Cemented Rockfill QA/QC Batching Study with Specific Focus on Different Sample Preparation Techniques

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Abstract
Cemented rockfill (CRF) is being used to backfill primary and secondary stopes at the Eagle Mine, an underground nickel and copper mine operated by Lundin Mining. The National Institute for Occupational Safety and Health (NIOSH) Spokane Mining Research Division (SMRD) is partnering with Eagle Mine to research the advancement of mine backfill QA/QC guidelines through batching and strength testing method studies, specifically through investigation of existing methods that best determine *in situ* properties of CRF. As part of this collaborative research, NIOSH researchers traveled to Eagle Mine and worked with mine staff to trial multiple 6 in QA/QC CRF cylinder preparation methods including ASTM C31, ASTM C1435, and a drop hammer compaction method to identify which method can best correlate to the *in situ* strength of CRF placed underground with the least operator bias and highest confidence. A total of 60 cylindrical samples (6 in) of CRF were cast at the mine and cured underground, in accordance with the three-cylinder preparation methods,. Samples were later transported to the SMRD laboratory to determine the strength and elastic properties of the CRF. Data collected from this study will help identify which test cylinder method provides consistent density and strength results that can better correlate with *in situ* density of CRF.

Key words: ASTM, cylinder preparation, backfill strength, underground mining

Introduction
Cemented rockfill (CRF) is a zero or low slump, coarse aggregate, concrete-like engineered material used for backfilling mined-out openings. The defining characteristics of CRF include: 1) large aggregate top size of 2 to 6 inches, 2) inclusion of fines from the crushing process, and 3) less than 1 in slump, which is essential for creating self-standing faces when jamming the material. According to Stone, aggregate gradation controls the density of the CRF, and therefore has a significant impact on CRF strength (Stone, 2007). When utilized in underground environments, backfill strength requirements are typically determined through a combination of analytical formulae (Mitchell 1991) and empirical design (Pakalnis, Caceres et al., 2005).

Previous cemented rockfill research at NIOSH
Research from Seymour et al. (2013) discovered that backfill failures in U.S. mines are usually attributed to inadequate backfill strength, insufficient or inconsistent quality control measures, or larger-than-expected mining spans. This 2013 study prompted researchers at the National Institute for Occupational Safety and Health (NIOSH) Spokane Mining Research Division (SMRD) to investigate the strength and mechanical properties of CRF used as part of the mining cycle at collaborating underhand cut-and-fill mining operations through backfill sample cylinder size effect studies (Warren, Raffaldi et al., 2018, Stone, Pakalnis and Seymour, 2019). Through this investigation, it was discovered that sample density of Quality Assurance/Quality Control (QA/QC) CRF cylinders has a significant effect on its resulting unconfined compressive strength (UCS). If there is a large variance in QA/QC cylinder density/strength due to the sampling procedure used and/or change in cylinder preparer, it can become difficult to confidently estimate strength properties of emplaced CRF in underground mine openings.

In 2021, a collaborative study between researchers at NIOSH and geotechnical engineers at Eagle Mine further investigated the correlation between CRF QA/QC cylinder density and strength (Bourgeois et al., 2023) with an additional research task of comparing the ASTM C31 and ASTM C1435 sample preparation techniques. A major conclusion of the study was that the ASTM C1435 sample preparation technique resulted in a more consistent density and UCS of QA/QC 6 × 12 in cylinders compared to that of ASTM C31, and that more data were needed to back up these initial findings. Therefore, this paper focuses on a follow-up study which provides more data points of the resulting strength properties of CRF QA/QC cylinders based on the currently used preparation techniques including ASTM C31, ASTM C1435, and a drop hammer compaction method.

Cemented rockfill QA/QC cylinder preparation methods used in this study

ASTM C31

The most commonly used standard for sampling CRF is ASTM C31 (2022): Standard practice for making and curing concrete test specimens in the field. For this study, 6 × 12 in cylinders were molded by rodding three layers of approximately equal depth at 25 roddings per layer. The process of molding by rodding according to C31 is shown in Figure 1a.

ASTM C1435

The second CRF sampling method used in this study was ASTM C1435 (2020): "Standard practice for molding roller-compacted concrete in cylinder molds using a vibrating hammer. This standard is more commonly used in civil engineering applications and was first explored by SMRD for use in CRF sampling in the Bourgeois et al. (2023) study. This method was investigated as the methodology and equipment use appeared to be a promising means of reducing variability in sample density due to operator bias. For this study, 6 × 12 in cylinders were molded through the following steps:

1. Vibrating hammer was placed with tamping plate into the 6 × 12-inch cylinder mold onto the CRF.
2. Vibrating hammer was started and CRF was allowed to consolidate either until the mortar formed a ring around the total perimeter of the plate or until 15 secs had passed.
3. Process was repeated for three layers of approximately equal depth (similar to ASTM C31).
4. Mold was completed by overfilling it with CRF and consolidating with the vibrating hammer and tamping plate to create a smooth and level top.

The process of molding by vibrating hammer according to ASTM C1435 is shown in Figure 1b.

Drop hammer compaction method

The final CRF method used in this study was a drop hammer method that was developed using a modified dynamic cone penetrometer which had a plat face plate in place of the cone, which was developed for use by Eagle Mine. The standard ASTM method D7380 for Soil Compaction Determination at Shallow Depths does not apply for this case, so through experience the mine had determined that 10 drops per lift (total of 3 lifts) to be adequate for proper compaction. The process of molding by the drop hammer compaction method is shown in Figure 1c).

Figure 1. Example of researcher constructing 6 × 12-inch CRF cylinder according to a) ASTM C31, b) ASTM C1435, and c) drop hammer compaction method.

Cemented Rockfill QA/QC Cylinder Construction at Eagle Mine

The principal mining method at Eagle is longhole open stoping with delayed rockfill emplacement. A detailed description of the mining sequencing, CRF material composition, mixing, transportation, and quality control practices can be found in Bourgeois et al., (2023). In June 2023, researchers at SMRD and geotechnical staff from Eagle Mine constructed 60 of 6 × 12 in cylindrical CRF cylinders in accordance with ASTM C31, ASTM C1435, and the drop hammer compaction method for strength testing at the SMRD lab in Spokane, WA.

CRF cylinder construction occurred underground at the -473 level stope of the Eagle workings where backfill was being poured and jammed into a mined-out stope that same day. The sixty constructed cylinders were made according to the three sample preparation methods in the following manner:

- 10 ASTM C31 (not-screened)
- 10 ASTM C31 (screened)
- 10 ASTM C1435 (not-screened)
- 10 ASTM C1435 (screened)
- 10 drop hammer (not-screened)
- 10 drop hammer (screened)

Screening refers to the removal of coarse aggregate larger than two inches in accordance with ASTM C31 (Figure 2), which requires removal of aggregate larger than one third the diameter of the test cylinder. In past NIOSH CRF studies, which primarily followed ASTM C31 for cylinder construction, wet-sieving for two inch plus aggregate was strictly followed when casting 6 × 12 in cylinders as some CRF mixes contained maximum aggregate sizes up to four inches (Stone, Pakalnis, and Seymour, 2019). In the case of the study outlined in this paper, with a maximum aggregate size of 3 in used at Eagle Mine, the research team wanted to see the effect that screening versus no-screening had on density and UCS for all sample preparation techniques. Additionally, the cylinder preparer's initials were noted according to each sample preparation method to capture the variable of preparer bias.

Figure 2. Process of screening two inch plus sized coarse aggregate for screened 6 × 12 in CRF cylinders.

After the 6 × 12 in CRF cylinders were constructed, they were left to cure at the -473 level stope underground for 15 days before being shipped to the SMRD lab for 28 day strength testing. A wooden container with foam inserts for secure cylinder placement was developed and bolted to a pallet for safe, undisturbed shipment of the CRF samples. Figure 3 shows samples after form removal.

Figure 3. Example of cured, not-screened samples after molds were removed a) ASTM C31, b) ASTM 1435, c) drop hammer compaction method.

Strength Testing Methodology

Prior to strength testing, the CRF cylinders were stripped from their forms and final dimensions were measured to identify discrepancies from their diameter and length. Every CRF cylinder was weighed to account for variations in density and the presence of voids. While the plan was to test the 6 × 12 in CRF cylinders at 28 day strength, the actual testing was delayed to 41 day strength due to extra time needed for sample preparation, particularly in cutting the ends of every sample to make them level for UCS testing according to ASTM standard C39 (2021). A 200,000 lbs capacity Tinius Olsen test machine was used for the 41 day strength testing with steel platens placed at each end of the CRF cylinder.

Strength Testing Results

UCS test results of each CRF cylinder constructed at the -473 level stope of Eagle Mine are summarized in Table 1. Average values of density and UCS, as well as coefficient of variation according to CRF cylinder preparation method is shown in Table 2. Figure 4 plots results of all 60 samples according to CRF cylinder preparation method, density, and resulting UCS. Figure 5 plots averages of the results shown in Figure 4.

Table 1. CRF cylinder measuring and UCS results according to compaction method and sampler.

Sample ID	Compaction Method	Sampler ID	Height (in)	Diameter (in)	Weight (lbs)	Density (lbs/ft^3)	UCS (psi)
S1*	ASTM C31	TE	11.604	6.035	27.87	145.1	361
S2			11.730	6.251	29.62	142.2	1,300
S3			11.451	6.006	29.15	155.3	1,580
S4			11.663	5.988	30.01	157.9	1,736
S5			11.549	5.980	30.23	161.0	2,107
S6		FR	11.479	5.986	29.98	160.4	2,231
S7			11.584	5.981	30.23	160.5	2,366
S8			11.448	5.964	29.14	157.4	1,874
S9			11.561	5.975	30.10	160.4	2,193
S10			11.610	5.987	29.62	156.6	1,881
US1			11.563	6.036	29.18	152.4	1,583
US2			11.043	6.038	27.92	152.6	1,705
US3			11.338	6.022	28.62	153.2	1,318
US4			10.960	6.032	28.63	158.0	2,014
US5			11.507	6.017	28.45	150.3	1,460
US6*		TE	10.780	6.045	23.66	132.2	585
US7			11.817	6.023	28.22	144.8	1,004
US8			11.508	6.046	28.13	147.1	1,479
US9			11.164	5.999	26.75	146.5	1,221
US10			11.673	6.020	29.67	154.3	1,664
S1	ASTM C1435	TE	11.600	6.068	30.53	157.2	2,190
S2			11.573	6.034	30.33	158.4	1,984
S3			11.631	6.066	30.73	158.0	2,107
S4			11.573	6.049	29.18	151.6	1,610
S5			11.485	6.053	28.97	151.5	1,582
S6		TL	11.519	6.022	29.24	154.0	1,600
S7			11.433	6.014	30.13	160.3	2,253
S8			11.587	6.023	30.41	159.2	2,167
S9			11.569	6.049	30.23	157.1	2,384
S10			11.578	5.995	30.32	160.3	2,223
US1		FR	11.566	6.060	30.51	158.0	1,890
US2			11.660	6.047	30.56	157.7	2,358
US3			11.492	6.014	30.48	161.4	2,262
US4			11.579	6.098	30.47	155.7	1,973

US5			11.373	6.103	28.86	149.9	1,437
US6		BS	11.589	6.022	29.76	155.8	1,361
US7			11.810	6.042	31.02	158.3	1,873
US8			11.652	6.037	30.51	158.1	2,029
US9			11.080	6.038	27.27	148.5	1,175
US10			11.698	6.052	30.53	156.8	1,808
S1	Drop Hammer	DP	11.325	6.020	29.23	156.7	2,078
S2			11.533	6.028	29.46	154.7	1,611
S3			11.308	5.924	28.67	158.9	1,747
S4			11.430	6.023	29.56	156.8	2,297
S5			11.420	5.977	28.65	154.5	1,713
S6		BS	11.492	6.050	29.40	153.8	1,853
S7			11.627	6.028	29.93	155.8	2,233
S8			11.500	6.045	29.78	155.9	1,763
S9			11.537	6.075	29.76	153.8	1,831
S10			11.428	6.015	28.76	153.1	1,805
US1		TE	11.543	5.982	29.64	157.9	2,006
US2			11.718	6.042	29.39	151.2	1,704
US3			11.550	6.033	29.34	153.6	2,099
US4			11.327	6.033	28.49	152.0	1,583
US5			11.612	5.961	29.67	158.2	1,912
US6		TL	11.506	6.018	29.47	155.6	1,756
US7*			11.483	5.942	27.02	146.6	875
US8			11.051	5.954	28.37	159.3	2,009
US9			11.721	5.877	29.75	161.7	1,688
US10			11.553	6.004	29.22	154.4	1,548

Note: 'S' stands for screened, 'US' stands for un-screened, '*' stands for anomalous test result which was discarded and not included in average values

Table 2. Average results excluding the three anomalous tests noted in Table 1.

Compaction Method	Screened or Un-Screened	Average Density (lbs/ft^3)	Average UCS (psi)	Coefficient of Variation (%)
ASTM C31	Screened	156.9	1,919	17.9
	Un-Screened	151.0	1,494	19.8
ASTM C1435	Screened	156.8	2,010	15.0
	Un-Screened	156.0	1,817	21.2
Drop Hammer	Screened	155.4	1,893	12.2
	Un-Screened	156.0	1,812	11.1

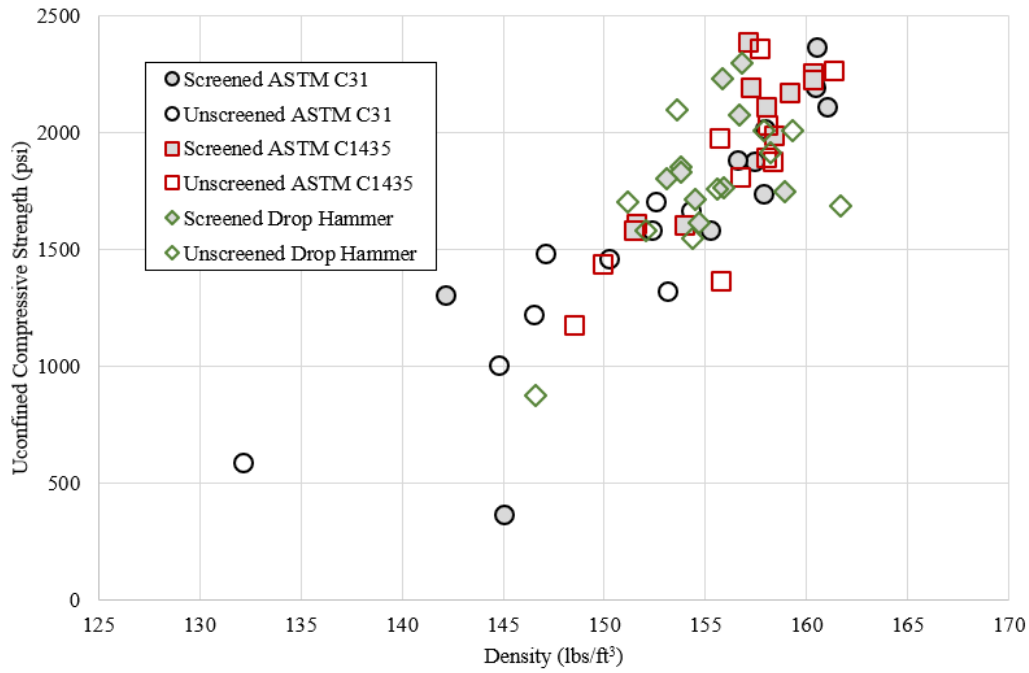

Figure 4. Unconfined compressive strength versus density of Eagle Mine CRF compaction study samples according to sampling method (n = 60).

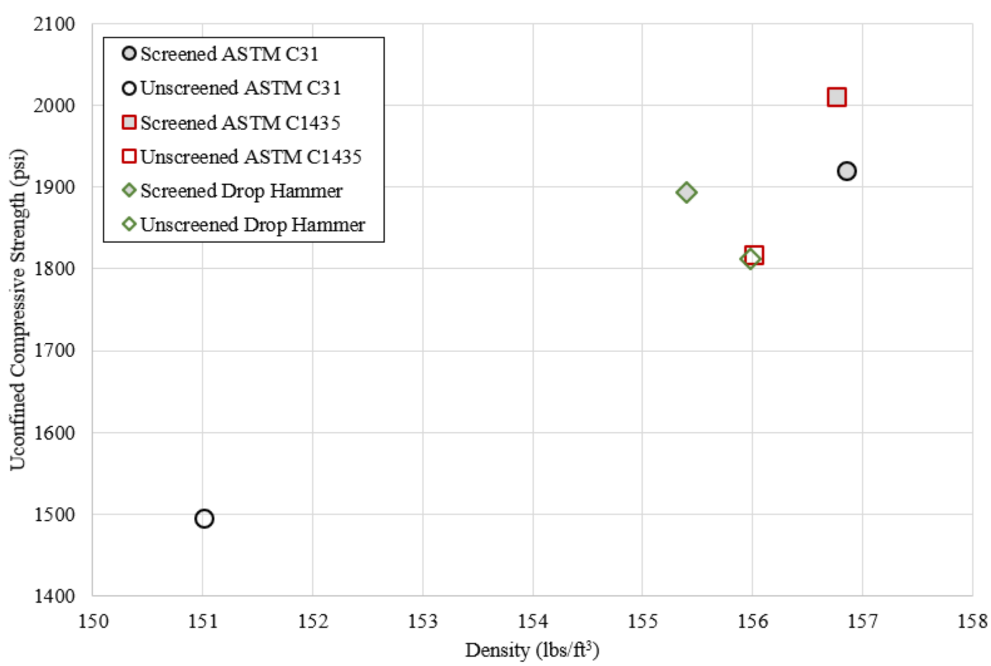

Figure 5. Average unconfined compressive strength versus density of Eagle Mine CRF compaction study samples according to sampling method excluding the three anomalous tests noted in Table 1 (n = 57).

The drop hammer compaction method demonstrated the least amount of variation in resulting UCS across all tested samples (Table 3). Additionally, there was minimal difference in average UCS when comparing the screened vs not-screened samples that were constructed using the drop hammer compaction method. Table 3 shows variation results specific to the sample preparer, further outlining how changing preparers for the same cylinder construction method can have a significant effect on the consistency of the UCS test. Interestingly, while the drop hammer compaction method resulted with the most consistent UCS results, it also resulted in average UCS values similar to that of the ASTM C31 screened samples, which is commonly used in the mining industry and past NIOSH studies. The difference in average UCS between the drop hammer screened method and ASTM C31 screened is 26 PSI while the difference between ASTM C1435 screened and ASTM C31 screened is 91 PSI. The ASTM 1435 was designed to achieve maximum density of cylinder compaction, so this may not be applicable if a particular mining operation achieves less than the maximum compaction when placing CRF.

Table 3. Coefficient of variation in resulting UCS according to sample preparer.

Compaction Method	Sampler ID	Screened or Un-Screened	Average UCS (psi)	Coefficient of Variation (%)
ASTM C31	TE	Screened	1,681	20.0
	FR	Screened	2,109	10.5
	TE	Un-Screened	1,342	21.6
	FR	Un-Screened	1,616	16.4
ASTM C1435	TE	Screened	1,895	14.9
	TL	Screened	2,125	14.3
	FR	Un-Screened	1,984	18.3
	BS	Un-Screened	1,649	22.0
Drop Hammer	DP	Screened	1,616	16.4
	BS	Screened	1,897	10.1
	TL	Un-Screened	1,750	11.0
	TE	Un-Screened	1,861	11.5

Conclusions

Based on testing data it was observed that:

- The modified drop hammer compaction test produced the most consistent test cylinders.
- The modified drop hammer method also produced the least variation in testing result.
- Molding cylinders per ASTM 1435 with a compaction hammer also produced more consistent test cylinders and less variation between individuals casting cylinders.
- The ASTM 1435 method is designed for achieving maximum density for the test cylinder and may not be applicable to operations that are employee placement techniques that do not achieve maximum density.
- ASTM 1435 cylinders need to be cast with proper support for the plastic cylinder molds or they may deform.
- Using ASTM C31 for unscreened material (backfill mix with maximum aggregate > 2 in) resulted in much lower UCS average value.
- ASTM C31 also produced one of the two highest and the single lowest UCS values tested.

NIOSH will continue researching additional methods applicable to the mining industry and based on this research may investigate these methods further. More work needs to be done to develop and mature the drop hammer test method before it could be adopted, such as the best or most available apparatus for the drop hammer and a standard test method for casting cylinders. The ASTM 1435 method also shows promise for potential use as a standard method or perhaps this method should be modified. Finally, more investigation could be done to see if limiting the time for running the compaction hammer can be controlled to limit the amount of compaction and create more consistent results.

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.

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