# Development of a Low Carbon Binder for Cemented Rockfill Operations

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**Abstract**
Mine backfilling, such as cemented rockfill (CRF), is a critical step of the underground mining cycle, enabling increased resource recovery and a resilient tailings storage solution. The use of chemical binders is critical to achieve the desired strength and stability of CRF mix designs; however, traditional cement binders can be responsible for approximately 70% of the greenhouse gas emissions in the entire mine backfill process. Most large mining corporations have made commitments to achieve net-zero greenhouse gas emissions in the next 20 years, so the development of low carbon alterative binders for mine backfill is a necessary step to achieve this goal. This paper shows results obtained through the development of a versatile engineered lime-based binder for mine backfill systems that can replace up to 50% of cement, with no compromise in long-term performance, while reducing the greenhouse gas footprint by up to 75% in comparison to traditional cement. The performance of the newly developed binder showed its adaptability as it was successfully reformulated to be used with a non-standard cement formulation used by mining operator's cemented rockfill operations.

Key words: mine backfill, cemented rockfill, binder optimization, GHG reduction

## Introduction

The use of mine backfill has provided a paradigm shift in underground mining operations. The ability to use waste rock to both stabilize and improve safety while enabling enhanced resource recovery explains why backfill has become a routine part of mine planning and development. Additionally, the use of mine tailings in paste backfill or waste rocks in rockfills virtually eliminates the need for external tailings and waste facilities and provides geochemical stability, reducing sulphidic pollution (Belem and Benzaazoua, 2004, Sheshpari et al., 2015). The safe extraction of critical metals such as copper and nickel could benefit from the use of backfill technologies, and these critical resources are essential for the energy transition to electrified automobiles and transport critical to achieve greenhouse gas (GHG) reduction goals worldwide (Azevedo et al., 2022).

While the importance of mining's role to provide the materials to support the energy transition is well established and highlights the importance of mining in a decarbonized future, mining operations themselves are under ever increasing environmental scrutiny (Azadi et al., 2020). A significant alliance of major international mining operators has recognized their need to improve their environmental performance, especially with respect to GHG emissions, and have made aggressive plans and promises to stakeholders including commitments to net-zero GHG operations. The GHG emissions encountered by mining operations are broadly divided into three categories:

- Scope 1: direct emissions from operations,
- Scope 2: indirect emission resulting from operations, such as electricity and fuel, and,
- Scope 3: indirect emissions through the supply and value chains, which includes cement to be used as backfill binders, shotcrete, etc.

Much of the GHG reduction successes enjoyed by mining operations are the result of adopted new technologies to lower Scope 1 emissions or conversion to cleaner energy sources to lower Scope 2 emissions, but there has been limited attention on reducing Scope 3 emissions. The lack of focus on reducing Scope 3 emissions is in no part due to the complexity of getting accurate emissions data from suppliers and standardized accounting methods that address the full cradle-to-grave lifecycle of these products and services (Patchell, 2018). The increased usage and acceptance of independently verified Environmental Product Declarations (EPDs) is a crucial step for mining operators to understand their Scope 3 emissions.

In mine backfill, understanding the Scope 3 emissions is of critical importance as traditional binders, such as Portland cement, can be responsible for up to 70% of the total GHG emission in the entire process (Safari, 2023); a theoretical CRF plant in the inter-mountain west of the United States using 40,000 tons of cement a year could produce up to approximately 47,000 tons of $CO_2$ based on the 1171 kg/ton cement GHG footprint for a Portland type ½ cement. Certain markets have been able to effectively utilize industrial co-products, such as fly ash or blast furnace slags, to significantly reduce their Scope 3 emissions. However, many markets such, as the inter-mountain west of the USA, do not have freight logistic supply of these co-products and continue to make significant use of cement in their operations. Reducing the Scope 3 emissions from mine backfill binders will be critical for mine operators to meet their net-zero GHG commitments.

The binders used in mine backfill rely primarily on the development of strength from calcium silicate hydrate (CSH) minerals and to a lesser extent calcium aluminate hydrate (CAH) minerals. These CSH minerals are traditionally produced through hydraulic cements such as Portland cement. However, there is an alternate mechanism to produce CSH minerals relying on pozzolanic reactions. These pozzolanic reactions require the alkaline activation of reactive silicates and aluminates, typically through their reaction with calcium hydroxide (ie, slaked lime) to produce the CSH and CAH minerals (Walker and Avia, 2011). The use of pozzolanic cements has existed for millennia, dating back to the Roman empire where volcanic ashes were reacted with lime to produce resilient cements that still exist to this day, eg, Rome's Parthenon. The pozzolanic cements, noted for their ability to self-heal, are typically slower to set and cure when compared to modern Portland cement formulations (Seymour et al., 2023). There are many potential sources of pozzolans that can be used in pozzolanic cements, which can be broadly divided into manufactured natural products, such as calcined clays and volcanic ashes, and industrial co-products, such as fly ashes and slags (Snellings et al., 2012).

Current mine backfill operations have leveraged industrial co-products to improve the economics, performance, and environmental footprint of the binders for mine backfill. In the inter-mountain west of the United States, the historical generation of power from coal provided an excellent source of fly ash used in mine backfill as supplementary cementitious materials (SCMs). Different geographical regions, such as Ontario and Quebec, instead prefer the use of ground granulated blast furnace slag (GGBFS), a byproduct of pig iron production, as a preferred SCM binder, in part for its ability to impart sulphate resistance (Benzaazoua et al., 2002). However, both of these co-products are associated with high GHG emission industrial processes, such as blast furnaces and coal-fired energy generation, which are being rapidly being replaced with more efficient processes, such as directly reduced iron and natural gas fired energy production. As the industrial processes required to generate these co-products phase out, the co-product availability is expected to plateau and then decline. This decline has been especially acute for fly ash, where a precipitous decline in fresh fly ash due to rapid closure of coal-fired power stations across the US has resulted in significant escalation in price and shortages in supply. This paper investigates the use of a new engineered binder developed by Graymont (GB) as an alternative SCM. This new binder is produced by combining lime products and naturally occurring pozzolanic materials to provide a low GHG-footprint product, security of supply (ie, not reliant on other industrial products such as fly ash), and customizability to adapt the binder to individual mine operations, which in this case is a CRF application in the western United States.

**Binder properties**

Refractory elemental analysis for the binder samples were carried out according to ASTM C1301-95 using a lithium tetraborate flux and a Perkin-Elmer Optima 7300 Radial view ICP-OES. A LECO 744 carbon/sulphur IR analyser was used to measure the $CO_2$ and S values. A loss on ignition test at was performed in accordance with ASTM C25-19 to 'balance-check' the summation of the measured elements. Soluble sulphate was analysed using a Dionex ICS-2100 Ion Chromatographer with a sodium hydroxide eluent and an IonPac AS-15 column. The elemental compositions of all the binders used in the work are presented in Table 1. The binders using the 'GB-' designation are different versions of the engineered lime-based binders developed as low-carbon cement alternatives for this study.

Table 1: Elemental composition of selected binders.

| Binder | CaO | MgO | $Fe_2O_3$ | $Al_2O_3$ | $SiO_2$ | $K_2O$ | $Na_2O$ | S | $CO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| Portland Type 1/2 | 60.9 | 1.5 | 5.4 | 4.0 | 23.8 | 0.4 | 0.2 | 1.2 | 1.7 |
| Non-standard Cement "Sample A" | 62.1 | 2.5 | 3.7 | 3.9 | 21.4 | 0.5 | 0.2 | 1.2 | 1.1 |
| Non-standard Cement "Sample B" | 63.5 | 1.0 | 2.6 | 4.0 | 19.7 | 0.6 | 0.1 | 1.3 | 4.4 |
| GB-A | 47.9 | 0.7 | 1.1 | 5.5 | 37.4 | 3.2 | 1.0 | 0.0 | 17.2 |
| GB-B | 47.9 | 0.7 | 1.1 | 5.5 | 37.4 | 3.2 | 1.0 | 0.0 | 15.1 |
| GB-C | 47.8 | 0.8 | 1.1 | 5.5 | 37.4 | 3.2 | 1.0 | 0.0 | 13.0 |
| GB-D | 57.2 | 0.9 | 0.9 | 4.5 | 30.3 | 2.6 | 0.8 | 0.0 | 17.2 |
| GB-E | 66.6 | 1.1 | 0.8 | 3.5 | 23.2 | 2.0 | 0.6 | 0.0 | 17.3 |
| GB-F | 57.2 | 1.0 | 0.9 | 4.5 | 30.3 | 2.6 | 0.8 | 0.0 | 13.0 |

**Sand properties**

The HM107 sand was purchased from Gilson Company and is a rounded silica sand containing nearly pure quartz mined from Ottawa, Illinois. The HM107 sand is manufactured to 100% pass a No. 20 sieve but be retained on a No. 30 sieve meeting the specification in ASTM C 778, thus the size of all the sand particles is between 0.60–0.85 mm.

**CRF aggregate properties**

The particle size distribution was performed using a Gilson Sieve stack by a consulting laboratory. This sieve stack covers the necessary range for larger sized rocks. The finer portions of the rocks were then additionally screened and analyzed using 8" Tyler sieves and a Ro-Tap sieve shaker. The particle size distribution of the CRF aggregate provided by the mine operator is presented in Figure 1.

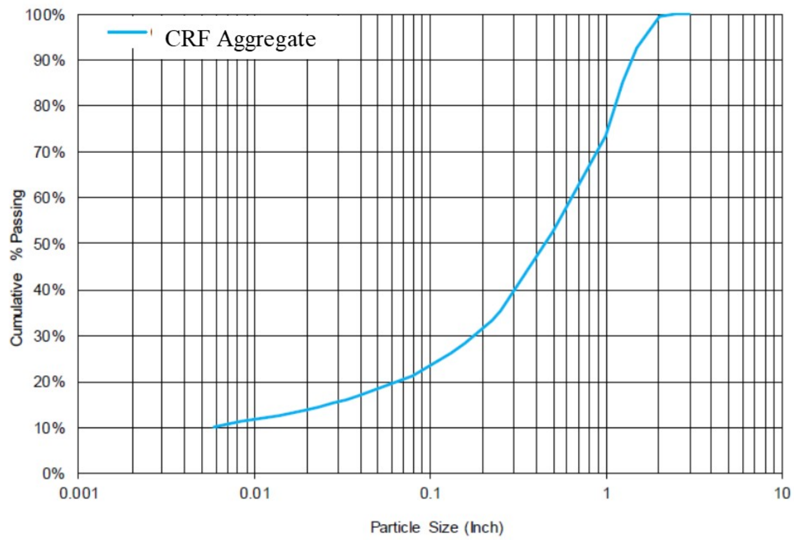


Figure 1: Particle size distribution of the CRF aggregate.

**X-Ray Diffraction (XRD) testing and quantification**
The impact of chemical treatment on the mineralogy of the rockfill materials was analyzed using a Bruker D-8 X-ray diffractometer using CuKα radiation powered to 40 kV at 40 mA. Approx 4.50 g of sample was mixed with 0.5 g of ZnO (internal standard) and 15 mL of ethanol, followed by milling for 5 min in a micronizer to eliminate preferential orientation of the particles. The suspension was then spray-dried in a heated chamber and side loaded prior to XRD analysis. The samples were scanned from 3–80° (2θ) for 60 min at 0.02°/s.

Mineral and phase identification was done by reference matching against the mineral collection data from the International Center for Diffraction Data (ICDD). Quantitative analysis of the minerals identified was performed using the TOPAS software.
**Testing program**Mortar method experiments were completed at Graymont's Central Laboratory in Sandy, Utah and the cylinder experiments with CRF aggregate were completed at the mining operator's site in the United States.

*Test Matrix and cube/cylinder preparation and curing*
Mortar cube testing was developed internally by Graymont and its partners to model the unique programs underway at different backfill operations. The purpose of this testing method was to understand how different binder compositions and blends, such as the presented alternative binder, can influence the ultimate strength of mine backfill. The system uses a standardized sand that approximates the fine cementing 'grout' that holds the wide size variation of waste rocks together in CRF. This system controls the particle size, unlike using native waste rocks in cemented rockfill that typically have poor control of particle size. The Graymont laboratory has historically found good correlation for strength results between 3"x6" cylinders and 2" cubes with this mortar method, thus 2 in cubes are typically used for convenience. However, it is recognized that this relationship cannot be extended to native backfill materials, which should be prepared in appropriately sized cylinders. Additionally, this method needs to be verified by using native backfill materials, ideally at the operating site. Mortar cube testing was performed with 2in × 2 in cubes using a 1:4 binder to sand ratio by weight, HM 107 20–30' sand matrix, a 0.5 water:binder ratio, and a make-up water step. The higher binder content is utilized to exaggerate the binder strengths and thus decrease relative error better to identify trends. The method must be verified using native materials at process binder concentration and water-binder ratios. This method has been internally verified to provide reasonable correlation with CRF backfill operation. However, the method is less effective for

paste backfill where the particle sizes of the tailings are a critical factor in the development of strength. It was found through testing that a 100% cement binder with the set parameters for the mortar mix design typically produces a 9% moisture after complete blending. A secondary water addition (ie, water make-up) was developed targeting a 9% moisture content after complete blending of GB mortar mixes. This step was found necessary to balance the increased water demand of GB against the cement control.

CRF backfill cylinder mix design was determined in accordance to the standards of the backfill operation. Aggregate was segregated and then re-blended to match the historical size distribution of the operation (Figure 1). Total binder content was measured to 7.2% by weight of solids. In this study, the water-to-binder (w:b) ratio was determined to be 1.19 for the cement control sample. The alternative binder is known to have an increased water demand. The water to binder ratio was adjusted in accordance with Table 2 to satisfy the alternative binder requirements and maintain a constant cement hydration across multiple binder scenarios. Master Builder 'MasterRheobuild 1000' plasticizer was added to each blend at 0.375% by weight of binder.

Table 2: Water to binder ratios used with CRF aggregate experiments

| | Cement Only | 50% Alternative Binder | | 40% Alternative Binder | | | |
|---|---|---|---|---|---|---|---|
| | | GB-A | GB-F | GB-A | GB-F | GB-A | GB-F |
| Water to Binder Ratio | 1.19 | 1.21 | 1.24 | 1.21 | 1.23 | 1.20 | 1.23 |

*Mortar cube mixing, casting, and storage*

All dry components were massed into a steel mixing bowl for attachment with a KitchenAid® stand mixer. The amount of material was calculated to produce enough material to cast three cubes for each sample-interval with at least 10% overage. A paddle attachment was used to blend the dry ingredients at a low speed for 1–2 mins, taking care to minimize air loss of the powder. The initial amount of water was added and the mortar was mixed for 2 mins at a low speed. After mixing, the mortar was sampled in triplicate to determine the initial moisture of the material using a moisture balance at 200°C. The required amount of water make-up determined was subsequently added and the mortar was mixed for an additional 30 s at a slightly faster rate. The mortar cubes were cast into moulds in accordance with ASTM C109/109M-20 and moved to a moist cabinet at 95% humidity. After 24 hours, the mortar cubes were removed from their moulds, labelled, and returned to the moist cabinet for testing at the designated intervals.

*CRF Backfill cylinder mixing, casting, and storage*

Cylinders were created in accordance with ASTM C192/192M-19 with deviation from section 8.2.1 – Slump or Slump Flow. The backfill operation does not use slump testing to qualify the plasticity of the mix. The methodology of plasticity testing used by the operation was determined to be error prone and was replaced with fixed water amounts for each sample. Mixing was done in a large paddle-style mixer with 9 $f^3$ of volume to produce enough material to cast three specimens of 6 in × 12in cylinders for each sample interval. After mixing, cylinders were cast and rodded in accordance with the specified ASTM standard, sealed, and moved to a temperature-controlled, humidity closet. The backfill cylinders were removed from their moulds immediately prior to UCS testing.

*Uniaxial compression strength (UCS) testing*

UCS testing for mortar cubes was carried out at designated intervals in accordance with ASTM C109/109M-20 using a Humboldt® 20,000 lbs load frame and 20,000 lbs load cell. The platens used were of brass material with the top platen placed on a ball joint below the load cell. The test specimen was centered between the top and bottom platen and the jog switch was applied to move the platens together until the digital display read 10–11 lbs of force. The test recording software was set to record and the testing toggle was switched on. Strain rate for all testing remained at 0.05 in/min. Each test was performed until the strength of the specimen fell by 10% from its peak and visual failure was apparent. The maximum UCS was recorded for the specimen. Each sample interval was tested with three specimens and the average of the results was calculated.

UCS testing for cylinders was carried out at designated intervals in accordance with ASTM C39/C39M-21 using a Forney F-250-VFD 250K load frame with an integrated cell. Steel platens were used with unbonded caps and a neoprene intermediary to protect against point-failures. The test specimens with unbonded caps were centered in the load frame and load was applied to the specimens at a rate of 35 psi/s. Load shut-off was performed after a break pattern was observed and load declined 10% from its peak. The maximum UCS was recorded for each specimen. Each sample interval was tested with three specimens and the average of the results was calculated.

## Results and Discussion

### Binder development with typical Portland cement

Previous investigations using a typical Portland type ½ cement identified the ideal chemical formulation for the alternative binder. A summary of the test conditions and UCS results obtained with the mortar system are shown in Table 3. The cement control produced a higher 7 day strength. However, after 28 days the 50% blend of the alternative binder (GB-A) with cement exceeded the strength of the cement control. The mortar system was effective at providing directional information to inform binder selection using strength activity indexes (SAI, ie the ratio of the strengths measured for the alternative binder blend to control cement only condition), where the general target is to have a strength activity index of ≥ 75%, which is comparable to the strength requirements in ASTM C618 for coal fly ash SCMs.

Table 3. Comparison of typical cement and alternative binder blend strengths on mortar systems.

| Binder Type | Portland Type 1/2 Cement | GB Alternative Binder | UCS Strength (MPa) | | Strength Activity Index | |
|---|---|---|---|---|---|---|
| | | | Day 7 | Day 28 | Day 7 | Day 28 |
| Cement Control | 20% | 0% | 13.3 | 12.7 | 100% | 100% |
| GB-A | 10% | 10% | 10.3 | 15.2 | 77% | 120% |

This alternative binder formula was used in conjunction with a sample of cement, identified as Sample A and provided by an active mining operations in the western United States. The strength results of the mortar system with Sample A are shown in Table 4 and the SAI is shown in Figure 2. It was observed that the GB-A formulation underperformed the cement only control by about 30% at 7, 14, and 28 days, which is below the 75% strength activity index target. This result was unexpected and it was discovered through discussion with the mine operator that the composition of the cement provided was based on a unique performance-based specification and not true Portland type ½ cement. These results were mirrored by field trial performance on the mine operator's site; despite this, the GB-A binder was noted to continue to develop strength through pozzolanic reactions beyond Day 28 and eventually achieve strength targets, though not in the desired time period.

Table 4. Comparison of non-standard cement and alterative binder blend strengths using the mortar method.

| Binder Type | Non-standard Cement "Sample A" | GB Alternative Binder | UCS Strength (MPa) | | | Strength Activity Index | | |
|---|---|---|---|---|---|---|---|---|
| | | | Day 7 | Day 14 | Day 28 | Day 7 | Day 14 | Day 28 |
| Cement Control | 20% | 0% | 14.6 | 16.7 | 23.1 | 100% | 100% | 100% |
| GB-A | 10% | 10% | 9.7 | 11.7 | 15.7 | 67% | 70% | 68% |
| GB-B | 10% | 10% | 11.5 | 13.0 | 17.2 | 79% | 78% | 74% |
| GB-C | 10% | 10% | 9.3 | 11.5 | 16.6 | 64% | 69% | 72% |
| GB-D | 10% | 10% | 7.8 | 10.5 | 14.1 | 54% | 63% | 61% |
| GB-E | 10% | 10% | 9.0 | 10.4 | 13.8 | 62% | 62% | 60% |
| GB-F | 10% | 10% | 13.4 | 14.4 | 19.1 | 92% | 86% | 83% |

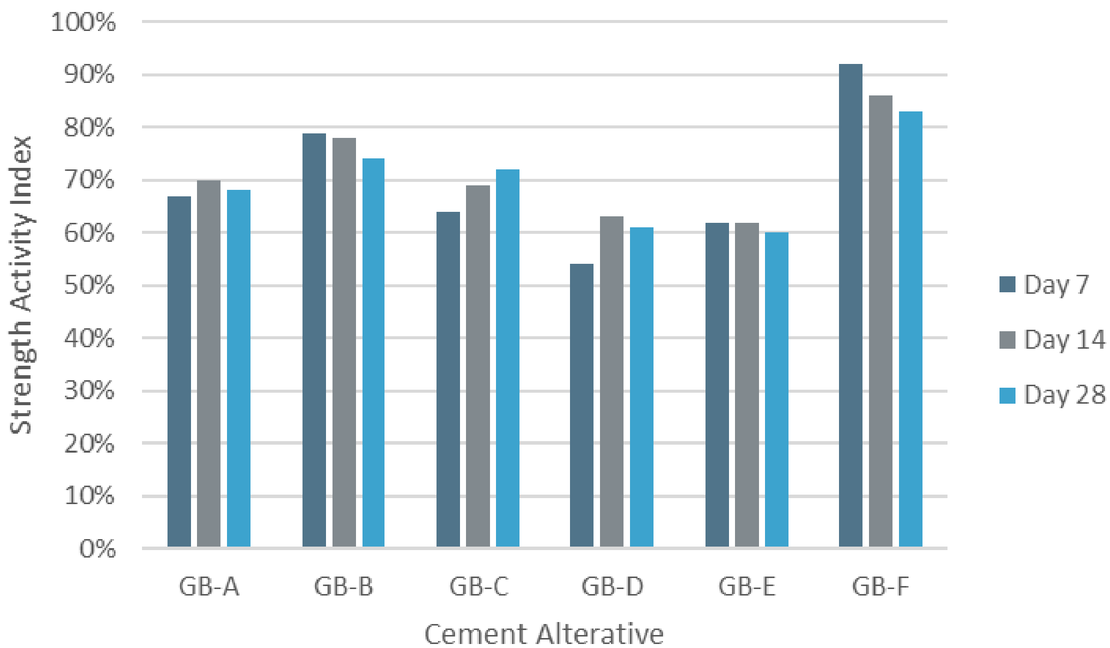


Figure 2: Strength activity index observed with 50% replacement of non-standard cement Sample A with a cement alternative.

**Characterization of non-standard cement**

The first step to assess the decline in performance was to better understand the composition of the non-standard cement. A summary of results from quantitative XRD (Table 5) show that the non-standard cement has significantly lower concentration of alite phases, about 14–18% less alite identified, compared to the values expected for a typical Portland type ½ cement. Correspondingly there was approx 20–27% of amorphous phases identified that is expected to be from an amorphous siliceous pozzolan, likely added to the cement to reduce cost and/or greenhouse gas footprint Both the lower quantity of free lime from hydration of cement due to the lower proportion of alite, and higher concentration of an added pozzolan require a reformulation of the alterative binder to improve and optimize performance.

Table 5. Summary of quantitative XRD results of cements used in this study.

| **Mineral Identified by XRD** | **Typical Portland Type 1/2 Cement (Stutzman 2016)** | **Non-Standard Cement** | |
|---|---|---|---|
| | | *Sample A* | *Sample B* |
| | **%** | | |
| Alite | 57 | 43 | 39 |
| Belite | 14 | 12 | 19 |
| Brownmillerite | 8 | 7 | 6 |
| Pozzolan* | 0 | 21 | 27 |
| Calcite | 2 | 2 | 8 |
| Other | 19 | 14 | 1 |

*Quantification of XRD amorphous phase

**Alternative binder reformulation for use with a non-standard cement**

Recognizing the differences between the typical and non-standard cement, a new matrix of alternative binder formulations were tested for strength development in the sand/mortar system. These new binder formulations are listed as GB-B through GB-F in Table 4 and the SAI presented in Figure 2. The best performing new formulation is GB-F, which exceed the desired 75% strength activity index at 7, 14 and 28 days. The GB-F binder is characterized by a higher lime content, which is unsurprising given the reduction in free lime in the non-standard cements and the added requirement of lime to react with pozzolans to generate strength through pozzolanic reactions.

The effect of the substitution ratio of the cement with the alternative binder is also an area of interest. This is because the early onset of strength is typically provided by the alite component of cement, which is already reduced in the non-standard cements and would be further limited by substitution with the alternative binder. The typical cement replacement of 50% with GB-F binder was compared to 40% and 35% replacement rates in Table 6 with the non-standard cement Sample B. In general, there was not much difference observed in the 7, 14, and 28 day strength measurements, though the best performance was observed at the 40% replacement. Again, a strength activity index above 80% was achieved, increasing to 91% for the 40% replacement at 28 days.

Table 6: Effect of non-standard cement and alternative binder blend ratios on strength.

| **Binder Type** | **Non-standard Cement Sample B** | **GB Alternative Binder** | **UCS Strength (MPa)** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **Day 7** | **Day 14** | **Day 28** | **Day 7** | **Day 14** | **Day 28** |
| Cement Control Cement | 20% | 0% | 13.5 | 18.3 | 18.4 | 100% | 100% | 100% |
| GB-F | 10% | 10% | 11.1 | 14.4 | 16 | 82% | 79% | 87% |
| GB-F | 12% | 8% | 11.7 | 15 | 16.8 | 87% | 82% | 91% |
| GB-F | 13% | 7% | 11.5 | 13.9 | 15.5 | 85% | 76% | 84% |

**Application of the alternative binder to a native CRF aggregate**

The successful results of the alternative binder refinement using the mortar testing program allowed for the use of the both alternative binders GB-A and GB-F to be tested on site at the mining operation for preliminary bench-scale experiment with native CRF aggregate from the mine site. The results of the 6 in × 12 in cylinder experiments are shown in Table 7 and Figure 3, where the operator's target strength at 28 days is approximately 4.1 MPa. In general, the higher substitution rates of the alternative binder yields lower strengths at the earlier measurements timepoints. This trend diverges from the observation in the mortar testing method and highlights the importance of verifying results with native backfill materials and using the mortar method only for directional studies. The binder observed to have the best performance is the 35% replacement of the cement with alternative binder GB-F which yielded 4.5 MPa at 28 days. The GB-F alternative binder at the 35% substitution rate is currently the subject of a pilot study with the mining operator. Of additional note is that the 35% and 40% replacements of GB-A and GB-F all exceed the 4.1 MPa target by day 56, demonstrating the resilient strength gain over time provided by pozzolanic cements.

Table 7. Comparison of non-standard cement Sample B and different substitution rates of alterative binder blend strengths using CRF aggregate.

| **Binder Type** | **Non-standard Cement Sample B** | **GB Alternative Binder** | **UCS Strength (MPa)** | | | |
|---|---|---|---|---|---|---|
| | | | **Day 7** | **Day 14** | **Day 28** | **Day 56** |
| Cement Control | 7.2% | 0.0% | 2.1 | 2.6 | 3.7 | 4.0 |
| GB-A | 3.6% | 3.6% | 0.8 | 1.3 | 1.8 | 2.7 |
| GB-A | 4.3% | 2.9% | 2.0 | 1.8 | 3.4 | 5.0 |
| GB-A | 4.7% | 2.5% | 2.1 | 3.0 | 3.6 | 4.7 |
| GB-F | 3.6% | 3.6% | 0.8 | 1.5 | 2.2 | 3.9 |
| GB-F | 4.3% | 2.9% | 2.1 | 2.7 | 3.2 | 5.2 |
| GB-F | 4.7% | 2.5% | 2.2 | 2.4 | 4.5 | 4.9 |

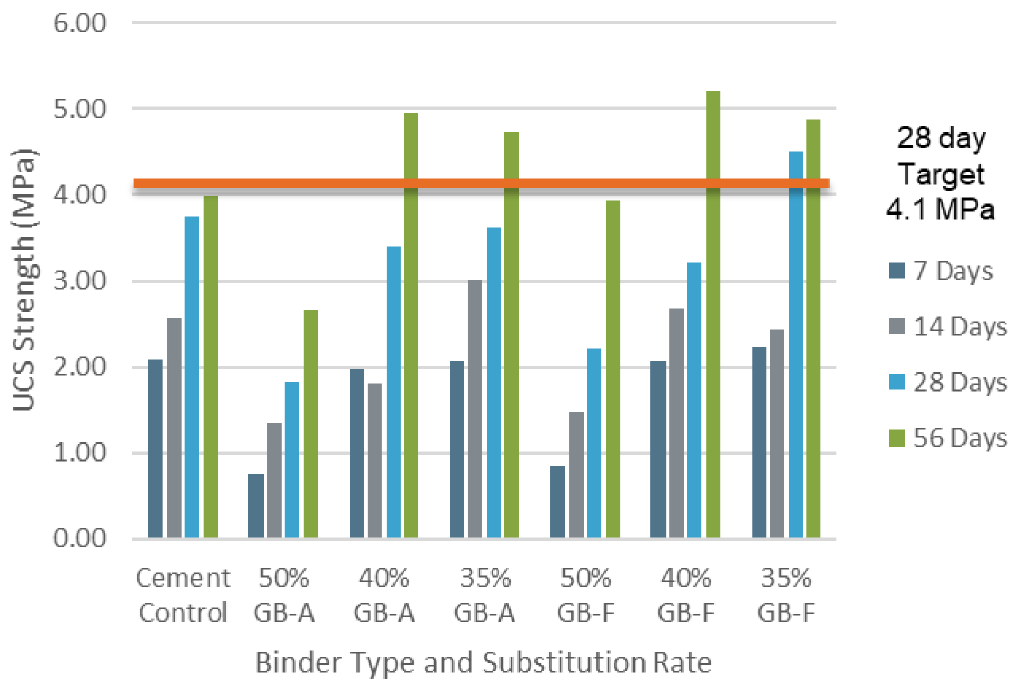


Figure 3: Effect of alternative binder substitution rates on UCS strength with a CRF aggregate.

**Potential impact on Scope 3: greenhouse gas emissions**

The potential reduction of scope 3 emissions using the alternative binders is presented in Table 8. The original GB-A binder is expected to have a 75% reduction in GHG emissions compared to a Portland type ½ cement typically used in the inter-mountain west region in the United States. When used in a 1:1 blend ration (50% cement replacement), it is expected that there will be a 38% reduction in GHG footprint, which would translate into a yearly carbon savings in excess of 18,000 tons of $CO_2$ for an operation using 40,000 tons of binder/yr. The reformulated GB-F has a larger GHG footprint compared to GB-A due to the higher proportion of quicklime in the formulation. The formulation is still expected to result in a 42% reduction in GHG emissions when compared to non-standard cement. This non-standard cement has a much lower estimated GHG footprint when compared to the typical Portland cement; however, the combined 1:1 ratio blend of the GB-F and the non-standard cement provides an absolute GHG footprint slightly lower than the GB-A and Portland cement system. This highlights the importance of looking at the complete lifecycle of the system rather than the individual components. The variations in cement production means that it is critical to complete a life cycle analysis of cement and other materials used as backfill binders, such as detailed in the recently published International Council on Mining and Metals (ICMM) framework document: Scope 3 Emissions Accounting and Reporting Guidance (ICMM 2023).

Table 8. Estimated GHG footprint and potential for Scope 3: GHG reduction.

| Binder Type | Estimated GHG Footprint ($CO_{2eq}$ kg/ton) | | | | |
|---|---|---|---|---|---|
| | **GB-Alternative Binder** | **Cement** | **1:1 Binder Blend Ratio** | **%** | **Metric Tons $CO_2$ (Assuming 40,000 Tons of Binder Use per Annum)** |
| Type ½ cement and GB-A | 285 | 1171 | 728 | 38% | 17,720 |
| Non-Standard cement and GB-F | 511 | 885 | 698 | 21% | 7,480 |

## Conclusions and Future Work

The development of new binders in mine backfill to supplement and replace a portion of cement are critical steps to improving environmental performance to enable mining operators to achieve their GHG commitments. This is especially important as many co-products traditionally used to reduce the GHG footprint of mine backfill processes, such as fly ashes and slags, are dwindling in supply due to changes in technology and increased competition for SCMs. This paper has highlighted a new, alternative binder that can be adapted to individual mining operators' unique backfill systems, while providing security of supply. The ability to adapt and reformulate to changes in cement composition, as shown through the evolution of from GB-A to GB-F, which achieved an acceptable strength (ie, > 75% strength activity index), is not possible with traditional co-product SCMs. The current investigation is being validated through pilot trialing at a mine site in the western United States. We are also actively seeking further collaborations to provide a mutually beneficial GB binder for both CRF and paste backfill operation for the benefit of the whole industry.


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## Acronyms

| | |
|---|---|
| CRF | Cement Rockfill |
| EPD | Environmental Product Declaration |
| GB | Graymont Binder |
| GHG | Greenhouse Gases |
| ICMM | International Council on Mining and Metals |
| SAI | Strength Activity Index |
| SCM | Supplementary Cementitious Materials |
| UCS | Uniaxial compression strength |
| XRD | X-Ray Diffraction |