRF samples demonstrated a significant decrease in strength with an increase in sample size regardless of the mine site.

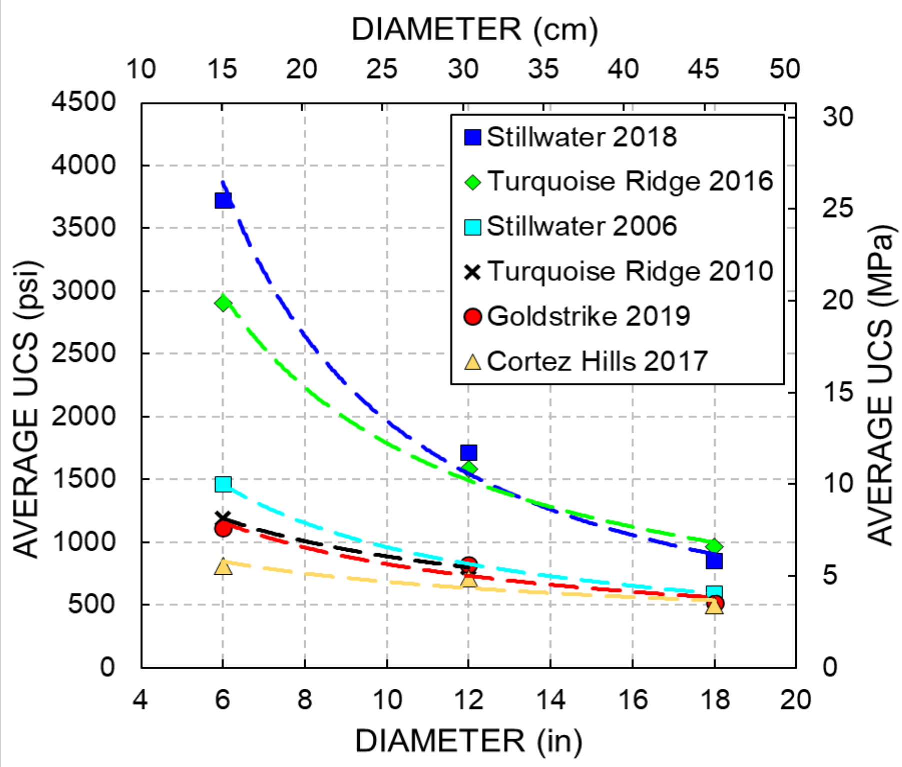

Figure 13. Effect of sample size on the compressive strength of CRF samples from several mines.

Depending on the specific CRF mix, the average UCS of 18 × 36 in (46 × 91 cm) CRF samples ranged from about 22–61% of the average UCS for standard 6 × 12 in (15 × 30 cm) samples (Warren et al., 2018b). In Figure 14, this reduction in strength is plotted as a scale factor and related to the maximum size of the aggregate used in the CRF mix (ie, nominal screen-size for the coarse aggregate). As the maximum size of the aggregate increases, more oversized material (aggregate larger than 1/3 the diameter of the cylinder) must be removed from the backfill mix when the 6 × 12 in (15 × 30 cm) cylinders are cast. Removing aggregate larger than 2 in (5 cm) essentially changes the backfill mix design, increasing the cement-to-aggregate ratio (Neville, 2009). This produces a relative increase in the strength of the standard 6 × 12 in (15 × 30 cm) cylinders as compared to the strength of the larger diameter cylinders and more than likely the in-place strength of the bulk material (Bureau of Reclamation, 1981). The greater the quantity of oversized aggregate screened from the mix, the greater the increase in sample strength (Neville, 2009). As explained by Stone et al. (2019), removal of the oversized aggregate changes the gradation of the mix, increasing the percentage of fines in the remaining aggregate and likely producing a higher density in the smaller sample. However, despite this increase in density, the increase in strength in the standard 6 × 12 in (15 × 30 cm) samples is largely attributed to an increase in the cement content.

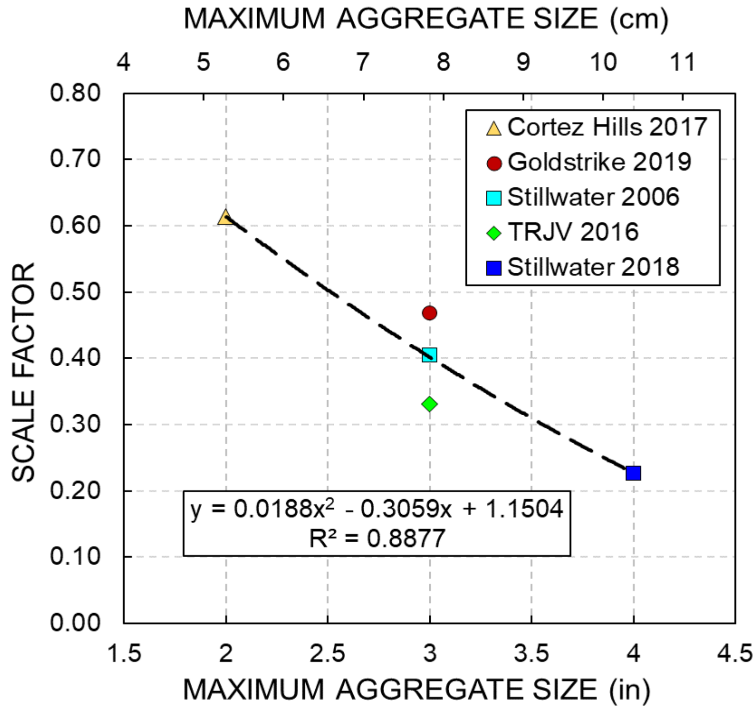

Figure 14. Scale factor (reduction in UCS for 18 × 36 in CRF samples) versus the maximum size of the coarse aggregate in the CRF mix from several mines.

As noted by Neville (2009), the sample size effect has been ascribed to a variety of causes, including a wall effect, where the maximum size of the aggregate is large in relation to the size of the mold and, thus, affects the packing of the concrete and the availability of fines to fill the space between large particles of coarse aggregate and the wall of the form. This is particularly noticeable with CRF samples composed of large sized aggregate, where the outer surface of the sample has a very bony appearance. However, as shown in Figures 2, 4,5, and 6, most of the Goldstrike CRF samples in this study had relatively uniform outer surfaces. In this case, the effect of sample size on CRF strength properties appears to largely be the result of unintended changes in mix design caused by the removal (wet screening or hand sorting) of oversized aggregate during the casting of the 6 × 12 in (15 × 30 cm) samples. However, as mentioned by ACI 207 5R-11, it becomes increasingly difficult to avoid segregation of the larger particles as the size range of the aggregate increases. Consequently, some of the loss in strength in the larger CRF samples could be caused by segregation, which negatively impacts the optimum gradation and provides less surface area for bonding the aggregate. Further research is needed with mix designs, having adjusted aggregate gradations with the oversized coarse aggregate removed but still retaining the original cement content by weight. Nevertheless, depending on the maximum size of the aggregate in the CRF mix, the resulting difference in strength for a standard 6 × 12 in (15 × 30 cm) sample in comparison to the strength of an 18 × 36 in (46 × 91 cm) sample can be substantial (Figure 14).

After UCS tests were conducted with the larger diameter samples, the CRF cylinders were broken apart with sledgehammers to observe the internal aggregate distribution, degree of aggregate bonding, and predominant failure mode. Even though the maximum size of the CRF aggregate was reported as a minus 3 in (7.6 cm), aggregate with an edge length of 3–4.5 in (7.6–11.4 cm) was present in the 12 × 24 in (30 × 61 cm) samples, and aggregate with an edge length up to 6–7 in (15–18 cm) was observed in the 18 × 36 in (46 × 91 cm) samples. For the Goldstrike CRF samples, the reduction in UCS based on sample size was determined to be about 47% as a percentage of the average strength of the 6 × 12 in (15 × 30 cm) cylinders. As shown in Figure 14, this size effect is equivalent to other CRF mixes having a similar maximum aggregate size of 3 in (7.6 cm). However, the binder content of the Goldstrike CRF is slightly lower than that of the other CRF mixes, which indicates that the maximum size of the aggregate may have a much greater effect on the strength reduction due to sample size than the binder content of the mix. Because numerous factors are involved in the production and placement of CRF (eg, aggregate gradation, rock type, binder type, binder content, water-to-cement ratio, chemical additives, mixing, transport, delivery, and placement), each backfill mix is likely to have specific issues that impact its engineered properties. As a result, the site-specific testing of large cylinders is currently the best means of assessing the magnitude of this strength reduction.

Elastic properties

The average modulus of elasticity of the CRF samples also decreased with increasing sample size, ranging from 551,000 psi (3.80 GPa) for the 6 × 12 in (15 × 30 cm) samples to 225,000 psi (1.55 GPa) for the 18 × 36 in (46 × 91 cm) samples. These average modulus values are within the range of those measured during similar CRF tests in previous NIOSH studies (Warren et al., 2018b). An average Poisson's ratio of 0.08 was determined from axial and circumferential deformation measurements during UCS tests with the 6 × 12 in (15 × 30 cm) CRF samples. This value may be low based on previous NIOSH test results with comparable CRF samples and reported values for concrete. Warren et al. (2018b) reported Poisson's ratio values ranging from 0.16 to 0.25 from NIOSH tests with CRF samples. Neville (2009) mentioned that the Poisson's ratio for concrete generally ranges from 0.15–0.22, depending on the properties of the aggregate. On the other hand, Wight and MacGregor (2009) stated that the Poisson's ratio for concrete varies from 0.11–0.21 and usually falls in the range from 0.15–0.20.

Splitting tensile strength

As noted by Neville (1973), splitting tensile tests with concrete are simple to perform and provide more uniform results than other tensile tests. This test method also provides a practical and convenient means of determining the tensile strength of CRF, particularly compared to direct tensile testing, where local defects in the test sample and eccentric loading can significantly affect the test results, or to flexural beam tests, which are more difficult to prepare and perform. As mentioned previously, the average STS for the 6 × 12 in (15 × 30 cm) CRF samples was 190 psi (1.31 MPa), ~ 17% or 1/6^{t} of the average UCS for the same backfill mix. As shown in Figure 15, all but one of the eight STS samples had indirect tensile strengths that were > 10% STS-to-UCS ratio that is typically assumed for the tensile strength of CRF in undercut span designs. These results are comparable to previous STS test results with similar CRF samples from other mines (Seymour et al., 2019, Warren et al., 2018b). Although STS tests are easy to conduct and provide useful information, the tensile strengths provided by this test method should be used with engineering judgment because they are likely larger than the actual direct tensile strength of the material. As mentioned by Neville (1973), the STS for concrete may be as much as 5–12% higher than its direct tensile strength.

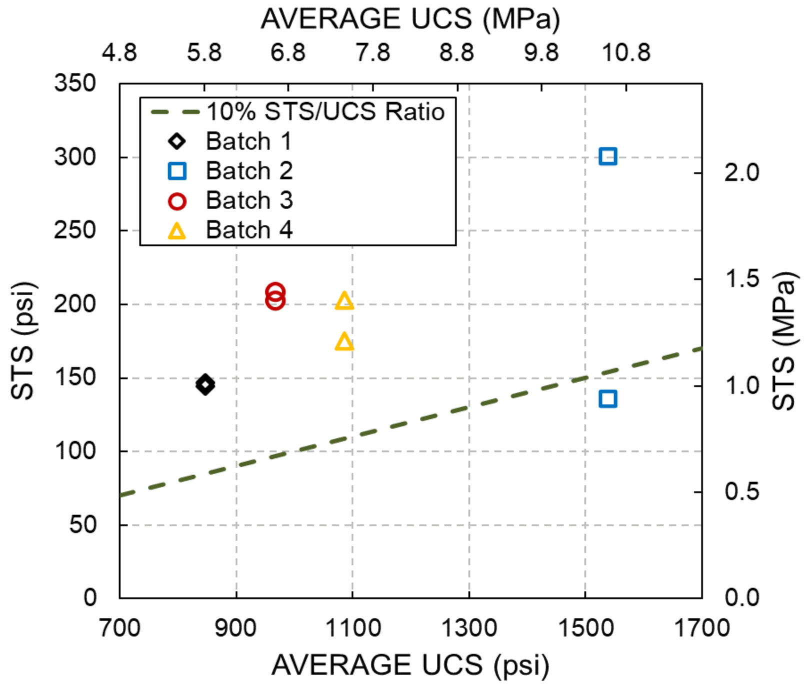

Figure 15. STS versus average UCS by batch number.

Conclusions

NIOSH researchers and Nevada Gold Mines personnel conducted a cooperative study to determine the strength and elastic properties of CRF samples from the Goldstrike (Meikle) Operation near Carlin, NV. Thirty-two CRF samples ranging in size from 6 × 12 in (15 × 30 cm) to 18 × 36 in (46 × 91 cm) were cast underground near the Meikle batch plant using four separate batches of a backfill mix designed for overhand, long-hole bench stoping. The CRF mix consisted of 5% Portland Type II cement and a waste rock aggregate crushed to a maximum screen-size of 3 in (7.6 cm). The CRF samples were cured and stored underground before being transported to Spokane, WA for testing. After the samples had cured for 28 days, UCS and STS tests were conducted with the samples to determine their strength and elastic properties. All sample preparation and testing methods followed as closely as possible the ASTM procedures for concrete.

The following conclusions were derived from this study:

1. The density of the CRF samples depended on the specific batch and cylinder size and ranged from about 127–143 pcf (2,028–2,291 kg/m^3), with an overall average density of 133 pcf (2135 kg/m^3).
2. Consistent with previous NIOSH research, the measured strength of a CRF sample was directly related to its density, with low density samples generally yielding lower UCS and STS test results.
3. UCS tests conducted with CRF samples, ranging in size from 6 × 12 in (15 × 30 cm) to 18 × 36 in (46 × 91 cm), clearly indicated that the size of the test sample affects its measured strength properties. Both the average UCS and average modulus of elasticity of the samples decreased as the size of the sample increased.
4. After 28 days of curing, the average UCS of the 18 × 36 in (46 × 91 cm) samples was 520 psi (3.59 MPa), only about 47% of the average UCS for the 6 × 12-in (15 × 30-cm) samples (1110 psi; 7.65 MPa). These results are consistent with previous tests with CRF samples from other mines, where the maximum size of the coarse aggregate was 3 in (7.6 cm).

5. UCS tests with instrumented CRF samples indicated that the average modulus of elasticity for the 18 × 36 in (46 × 91 cm) samples was 225,000 psi (1.55 GPa), about 41% of the average modulus of elasticity for the 6 × 12 in (15 × 30 cm) samples, which was 551,000 psi (3.80 Gpa).
6. STS tests provided a practical and convenient means of measuring rather than estimating the tensile strength of CRF. STS test results with 6 × 12 in (15 × 30 cm) CRF samples indicated that the average indirect tensile strength of the CRF was 190 psi (1.31 MPa), ~ 1/6ᵗ or 17% of the average UCS for the same backfill mix. This tensile-to-compressive strength ratio is significantly larger than the 1/10 ratio that is normally used for concrete and is commonly adopted for estimating the tensile strength of CRF in undercut span designs.
7. NIOSH test results indicate that there is a significant reduction in the strength of CRF cylinders with increasing sample size. This strength reduction is largely, but not entirely, due to unintended changes in mix design caused by the removal of oversized aggregate, as required by the ASTM standards for concrete, during the casting of standard 6 × 12 in (15 × 30 cm) samples. Depending on the maximum size of the aggregate in the CRF mix, the average UCS of 18 × 36 in (46 × 91 cm) CRF samples ranged from about 22–61% of the average UCS for standard 6 × 12 in (15 × 30 cm) samples. Because many factors contribute to this CRF sample-size effect, the site-specific testing of large cylinders is currently the best means of assessing the magnitude of this strength reduction.

Because of its unique nature and physical characteristics, standard industry practices need to be developed for collecting, preparing, and testing CRF samples. Further research is needed to examine the influence of sample size on measured strength properties and the consequences of unintended changes in CRF mix design during sampling. More importantly, appropriate methods need to be developed for relating the strength of CRF samples to the properties of in-stope material. A better understanding of the properties of standard 6 × 12 in (15 × 30 cm) samples in relation to the *in situ* properties of in-stope CRF will lead to more clearly defined target strengths, more appropriate factors of safety, and, thus, safer backfill mine designs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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References

ACI 207.5R-11 (2011) Report on Roller-Compacted Mass Concrete. American Concrete Institute, Farmington Hills, MI.

ACI 318-19.2.2 (2023) Modulus of elasticity. Building Code Requirements for Structural Concrete. Chapter 19, Concrete: Design and Durability Requirements. American Concrete Institute, Farmington Hills, MI.

ASTM C31/C31M-22 (2022) Standard Practice for Making and Curing Concrete Test Specimens in the Field. ASTM International, West Conshohocken, PA.
ASTM C39/C39M-21 (2021) Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA.
ASTM C469/C469M-14 (2014) Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. ASTM International, West Conshohocken, PA.
ASTM C496/C496M-17 (2017) Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA.
ASTM C617/C617M-15 (2015) Standard Test Method for Capping Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA.
ASTM C1435/C1435M-20 (2020) Standard Practice for Molding Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Hammer. ASTM International, West Conshohocken, PA.
Barrett, J.R., Stewart, J.E., and Brock, J.G. (1983) Cemented gravel fill for a small underground mine. In, Proceedings of the International Symposium on Mining with Backfill, June 7-9,1983, Luleå, Sweden, pp. 69-78.
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.
Bourgeois, J., Emery, T., Seymour, B., Sweet, D., and Porter, D. (2023) Cemented rockfill size effect study with specific focus on different sample preparation techniques. In, Proceedings of the SME Annual Meeting, Feb 26 - Mar 01, 2023, Denver, CO, Society for Mining, Metallurgy & Exploration, Englewood, CO, Preprint 23-046, 6 pp.
Hoek, E. and Brown, E.T. (2003) Underground Excavations in Rock, rev 1st edn, Institution for Mining and Metallurgy, London.
Neville, A.M. (1973) Properties of Concrete, 2nd edn, John Wiley & Sons, New York.
Neville, A.M. (2009) Properties of Concrete, 4th edn, Pearson Prentice Hall, Harlow, England.
O'Toole, D. (2005) A review of some important aspects of cemented aggregate fill. Handbook on Mine Fill. Chapter 8, Section 8.8, pp.136.
Sainsbury, B., Gharehdash, S., and Sainsbury, D. (2021) Large-scale characterisation of cemented rock fill performance for exposure stability analysis. Construction and Building Materials 308 (2021) 124995. https://doi.org/10.1016/j.conbuildmat.2021.124995
Seymour, J.B., Martin, L.A., Raffaldi, M.J., Warren, S.N., and Sandbak, L.A. (2019) Long-term stability of a 13.7×30.5-m (45×100-ft) undercut span beneath cemented rockfill at the Turquoise Ridge Mine, Nevada. Rock Mechanics and Rock Engineering (2019) 52:4907–4923. https://doi.org/10.1007/s00603-019-01802-y
Stone, D.M.R. (1993) The optimization of mix designs for cemented rockfill. In, Proceedings of Minefill 93: The South African Institute of Mining and Metallurgy Symposium Series S13, Johannesburg, ed. H.W. Glen, SAIMM, Johannesburg, pp. 249-253.
Stone, D.M.R. (2007) Factors that affect cemented rockfill quality in Nevada mines. In, Proceedings of the Ninth International Symposium on Mining with Backfill (Minefill 2007), Montreal, Quebec, Canada, April 29 - May 3, 2007, eds. F. Hassani et al., Paper No. 2539, 14 pp.
Stone, D., Pakalnis, R., and Seymour, B. (2019) Interpreting backfill QA/QC test data: do we need an industry standard? In, Proceedings of the SME Annual Meeting, Denver, CO, Feb 24-27, 2019, Preprint 19-043, 6 pp.
U.S. Bureau of Reclamation (1981) Concrete Manual. Department of the Interior, 8th edn, 627 pp.
Warren, S.N., Raffaldi, M.J., Dehn, K.K., Seymour, J.B., Sandbak, L.A., and Armstrong, J. (2018a) Estimating the unconfined compressive strength (UCS) of emplaced cemented rockfill (CRF) from QA/QC cylinder strengths. In, Proceedings of the SME Annual Meeting, Feb 25-28, 2018, Minneapolis, MN, Society for Mining, Metallurgy & Exploration, Englewood, CO, Preprint 18-031, 9 pp.
Warren, S.N., Raffaldi, M.J., Dehn, K.K., Seymour, J.B., Sandbak, L.A., Armstrong, J., and Ferster, M. (2018b) Estimating the strength and mechanical properties of cemented rockfill for underhand cut-and-fill mines. In, Proceedings of the 52nd US Rock Mechanics / Geomechanics Symposium, June 17-20, 2018, Seattle, WA, Paper No. ARMA 18-873, 14 pp.
Wight, J.K. and MacGregor, J.G. (2009) Strength under tensile and multiaxial loads. Reinforced Concrete Mechanics and Design, 5th edn, Pearson Education, Inc., New Jersey, USA, pp. 56-64.