Lessons Learned: Self-Hardening Slurries in Slurry Trenching

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ABSTRACT
Vertical barriers constructed using self-hardening slurries such as cement-bentonite were in use by the early 1970's and slag-cement-bentonite (slag-CB) slurries were first used in the UK in 1975 (Jefferis, 1997). Since then, a number of studies have been conducted to assess the properties of slag-CB, although the vast majority are laboratory or theoretical studies. In this paper, the authors extract data and observations from recent field applications of slag-CB slurry. The observations from these field studies offer both new insight as well as reinforcement of certain existing understandings of self-hardening slurry walls. Topics addressed include:

1. Long term performance development including strength and hydraulic conductivity
2. Strength variability
3. Relationship between trench sample density and strength.
4. Effect of sample size on strength
5. Effect of sample handling on performance

For each topic, potential practical implications associated with the observations are given as well as recommendations for improvement in the standard of practice.

RÉSUMÉ
Les barrières verticales construites à l'aide de boues autodurcissantes comme le ciment-bentonite étaient bien établies au début des années 1970 et les boues de laitier-ciment-bentonite (scories-CB) ont été utilisées pour la première fois en 1975. Depuis, un certain nombre d'études ont été menées. les propriétés du scories-CB, bien que la grande majorité soit des études de laboratoire ou théoriques. Dans cet article, les auteurs extraient des données et des observations d'applications récentes sur le terrain de la suspension de scories-CB. Les observations de ces études de terrain offrent à la fois de nouvelles perspectives et un renforcement des connaissances existantes. Les sujets abordés comprennent:

1. Développement à long terme de performance comprenant la force et la conductivité hydraulique
2. Variabilité de la force
3. Relation entre la densité de l'échantillon de tranchée et la résistance.
4. Effet de la taille de l'échantillon sur la force
5. Effet de la manipulation de l'échantillon sur la performance

Pour chaque sujet, des implications pratiques potentielles associées aux observations sont données ainsi que des recommandations pour améliorer la norme de pratique.

1 INTRODUCTION

The slurry trench installation method is widely used for the installation of cutoff walls. Although soil-bentonite walls are the most common choice in North America, self-hardening slurry trench cutoff wall methods, e.g. cement-bentonite (CB) or slag-cement-bentonite (slag-CB), have been used to install barriers to groundwater flow for decades and are the primary cutoff wall installation technique used in the United Kingdom (Evans and Dawson, 1999). This paper presents performance data and lessons learned from recent self-hardening slurry trenching projects in Calgary, AB and Hawkesbury, ON and these lessons are compared to previously published findings. Specifically, this paper presents data from CB and slag-CB installations showing how key properties, strength and permeability, of these walls change over time, the variability of these properties, and key contributing factors to observed variability. The discussions and conclusions herein include recommendations for the improvement of future installations and provide suggested topics for future research.

2 PROPERTY DEVELOPMENT

It is well documented that the strength and hydraulic conductivity, *k*, of self-hardening slurry backfill mixes containing slag, referred to as slag-CB herein, continue to improve well past 28 days of cure. However, despite this common knowledge, specifications continue to be based on performance of the material after 28 days of curing with no consideration of further improvement. Previous research shows that strengths will continue to increase out to more than 90 days (Jefferis 1981, Opdyke and Evans 2005, Soga and Joshi 2010). Studies show that the *k* of these mixes continues to decrease out beyond 90 days (Opdyke and Evans 2005, Soga and Joshi 2010) and some data suggests there could be further decreases out to 3 years (Soga and Joshi 2010). This long term strength and *k* improvement can be attributed to the pozzolanic reaction provided by the slag. It is suggested that slag reacts more slowly than Portland cement and ultimately develops a denser microstructure as it cures (Soga et al. 2013).

2.1 Unconfined Compressive Strength (UCS)

Consistent with previous findings regarding long term strength gain, the sample data from a project in Calgary, AB, showed significant strength gains out to 168 days (approximately 6 months). These data are presented in Figure 1. The average UCS increased from ~400 kPa at 28 days (~1 month), to ~700 kPa at 56 days (~2 months), and to over ~1000 kPa at 168 days (~6 months). The black line in Figure 1 shows the average UCS. The red lines show +/- 1 standard deviation. The plot shows that the average rate of strength gain is nearly constant from 0 to 84 days. After 84 days, the rate of strength gain appears to slow, but the gains continue to be significant out to at least 168 days (~6 months). While the 28-day strength is often specified, the average 28-day strength is only 30% of the average 168 day strength. UCS testing on these specimens was performed in accordance with ASTM D2166.

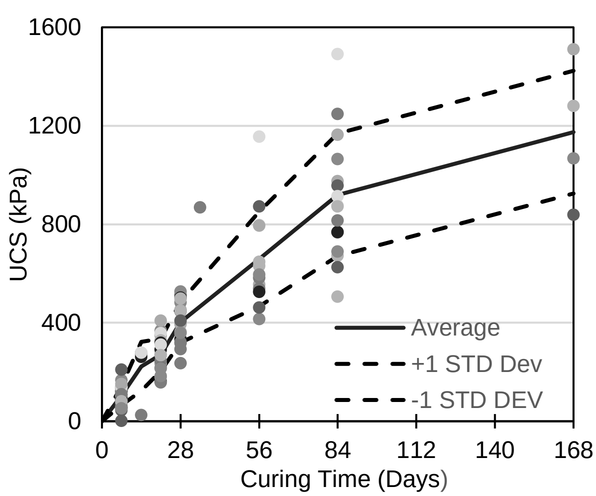

Figure 1. UCS vs set-time of slag-CB samples

2.2 Hydraulic Conductivity

Hydraulic conductivity tests performed on samples from the same project site in Calgary (see Figure 2) show that the average *k* reduced a full order of magnitude from 28 to 56 days with some samples achieving hydraulic conductivity values less than 1x10^-8 cm/s. Although data on *k* was not collected past 56 days, *k* may be reasonably expected to continue to decrease with time. The trend of increasing strength and decreasing *k* with curing time is clear. For this data set, not every sample was tested for *k* at 56 days. Once a sample set achieved the target of $1x10^{-7}$ cm/s or less, further testing of that set was not undertaken. Hence, the 56 day average *k* is unrealistically high compared to the expected average should all samples have been tested at 56 days. Hydraulic conductivity testing was performed in accordance with ASTM D5084.

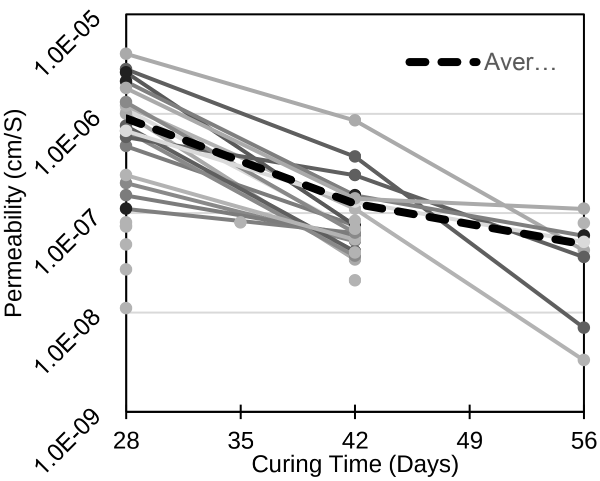

Figure 2. Hydraulic conductivity vs set-time of Slag-CB samples

3 STRENGTH VARIABILITY

Using data from another project, in Hawkesbury, ON, the variability of performance of “identical” slag-CB samples was evaluated. The samples used for this study were samples collected as liquid slurry from the slurry trench itself. This sample type is commonly known as “trench” or “field” samples. These samples were all tested for UCS after approximately one year of curing. The results from these UCS tests are provided in the histogram in Figure 3.

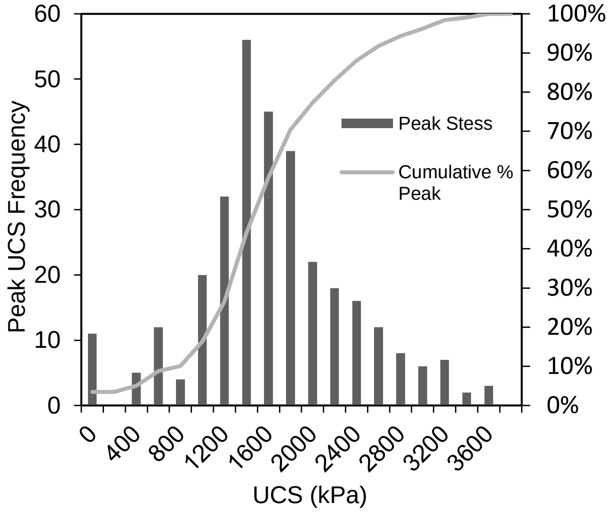

Figure 3. Histogram of slag-CB UCS variability

In total, 307 UCS tests were performed. The mean of this data set is 1,555 kPa, the median is 1,495 kPa, and the coefficient of variation (CV) is 44.7%. Measured strengths from this data set ranged from a minimum of 235 kPa to a maximum of 3,595 kPa. As might be expected, the distribution of UCS results mostly followed a normal "bell curve" distribution with relatively little skew. The shape of the distribution is what the authors would have anticipated, but, the range and CV were larger than anticipated considering the tests were performed on an engineered fluid with the same proportion of components.

4 PROPERTY VARIABILITY INFLUENCES

In addition to the general variability between samples and long term property improvement trends, the data generated from the slag-CB field samples provide some interesting information on other factors that could influence the ultimate properties. These factors include the effects of collecting samples from the trench versus the batch plant, the effects of sample specimen size, and the effects of sample handling & curing.

4.1 Trench vs. Plant Samples

The slag-CB "field" samples collected in Hawkesbury also provided valuable information on the difference in measured properties of samples collected from the trench versus "fresh" slag-CB samples obtained from the batch plant prior to being placed in the trench. Based on past experience, the authors expected that the samples collected from the trench would have lower strengths and higher variability than the samples obtained from the batch plant. Testing performed as part of this study confirmed that hypothesis. At least one previous study of a slag-CB wall at a disused gas works site (Soga et al. 2013), concluded that field samples tend to have lower strengths, higher *k*, and higher property variability due to *'heterogeneity caused by aggressive environments and impurities'*. In the case of the Hawkesbury samples, impurities, in the form of soil inclusions suspended in the slag-CB slurry as a result of the excavation process, were certainly a component of the trench samples. The results from these UCS tests performed on trench and batch plant samples are provided in the histogram in Figure 4.

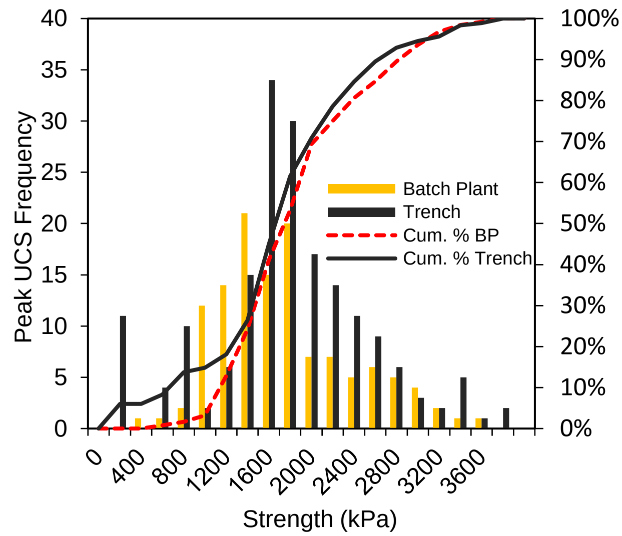

Figure 4. UCS Histogram of Trench vs. "Fresh" samples

A scatter plot of UCS vs density for both the trench and batch plant sample sets was also created, see Figure 5.

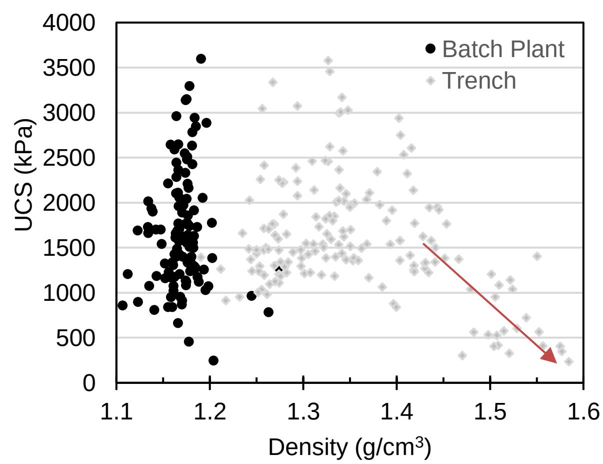

Figure 5. Scatter plot of sample strength vs density

4.2 Sample Size

Another observation made from the Hawkesbury slag-CB sample set was the effect of sample size on the UCS. Common diameters of sample cylinders used for slag-CB mixes are 2" and 3". The UCS results for tests performed on specimens of both 2” and 3” diameter are displayed on the histogram in Figure 6.

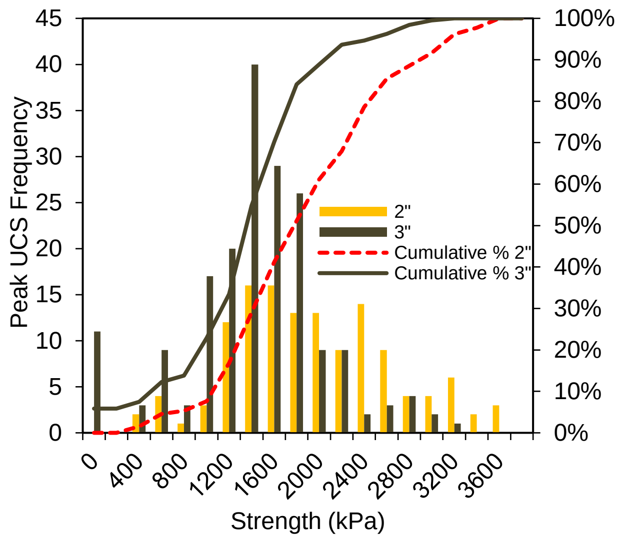

Figure 6. UCS Histogram of 3" vs 2" diameter samples

4.3 Sample Handling and Curing Conditions

Another observation made from the Calgary slag-CB sample set revolved around the effects of sample handling and curing conditions on strength.

The first sample handling observation was the effect that temperature changes of the sample had on strength, specifically sub-freezing temperatures. During shipment of a few sets of samples from Calgary, AB during winter months, the samples were subjected to sub-freezing temperatures and were frozen when the lab received them. When attempting to test these samples for UCS, most of the samples crumbled upon extraction from the cylinder and the few that were removed intact exhibited only 30% to 50% of the strengths of identical samples that were never frozen. This result is expected and the negative impact on strength is an outcome of pore water volume change resulting from freezing coupled with the high water content of slag-CB mixes. Being 70% to 80% water at the time of mixing, slag-CB mixes are particularly susceptible to damage associated freezing. When the water in the sample freezes it expands and in doing so breaks the cement and slag bonds. There is no mechanism for repairing the broken bonds so lower strengths would be expected.

Another observation was made when comparing samples stored with plastic caps and those capped with plastic wrap and tape. Some of the slag-CB samples were cast in cylinders and capped using the regular plastic cap while others were capped with plastic-wrap and tape. After one year of storage, the samples with the caps were still moist on the top when the cap was removed while the samples with plastic-wrap were dry and showed signs of significant desiccation near the top. The difference was also present in the UCS results as the capped cylinders performed almost 70% better than those with just plastic wrap caps.

5 DISCUSSIONS & RECCOMENDATIONS

A variety of lessons may be drawn from the information presented in Sections 2, 3, and 4 above.

5.1 Long Term Property Improvement

The results of the tests performed on the Calgary, AB field samples are consistent with previous findings showing long term performance improvement of slag-CB. In the case of UCS, the observed improvements demonstrated that the strength gain continues to at least 6 months. This finding could have significant implications for the cutoff wall design and construction industry.

As touched upon in Section 2, it is still common for specifications to require sample results to meet the project objectives at 28 days on slag-CB projects. Based on the results presented herein, this is very conservative and can be costly to the project. The UCS results (Figure 1) show that the ultimate strength of these samples can be 3 times higher than the 28 day strength. By not accounting for improvement past 28 days, the construction team could end up spending more on materials than needed or could also incur unnecessary cost and schedule impacts associated with re-work from a specification that requires passing results at 28 days without consideration of inevitable further improvement in strength and hydraulic conductivity.

The authors suggest two alternatives to the conservative practice of verifying mix performance using only tests performed after 28 days of curing. The first option would be to eliminate specifying a particular time of curing for testing of slag-CB samples for compliance. This would allow samples to be tested after longer set times and would therefore allow for the realization of more of the ultimate performance. The downside of this is that 90 days (or more) is a long time to wait for sample results and could negatively impact the project schedule. A second opn is for the 28 day testing schedule to be maintained, but the acceptance criteria be modified appropriately such that the 28 day result would be compared to a target value that has been calculated accounting for the expected gains beyond 28 days. For example, using this data set, if a project required a 1,000 kPa UCS slag-CB material, the specification could require a 400 kPa UCS at 28 days knowing that a mix with 400 kPa UCS at 28 days would predictably reach an ultimate strength of over 1,000 kPa.

A related consideration associated with the long term stress-strain behavior of slag-CB is the strain at failure. Some projects, (and with increasing frequency), specify a minimum strain to failure for slag-CB materials. In many cases, the design basis for a minimum strain at failure is not clear. In the instances where a minimum strain at failure is specified, a sample that meets the final strength and/or k requirement may ultimately fail to achieve the strain requirements. Essentially, it is difficult to design a mix that can meet all three requirements (strain at failure, k, and strength). In a previous study (Garvin and Hayles 1999), the authors discussed project requirements of 5% strain at failure and a k of 10^{-7} cm/s, noted that a mix containing slag that meets these criteria at 28 days would be expected to continue to cure, becoming more brittle with time and eventually may no longer meet the strain requirement. As an alternative, the Garven and Hayles study suggests that a permeability of 10^{-6} cm/s at 28 days could be specified and achieved by a mix that would ultimately be less brittle, but still reach the 10^{-7} cm/s *k* target eventually.

As discussed, specifying a factored target for comparison to 28 day results and relying on continued development up to and past 90 days can help improve project cost. However, this approach requires an understanding of the relationship between the desired properties (strength, hydraulic conductivity and strain at failure) as a function of curing time. As long as proper data is collected prior to construction, the specifications can be developed in a way that ensures all objectives will be met. A thorough bench scale study is required to provide the data necessary to appropriately factor the 28 day strength, *k*, and strain to achieve ultimate performance in line with all objectives.

5.2 Strength Variability

The observed variability of the measured strengths from the Hawkesbury project shows the importance of understanding statistically significant variability of slag-CB so that specifications can be appropriately structured. Specifications which specify a single value for the minimum UCS or maximum *k* are not uncommon. For example, if the specification for this data required a minimum UCS of 1,000 kPa, 41 of the 307 tests (approximately 13%) would have failed despite the fact that the overall data set has a mean of approximately 1,500 kPa which is 50% above the minimum requirement (see Figure 3). Using this example, a specification written to account for statistical variability might be structured like the following: "a target UCS of 1,000 kPa with no more than 10% of the samples falling below 1,000 kPa". The authors note that some recent specifications are being structured with a statistical component.

The differences in specification language in the example above are important for the construction team. Team members need to understand the strength variability of the slag-CB relative to the specification language in order to balance the potential cost of re-work vs. the cost of materials and should be interested in an efficient overall cost by providing appropriately flexible specification language. A rigid specification generally results in overly conservative assumptions about material addition rates to reduce failures. The additional cost of these conservative material addition rate assumptions are reflected in a higher project cost.

A second relevant observation from the Hawkesbury data set is the relatively high strength achieved. While this project had no strength requirement, the material addition rates required to meet the target hydraulic conductivity of less than $1x10^{-7}$ cm/s also resulted in relatively high strengths for a slag-CB material. Previous UCS studies on slag-CB material (Manassero 1994, Soga et al. 2013) show ultimate strengths for slag-CB of around 1,000 kPA. In this data set, more than half of the UCS test results were above 1,500 kPa with a peak of over 3,500 kPa showing the potential to develop higher strengths than previous studies have shown.

5.3 Trench vs. Batch Plant Samples

Figure 4 shows that both the trench samples and the batch plant samples generally follow a normal distribution with similar medians. The most noticeable difference between the two sample sets is the lower end of the cumulative distribution plot. The variability and lower strength of the trench samples appears in this range as nearly 15% of trench samples fell below 1,000 kPa compared to only 3% of the batch plant samples.

Figure 5 shows the lower variability of the batch plant sample density, with results close to the theoretical mix density of 1.17 g/cm^3. The measured strengths for the batch plant samples do show the overall variability in UCS of slag-CB samples even for "identical" samples.

The results from the trench samples show some interesting trends. Based on a review of the strength results from testing on the trench samples, it seems that higher density samples tend to have lower measured strengths. The lower strength is likely a result of soil inclusions/particles suspended in the slag-CB material. Soil particles have a higher specific gravity (higher density) than the density of the slag-CB mixture. In the range of 1.2 and 1.45 g/cm^3 the strength results show even scatter with no discernable trends indicating that soil inclusions resulting in densities in this range have little or no effect on UCS. However, a trend appears to develop in samples with densities greater than 1.45 g/cm^3 after which there is a strong negative correlation between strength and density highlighted by the red arrow on the figure. The negative correlation in this density range indicates that there may be a threshold crossed around the 1.45 g/cm^3 mark. After this threshold is reached, it is possible that the proportion of soil inclusions suspended in the slag-CB results in weak spots or preferential failure planes. Note that an earlier field study comparing excavation tools found lower strength with a long reach excavator than with a clam shell and attributed this difference to the greater inclusion of soil associated with the long reach (Axtell et al. 1999)

5.4 Sample Specimen Size

The histograms (see Figure 6) for each sample size tested in this study again show relatively normal distributions with little skewness. The cumulative distribution plots clearly show the possible effect of sample size on UCS. The two cumulative distribution plots are relatively the same shape but the plot of strength results from testing of the 3" specimens is shifted to the left. The mean and median for the 2" samples was 1,867 kPa and 1,822 kPa respectively whereas the same parameters for the 3" samples were 1,405 kPa and 1,384 kPa, respectively. On average, the 3" samples from this study achieved only 75% of the UCS of a 2" cylinder cast from "identical" material.

Although this difference may not be attributed to any single variable, there are several factors that may have led to the finding that tests on the 2" diameter samples resulted in higher strengths than those on the 3" diameter samples. The first factor relates to the assumption that a cast slag-

CB sample is homogenous. The larger sample volume increases the probability of an imperfection being included in the sample resulting in a preferential failure plane within the sample. A second factor is also based on the assumption that a cast slag-CB sample is homogenous but relates to the application of the load during testing. A higher force is needed to provide an equivalent stress on a 3” diameter sample versus a 2” diameter sample and that greater force may have an effect on defects or imperfections within the sample causing it to fail at lower stresses. If a defect creates a load concentration along a preferential failure plane within the sample this could certainly be the case. To make stronger conclusions about the cause of this correlation, additional research is needed. Additional research is also needed to determine which sample size presents the more accurate representation of the macro performance of the system. For example, in another study, samples obtained from block samples carved from the trench produced UCS strengths less than those from field cast samples (Soga et al. 2013).

This finding is important relative to specification language about what sample size should be used for compliance testing. For instance, if 2” diameter samples are used for UCS in the mix design, but 3” cylinders are specified to be tested on field samples, lower UCS strengths would be expected due solely to sample size. From the construction team’s perspective, this may result in an increased number of failures compared to expectations and/or the mix design could be too conservative.

5.5 Sample Handling and Curing

The observations made about the effects of sample freezing show the importance of proper sample handling and highlight the need to protect the slag-CB in the field after it has set. A well designed and properly placed “cap” in the field should be used to protect a slag-CB installation from temperature and drying effects.

6 CONCLUSIONS

Using data sets of samples collected from two slag-CB projects in Canada, several interesting and important observations were made regarding the performance of slag-CB.

The data shows that slag-CB sample properties continue to improve, i.e. higher strength and lower *k*, with age up to at least 6 months. Although this characteristic was well documented previously with respect to *k* reduction, previous studies showed UCS improvement plateauing after only 3 months of cure.

The data also demonstrated the importance of several other factors, including sample density, sample size, and sample handling. In general, as the density increased due the inclusion of formation soil, there was little effect on UCS until a threshold was surpassed. Beyond that threshold (in this case 1.45 g/cm^3) there was a strong negative correlation between density and UCS. The data on sample size demonstrated that 3” diameter samples produce strengths that are only approximately 75% of the strength of 2” diameter samples cast from an identical material. It was also observed that capping samples while stored with plastic caps was effective in preventing desiccation whereas plastic wrap and tape did not. Lastly, as expected, sub-freezing environments substantially reduced the UCS strength of samples that were frozen compared with unfrozen samples.

These observations are important for the development of specifications and designs for projects involving slag-CB. Owners and construction team members need to understand how slag-CB behaves not only for quality control purposes, but also for specification and contractual purposes. A better understanding of slag-CB’s behavior can also provide cost efficiency improvements to owners which ultimately may expand the use of slag-CB to other project sites and applications.

7 FUTURE STUDY TOPICS FOR SLAG-CB

Although this is not a complete list of topics related to slag-CB deserving of future study, the authors have identified a few areas of potential research:

- Strain at failure: How does strain at failure vary with curing age? How variable is this parameter?
- Testing procedures for evaluating stress and strain of slag-CB: How does strain at failure vary with test method and conditions (e.g. drained vs. undrained, confined vs. unconfined)?
- Compatibility of slag-CB with contaminants: While some laboratory work has been done in this area, what field data is available to substantiate laboratory findings?
- Tensile strength of slag-CB: What changes in construction methods and/or mix designs could be implemented to improve tensile strength?
- Curing temperature: What is the influence of mixing water and ground temperature on properties?
- Set acceleration/retardation of slag-CB slurries: What is the impact of the additives commonly used upon the slag-CB properties.

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