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Effect of sample size on the unconfined compressive strength of cemented mill tailings

Seymour, J.B., Sweet, D.J., Emery, T.M., Murray, S.A., and Feagan, G.D.
National Institute for Occupational Safety and Health, Spokane, WA, USA
Bourgeois, J.P.
Formerly with National Institute for Occupational Safety and Health, Spokane, WA, USA

ABSTRACT: To determine if the size of a cemented mill tailings sample affects its unconfined compressive strength (UCS), researchers with the National Institute for Occupational Safety and Health (NIOSH) conducted three series of UCS tests with cylindrical samples of cemented paste backfill (CPB), ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm), after the samples had cured for 28, 90, and 180 days. The average strengths of the standard sized samples were comparable, indicating that 2×4-inch (50×100-mm) cylinder molds provide a reasonable alternative to larger sized cylinders. A comparison of UCS test results and sample aspect ratios (i.e., surface area divided by volume) demonstrated that the size of a CPB sample does not significantly affect its measured compressive strength until the dimensions of the test specimen are smaller than 1×2 inches (25×50 mm). The 0.5×1.0-inch (13×25-mm) samples exhibited a heightened response to strength gain or loss with curing age, which appeared to be related to the physical dimensions of the sample and its hydration rate. The development of more appropriate and consistent methods for collecting, preparing, and testing samples of cemented mill tailings will lead to more accurate quantification of mix design strengths and more effective quality control measures.

1. INTRODUCTION

As environmental restrictions become increasingly more stringent regarding the surface disposal of mining waste products, the use of mill tailings as a primary component of mine backfill is gaining broader acceptance. Mill tailings are now more commonly used in conjunction with cemented hydraulic fill (CHF) and cemented paste backfill (CPB) to provide ground support for cut-and-fill mining methods in underground metal mines. To assess the quality and strength of the backfill, unconfined compression tests are typically conducted with samples of cemented mill tailings collected at the batch plant in 3×6-inch (75×150-mm) or 4×8-inch (100×200-mm) cylinder molds. However, depending on the preparation and testing of the backfill sample, the resultant unconfined compressive strength (UCS) may not be representative of the in-stope fill. Often, these samples are not prepared or tested in a consistent manner. Conventional concrete test criteria are not always applicable for cemented tailings, given the differences in mix constituents, and standard industry practices have not yet been developed for this material. An accurate assessment of backfill strength is important because, depending on the mining method being used, underground miners are working either adjacent to backfill exposures or beneath backfill undercut spans.

To address this concern, the National Institute for Occupational Safety and Health (NIOSH) has been conducting research to develop better methods for preparing and testing samples of cemented mill tailings, as well as more effective means of relating the material properties of in-stope backfill to test results obtained from standard-sized samples. This paper presents the results of a series of tests conducted with samples of cemented mill tailings using materials and mix designs obtained from a cooperating underground metal mine. To determine if the size of a CPB sample affects its strength, three series of UCS tests were conducted at the NIOSH Spokane Research Laboratory (SRL) with cylindrical samples of cemented mill tailings, ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm), after they had cured under controlled temperature and humidity conditions for 28, 90, or 180 days. An analysis of the effect of the size of a sample on its UCS is explained in terms of the specimen's dimensions, surface area, volume, and aspect ratio (i.e., surface area divided by volume). Furthermore, the influence of density, curing age, and moisture content are discussed along with sample preparation and testing parameters such as mix segregation and settling, specimen end condition, unintended variations in backfill mix design, size of the test fixtures, and test displacement rates. The development of more appropriate and consistent methods for collecting, preparing, and testing samples of cemented mill tailings will lead to more accurate quantification of mix design strengths and more effective quality control measures.

2. SAMPLE SIZE EFFECT

Many materials, including rock (Hoek and Brown, 2003), exhibit a general decrease in strength with increasing sample size. As shown in Figure 1, the influence of sample size on the strength properties of concrete has been well documented (Blanks and McNamara, 1935; U.S. Bureau of Reclamation, 1981). As the size of a concrete cylinder increases, the UCS of the sample decreases.

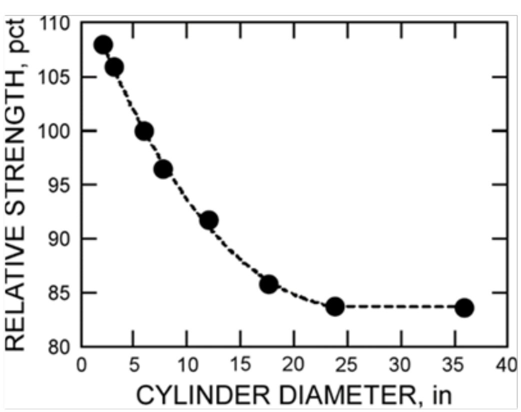

Fig. 1. Relative compressive strength of concrete versus cylinder size (Blanks and McNamara, 1935).

This reduction in compressive strength diminishes when the diameter of the sample approaches 18 to 20 inches (457 to 508 mm), 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 of standard 6×12-inch (150×300-mm) cylinders, or about a 17% reduction in compressive strength (Neville, 1973).

Cemented rockfill (CRF) exhibits an even larger reduction in UCS with increasing sample size. As shown in Figure 2, depending on the nominal screen size (i.e., the maximum size) of the aggregate in a CRF mix, the UCS of large 18×36-inch (457×914-mm) samples can range from about 22% to 61% of the UCS for standard 6×12-inch (150×300-mm) samples (Warren et al., 2018; Seymour et al., 2024). This is a substantially larger relative decrease in compressive strength than with concrete.

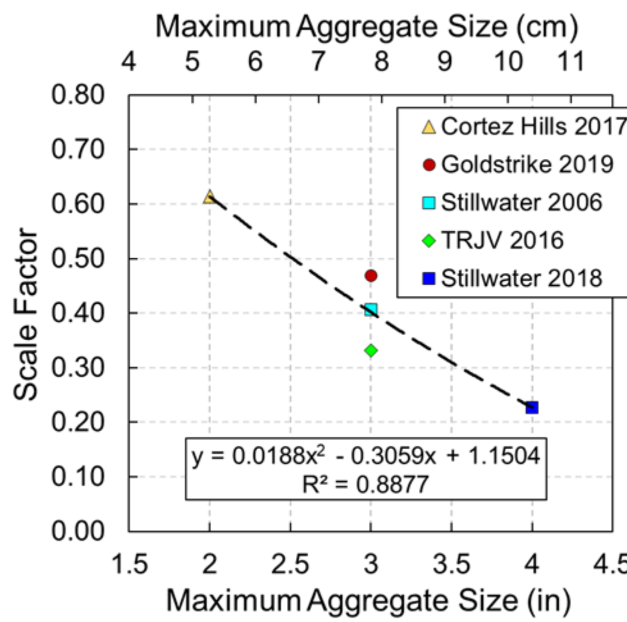

Fig 2. Scale factor (reduction in UCS for 18×36-inch CRF samples) versus the maximum size of the coarse aggregate in the CRF mix from several mines (after Seymour et al., 2024).

As the maximum size of the aggregate increases, more oversized material (aggregate larger than ⅓ the diameter of the cylinder) must be removed from the backfill mix when 6×12-inch (150×300-mm) cylinders are cast. Removing aggregate larger than 2 inches (50 mm) 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-inch (150×300-mm) 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). NIOSH test results have indicated that the reduction in strength of CRF cylinders with increasing sample size is largely due to unintended changes in mix design caused by the removal of oversized aggregate during the casting of standard

6×12-inch (150×300-mm) samples (Seymour et al., 2024).

Due to the fine gradation of mill tailings, oversized aggregate does not have to be removed when casting cemented tailings samples. Consequently, unintended changes in mix design are not a problem as with CRF. Normally, CHF or CPB samples are collected at the batch plant in 3×6-inch (75×150-mm) or 4×8-inch (100×200-mm) cylinder molds. To minimize the standard deviation of UCS test results, Henderson et al. (2005) recommended using paste fill samples that are at least 3 inches (75 mm) in diameter with a length-to-diameter (L/D) ratio of 2:1. However, the use of smaller samples offers several advantages. As noted by Stone (2021), smaller-sized samples require less space for curing and storage and are easier and safer to handle than full-size samples. Furthermore, the force or loading capacity of on-site test equipment can be significantly reduced if UCS tests are conducted with smaller-sized samples. One of the research objectives of this study was to determine if a practical minimum limit for the size of a CPB sample could be identified for obtaining consistent UCS test results. This size effect study was conducted under controlled laboratory conditions to minimize the influence of variations in CPB mix designs and to maintain consistent procedures for batching, curing, preparing, and testing the samples.

3. CPB MIX DESIGN

As mentioned above, three separate series of tests were conducted in this study to determine if the size of a CPB sample affects its UCS. Although all of the CPB samples were prepared using a similar backfill mix design, there were some notable differences between the three series of tests. Because of the limited capacity of our laboratory mixing equipment, three individual batches of the same CPB mix were needed to cast the samples for the first test series (Batch 1, Batch 2, and Batch 3). CPB samples for the second and third test series were prepared using a single batch. The same cement binder was used for both the first and second test series (Batch 4), but a blended slag-cement binder was used for the third test series (Batch 5). The moisture content of the tailings was measured and accounted for in the mix design for the first and third test series. However, the tailings for the second test series were dried in an oven to eliminate moisture before batching. As noted below, the tailings and blended slag-cement binder used in this study were provided by a mining company that is cooperating with NIOSH on other research.

3.1. Tailings

Approximately 37% of the volume of tailings produced during the milling process at the cooperating mine is returned underground as cemented backfill. The classified tailings used in this study were collected at the mine's backfill tailings storage facility, after they had been dewatered using a combination of cyclone, thickener, and filter. Prior to batching CPB samples for each of the three test series, a separate shipment of classified tailings was collected at the mine.

3.2. Binder

For the first and second test series, an 8% binder composed of Type I-II Portland cement was used for the CPB mix, whereas an 8% blended binder, consisting of 75% Type 100 ground granulated blast-furnace slag and 25% Type IL Portland cement, was used for the third test series. The Type I-II Portland cement was obtained from a local supplier, while the blended slag-cement binder was provided by Lafarge North America through arrangements with the collaborating mining company. An 8% blended-binder mix has traditionally been used in underhand cut-and-fill production stopes at the cooperating mine; therefore, an 8% binder was also selected for this study to provide additional background information for on-going research explained in further detail by Emery et al. (2022) and Sweet et al. (2022).

3.3. Water-to Cement Ratio

SRL tap water was used for all of the CPB mixes, with water-to-cement ratios ranging from about 3.79 to 4.32 for the three tests series. The moisture contents of the tailings for the first and third test series were measured at 12% and 11.5%, respectively, whereas the tailings for the second test series were dried in an oven to remove moisture prior to batching. For all of the mixes, the tailings were assumed to have a moisture absorption rate of 1.05%. The solids content of the backfill mixes ranged from about 74% to 77% solids by weight.

Fig. 3. Using a portable rotary mixer to prepare a CPB batch.

4. SAMPLE COLLECTION AND HANDLING

All of the CPB samples mentioned in this study were prepared and tested by NIOSH researchers at SRL. A portable, electric concrete mixer with a 10-ft^3 (0.28-m^3) capacity was used to mix all of the CPB batches (Figure 3). Given the fluid consistency of the CPB mix, the working capacity of the rotary mixer was only about 2 to 3 ft^3 (0.06 to 0.08 m^3). As a result, samples for the first test series were cast on May 13, 2021, using three separate batches of the same CPB mix (Batches 1-3). A total of 108 samples, ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm), were prepared for UCS tests as indicated in Table 1. All of the cylindrical samples had a 2:1 L/D ratio. The 2-inch (50-mm), 3-inch (75-mm), 4-inch (100-mm), and 6-inch (150-mm) diameter samples were cast in standard plastic cylinder molds, whereas the 0.5-inch (13-mm), 1-inch (25-mm), 1.5-inch (40-mm), and 2.5-inch (65-mm) diameter samples were cast in reusable custom-designed plastic forms (Figure 4).

Table 1. UCS samples prepared for the first test series

Cylinder Dimensions (in)	Number of Samples	Batch Number	Curing Age (days)
0.5 × 1.0	12	1, 1, 3	28, 90, 180
1.0 × 2.0	12	1, 1, 3	28, 90, 180
1.5 × 3.0	12	1, 1, 3	28, 90, 180
2.0 × 4.0	15	1, 3, 3	28, 90, 180
2.5 × 5.0	12	1, 1, 3	28, 90, 180
3.0 × 6.0	15	1, 2, 2&3	28, 90, 180
4.0 × 8.0	15	1, 1, 2	28, 90, 180
6.0 × 12.0	15	1, 2, 2	28, 90, 180

Table 2. UCS samples prepared for the second test series

Cylinder Dimensions (in)	Number of Samples	Batch Number	Curing Age (days)
0.5 × 1.0	12	4	28, 90, 180
1.0 × 2.0	12	4	28, 90, 180
1.5 × 3.0	12	4	28, 90, 180
2.0 × 4.0	15	4	28, 90, 180
2.5 × 5.0	12	4	28, 90, 180
3.0 × 6.0	15	4	28, 90, 180

Fig. 4. Casting odd sized CPB samples using custom-made cylinder forms.

For the second test series, a total of 81 samples, ranging in size from 0.5×1.0 inch (13×25 mm) to 3×6 inches (75×150 mm), were cast from a single batch (Batch 4) of the same CPB mix on July 14, 2022. As indicated in Table 2, 78 samples were prepared for UCS tests, and three additional 3×6-inch (75×150-mm) cylinders were cast for splitting tensile strength (STS) tests (Table 3).

Table 3. STS samples prepared for the second test series

Cylinder Dimensions (in)	Number of Samples	Batch Number	Curing Age (days)
3.0 × 6.0	3	4	28

The samples for the third test series were cast from a single batch (Batch 5) of the same CPB mix on May 18, 2023, using a blended slag-cement binder. Again, a total of 78 samples, ranging in size from 0.5×1.0 inch (13×25 mm) to 3×6 inches (75×150 mm), were prepared for UCS tests (Table 4).

Table 4. UCS samples prepared for the third test series

Cylinder Dimensions (in)	Number of Samples	Batch Number	Curing Age (days)
0.5 × 1.0	12	5	28, 90, 180
1.0 × 2.0	12	5	28, 90, 180
1.5 × 3.0	12	5	28, 90, 180
2.0 × 4.0	15	5	28, 90, 180
2.5 × 5.0	12	5	28, 90, 180
3.0 × 6.0	15	5	28, 90, 180

4.1. Application of ASTM Standards

As explained 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 or rock are loosely adapted for use with CPB, a much softer material. All of the CPB samples for this study were prepared following as closely as practical procedures specified for concrete by the American Society for Testing and Materials—ASTM C31/C31M-22, Standard Practice for Making and Curing Concrete Test Specimens in the Field, and ASTM C192/C192M-19, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. Due to the fluid consistency of the CPB mix and its relatively low strength, ASTM procedures for controlled low-strength material (CLSM) were also followed, including ASTM D4832-16, Standard Test Method for Preparation and Testing of Controlled Low-Strength Material (CLSM) Test Cylinders; ASTM D5971/D5971M-16, Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material; and ASTM D6103/D6103M-17, Standard Test Method for Flow Consistency of Controlled Low-Strength Material (CLSM). ASTM D4832 defines CLSM as a mixture of soil, cementitious materials, water, and sometimes admixtures that hardens into a material with a higher strength than soil but less than 1,200 psi (8,400 kPa).

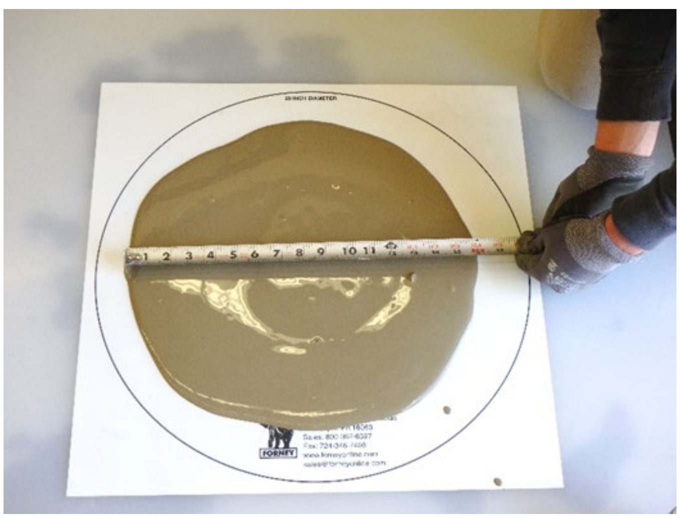

Fig. 5. Spread test for determining consistency of CPB mix.

As mentioned above, the CPB mixes used in this study had a solids concentration ranging from about 74% to 77% solids by weight. This solids content is within the typical range of 75% to 85% solids by weight for paste fill used in underground hard rock mines. However, the CPB mixes used in this study did not meet other traditional characteristics of paste fill, most notably a homogeneous single-phase slurry that is non-settling or non-segregating, with limited production of bleed water after placement, and a slump of less than 9 inches (23 cm) (Henderson et al., 2005). For CHF, the suggested target slurry density (% solids by weight) for tailings, having a similar specific gravity (2.91), is about 72.4% with recommended operating slurry densities ranging from 70.4% to 74.4% (Grice, 2005). Consequently, the backfill mixes used in this study would more than likely be classified as hybrid mixes, somewhere between CHF and CPB.

Because of the fluid nature of these CPB mixes, a spread test rather than a slump test was conducted to measure the consistency or workability of each CPB batch (Figure 5). Following the procedures in ASTM D6103, the spread test measurements for the three batches that were used to cast the CPB samples in first test series were 16, 17 and 18 inches (40.6, 43.2, and 45.7 cm), respectively. The spread test measurement for the single CPB batch of the second test series was also 16 inches (40.6 cm), while the measurement for the third test series with the blended slag-cement binder was 13.25 inches (33.7 cm).

As noted in ASTM D4832, some CLSM mixtures will bleed rapidly, releasing free water in the mixing receptacles and sample molds. Consequently, it is recommended that the material be mixed thoroughly, and the cylinder molds filled quickly to avoid settling or segregation of the solids. During preparation of the CPB samples for this study, the portable concrete mixer was run almost continuously, and a paddle mixer attached to a cordless hand drill was used to further agitate the mix while the sample molds were being filled (Figure 6). These measures helped reduce segregation or gravity separation of the solids but did not prevent it, as discussed in further detail below. Shortly after filling the cylinder forms, additional mix was added to the top of samples to displace bleed water from the forms, following the suggested procedures in ASTM D4832.

Fig. 6. Additional agitation of backfill mix during casting of CPB cylinders to prevent gravity separation of solids.

4.2. *Curing of CPB Samples*

After the CPB sample forms were filled, the standard plastic cylinder molds were sealed with plastic lids, and the custom-made forms were covered with plastic sheeting. All of the CPB samples were stored in a climate-controlled curing room (fog room) and allowed to cure for a selected period of time (e.g., 28, 90, or 180 days) before being tested.

5. CEMENTED PASTE BACKFILL TESTING

5.1. *Sample Preparation*

After the CPB samples had cured for a specified number of days, they were removed from the fog room and stripped from their forms. As the samples cured, the solids settled or segregated despite the measures previously mentioned, and excess bleed water accumulated at the top of the forms. As shown in Figure 7, this consolidation of the samples during the initial stages of curing was particularly evident for the larger-sized cylinders.

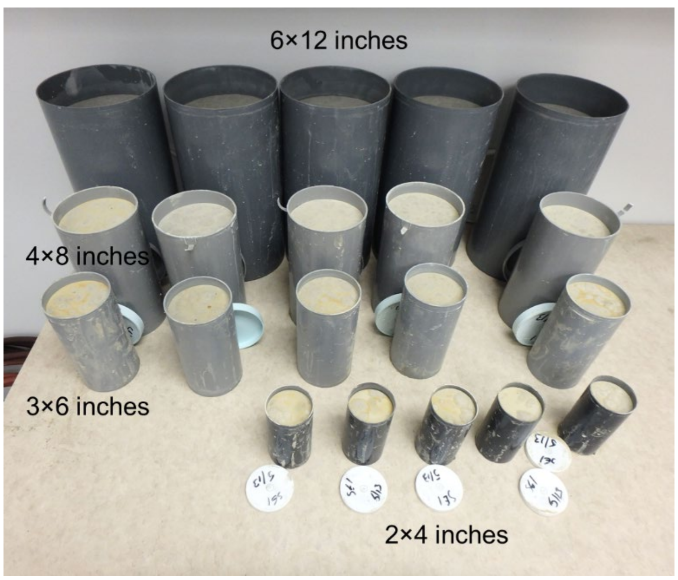

Fig. 7. Standard-sized cylinders after curing.

To roughly achieve the end-parallelism requirements cited in ASTM C39/C39M-21, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, the uneven ends of the cylinders, primarily their top surfaces, were leveled using a stationary belt sander (Figure 8). Regardless of the size of the CPB cylinder, all of the UCS test samples were prepared in a similar manner to avoid introducing inconsistencies in the test results caused by different capping procedures or materials. The final dimensions of each cylinder were measured to identify differences from their nominal diameter and length, and each cylinder was weighed to account for variations in density.

No special end-preparation procedures were required for the STS test samples. The Brazilian disks were cut perpendicular to the longitudinal axis of the 3×6-inch (75×150-mm) CPB cylinders. After the samples were prepared, they were returned to the fog room and covered with plastic. Prior to testing, the samples were removed, and their outer surfaces were allowed to air dry before a UCS or STS test was initiated.

Fig. 8. Preparing the end of a CPB sample.

5.2. *Unconfined Compressive Strength Tests*

To determine the influence of sample size on compressive strength, three series of UCS tests were conducted with cylindrical samples of CPB, ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm). After the samples had cured for 28, 90, or 180 days, UCS tests were conducted using a servo-controlled hydraulic, stiff-frame test machine having a 200,000-lbf (1,000-kN) capacity (Tinius Olsen 1000SL). The UCS tests were performed following as closely as practical the procedures outlined in ASTM C39 and ASTM D4832. Summaries of the physical characteristics of the UCS samples for the first, second, and third test series are provided in Tables 5, 6, and 7, respectively.

The configuration of a typical UCS test with one of the 2×4-inch (50×100-mm) CPB cylinders is shown in Figure 9. Depending on the size of the test specimen, two different spherical loading heads with diameters of 6.5 inches (165 mm) or 3.25 inches (83 mm) were used for the tests, along with false steel platens that were properly sized for the samples and met the requirements of 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 to 3 minutes. Depending on the size and strength of the samples, the displacement rate varied from 0.005 to 0.025 in/min (0.13 to 0.64 mm/min), and the test duration ranged from about 1 to 6 minutes. The UCS samples typically exhibited a failure mode that was consistent with either a Type 1 fracture pattern, well-formed cones on both ends of the sample, or a Type 2 fracture pattern, a well-formed cone on end of the sample with vertical cracks through the remainder of the sample, as explained in ASTM C39.

Table 5. Summary of the physical characteristics of UCS samples for first test series

Cylinder Dimensions (in)	Average Diameter (in)	Average Length (in)	Average Density (pcf)[1]	Average L/D Ratio[2]
0.5 × 1.0	0.499	0.963	132.1	1.93
1.0 × 2.0	1.001	1.924	140.8	1.92
1.5 × 3.0	1.502	2.846	138.9	1.90
2.0 × 4.0	2.000	3.410	142.0	1.71
2.5 × 5.0	2.502	4.551	141.8	1.82
3.0 × 6.0	2.998	5.226	142.0	1.74
4.0 × 8.0	3.996	6.922	144.7	1.73
6.0 × 12.0	6.006	10.225	141.7	1.70

[1]Pounds per cubic foot
[2]Average length-to-diameter ratio

Table 6. Summary of the physical characteristics of UCS samples for second test series

Cylinder Dimensions (in)	Average Diameter (in)	Average Length (in)	Average Density (pcf)[1]	Average L/D Ratio[2]
0.5 × 1.0	0.500	0.986	135.8	1.97
1.0 × 2.0	1.002	1.970	138.7	1.97
1.5 × 3.0	1.505	2.875	138.2	1.91
2.0 × 4.0	1.999	3.519	143.7	1.76
2.5 × 5.0	2.502	4.677	140.4	1.87
3.0 × 6.0	3.005	5.281	142.2	1.76

[1]Pounds per cubic foot
[2]Average length-to-diameter ratio

Table 7. Summary of the physical characteristics of UCS samples for third test series

Cylinder Dimensions (in)	Average Diameter (in)	Average Length (in)	Average Density (pcf)[1]	Average L/D Ratio[2]
0.5 × 1.0	0.500	0.895	136.2	1.79
1.0 × 2.0	1.005	1.894	141.9	1.88
1.5 × 3.0	1.506	2.804	141.6	1.86
2.0 × 4.0	2.003	3.494	143.3	1.74
2.5 × 5.0	2.507	4.503	143.3	1.80
3.0 × 6.0	3.007	5.351	142.7	1.78

[1]Pounds per cubic foot
[2]Average length-to-diameter ratio

Fig. 9. UCS test with a 2×4-inch CPB sample.

5.3. Splitting Tensile Strength Tests

After the samples from the second test series had cured for 28 days, STS tests were conducted with Brazilian samples cut from three of the 3×6-inch (75×150-mm) cylinders. A total of nine STS tests were conducted, using three disk-shaped samples from each CPB cylinder. The STS tests were performed using a Tinius Olsen 1000SL test machine and following as closely as practical the test procedures outlined in ASTM D3967-16, Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens, and ASTM C496/C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. The Brazilian test samples consisted of circular disks of CPB with average thicknesses ranging from 1.567 to 1.688 inches (39.80 to 42.88 mm), average diameters ranging from 2.977 to 3.006 inches (75.62 to 76.35 mm), and densities ranging from 116 to 127 pcf (1852 to 2040 kg/m^3). A summary of the physical characteristics of the Brazilian test samples is provided in Table 8.

Table 8. Summary of the physical characteristics of Brazilian STS test samples

Number of Samples	Average Thickness (in)	Average Diameter (in)	Average Density (pcf)[1]	Average T/D Ratio[2]
9	1.645	2.995	121.2	0.55

[1]Pounds per cubic foot
[2]Average thickness-to-diameter ratio

The configuration of a typical STS test with one of the Brazilian test specimens is shown below in Figure 10, demonstrating the distinctive tensile failure crack along the vertical axis of the applied load. For consistency, all STS tests were conducted at a constant displacement rate of 0.030 in/min (0.76 mm/min), which caused the CPB samples to fail within about 1 minute.

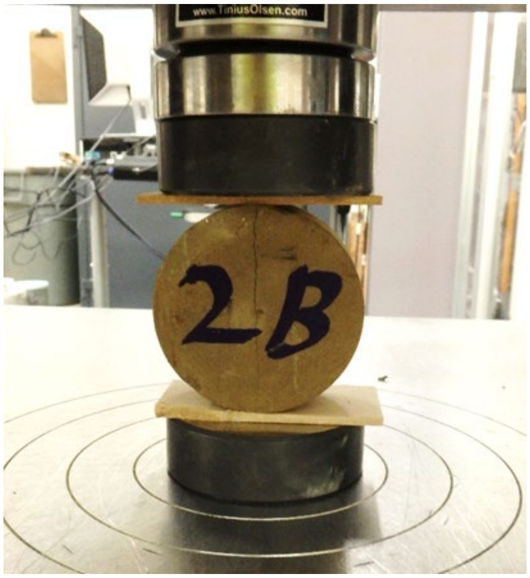

Fig. 10. Brazilian STS test with a disk-shaped CPB sample.

6. TEST RESULTS

6.1. Sample Density

Prior to destructive testing, the CPB cylinders were measured to determine their average dimensions (diameter and length) and weighed to facilitate density calculations. The overall average density of the CPB samples prepared for UCS tests was 142 pcf (2267 kg/m^3), but the densities of individual samples ranged from about 120 to 149 pcf (1927 to 2393 kg/m^3), depending on the test series, batch number, and cylinder size.

Table 9. Average density of UCS test samples by cylinder size

Cylinder Dimensions (in)	Average Density (pcf)[1]	Standard Deviation (pcf)	Coefficient of Variation (%)
0.5 × 1.0	134.7	2.8	2.1
1.0 × 2.0	140.5	1.0	0.7
1.5 × 3.0	139.6	1.9	1.4
2.0 × 4.0	143.0	0.6	0.4
2.5 × 5.0	141.8	0.6	0.4
3.0 × 6.0	142.3	0.7	0.5
4.0 × 8.0	144.7	1.6	1.1
6.0 × 12.0	141.7	1.0	0.7
Average	141.0	1.3	0.9

[1]Pounds per cubic foot

Cylinder forms less than 2 inches (50 mm) in diameter were more difficult to fill. As a result, the smaller diameter samples usually had lower and less consistent densities as noted by the average density values listed in Tables 5-7 and Table 9. Although a similar mix design was used for all five CPB batches, there were noticeable differences in density depending on the test series, batch number, and cylinder size (Figure 11). Despite these apparent differences, the average densities of the CPB samples were still fairly consistent as indicated by the statistical summaries in Tables 9 and 10.

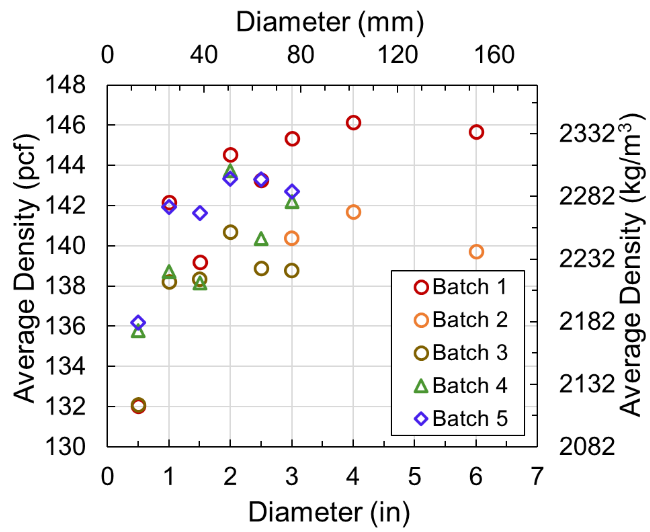

Fig. 11. Average density of UCS test samples by cylinder size and batch number.

Table 10. Average density of UCS test samples by test series and batch number

Test Series	Batch Number	Average Density (pcf)[1]	Standard Deviation (pcf)	Coefficient of Variation (%)
1	1	142.3	1.7	1.2
1	2	140.6	1.3	0.9
1	3	137.8	1.1	0.8
1	Avg 1-3	140.2	1.4	1.0
2	4	139.8	1.1	0.8
3	5	141.5	1.2	0.9
1-3	Avg 1-5	140.5	1.2	0.9

[1]Pounds per cubic foot

6.2. Unconfined Compressive Strength

To determine if the compressive strength of CPB is affected by the size of the sample, three series of UCS tests were conducted with cylindrical samples of CPB, ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm). The UCS tests were conducted after the samples had cured for 28, 90, or 180 days to more closely assess whether the size of the CPB sample affected the rate of hydration of the binder in the CPB mix and, thus, influenced the resultant compressive strength of the sample. A total of 264 CPB samples were prepared for UCS testing—108 for the first test series and 78 each for the second and third test series. The unconfined compressive strength of a CPB sample was determined by dividing the maximum load applied to the sample by the average cross-sectional area of the sample using the following equation:

$$\sigma_c = \frac{P}{(\pi D^2)/4} \quad (1)$$

where:

σ_c = unconfined compressive strength, psi (MPa)
P = maximum load, lbf (N), and
D = diameter of the specimen, inches (mm).

Due to segregation and settling of solids during the initial stages of curing, the CPB samples typically consolidated at heights shorter than their nominal cylinder lengths as indicated by the average sample lengths listed in Tables 5-7. As a result, the sample's L/D ratio was usually less than the intended 2:1 ratio recommended for UCS test specimens. To compensate for this loss of height, the UCS value computed using Eq. (1) was reduced based on the sample's L/D ratio by multiplying the calculated value by a correction factor interpolated from a table of correction factors for concrete listed in ASTM C39. These height corrections factors were applied as needed and ranged from 0.9350 for a L/D ratio of 1.291 to 0.9995 for a L/D ratio of 1.994.

Fig. 12. Typical UCS test samples from the first test series ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm).

A post-test photograph of typical UCS test samples from the first test series is shown in Figure 12, and the average UCS test results are plotted versus cylinder diameter according to curing age in Figure 13. A more complete listing of the average UCS test results by cylinder size and curing age is provided in the Appendix in Table A. Depending on the curing age and size of the CPB sample, individual UCS test results ranged from 148 psi (1.02 MPa) to 551 psi (3.80 MPa). Average UCS values by cylinder size ranged from 193 psi (1.33 MPa) to 476 psi (3.28 MPa) with coefficients of variation ranging from 1.7% to 17.4%.

Depending on curing age, some of the smaller samples, particularly the 0.5-inch (13-mm) diameter samples, tended to have higher strengths. Because the smaller samples tended to dry out more during preparation and testing, these larger UCS values may have been caused by discrepancies in moisture content. To determine if a lack of moisture in the sample prior to testing increased its rate of hydration and, thus, its UCS, the aspect ratio (i.e., surface area divided by volume) was calculated for each sample as noted in Table A to compare the relationship between sample size, hydration rate, and UCS. After 180 days of curing, all of the CPB samples had relatively similar strengths regardless of cylinder size.

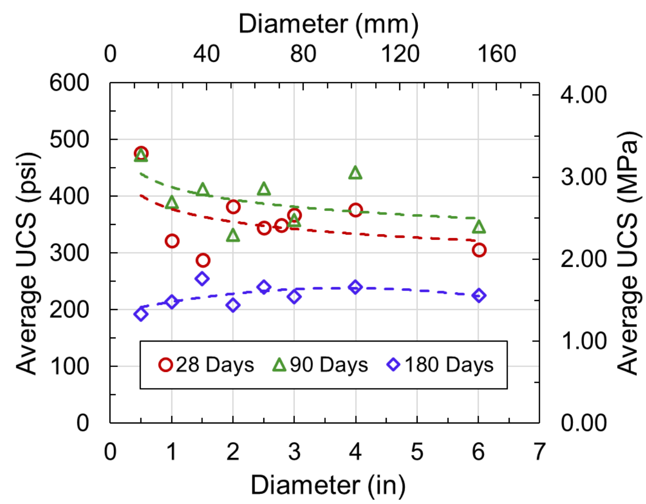

Fig. 13. Average UCS of CPB samples from the first test series by cylinder size and curing age.

As shown in Figure 13, curing age noticeably affected the strength of the CPB samples. The 180-day UCS values were significantly less than the 28-day and 90-day strengths. The average UCS of the 180-day samples was 225 psi (1.55 MPa), whereas the average UCS of the 28-day and 90-day samples was 358 psi (2.47 MPa) and 397 psi (2.73 MPa), respectively. The hydration rate, aspect ratio, and strength loss with curing time are discussed in further detail in Section 7 below.

The samples for the first test series were cast using three separate batches of the same CPB mix (Batches 1-3). As discussed above, these three different batches produced some inconsistencies in the UCS test results, causing the densities of the samples to vary depending on the batch number and cylinder size. To more closely control the mix design, a second series of samples were prepared using a single batch of the same CPB mix. To produce more consistent sample densities, the CPB mix was intentionally agitated while casting the samples to reduce the impact of segregation and settling of the solids. In addition, the moisture content of the samples was more closely controlled during preparation and testing to prevent the smaller samples from drying out completely.

Fig. 14. Typical UCS test samples from the second test series ranging in size from 0.5×1.0 inch (13×25 mm) to 3×6 inches (75×150 mm).

Because the UCS values of the larger sized samples were relatively equivalent, the tests for the second test series were conducted with samples ranging in size from 0.5×1.0 inch (13×25 mm) to 3×6 inches (75×150 mm) as shown by a post-test photograph of typical UCS samples in Figure 14. The average UCS test results for the second test series are plotted versus cylinder diameter according to curing age in Figure 15 and listed in the Appendix in Table B.

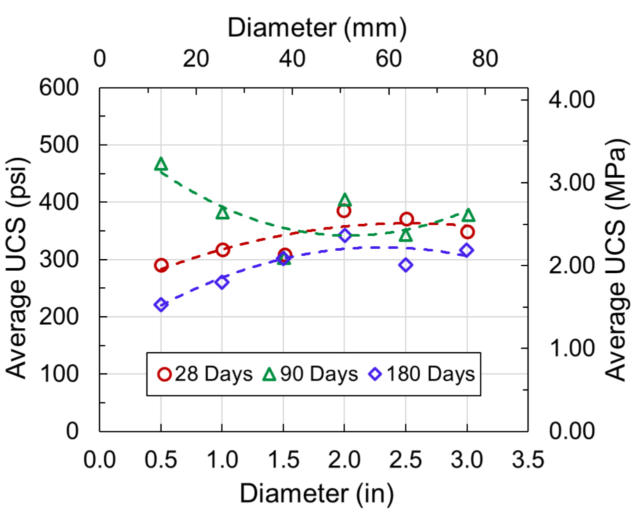

Fig. 15. Average UCS of CPB samples from the second test series by cylinder size and curing age.

Individual UCS test results ranged from 210 psi (1.44 MPa) to 519 psi (3.58 MPa), depending again on the curing age and size of the sample. Average UCS values by cylinder size ranged from 222 psi (1.53 MPa) to 467 psi (3.22 MPa) with coefficients of variation ranging from 0.1% to 15.6%. As shown in Figure 15, curing age did not as obviously affect the strength of the samples as in the first test series. However, the 180-day UCS values were still noticeably less than the 28-day and 90-day strengths. For the second test series, the average UCS of the 180-day samples was 289 psi (1.99 MPa) while the average UCS of the 28-day and 90-day samples was 337 psi (2.32 MPa) and 380 psi (2.62 MPa), respectively. The UCS test results for samples less than 1.5 inches (38 mm) in diameter appeared to be more influenced by curing age than the larger diameter samples (Figure 15).

Under favorable conditions, cemented backfill samples will generally continue to gain strength with age, but the rate of this strength gain gradually diminishes with prolonged curing time (Seymour et al., 2019). To gather further information regarding the strength loss of the 180-day samples, a third test series was conducted using a similar CPB mix with a blended slag-cement binder. As shown by the post-test photograph in Figure 16, the CPB samples for the third test series also ranged in size from 0.5×1.0 inch (13×25 mm) to 3×6 inches (75×150 mm).

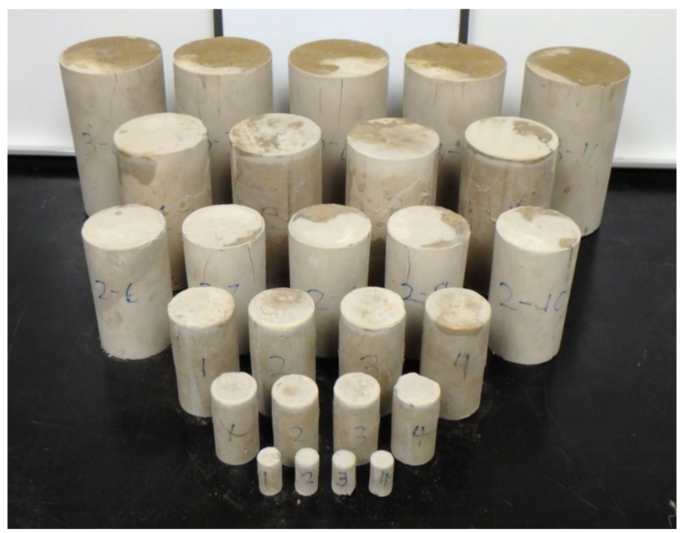

Fig. 16. Typical UCS test samples from the third test series ranging in size from 0.5×1.0 inch (13×25 mm) to 3×6 inches (75×150 mm).

Once again, individual UCS test results depended on the curing age and size of the sample and ranged from 137 psi (0.94 MPa) to 662 psi (4.56 MPa). As noted by Table C in the Appendix, average UCS values by cylinder size ranged from 155 psi (1.07 MPa) to 605 psi (4.17 MPa) with coefficients of variation ranging from 2.1% to 30.1%. Average UCS test results for the third test series are plotted versus cylinder diameter according to curing age in Figure 17. The UCS test results were relatively consistent regardless of cylinder size for samples with the same curing age, except for the 0.5-inch (38-mm) diameter samples that typically had the lowest densities in their test group and appeared to be more influenced by curing age.

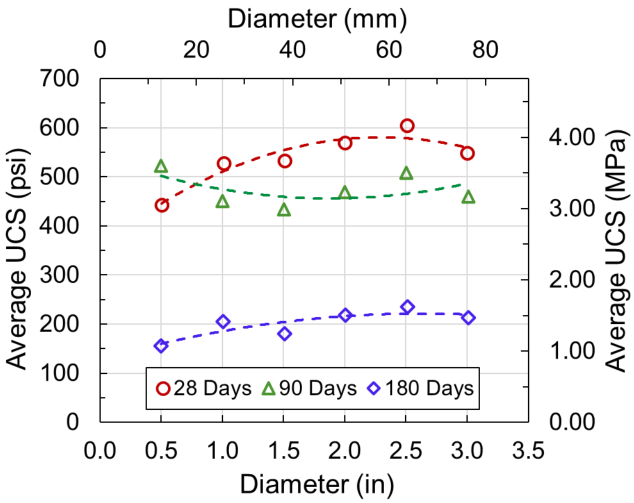

Fig. 17. Average UCS of CPB samples from the third test series by cylinder size and curing age.

As shown in Figure 17, the CPB samples for the third test series exhibited an even larger decrease in UCS with curing time. The 180-day UCS values were substantially lower than the 28-day and 90-day strengths, and unlike the first two test series, the 28-day UCS values were generally higher than either the 90-day or the 180-day strengths. For the third test series, the average UCS of the 28-day samples was 538 psi (3.71 MPa), whereas the average UCS of the 90-day and 180-day samples was 474 psi (3.27 MPa) and 201 psi (1.39 MPa), respectively.

6.3. Splitting Tensile Strength

After 28 days of curing, STS tests were conducted with nine Brazilian samples cut from three of the 3×6-inch (75×150-mm) cylinders, which were cast with the Batch 4 CPB mix during the second test series. The indirect tensile strengths of the Brazilian test samples were determined using the following equation:

$$\sigma_t = \frac{2P}{\pi L D} \qquad (2)$$

where:

σ_t = splitting tensile strength, psi (MPa)
P = maximum load, lbf (N)
L = thickness of specimen, inches (mm), and
D = diameter of the specimen, inches (mm).

As shown in Figure 18, the STS of the Brazilian CPB samples ranged from about 37 psi (0.26 MPa) to 85 psi (0.59 MPa) and depended not only on the 3×6-inch (75×150-mm) cylinder from which the Brazilian sample was cut but, more importantly, on the relative location of the sample within the CPB cylinder (i.e., top, middle, or bottom). As noted in Table 11, the average indirect tensile strength of the CPB samples was 59 psi (0.40 MPa), which is approximately 17% or 1/6th of the average 28-day UCS for 3×6-inch (75×150-mm) samples cast from the same CPB batch—349 psi (2.40 MPa). This STS-to-UCS ratio is higher than the 10% or 1/10th value that is typically used to estimate the tensile strength of CPB.

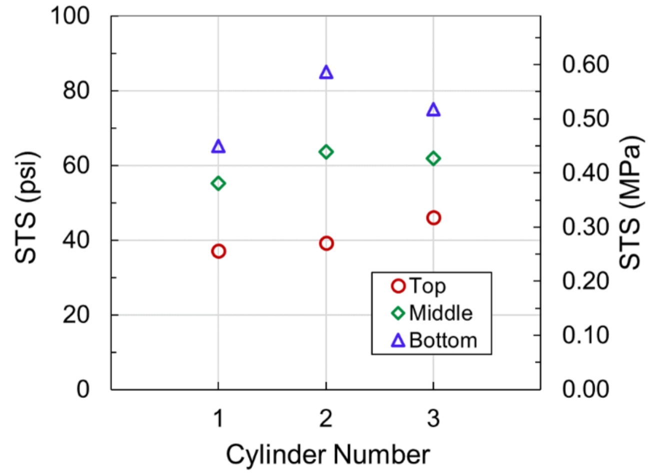

Fig. 18. 28-day STS of Brazilian CPB samples by cylinder number and sample location.

Table 11. Summary of STS tests results with Brazilian CPB samples

Number of Samples	Average STS[1] (psi)	SD[2] (psi)	CV[3] (%)	STS/UCS[4] Ratio (%)
9	58.7	16.0	27.3	16.8

[1]Brazilian splitting tensile strength after 28 days of curing
[2]Standard Deviation
[3]Coefficient of Variation
[4]Average unconfined compressive strength of 3×6-inch (75×150-mm) cylinders after 28 days of curing

Although the STS tests were performed in a consistent manner with identical displacement rates and similar test durations, differences in the densities of the samples significantly impacted the test results as evidenced by the range of tensile strengths shown in Figure 18 and the high coefficient of variation listed in Table 11. Segregation and settling of solids in the CPB mix during the early stages of curing produced noticeable differences in density along the height (vertical length) of the 3×6-inch (75×150-mm) cylinders. As a result, the densities of the Brazilian samples were largely determined by their relative locations within the CPB cylinders and ranged from about 116 pcf (1852 kg/m^3) to 127 pcf (2040 kg/m^3). As shown in Figure 19, a Brazilian sample cut from the top of a CPB cylinder had a significantly lower density and, thus, a much lower tensile strength than a corresponding sample prepared from the middle or bottom of the same cylinder. The impact of density on STS is discussed in further detail in Section 7 below.

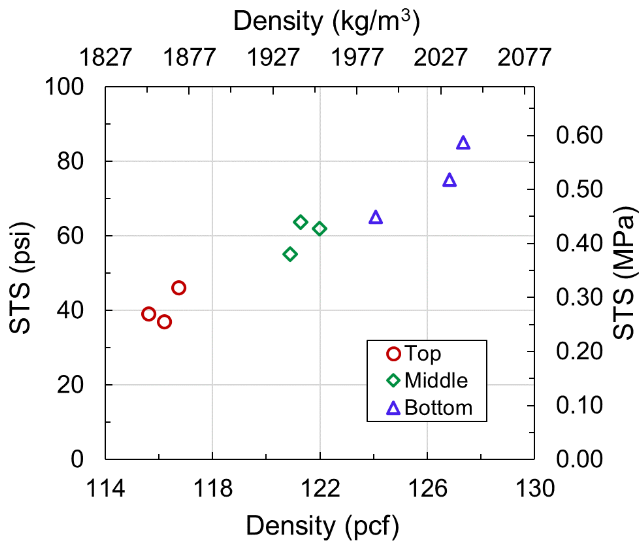

Fig. 19. 28-day STS versus density of Brazilian CPB samples by sample location.

7. DISCUSSION

As explained 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 or rock are loosely adapted for use with CPB, a much softer material. The CPB sampling methods and testing procedures that were used for this study followed as reasonably as possible the guidelines developed for concrete and rock core by the American Society of Testing and Materials (ASTM) and the American Concrete Institute (ACI).

7.1. Density

As mentioned above, the CPB samples for this study were cast using five batches of a similar backfill mix. Even though a similar mix was used for all of the samples, the density of the CPB samples varied depending on the test series, batch number, and cylinder size as indicated previously in Figure 11 and Table10. Differences in sample density were more than likely caused by unintended changes in the mix constituents during batching, in part reflected by the different spread test measurements mentioned in Section 5.1, and also by inconsistent sampling procedures while filling the sample molds, particularly insufficient agitation of the mix while casting the smaller diameter samples.

Usually, the density of a CPB sample directly affects its strength with more dense samples typically having higher UCS and STS values than less dense but similarly sized samples. In this study, the relationship between density and compressive strength was not as straight forward. The smaller diameter samples generally had densities that were lower and less consistent than the other samples, but they also tended to be more affected by either a gain or loss of compressive strength with curing age than the larger samples. The average density and average UCS of the CPB samples for the three test series in this study are listed by cylinder size, batch number, and curing age in Tables A, B, and C in the Appendix. This information is in turn summarized by the range of cylinder sizes that were cast using a particular batch in Table 12.

Table 12. Average density and average UCS of CPB samples by batch number, range of cylinder sizes, and curing age

Batch Number	Sample Diameter (in)	Curing Age (days)	Average Density (pcf)[1]	Average UCS (psi)
1	0.5-6.0	28	141.1	358.2
1	0.5-1.5, 2.5, 4.0	90	142.5	426.9
2	3.0, 6.0	90	140.8	352.6
2	3.0-6.0	180	140.1	234.1
3	2.0	90	141.9	332.6
3	0.5-3.0	180	137.6	219.3
4	0.5-3.0	28	141.1	337.1
4	0.5-3.0	90	137.8	379.8
4	0.5-3.0	180	140.2	288.9
5	0.5-3.0	28	142.6	537.8
5	0.5-3.0	90	142.8	474.0
5	0.5-3.0	180	139.1	201.2

[1]Pounds per cubic foot

The average UCS values listed in Table 12 are plotted versus average density by batch number in Figure 20. With a few obvious exceptions, the denser CPB samples generally exhibited higher UCS values than the less dense samples regardless of batch number. The low UCS values for batches 2, 3, 4, and 5 correspond with compressive strength losses after 180 days of curing.

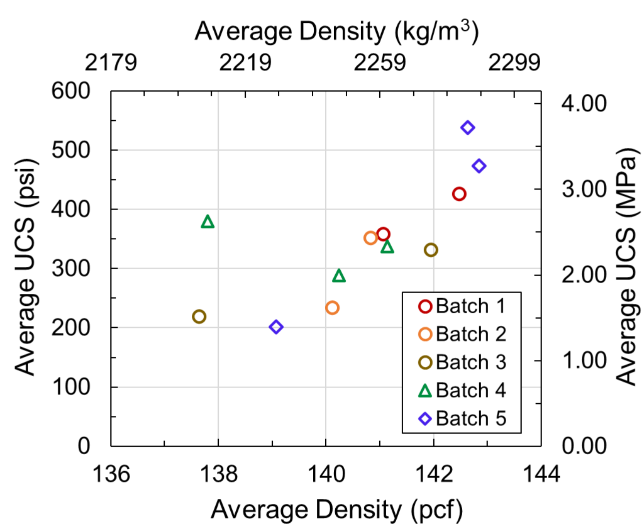

Fig. 20. Average UCS versus average density of all CPB samples by batch number.

As noted in Table 12, a single batch of CPB mix was used to cast the samples for the second and third test series (Batch 4 or 5, respectively), whereas multiple batches were used to cast the samples for the first test series (Batches 1, 2, and 3). To eliminate the confusion of multiple batches with different cylinder sizes and curing ages, the densities and 28-day UCS values were compared for 3×6-inch (75×150-mm) samples cast from Batches 1, 4, and 5 (Figure 21). As explained previously, an 8% cement binder was used for Batches 1 and 4, but an 8% blended slag-cement binder was used for Batch 5, producing noticeably higher 28-day UCS values. As shown in Figure 21, a direct relationship between 28-day UCS and density was not clearly obvious for these samples.

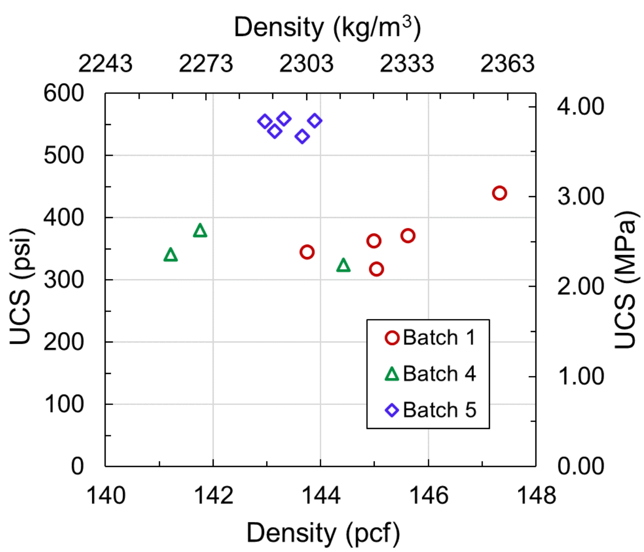

Fig. 21. 28-day UCS versus density of 3×6-inch (75×150-mm) CPB samples by batch number.

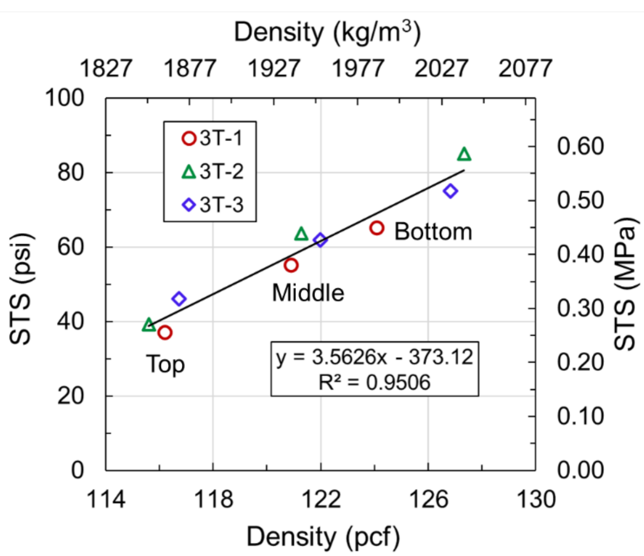

Fig. 22. 28-day STS versus density of Brazilian CPB samples by cylinder number and sample location.

Nine Brazilian STS samples were also cut from three of the 3×6-inch (75×150-mm) cylinders cast with the Batch 4 mix. In contrast, the densities of these samples did directly affect their 28-day STS values as shown in Figure 22.

7.2. Unconfined Compressive Strength

As mentioned previously, three series of UCS tests were conducted to determine if the size of a CPB sample affects its measured compressive strength. During the first test series, UCS tests were conducted with CPB samples ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm) after they had cured for 28, 90, and 180 days. The results of these tests indicated that the UCS values were roughly equivalent for samples that were 2 inches (50 mm) in diameter or larger. After 180 days of curing, all of the samples, regardless of cylinder size, had similar strengths.

Because the strengths of the larger sized samples were reasonably comparable, UCS tests for the second and third test series were conducted with CPB samples ranging in size from 0.5×1.0 inch (13×25 mm) to 3×6 inches (75×150 mm). To avoid the confusion of multiple mixes with different cylinder sizes and curing ages, single batches were used to cast the samples for the second and third test series. As noted earlier, CPB samples less than 2 inches (50 mm) in diameter generally had lower and less consistent densities than the larger samples, were more susceptible to moisture loss, and tended to be more affected by a gain or loss of strength with curing age. To simplify these issues and to gain a clearer indication of the effect of sample size on compressive strength, the UCS values for the different batches, cylinder sizes, and curing ages were normalized in terms of the average UCS of the 3×6-inch (75×150-mm) samples for each curing age curve as shown in Figures 23-25.

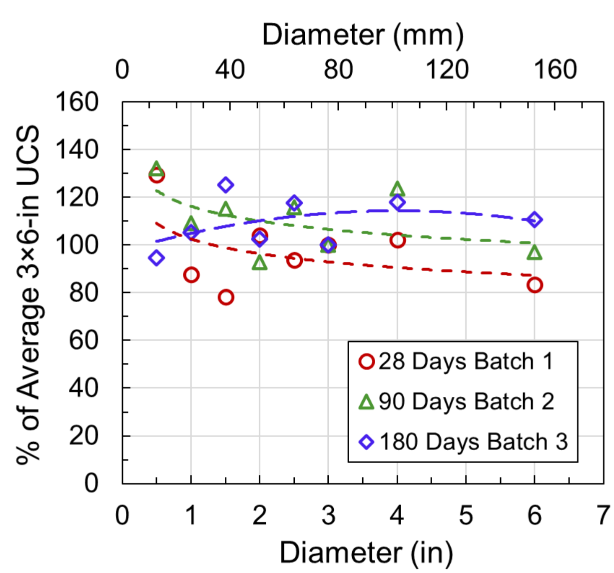

Fig. 23. Relative UCS of CPB samples cast with Batches 1, 2 and 3 for the first test series by cylinder size and curing age.

As noted in Table A in the Appendix, all of the 28-day samples in the first test series were cast using Batch 1, but a combination of batches were used to cast the 90-day and 180-day samples. The curves for these samples were normalized using the average UCS values for 3×6-inch (75×150-mm) cylinders from Batch 2 and Batch 3, respectively as indicated in Figure 23.

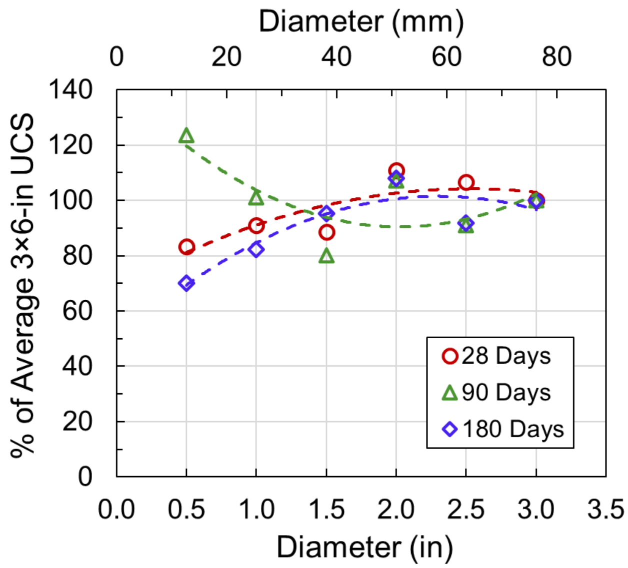

Fig. 24. Relative UCS of CPB samples cast with Batch 4 for the second test series by cylinder size and curing age.

In addition to mix design, the density and moisture content of the samples were also more closely controlled during the second and third test series. The CPB mix was continuously agitated during casting of the samples to obtain more consistent densities, and the surface moisture of the samples was carefully monitored during preparation and testing to prevent the smaller diameter samples from drying out completely.

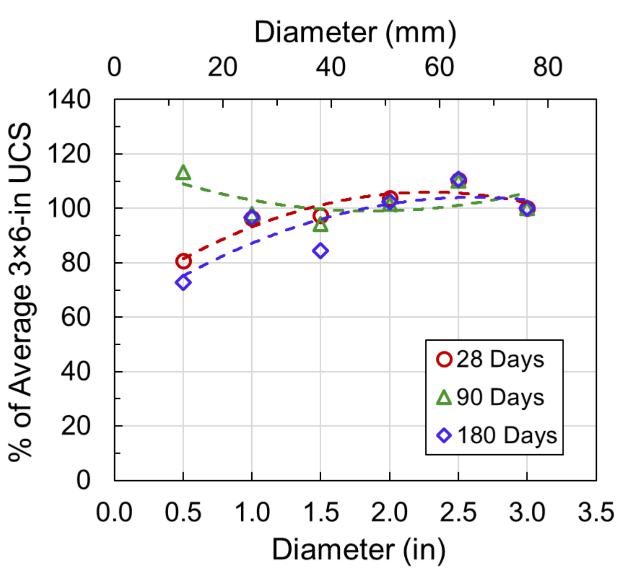

Fig. 25. Relative UCS of CPB samples cast with Batch 5 for the third test series by cylinder size and curing age.

UCS tests are normally conducted with cylindrical samples having a L/D ratio of 2:1. For CPB, 3×6-inch (75×150-mm) or 4×8-inch (100×200-mm) cylinders are typically used to cast samples for these tests. As shown by the relative UCS curves in Figures 23-25, the 2-inch (50-mm) diameter samples, irrespective of CPB batch or test series, provided almost the same average UCS strengths as the 3-inch (75-mm) diameter samples. Slight differences in average UCS values for these two sample sizes were more than likely caused by minor differences in density as noted in Tables A, B, and C in the Appendix. Therefore, standard 2×4-inch (50×100-mm) cylinder molds should be a good, practical substitute for larger sized cylinders when casting CPB samples for UCS testing.

To confirm this finding and examine in further detail the influence of moisture content, rate of hydration, and curing age, the average UCS values for the different sized samples were compared with their aspect ratios (surface area divided by volume) as shown in Figures 26-28. As the size of a cylindrical sample decreases, its surface area increases with respect to its volume, and consequently, its aspect ratio increases. As noted in Tables A, B, and C in the Appendix, a sample's aspect ratio increases rapidly as the size of the sample decreases below about 2×4 inches (50×100 mm).

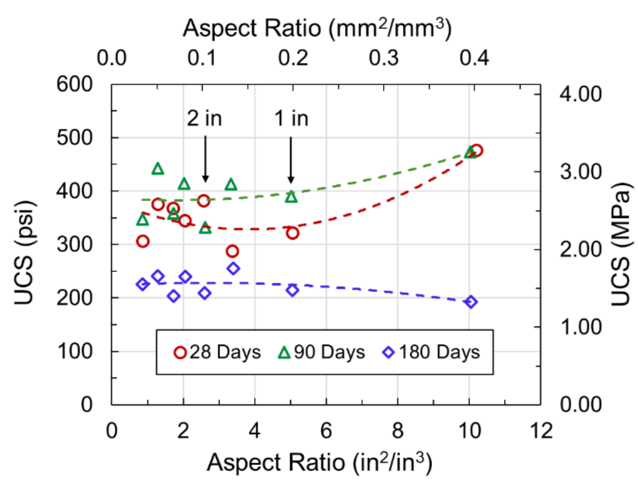

Fig. 26. Average UCS of CPB samples from the first test series by aspect ratio and curing age.

As shown by the curing age curves in Figures 26-28, the average UCS values for the different sized samples were relatively comparable, regardless of test series and CPB batch, until the size of the sample decreased below about 1×2 inches (25×50 mm). Consequently, these test results appear to indicate that the size of a CPB sample does not significantly affect its measured compressive strength until the dimensions of the UCS test specimen are less than about 1×2 inches (25×50 mm).

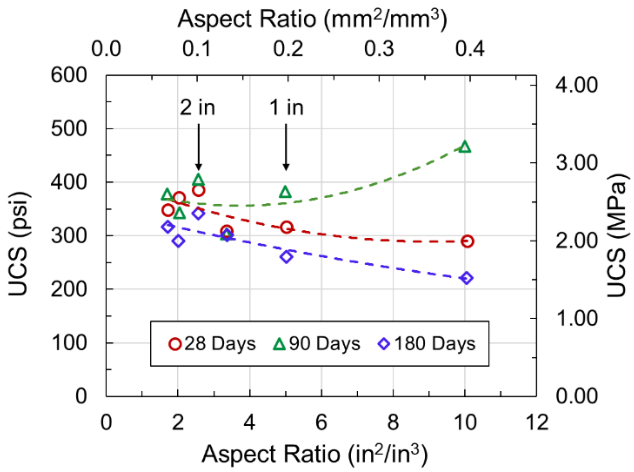

Fig. 27. Average UCS of CPB samples from the second test series by aspect ratio and curing age.

As shown in Figures 26-28, the average UCS values for the 0.5-in (13-mm) diameter samples were often much different than the larger sized samples. Particularly after 28 days or 90 days of curing, the 0.5×1.0-inch (13×25-mm) samples appeared to have a heightened response to either a strength gain or strength loss with curing age. This heightened response diminished after the samples had cured for 180 days, indicating that these anomalous UCS values were more than likely related to the physical dimensions of the sample and its hydration rate. The 0.5-inch (13-mm) diameter samples were much more difficult to prepare and test as reflected by the higher coefficients of variation listed for that sample size in Tables A, B, and C in the Appendix.

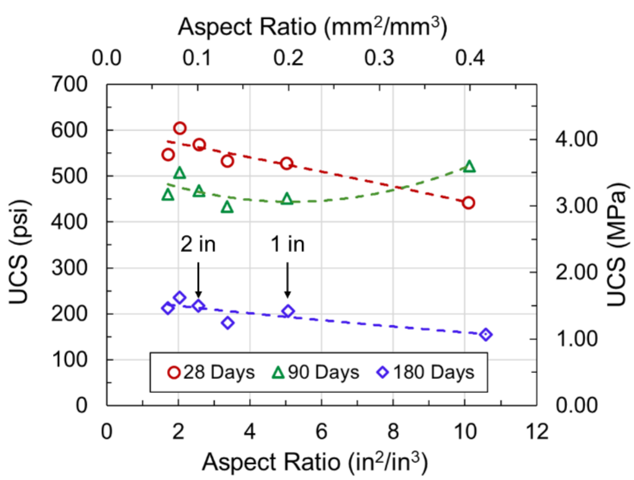

Fig. 28. Average UCS of CPB samples from the third test series by aspect ratio and curing age.

During preparation and testing of the CPB samples, it was noted that as the size of the sample decreased, a higher percentage of the total volume of the sample dried out, particularly for samples smaller than 3×6 inches (75×150 mm). Because testing samples at different levels of saturation can affect the strength results due to changes in internal pore pressure, additional precautions were taken to avoid excessive moisture loss, such as covering the prepared samples with wet burlap or placing them back in a curing room prior to testing. In practice, UCS test results from CPB samples smaller than 2×4 inches (50×100 mm) should be used with engineering judgement due to inconsistent densities, moisture loss, and problems preparing and testing the samples.

All of the samples in this study exhibited a decrease in UCS after 180 days of curing regardless of the CPB batch. Not only did the samples cast with a cement-based binder in the first and second test series lose strength with extended curing time (Figures 13 and 15, respectively), but also the samples from the third test series that were cast using a blended cement-slag binder (Figure 17). As mentioned by Neville (2009) and reported by Tesarik et al. (1996), the use of ground granulated blast-furnace slag is usually associated with a long-term gain in strength; therefore, some unidentified element or chemical in the binder or tailings must be interfering with the hydration process. As mentioned previously, three separate shipments of tailings were used to batch the CPB samples for the three test series. Consequently, some chemical or mineralogical difference in the tailings may have contributed to the different responses of the CPB samples to curing age. There may have also been some acid-alkali reaction between the tailings and the binder. However, further research, beyond the scope of this study, is needed to confirm the actual cause of this strength loss.

7.3. *Splitting Tensile Strength*

As previously mentioned, the average 28-day STS for Brazilian samples prepared from 3×6-inch (75×150-mm) CPB cylinders was 59 psi (0.40 MPa), approximately 17% or 1/6th of the average 28-day UCS for the same backfill mix. As shown in Figure 29, all nine of the STS samples had indirect tensile strengths that were greater than the 10% STS-to-UCS ratio that is typically assumed for the tensile strength of CPB in undercut span designs. These results are comparable to previous STS test results with similar CPB mixes (Johnson et al., 2015; Raffaldi et al., 2019; Emery et al., 2022).

As explained by Neville (1973), splitting tensile tests with concrete are simple to perform and provide more uniform results than other tensile tests. The Brazilian test method is a simplified version of the splitting tensile test because it is performed with disk shaped samples rather than full length cylinders. Brazilian tests provide a practical and convenient means of determining the tensile strength of CPB, 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. Although Brazilian 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% to 12% higher than its direct tensile strength. Johnson et al. (2015) noted that with similar CPB samples, the average direct tensile strength was only about half the average indirect tensile strength determined through Brazilian tests and splitting tensile tests.

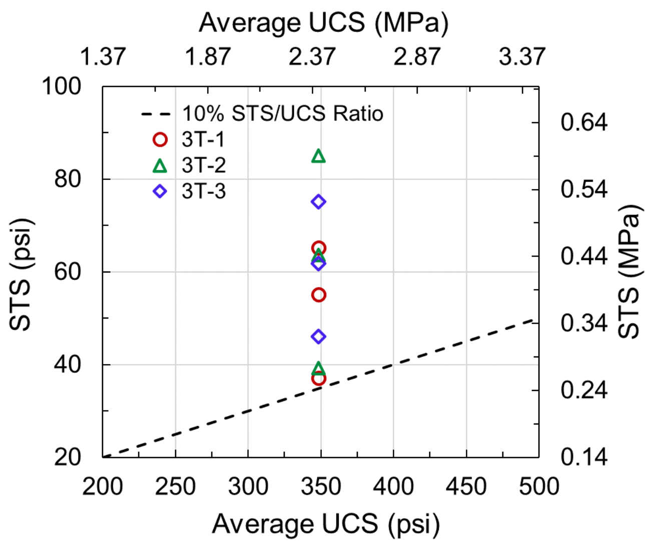

Fig. 29. 28-day STS versus average UCS for Brazilian CPB samples by cylinder number.

8. CONCLUSIONS

To determine if the size of a cemented mill tailings sample affects its compressive strength, NIOSH researchers conducted three series of UCS tests with cylindrical samples of cemented paste backfill (CPB), ranging in size from 0.5×1.0 inch (13×25 mm) to 6×12 inches (150×300 mm), after the samples had cured under controlled temperature and humidity conditions for 28, 90, and 180 days. A total of 264 samples were prepared for UCS tests using five separate batches of a similar CPB mix that consisted of an 8% binder and classified mill tailings at water-to-cement ratios ranging from about 3.79 to 4.32 and solids contents ranging from about 74% to 77% solids by weight.

The following conclusions resulted from this study:

- The density of the CPB samples depended on the test series, batch number, and cylinder size and ranged from 120 to 149 pcf (1927 to 2393 kg/m^3), with an overall average density of 142 pcf (2267 kg/m^3).
- Consistent with previous NIOSH research, the measured strength of a CPB sample was usually related to its density, with higher density samples generally yielding higher UCS and STS test results.
- CPB samples less than 2 inches (50 mm) in diameter were more difficult to cast, prepare, and test. These smaller sized samples usually had lower and less consistent densities, were more susceptible to moisture loss, and appeared to be more affected by a strength gain or loss with curing age.
- Moisture loss should be monitored while preparing and testing CPB samples, especially for samples smaller than 3×6 inches (75×150 mm).
- Particularly with longer curing times, average UCS tests results were comparable for standard sized samples, indicating that 2×4-in (50×100-mm) cylinder molds provide a reasonable alternative to larger sized cylinders.
- A comparison of UCS test results and sample aspect ratios demonstrated that the size of a CPB sample does not significantly affect its measured compressive strength until the dimensions of the UCS test specimen are less than about 1×2 inches (25×50 mm).
- The 0.5×1.0-inch (13×25-mm) CPB samples exhibited a heightened response to strength gain or strength loss with curing age. This heightened response diminished after 180 days of curing, indicating that the unusual UCS test results were more than likely related to the physical dimensions of the sample and its hydration rate.
- Brazilian STS tests provided a practical and convenient means of measuring rather than estimating the tensile strength of CPB.
- The average 28-day indirect tensile strength of Brazilian samples cut from 3×6-inch (75×150-mm) cylinders of CPB was 59 psi (0.40 MPa), about 1/6th or 17% of the average 28-day UCS for the same backfill mix.
- This tensile-to-compressive strength ratio is significantly larger than the 1/10th ratio that is normally used to estimate the tensile strength of CPB.

Because of the unique nature and physical characteristics of cemented mill tailings, developing standard industry practices for collecting, preparing, and testing samples of CPB will lead to more accurate quantification of mix design strengths and more effective quality control measures.

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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APPENDIX: AVERAGE UCS TEST RESULTS

Table A. Average physical characteristics and average UCS for CPB samples from the first test series by cylinder size, batch number, and curing age

Cylinder Dimensions (in)	Batch Number	Curing Age (days)	Surface Area (in^2)	Volume (in^3)	Aspect Ratio (in^2/in^3)	Density (pcf)	UCS (psi)	Standard Deviation (psi)	Coefficient of Variation (%)
0.5 × 1.0	1	28	1.826	0.179	10.192	132.5	476.3	60.6	12.7
1.0 × 2.0	1	28	7.529	1.492	5.048	139.0	322.2	22.0	6.8
1.5 × 3.0	1	28	16.833	4.992	3.372	134.0	288.4	18.4	6.4
2.0 × 4.0	1	28	28.755	11.238	2.559	144.5	382.5	385	10.1
2.5 × 5.0	1	28	45.113	22.071	2.044	142.1	345.2	17.8	5.2
3.0 × 6.0	1	28	64.870	38.047	1.705	145.3	367.8	45.7	12.4
4.0 × 8.0	1	28	112.733	87.557	1.288	145.5	376.3	12.2	3.2
6.0 × 12.0	1	28	247.128	285.964	0.864	145.7	306.6	24.1	7.8
0.5 × 1.0	1	90	1.944	0.194	10.035	131.6	473.5	20.1	4.2
1.0 × 2.0	1	90	7.757	1.546	5.017	145.3	390.7	17.0	4.3
1.5 × 3.0	1	90	17.560	5.267	3.334	144.3	412.9	20.9	5.1
2.0 × 4.0	3	90	27.106	10.409	2.604	141.9	332.6	16.5	5.0
2.5 × 5.0	1	90	46.843	23.154	2.023	144.4	414.6	45.6	11.0
3.0 × 6.0	2	90	62.502	36.253	1.724	141.3	358.0	6.2	1.7
4.0 × 8.0	1	90	111.980	86.819	1.290	146.7	442.9	28.5	6.4
6.0 × 12.0	2	90	250.555	291.160	0.861	140.4	347.1	19.7	5.7
0.5 × 1.0	3	180	1.938	0.193	10.043	132.1	192.9	33.5	17.4
1.0 × 2.0	3	180	7.575	1.500	5.049	138.2	214.7	32.5	15.1
1.5 × 3.0	3	180	16.532	4.871	3.394	138.3	255.6	9.1	3.6
2.0 × 4.0	3	180	27.247	10.481	2.600	139.5	208.9	18.0	8.6
2.5 × 5.0	3	180	44.858	21.899	2.048	138.9	240.0	8.9	3.7
3.0 × 6.0	3	180	62.545	36.292	1.723	138.8	203.8	9.1	4.5
3.0 × 6.0	2	180	62.740	36.450	1.721	139.5	235.9	143.1	6.0
4.0 × 8.0	2	180	111.253	86.094	1.292	141.7	240.8	11.5	4.8
6.0 × 12.0	2	180	251.024	291.801	0.860	139.1	225.4	12.7	5.6

Table B. Average physical characteristics and average UCS for CPB samples from the second test series by cylinder size, batch number, and curing age

Cylinder Dimensions (in)	Batch Number	Curing Age (days)	Surface Area (in^2)	Volume (in^3)	Aspect Ratio (in^2/in^3)	Density (pcf)	UCS (psi)	Standard Deviation (psi)	Coefficient of Variation (%)
0.5 × 1.0	4	28	1.918	0.191	10.059	138.2	290.4	45.3	15.6
1.0 × 2.0	4	28	7.697	1.535	5.015	141.9	317.1	0.4	0.1
1.5 × 3.0	4	28	17.192	5.135	3.348	138.8	308.6	29.7	9.6
2.0 × 4.0	4	28	28.393	11.037	2.573	144.7	386.1	36.3	9.4
2.5 × 5.0	4	28	46.722	23.086	2.024	140.7	371.6	29.9	8.0
3.0 × 6.0	4	28	63.435	37.057	1.712	142.5	348.5	28.9	8.3
0.5 × 1.0	4	90	1.970	0.197	9.992	131.0	467.0	42.2	9.0
1.0 × 2.0	4	90	7.902	1.584	4.988	135.4	382.4	19.8	5.2
1.5 × 3.0	4	90	17.101	5.101	3.353	135.7	303.2	37.1	12.2
2.0 × 4.0	4	90	28.250	10.988	2.571	143.2	405.1	18.3	4.5
2.5 × 5.0	4	90	45.472	22.286	2.040	140.3	343.5	23.9	6.9
3.0 × 6.0	4	90	64.355	37.748	1.705	141.2	377.8	12.4	3.3
0.5 × 1.0	4	180	1.934	0.193	10.042	136.3	221.5	17.0	7.7
1.0 × 2.0	4	180	7.738	1.541	5.021	138.8	260.7	19.3	7.4
1.5 × 3.0	4	180	17.158	5.106	3.360	140.0	301.8	16.0	5.3
2.0 × 4.0	4	180	28.360	11.043	2.568	143.4	342.1	5.7	1.7
2.5 × 5.0	4	180	47.621	23.633	2.015	140.0	290.7	14.0	4.8
3.0 × 6.0	4	180	64.142	37.482	1.711	142.9	316.5	8.6	2.7

Table C. Average physical characteristics and average UCS for CPB samples from the third test series by cylinder size, batch number, and curing age

Cylinder Dimensions (in)	Batch Number	Curing Age (days)	Surface Area (in^2)	Volume (in^3)	Aspect Ratio (in^2/in^3)	Density (pcf)	UCS (psi)	Standard Deviation (psi)	Coefficient of Variation (%)
0.5 × 1.0	5	28	1.874	0.186	10.097	139.9	442.9	17.6	4.0
1.0 × 2.0	5	28	7.656	1.528	5.012	142.5	528.4	61.9	11.7
1.5 × 3.0	5	28	16.941	5.038	3.362	142.3	533.3	24.9	4.7
2.0 × 4.0	5	28	28.086	10.903	2.576	144.2	569.2	51.0	9.0
2.5 × 5.0	5	28	45.385	22.259	2.039	143.4	604.8	22.9	3.8
3.0 × 6.0	5	28	64.792	37.985	1.706	143.4	548.0	12.3	2.2
0.5 × 1.0	5	90	1.878	0.186	10.122	141.6	522.0	157.2	30.1
1.0 × 2.0	5	90	7.617	1.514	5.032	142.1	451.2	18.0	4.0
1.5 × 3.0	5	90	16.896	5.015	3.369	141.9	434.1	30.3	7.0
2.0 × 4.0	5	90	28.323	11.021	2.570	143.9	468.4	36.7	7.8
2.5 × 5.0	5	90	45.338	22.206	2.042	144.5	507.7	20.5	4.0
3.0 × 6.0	5	90	64.664	37.949	1.704	143.0	460.4	33.9	7.4
0.5 × 1.0	5	180	1.649	0.157	10.577	127.0	155.2	27.7	17.8
1.0 × 2.0	5	180	7.430	1.467	5.064	141.2	205.7	15.0	7.3
1.5 × 3.0	5	180	16.641	4.926	3.378	140.7	179.8	11.8	6.6
2.0 × 4.0	5	180	28.467	11.111	2.562	141.8	218.1	17.3	7.9
2.5 × 5.0	5	180	45.279	22.210	2.039	142.0	235.5	4.9	2.1
3.0 × 6.0	5	180	64.803	38.070	1.702	141.7	212.9	23.8	11.2