

INTERPRETING BACKFILL QA/QC TEST DATA: DO WE NEED AN INDUSTRY STANDARD?

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ABSTRACT

Most mines using backfill routinely carry out quality control (QC) testing of backfill mixes with unconfined compression test cylinders. This is true for paste operations, hydraulic fill operations, and cemented rockfill operations worldwide. However, a large number of mines simply do not prepare and test the backfill samples in a consistent manner and fail to properly analyze or interpret the test results. Conventional concrete test criteria are not applicable given the differences in the mix constituents and the fact that a large number of the backfill QC test cylinders typically fail to achieve the target strength.

Standard industry practices are needed to improve the analysis and interpretation of QC test results and to provide a better means of determining if the backfill is achieving its intended target strength. This paper will attempt to lay the groundwork for standard industry practices and will address several key questions raised by operators, such as how laboratory test data compares to in-stope performance, and how many QC tests should fail before a red flag should be raised.

INTRODUCTION

Although paste backfill is widely used throughout the mining industry, cemented rockfill (CRF) remains as the backfill of choice in places like Nevada where very poor ground conditions mandate the use of underhand mining. The safety and stability of undercut entries beneath backfill is a function of the quality of the cemented fill, which is typically assured through routine quality control testing.

In the absence of a backfill quality standard, most mines rely on concrete standards to design and interpret their backfill quality control programs. In the USA, these standards are developed and published by organizations such as the American Society of Testing and Materials (ASTM) and the American Concrete Institute (ACI). However, the application of these standards to cemented backfills can be very difficult owing to the high degree of variability in backfill mixes and the resulting variability in test results.

To illustrate, the concrete industry standards denote that an acceptable (passing) test result occurs when the average strength of the duplicate test cylinders exceeds the target strength and no single test result deviates from the target strength by more than 10% (ACI 214R). Remedial measures must be taken if three consecutive tests fail. With mine backfills, it is safe to say that these criteria are rarely achievable.

A further, more dramatic example is the accepted coefficient of variation for concrete QC cylinders. According to ACI 214R, the coefficient of variation (CV) should range from below 3% (excellent rating) to above 6% (poor rating). However, if this analysis method is applied to several backfill QC databases from operating mines, coefficients of variation are calculated on the order of 50%.

Clearly, there is a need to develop better industry practices for assessing the quality of mine backfill and to assist mine operators with the interpretation of test results and the development of action plans in the event of undesired outcomes.

QUALITY CONTROL VERSUS QUALITY ASSURANCE

First, it is important to understand the difference between quality control and quality assurance. Quality control is defined as the activities to ensure quality, which in the context of backfills means routine sampling and testing of uniaxial compression cylinders. Quality assurance, on the other hand, is the set of actions and processes to ensure quality. In this case, it would relate to the analysis and interpretation of the test data, as well as to any corrective actions taken.

QUALITY CONTROL IN CEMENTED ROCKFILL VERSUS CEMENTED PASTE FILLS

While routine quality control sampling is commonplace for both cemented rockfills and cemented paste fills, there are some important differences that should be understood. First, cemented rockfills are highly variable owing to the size gradation of the aggregate, which can vary dramatically over even short periods of time. Cemented paste fills, on the other hand, tend to be less variable because the mix ingredients are far better controlled. As such, there tends to be far less variability in the quality control test data for cemented paste fill as compared to cemented rockfills.

While this paper is directed at cemented rockfills, all of the principles discussed herein are equally applicable to cemented paste fills.

FACTORS THAT IMPACT UCS

The unconfined compressive strength (UCS) of cemented backfill is affected by several factors including the method of sampling the material, the physical dimensions of the sample, the curing and preparation of the sample for testing, and also the test procedures that are used to determine the strength of the sample. Each of these factors is discussed in further detail below.

Sampling Method

In the case of cemented rockfill (CRF), routine sampling is typically done from the back of a truck at the batch plant or from the bucket of an underground loader or scooptram in the stope. Experience has shown that the sampling location has little impact on the unconfined compressive strength (UCS) of QC cylinders, provided the samples are cured in a proper environment.

With paste, the collection of QC test samples is invariably done at the paste plant. Given that the majority of paste plants are located on the surface, the curing of samples must be done in a humidity room or cabinet. As with CRF, experience has shown that the location of the sampling has little impact on UCS strengths (Hughes et al., 2013).

However, one of the variables that is hard to control with the sampling of CRF is the variation in the quality of cylinders produced by different operators or different crews. CRF batch samples should always be labelled by crew number because, invariably, different crews produce different results. The variability introduced by different operators can range from samples that are over-tamped and on the verge of being concrete to cylinders with excessive voids, poor end preparation, or in some extreme cases, cylinders that are not completely filled. The majority of the reject cylinders are usually produced by one operator. Therefore, crew training is highly

recommended to avoid issues with poor sampling methods (Stone, 2007). As mentioned by Warren et al. (2018), further research is needed to develop more reliable, automated practices for casting CRF cylinders with consistent compaction or density values.

Size of the Sample

In order to comply with ASTM C31, the oversized aggregate must be screened or hand-picked from the sample before casting the UCS cylinder. Hence, some operators believe that 15x30-cm (6x12-inch) cylinders are not representative of the in-stope CRF, if the emplaced aggregate exceeds 76 mm (3 inches) or more.

In the concrete industry, 15x30-cm (6x12-inch) quality control samples are accepted as representative of the field strength of the concrete, as long as the number of test cylinders for a given pour exceeds 30. But in concrete, the maximum aggregate size rarely exceeds one third of the cylinder diameter, so the aggregate for the test sample does not need to be screened.

With recent increases in concrete strengths and limitations on the capacity of test apparatus, ACI and ASTM have begun to accept 10x20-cm (4x8-inch) test cylinders for routine quality control testing of concrete. However, as with 15x30-cm (6x12-inch) cylinders, the maximum aggregate size is limited to one third of the diameter of the test mold.

For concrete, the average strength of 10x20-cm (4x8-inch) test cylinders has been found to be consistently higher than that of 15x30-cm (6x12-inch) cylinders, even when the samples are cast from the same mix. The maximum difference is about 10% and increases over time. As a result, most agencies de-rate the concrete strength values for the 10x20-cm (4x8-inch) cylinders by about 6%. This size-effect relationship, wherein larger test samples exhibit lower strengths, is discussed in further detail by Neville (2009) in regard to the compressive, tensile, and flexural strengths of concrete.

With CRF, the reduction in strength for the larger size samples is even more substantial. A comparison of the strengths of CRF cylinders ranging from 15x30-cm (6x12-inch) to 46x91-cm (18x36-inch) is shown in Figure 1. These test results indicate that, depending on the backfill mix, the UCS of a 46x91-cm (18x36-inch) CRF sample can range from 22% to 61% of the UCS for a standard 15x30-cm (6x12-inch) sample (Warren et al., 2018).

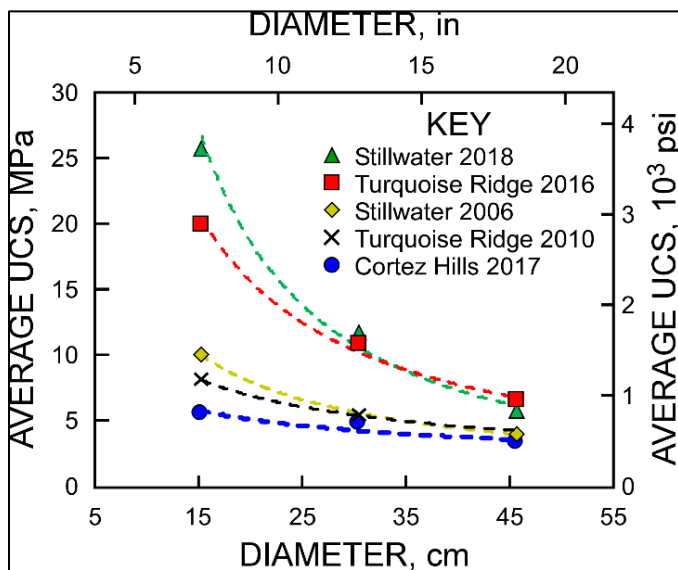


Figure 1. Variation in the unconfined compressive strength of CRF due to sample size.

For concrete, UCS tests with 10x20-cm (4x8-inch) cylinders usually exhibit a higher degree of variability compared to tests with 15x30-cm (6x12-inch) cylinders. Consequently, ASTM and ACI suggest performing 10x20-cm (4x8-inch) tests in triplicate versus duplicate cylinders for 15x30-cm (6x12-inch) tests. UCS tests with

cemented backfill generally exhibit a similar trend, with the larger test cylinders having a lower variability in their test results.

In order to explain the reduction in strength for the larger cylinders, consider the fact that 15x30-cm (6x12-inch) cylinders require the removal of aggregate particles greater than 51 mm (2 inches). So, what is the impact of removing the larger aggregate fraction?

Consider a hypothetical 152-mm (6-inch) minus aggregate with the plus 51-mm (2-inch) fraction removed. Starting with an ideal grading with a Talbot N value of 0.5, Figure 2 shows the shift in the grading curve when the oversized aggregate is removed. The removal of the plus 51-mm (2-inch) fraction requires the removal of just over 40% of the sample. The coarse/fines split at 9.5 mm (0.375 in) shifts from 25% in the original mix to 45% in the modified mix—equivalent to a Talbot N of 0.35. This shift would have a noticeable impact on the sample density, as more fines should result in a higher density and, hence, a higher strength in the smaller sample. The impact of the lower N value on UCS is demonstrated further in Stone, 2007.

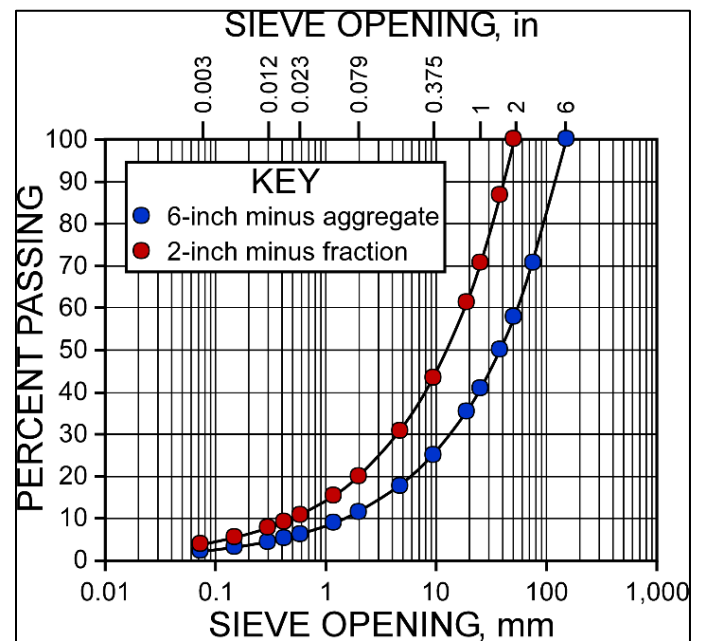


Figure 2. Grading of a hypothetical 152-mm (6-inch) minus backfill compared to the relative grading with the plus 51-mm (2-inch) fraction removed.

A comparison of the densities for small versus large cylinders cast from the same CRF batch is shown in Figure 3. As expected, the 15x30-cm (6x12-inch) samples had a higher density than their respective 46x91-cm (18x36-inch) samples for most of these mixes.

Although removal of the oversized aggregate produces a higher density in the smaller sample, the overall change in the binder content of the CRF mix has a much more significant effect on the subsequent strength of the sample. Removing 40% of the aggregate while casting the sample does not necessarily produce a corresponding 40% reduction in the binder content of the mix. Removal of the oversized aggregate typically causes an increase in the cement content and the water content, with the water/cement ratio remaining essentially unaltered (Neville, 2009). As a result, removing a greater quantity of oversized aggregate from the mix should produce a greater increase in the strength of the sample.

As previously mentioned, NIOSH tests indicated that the UCS of a 46x91-cm (18x36-inch) CRF sample ranged from 22% to 61% of the UCS for a standard 15x30-cm (6x12-inch) sample. In Figure 4, this reduction in strength is plotted as a scale factor and related to the maximum size of the aggregate used in the CRF mixes (i.e., maximum aggregate screen size). As the size of the aggregate increases, more oversized material must be removed from the mix when the 15x30-cm

(6x12-inch) cylinders are cast. This in turn produces increasingly higher strengths in the smaller samples and, by comparison, increasingly larger reductions in strength for the larger samples.

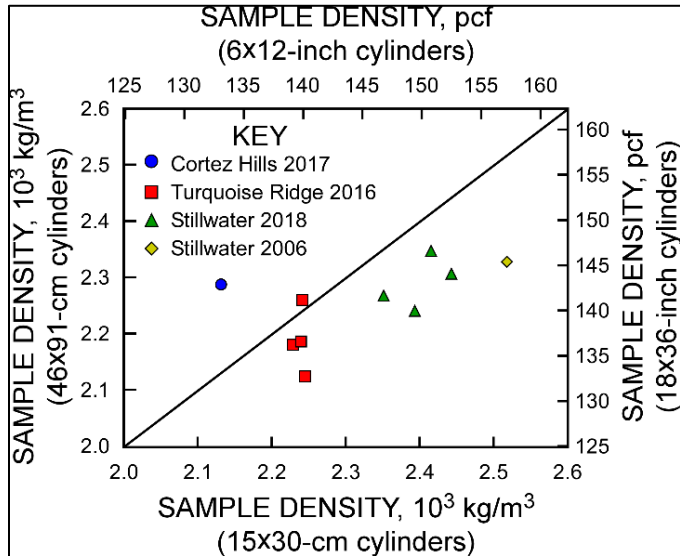


Figure 3. Comparison of sample densities for small versus large diameter cylinders.

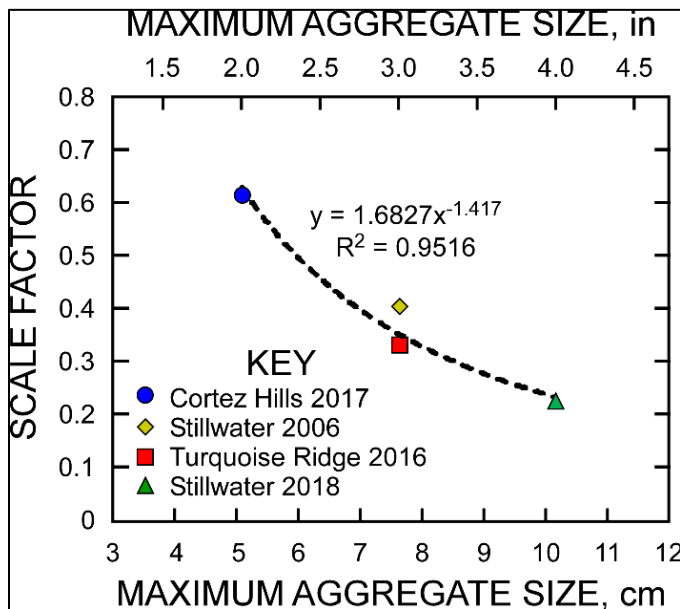


Figure 4. Scale factor for CRF samples versus aggregate top size, after Warren et al. (2018).

Further research is needed to more clearly define the influence of sample size on the strength of cemented backfill samples and to investigate the effects of unintended changes in mix design and other site-specific issues during sampling of the CRF. More importantly, methods need to be developed for relating the strength of the CRF samples to the properties of in-stope material.

Sample Preparation Procedures and Testing Methods

Currently, there are no established standards for preparing and testing cemented backfill samples, and as a result, standards for other materials such as concrete are loosely applied to backfill. CRF generally has a lower cement content, higher water-to-cement ratio, and a drier consistency than typical concrete and, as a result, develops its own unique strength characteristics. Nevertheless, experience has shown that many of the factors addressed in ASTM Standards or the ACI Practices for concrete are also applicable to cemented backfill.

More consistent test results can typically be obtained by carefully following these recommendations or at least thoughtfully considering them.

Even though cemented backfill is generally weaker and softer than concrete, the end conditions of the sample are still important. End parallelism tolerances can be achieved by sulfur capping or applying Hydro-Stone® to the ends of the sample or by using capping pads. Furthermore, properly sized steel platens should be used to ensure that the load is uniformly applied to the sample.

The type of test machine or loading frame can also affect the results of backfill tests. QC testing with backfill samples is usually conducted at a mine site using a small hydraulically controlled, stiff-frame test machine. The loading rate for the tests is typically controlled by adjusting a hydraulic pressure valve. Anomalous test results are common because the tendency is to quickly load the backfill sample to failure rather than to maintain an appropriate test duration.

Backfill tests conducted using more sophisticated laboratory test machines have shown that better test results can be obtained if the load applied to the sample is controlled using the test machine's stroke or displacement control function rather than its load control function. This provides a more accurate measurement of the yield point or ultimate strength of the sample and also allows the duration of the test to be more closely maintained. More consistent test results are achieved if the displacement rate of the test machine's loading head is adjusted so that the backfill sample fails within about 2 to 5 minutes after initiating the load.

INTERPRETATION OF QC TEST RESULTS

The majority of mines enter their backfill QC test results into a computer spreadsheet program and then produce a basic quality control chart, such as the x-y plot of UCS versus time shown in Figure 5. When the test data falls outside of the desired limits, it should serve as a trigger that indicates some form of action is needed. However, because so many QC cylinders fail to achieve their intended target strength, most mines do not understand the triggering mechanisms coming from this type of plot.

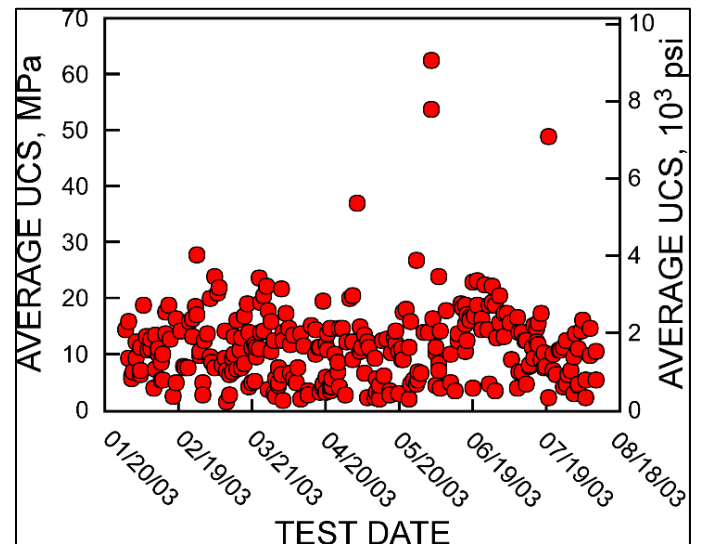


Figure 5. Basic quality control chart, after Stone (2007).

The preferred method for periodic review of backfill QC test data is the cumulative sums (CUSUMS) chart in accordance with ACI 214R-02. The CUSUMS chart is a cumulative summation of the deviation from an average for a series of tests over time. It provides a method for detecting relatively small changes in the average strength of QC cylinders. The CUSUMS chart can help to identify when the change occurred and the approximate magnitude of the shift in strengths. As noted in ACI-214R, the charts provide greater sensitivity in detecting small, systemic changes in the average strength as compared to the

basic quality control chart. A good example of the power of a CUSUMS chart is provided by Stone (2007).

COEFFICIENT OF VARIATION

Under normal conditions, the QC test results are expected to fit into a normal frequency distribution curve clustered around the average. The dispersion of the test data is typically measured by calculating the standard deviation. However, in the case of backfill QC test data, a better measure of the variability of the test data is the coefficient of variation (CV) or relative standard deviation. The CV tends to be less affected by the variation in mean strength values and, hence, provides a more useful measure of the variability over a wide range of strengths.

As noted in the introduction, CV values for concrete can range up to 10%, which is notably different than mine backfills. Helinski and Merrikin (2017) reported that CV values for Australian paste projects ranged from 15% to 30%. A review of client QC databases for a number of backfill projects indicated that CV values ranged from a low of 20% in paste fills to a peak of 80% in CRF. As shown in Table 1, most of the test data clustered around a CV value of 50%.

Table 1. Coefficient of Variation (CV) values from operating mines.

Mine	Type	CV
Project A	Paste	0.22
Project B	Paste	0.55
Project C	Paste	0.60
Project D	CRF	0.35
Project E	CRF	0.53
Project F	CRF	0.63
Project G	CRF	0.76
Project H	CRF	0.78
Project I	CRF	0.55
Project J	CRF	0.72
Project K	CRF	0.63

The CV values listed in Table 1 are indicative of field-prepared QC samples. Results from laboratory testing are typically much more consistent. For example, the CV is generally about 10% to 20% for UCS tests conducted with cemented backfill by NIOSH.

LABORATORY STRENGTHS VERSUS IN-STOPE STRENGTHS

Twenty years ago, the backfill industry adopted a rule of thumb wherein the in-stope UCS was 65% of the laboratory UCS value (Stone, 2007). This strength reduction was meant to account for the fact that laboratory-tested samples were generally much more uniformly mixed, the samples were denser, and the oversized aggregate was removed. This rule of thumb was first developed at Kidd Creek, which used run-of-mine waste rock without crushing or screening and did not use a mixing plant to prepare the CRF. As a result, severe segregation occurred in the stopes.

However, this rule of thumb no longer applies when there is a crushed and graded aggregate not exceeding 76 mm (3 inches) top-size, the CRF product is well-mixed, and not much segregation is created during re-handling. In cut-and-fill stopes in Nevada, for example, the in-stope UCS value is typically found to be higher than the laboratory value, as evidenced by the results of tests on CRF blocks cut from stopes. With modern mixing plants and stopes without segregation issues, the average laboratory strengths are typically about 75% of the in-stope “mass” strengths. This is because strength is a function of density, and in-stope densities are generally higher than laboratory densities.

This latter observation is especially true with cemented paste fill systems where the density is tightly controlled, segregation is not an issue, and the in-stope fill properties are essentially the same as at the batch plant. Most paste fills experience some water bleed or self-consolidation during curing of the binder. As a result, core samples at several paste fill operations show in-stope strengths that are significantly higher than the laboratory quality control samples.

However, the curing age of the cemented backfill should be considered whenever the strength of laboratory samples is compared with the strength of in-stope samples. As shown in Figure 6, CRF samples under controlled curing conditions continue to gain strength with age similar to concrete (Seymour et al., 2018). Consequently, to avoid false comparisons, the curing age of the laboratory and in-stope samples should be equivalent, or the strength of the samples should be adjusted accordingly.

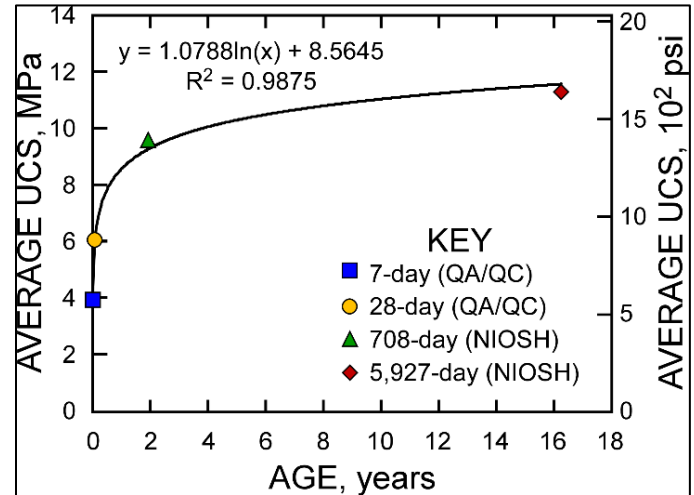


Figure 6. Average UCS versus curing age for CRF samples.

Nevertheless, the de-rating of laboratory UCS strengths to determine in-stope strengths still applies to backfills that employ coarser run-of-mine waste that is subject to segregation. Segregation creates voids in the fill mass, thereby reducing the mass strength. Furthermore, as previously shown, removal of the coarser fraction to satisfy ASTM sample protocols leads to anomalously high laboratory strengths.

Helinski and Merrikin (2017) propose a methodology for de-rating the laboratory UCS values based on the CV from routine QC testing. If the CV value is under 60%, and at least 66% of the QC cylinders exceed the target strength, then the in-stope UCS can be calculated using the equation shown below.

$$UCS_{stope} = UCS_{lab}(1 - 0.413 * CV) \tag{1}$$

where,
 UCS_{stope} = Unconfined compressive strength of emplaced CRF
 UCS_{lab} = Average unconfined compressive strength of standard laboratory samples of CRF
 CV = Coefficient of Variation.

Hence for a CV of 60%, the in-stope strength is calculated to be 75% of the laboratory mean UCS value.

EVALUATING QUALITY CONTROL DATA ON A PER STOPE BASIS

As noted previously, backfill QC test results typically exhibit considerable scatter and also a significant number of “failures” (cylinders with UCS values under the target strength). This is normal in a mine environment due to variations in the aggregate grading, aggregate quality, temperature, binder quality, mix water quality, and sampling procedures.

In Nevada, for example, the author has noted QC cylinder failure rates varying from 10% to 33%. However, in all of these cases, the backfill performance was considered acceptable, and no significant backfill failures were noted. As a result, the following practices are suggested:

- The acceptable failure rate in test samples for a given stope should be about 1 in 4 or 25%.

- The average value of all QC testing for a stope should be above the target strength, thereby implying that the in-stope “mass” strength will be higher than the target strength.

A failure rate in excess of 1 in 4 could indicate a quality control issue with the fill and that the in-stope mass strength is likely less than the target strength. This conclusion is consistent with Monte Carlo simulations in FLAC3D models reported by Helinski and Merrikin (2017). They concluded that for CV values less than 60%, the fill mass is expected to remain stable, provided that 66% of the laboratory values exceed the target fill strength. Consequently, the 25th percentile value adopted herein is conservative.

EVALUATING QUALITY CONTROL DATA ON A DAILY BASIS

Given that test failures are accepted, guidelines are needed to determine if the fill being placed is acceptable. The ultimate goal is to prevent the placement of large quantities of poor quality fill.

So what are the consequences if both of the duplicate sample cylinders tested on the same day fail to meet the intended target strength? With concrete, this would be considered a failure. However, after reviewing several mine QC databases, it appears that this is a very common event with backfill. In one Nevada mine database, about 50% of the failed test results were related to the failure of both duplicate samples on a given day.

What about the failure of both samples over 2 consecutive days? Again, this seems to be a common occurrence and, hence, not a reliable measure of substandard backfill. Even more failures would be expected if multiple stopes were being filled simultaneously.

However, if the failures persist for 3 days in a row, then a threshold has likely been reached where action may be warranted. A review of client databases confirms that this is a relatively rare occurrence and, hence, may be a suitable benchmark for flagging CRF quality issues.

MINIMUM FACTORS OF SAFETY

Factors of safety employed in backfill designs can vary owing to uncertainties in the design inputs, a lack of operating experience at a given location, varying risk factors, impacts on production, impacts on dilution, and variations in material quality. There are no specific industry standards for factors of safety, and hence, the decision is generally made on a mine-by-mine basis.

Some mines use factors of safety as low as 1.2, and others employ factors of safety as high as 2.5. The guiding principle is to appropriately assess the risk in the event of failure. Consequently, higher factors of safety would be used for an underhand cut-and-fill design as compared to a longitudinal longhole retreat method with sidewall fill exposures.

However, for the factor of safety to be meaningful, it must address the most pertinent type of failure. For example, in the absence of rotational instability and closure stresses, flexural stability is the most critical failure mechanism for most backfill undercut spans (Stone, 1993; Pakalnis et al., 2005). Figure 7 shows a database of successful span designs compiled by Pakalnis et al. (2005) that are plotted onto a stability chart adapted from Stone (1993) for backfill spans with vertical sidewalls and a factor of safety of two.

Dilution is a direct function of backfill strength; therefore, the higher the fill strength, the lower the volume of dilution from backfill. In some cases, a trade-off between the cost of dilution and the cost of cement is applicable.

For most mines, a factor of safety of about 1.3 is adequate to cover variations in backfill strength due to batching and sampling differences. This factor of safety is also comparable with the in-stope strength de-rating factor of 0.75 for a CV of 60%, which was discussed earlier in regard to Equation 1 (e.g., FOS = 1 / 0.75 = 1.3).

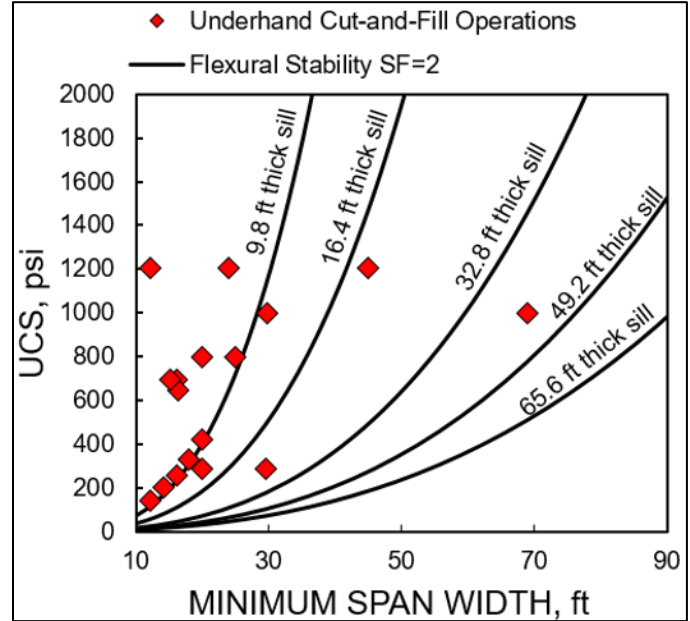


Figure 7. Flexural stability design chart and backfill span database modified from Stone (1993) and Pakalnis et al. (2005).

Another methodology for calculating the minimum factor of safety based on the variability of the UCS data is as follows:

$$FOS = UCS_{median} / UCS_{25th\ percentile} \quad (2)$$

where,

FOS = Factor of Safety

UCS_{median} = Unconfined compressive strength corresponding to the median or 50th percentile value of all QC testing for a stope

$UCS_{25th\ percentile}$ = Unconfined compressive strength corresponding to the 25th percentile value of all QC testing for a stope

CONCLUSIONS

The variability in the unconfined compressive strengths of QC test cylinders is not unexpected given the broad range of factors that can influence the test results. These factors include crew training and sampling procedures, sample quality, sample density, and testing procedures, just to name a few.

Applying concrete standards to the evaluation of backfill quality control samples has been shown to be very difficult. Hence, the authors have developed the following assessment criteria based on a review of QC data from operating mines (Table 2).

Table 2. Suggested assessment criteria for routine QC cylinders.

Criteria	Action Needed
Failure of both duplicate cylinders on the same day	None – frequent occurrence
Failure of test cylinders over two consecutive days	None – common occurrence
Failure of test cylinders over three consecutive days	Yes – early warning of batching issues.
Failure of >25% of QC cylinders for a stope	Yes – early warning of CRF quality issues.
Mean value of all QC testing for a stope is less than the target UCS	Yes – in-stope UCS is likely lower than design UCS

Further research is needed to develop standard industry practices for collecting, preparing, and testing samples of cemented backfill and to address several important issues, including a size-effect relationship for the strength of backfill samples, the consequences of unintended changes in CRF mix design during sampling, and appropriate methods for relating the strength of CRF samples to the properties of the in-

stope material. A better understanding of the strength properties of QC samples in relation to the emplaced fill will lead to more clearly defined target strengths, more appropriate factors of safety, and, thus, safer backfill mine designs.

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DISCLAIMER

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

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