Effects of Bioleached High-Pyrrhotite Content Tailings on Mine Backfill Performance

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Abstract

Underground backfilling allows for the effective disposal of mine waste; however, the backfill must also be able to withstand a certain load, as in most cases it is used as an underground construction material such as in cut-and-fill mining methods. Therefore, the composition of the mill tailings utilized in the backfill must be such that when combined with a binding agent and pumped underground, the slurry or paste is then able to withstand a certain load within a specified period of time. High-pyrrhotite content tailings are commonly found on mine sites throughout Ontario and Quebec. These high-pyrrhotite tailings are reactive and can easily oxidize, producing acidity and/or metal-laden drainage under certain disposal conditions. This means that the pyrrhotite in the tailings can result in acid mine drainage if stored on surface, but can also cause strength degradation if used in excessive concentrations in underground mine backfill. Bioleaching processes can be used in an attempt to neutralize the tailings, reducing the resultant strength degradation. These bioleaching processes can provide an additional benefit by transforming mine waste from an environmental hazard to an economic opportunity, as the tailings may contain significant metal values.

CanmetMINING has developed a novel stirred-tank bioleaching process for recovering nickel and cobalt (both critical for vehicle electrification) that incorporates both partial neutralization and iron removal in the bioleaching circuit; bench-scale tests have resulted in excellent nickel and cobalt recovery over a range of temperatures. The resulting process residue contains a significant proportion of jarosite, which can be problematic for long-term disposal. This paper reports on research designed to evaluate different options for disposal of the high-jarosite residue into a suitable underground mine backfill material.

Key words: pyrrhotite, jarosite, oxidize, acid mine drainage, backfill strength degradation, hydraulic backfill, bioleaching, Acti-Gel®208

Introduction

Backfill material and additives

Backfill is an integral part of any underground mining operation; functioning to ensure the safety of the underground openings and as an environmental remediation strategy through repurposing operational waste into underground construction material. There are numerous sources selected for backfill material; however, mining corporations typically choose materials locally available and therefore economical, such as mill tailings. Hydraulic fill has generally been preferred over paste fill due to its ease of pouring; however, hydraulic fill typically settles rapidly in the pipe during transport, compounding the issue of pipe blockage.

Backfill velocity is clearly associated with the effect of solids concentration. At low solids concentration, high velocities must be sustained to achieve optimal flow regimes. Ackim (2011) also stated that hydraulic slurry backfill must be transported in pipelines at high velocities to maintain turbulent flow to keep its solid phase in suspension. As finer particle fractions of the hydraulic backfill slurry often settle at significantly slower rates when compared to coarse fractions, the phenomenon known as segregation or stratification may occur. Backfill material in the stope will exhibit grading if the fine fractions are carried away in the decant water. Segregation causes the subsequent fill mass to be non-homogenous and may result in an overall reduction in fill strength due to the creation of planes of weakness and areas of lower binder content (Ackim, 2011).

Backfill, regardless of the type, plays an essential role in the process of ore extraction in underground mining operations. Depending on the mining method used, backfill provides a working surface, stabilizes stope and pillar walls as well as the surrounding rock mass, and controls caving of stope backs. The economic feasibility of many mining techniques depends on the ability to place competent backfill in the underground voids to ensure safe working conditions; in some mining techniques, the backfill must be as stable as a free-standing wall when it is exposed during pillar recovery. To ensure this competency, binding agents, such as Portland cement, are used to solidify backfill, which generates a major financial cost for mining operations. In addition, the manufacturing of said cement produces a considerable amount of CO_2 emissions, raising environmental concerns and considerations with its frequent use. Therefore, the search for alternatives or additives which allow for the reduction of the required cement content in backfill has been ongoing for decades. Some alternatives studied as full or partial replacements for Portland cement include sulphate resistant cements, artificial pozzolans, natural pozzolans, calcium sulphate substances, and sodium silicates (Tariq & Yanful, 2013).

Various additives have been studied with the aim of allowing dense fill-like materials to recommence flow after a shutdown within long distance pipeline transportation (Wang et al., 2011). The purpose of the investigation by Wang et al. (2011) was to find suitable stabilizing additives to prevent sedimentation during periods of interruption in pipelining. Additives which have the potential to improve rheological properties of slurry backfills, such as reducing the risk of segregation, will be an extremely important asset in deep mining due to the increased distances required to transport the slurry. The additive Acti-Gel®208 is a highly purified magnesium aluminosilicate that acts as a high-performance anti-settling agent and rheology modifier, and is used in a wide variety of water-based industrial applications. Studies have shown that when Acti-Gel®208 is utilized as an additive in paste and hydraulic backfill, it results in improved strength and flow properties, such as lower friction loss and less segregation.

Bioleaching process and residues

The growing demand for critical minerals needed for electronic devices and batteries to power electric vehicles (EV) and other clean energy technologies of the future is putting immense pressure on sourcing raw materials, such as nickel and cobalt. As part of Natural Resource Canada's Critical Minerals Strategy, there is a focus on Mining Value from Waste, with the goal of recovering valuable minerals from waste materials, such as mill tailings. These tailings often contain residual sulphides, with the potential to generate acidity. On account of this, these tailings must be stored in large ponds that require perpetual monitoring and treatment to avoid the production of acidic drainage.

Due to permanent observation and management requirements, high sulphide-containing tailings and waste rock often represent a significant financial liability for mining companies. Depending on jurisdictions in which they are located, it is often very costly for companies to fund perpetual management of these wastes and therefore to mitigate future risks to the environment and surrounding human populations. Issues arise when the sulphide materials in tailings ponds are exposed to air and moisture, which leads to oxidation. The oxidation of sulphide materials generates sulphuric acid, ultimately promoting the release of toxic heavy metals and runoff into the surrounding surface streams and underground water (Ameri, 1999).

Mine wastes are increasingly being considered as the 'ores' of the future, as they can contain significant metal values. As a result, there has been a considerable effort to valorise the billions of dollars of metals contained in mine waste in recent years. Zinck et al. (2018) provides examples of financial liabilities associated with mine wastes in Canada and discusses the opportunities for reprocessing and repurposing some waste types. Most sulphide tailings are amendable to bacterial leaching for metal extraction via either bioleaching or bio-oxidation.

During the bacterial leaching process, the sulphide content of the material is significantly depleted, greatly reducing the potential production of acid drainage from the resultant process residue. Utilizing bioleaching to reprocess tailings has the potential to produce new process residues that are less reactive, while generating revenue from the recovery of valuable metals, in this case nickel and cobalt, which are both critical to the green economy due to their use in EV batteries. As an added benefit, reprocessing these wastes and depleting the sulphide content may also facilitate the repurposing at least a portion of the remaining residues, generating a net reduction in environmental liabilities, tailings footprints, and the corresponding financial costs.

According to Peek et al. (2011), there are an estimated 50–100 million dry metric tonnes of pyrrhotite-rich tailings containing significant nickel within the Sudbury area. Depending on its genesis, pyrrhotite-rich waste can have significant levels of cobalt, copper, and various precious metals (including gold, silver, platinum, palladium and rhodium), resulting in a contained *in situ* value exceeding 100 US$/tonne. Several commercial processes have operated to recover nickel from high-pyrrhotite waste in the Sudbury region dating back to the 1950s, and all have ceased operation for environmental or economic reasons. Peek et al. (2011) thoroughly reviewed historical pyrrhotite processing flowsheets, examining their technical challenges, environmental issues, and additional options for recovering value from this waste. Numerous studies have reported on reprocessing of tailings, mostly focusing on the leaching of valuable metals and giving minimal consideration to other aspects of process development, including what to do with the newly produced process residue. Oxidizing pyrrhotite (a sulphide) to a sulphate-based residue is a process likely to create significantly more waste (mass and volume) compared to the original tailings; this will necessitate larger tailings ponds in the event some of the new waste cannot be reduced or repurposed. The study underway at CanmetMINING for the reprocessing of pyrrhotite-rich tailings utilizing bioleaching has considered all aspects of the process development, including options for recovering the large amount of iron and sulphur produced, thereby: 1) minimizing the final waste that would otherwise need to be stored in a new tailings facility (Beauchemin et al., 2020; Gamage McEvoy et al., 2020; Thibault et al., 2020), and: 2) ultimately repurposing the remaining low-sulphide residue into backfill.

Pyrrhotite-rich tailings in Sudbury, Ontario are estimated to contain approximately 8–10 billlion C$ in recoverable nickel. Processing this material could be a significant new source of nickel and cobalt sulphate salts, which could be used to help establish an EV battery manufacturing supply chain in Canada (Peek et al., 2011). The goal of the bioleaching research and development at Natural Resources Canada CanmetMINING branch is to recover nickel and cobalt as sulphate salts (battery precursors) from the pyrrhotite-rich tailings in Sudbury while also reducing toxicity, reactivity, and acid generating potential of the remaining residues, making them more amenable to underground disposal as backfill. Based on efforts focusing on bioleaching of different nickel sulphide materials from various mineralogies originating from different geographic locations across Canada (six different materials detailed in Cameron et al., 2013), a novel stirred-tank bioleaching process for recovering nickel and cobalt that incorporates partial neutralization and iron removal within the bioleaching circuit has been developed. Bench-scale tests have resulted in excellent nickel and cobalt recovery over a wide range of temperatures and operating pH levels, demonstrating a robust process (Cameron et al., 2021).

The novel process (described in Cameron et al., 2021) operates at high pH levels relative to conventional bioleaching: approx pH 3 compared to the typical pH range of 1.4–2.0 for conventional operations. The primary advantage of the improved bioleaching process is a significant reduction in reagent consumption, including both the acid in the bioleaching circuit and the neutralizing chemicals in the iron removal unit operation. It may be possible to completely eliminate the iron removal unit operation, as the iron is almost entirely precipitated as jarosite within the bioleaching circuit. This would result in measureable capital and operating cost savings for a full-scale process. In batch tests at pH 3, the total iron in the pregnant leaching solution (PLS) is in the range of 100–300 ppm (vs 20–30 g/L at pH 1.6–3.0). In addition, jarosite precipitation often has the following advantages over conventional iron removal: iron precipitation via jarosite generates less acidity per mole of iron removed compared to iron removal via ferric-hydroxide sludge (Cameron et al., 2021), better settling and filtering characteristics (Dutrizac and Jambor, 2000), and it co-precipitates lower levels of nickel (Kaksonen et al., 2014). Additionally, Steemson and Smith (2009) found conventional iron removal with similar PLS (lateral heap leaching) co-precipitated approximately 15–20% of the contained nickel. A conventional iron removal circuit would generate a large volume of sludge containing gypsum and ferric oxyhydroxides, representing important solids handing challenges (Kaksonen et al., 2014).

However, the high jarosite containing process residue may be problematic for long-term disposal. Jarosite may not be stable under the desired disposal method, and microbial processes within the tailings environment may result in jarosite dissolution, thereby mobilizing the contained metals and sulphate. Bridge and Johnson (2000) demonstrated the dissolution of jarosite by iron-reducing bacteria under acidic conditions, comparable to what may occur within the tailings environment. There are several different methods to either reduce the reactivity of jarosite or transform it into more stable iron-containing compounds. At CanmetMINING, options for recovering the large amount of iron and sulphur produced, with the intention of minimizing the final waste that must be stored in a new or larger tailings facility, were investigated thoroughly (Beauchemin et al., 2020; Gamage McEvoy et al., 2020; Thibault et al., 2020). A preferable method for disposing of the newly generated high-jarosite waste is to incorporate it in underground backfill, which is the subject of this study.

There are problems associated with underground disposal of sulphide tailings due to the tendency of pyrrhotite to oxidize quickly, and the vulnerability of Portland cement to sulphate attack (Ameri, 1999). Deterioration of concrete due to sulphate attack tends to occur over time, generally leading to a progressive loss of strength (Ameri, 1999). Conversely, Singh (2019) investigated partial replacement of Portland cement with jarosite functioning as an alternative binder in a paste backfill mix, and found that in some instances, it performed adequately as an alternative binder.

CanmetMINING in Sudbury, Ontario, Canada recently designed and performed a research study to evaluate different options for the disposal of high-jarosite residue into suitable underground mine backfill material. The CanmetMINING stirred tank bioleaching process is currently being demonstrated at pilot scale through a collaboration with MIRARCO Mining Innovation in Sudbury, Ontario, Canada. As the pilot plant was not producing sufficient high-jarosite residue until early 2024, the jarosite material used for the preliminary scoping study (Trial Set 1) was produced at bench-scale. Jarosite material for the additional scoping study (Trial Set 2) was sourced directly from the pilot plant.

Methodology

Materials

To determine the effect of varying amounts of the bioleaching process residue (jarosite) on the standard backfill mix at a base metal mine in Sudbury, Ontario, Canada, Trial Set 1 was prepared in December 2023 and consisted of eight distinct batches of hydraulic fill. The standard backfill mix utilized generally contained a dosage of 0.03 wt% Acti-Gel®208 additive. Raw materials, including base metal classified tailings at binder (Terraflow binder) contents, ranged from 25:1 to 15:1 by weight (3.8 and 6.25 wt% representing the 'body' and the 'plug' backfill pours, respectively). The jarosite residue content within the eight batches of Trial Set 1 ranged from 2–8 wt%.

As the pilot plant was not yet producing sufficient high-jarosite residue in December 2023, jarosite for Trial Set 1 of this research study was synthesized using a batch ambient pressure method, in which 125 g/L ferric sulphate was mixed with 20 g/L K_2SO_4, brought to pH 1.8 using sulphuric acid, and then placed in a 2.5 L Erlenmeyer flask on a hot plate with slow stirring for seven hours at near boiling point (95–96 ºC). With the small stoichiometric excess of potassium, almost 100% of the iron precipitated. The residue was then dried at 40 ºC for 48 h. X-ray diffraction (method from Cameron et al., 2021) was used to positively identify potassium jarosite as the only detectable solid phase, which was consistent with chemical analysis.

Trial Set 2 was prepared in February 2024, to understand further the effect of varying amounts of the bioleaching process residue (jarosite) on the standard backfill mix at the same base metal mine in Sudbury, Ontario, Canada. For Trial Set 2, 12 distinct batches were prepared with hydraulic fill, again made utilizing a dosage of Acti-Gel®208 additive, and raw materials, including base metal classified tailings at binder (Terraflow binder) contents, ranging from 25:1 to 15:1 by weight (3.8 and 6.25 wt%; representing the 'body' and the 'plug' backfill pours, respectively); However, the jarosite residue content within the twelve batches of Trial Set 2 ranged from 1–5 wt% and was sourced directly from the pilot scale stirred tank bioleaching process at MIRARCO Mining Innovation in Sudbury, Ontario, Canada.

It is important to note that the jarosite reside utilized in Trial Set 2 differs slightly from the laboratory synthesized jarosite utilized in Trial Set 1, as it was produced and sourced directly from the pilot scale stirred tank bioleaching process at MIRARCO Mining Innovation in Sudbury, Ontario, Canada. This bioleaching process residue sourced from the pilot plant is not as pure as the laboratory synthesized material utilized in Trial Set 1. Complete chemical analysis information for the pilot plant jarosite residue can be observed in Figure 1. Trace amounts (<1%) of manganese oxide (MnO), titanium dioxide (TiO_2), and phosphorus pentoxide (P_2O_5) were also found though chemical analysis but not shown in the following depiction due to their minimal quantity.

The overall jarosite content of the residue used in Trial Set 2 was taken into account when determining the content to be added to the backfill batches. Since the pure jarosite content only represented approximately 50 wt% of the residue, a 5 wt% addition of the residue translates to only a 2.5 wt% jarosite addition.

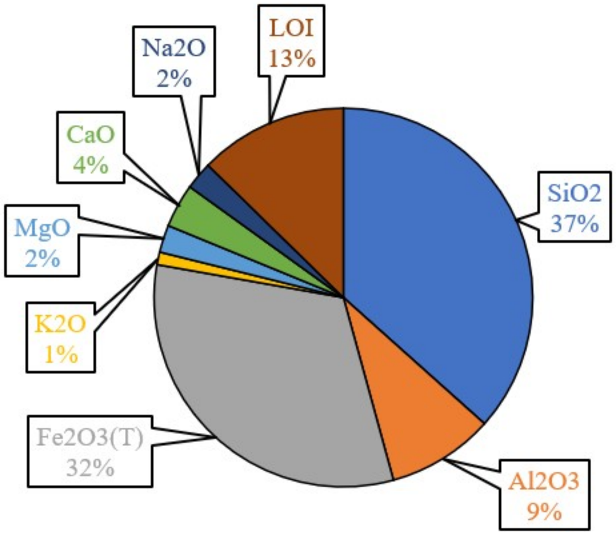

Figure 1. Chemical analysis summary of pilot plant jarosite residue used in Trial Set 2.

Laboratory strength determination

Methods for determining the validity of backfill design in the laboratory were described by Lukaszewski (1973) as follows:

- physical properties
- response to deformation under external loading
- ability to withstand deformational forces, and
- long term stability and durability

Numerous samples for uniaxial compressive strength (UCS) determination were prepared at curing periods ranging from 28–180 days (Trial Set 1), and 7–180 days (Trial Set 2). Longer curing periods were selected to study the effects of jarosite residue addition on the backfill performance over time, since sulphate attack generally takes place gradually.

All batches of Trial Sets 1 and 2 were prepared by adding the materials into a propeller mixer, using a standard mixing sequence as follows: water, tailings, binder, and Acti-Gel®208 additive, followed by jarosite residue. The batches were then mixed for 10 mins prior to casting. To achieve the desired solids content, the initial moisture content of the raw materials was considered when determining the amount of water to add to each individual mix.

Testing protocols have been developed by CanmetMINING and its partners to reflect underground conditions and reduce the amount of variability in the tests. For this study, samples of 76 mm (3 in) in diameter and 152 mm (6 in) in height were used. Collars of approximately 50 mm (2 in) in height were affixed to the moulds prior to casting, in an attempt to ensure proper sample height after the settling of solids has occurred. The samples were then cured in a controlled environment of approximately 60% relative humidity and 20° ± 3°C.

The eight batches of backfill created in Trial Set 1 were prepared using two different binder contents (representing the ‘body’ and the ‘plug’ backfill pours), two Acti-Gel®208 additive dosages, and three distinct jarosite residue contents (including 2, 4 and 8 wt%). In order to simulate the standard backfill mix, the target solids content for each batch was 72 wt%. For each batch, at least three duplicate samples were prepared at each curing period. Curing periods for Trial Set 1 included 28, 56 and 180 days.

Similarly, the twelve additional batches of backfill created in Trial Set 2 were prepared using two different binder contents (again representing the ‘body’ and the ‘plug’ backfill pours), two Acti-Gel®208 additive dosages, and three distinct residue contents (including 1, 3 and 5 wt%, representing 0.5, 1.5 and 2.5 wt% jarosite, respectively). In order to simulate the standard backfill mix, the target solids were 72 wt%. For each batch, at least three duplicate samples were prepared per curing period. Curing periods selected for Trial Set 2 included 7, 28, 56 and 180 days.

Flow properties determination

As the flowability of backfill slurries is essential in hydraulic backfilling operations and may vary with changes in aggregate, binder content, solid concentration and additional additives (such as jarosite residue), all twelve raw material mixes of Trial Set 2 were evaluated using a standardized flow cone to provide an initial scope on the effects of addition of jarosite residue on the flowability of the backfill.

After raw material mix preparation was completed, the flow properties of each individual batch of Trial Set 2 were investigated using a standardized flow cone, where time of efflux was recorded. Using a dampened flow cone on a flat level surface, the individual backfill raw material mixes were added to the standardized flow cone until the backfill material was just contacting the point gauge (1725 ± 5 mL of backfill material), where the discharge valve was then opened. Time of efflux was recorded simultaneously with the opening of the discharge valve and ended with the first break in continual flow Time of efflux was recorded with a stopwatch. This procedure was repeated twice for each distinct backfill slurry mix of Trial Set 2. A video record was also taken of all flow property tests.

Results and Discussion

Testing matrix review

In December 2023, it was determined that due to the limited amount of jarosite available, a feasible and representative starting point would be to create eight batches of hydraulic backfill; with five batches covering the effects of jarosite addition on the ‘body’ pour of the backfill at 25:1 binder content, and three batches covering the effects of jarosite addition on the ‘plug’ pour of the backfill at 15:1 binder content (Table 1). Fewer high binder content batches were created in Trial Set 1, since it was deemed to be of less importance than the lower binder content batches, as negative strength effects were expected from the addition of jarosite, and it would therefore be unlikely for a mining operation to choose to compromise the integrity of the ‘plug’.

Table 1. Trial Set 1 testing matrix.

Solids wt%	Binder wt%	Jarosite wt%	ActiGel wt%	Curing Period	# of cylinders
72	3.85 (25:1)	0	0.03	28	3
				56	3
				180	3
		2	0.03	28	3
				56	3
				180	3
		4	0.03	28	3
				56	3
				180	3
		8	0.03	28	3
				56	3
				180	3
		8	0.06	28	3
				56	3
				180	3
	6.25 (15.1)	0	0.03	28	3
				56	3
				180	3
		2	0.03	28	3
				56	3
				180	3
		8	0.03	28	3
				56	3
				180	3

In February 2024, as the bioleaching pilot plant became operational and subsequently more jarosite residue became available, an additional twelve batches of hydraulic backfill were prepared; six batches covered the effects of jarosite residue addition on the ‘body’ pour of the backfill at 25:1 binder content, and six batches covered the effects of jarosite residue addition on the ‘plug’ pour of the backfill at 15:1 binder content (Table 2). Additional high binder content batches were created in Trial Set 2 due to the greater availability of materials, and unexpected results observed from the preliminary testing of Trial Set 1.

Table 2. Trial Set 2 testing matrix.

Solids wt%	Binder wt%	Jarosite wt%	ActiGel wt%	Curing Period	# of cylinders
72	3.85 (25:1)	0	0	7	3
				28	3
				56	3
				180	3
		0	0.03	7	3
				28	3
				56	3
				180	3
		0	0.06	7	3
				28	3
				56	3
				180	3
		0.5	0.03	7	3
				28	3
				56	3
				180	3
		1.5	0.03	7	3
				28	3
				56	3
				180	3
		2.5	0.03	7	3
				28	3
				56	3
				180	3
	6.25 (15:1)	0	0	7	3
				28	3
				56	3
				180	3
		0	0.03	7	3
				28	3
				56	3
				180	3
		0	0.06	7	3
				28	3
				56	3
				180	3
		0.5	0.03	7	3
				28	3
				56	3
				180	3
		1.5	0.03	7	3
				28	3
				56	3
				180	3
		2.5	0.03	7	3
				28	3
				56	3
				180	3

Laboratory strength determination–low binder content

As curing periods > 56 days have not yet occurred, a limited number of low binder content sample test results are presented in this paper and therefore, this study should be considered preliminary. The average UCS as a function of total jarosite residue content (wt%) for the lower binder content (25:1) batches of Trial Set 1 can be seen in Figure 2, where an obvious and drastic effect on strength can be observed in both 28 day and 56 day curing periods. Average UCS decreases greatly from the conventional (0% jarosite residue addition) values of 0.58 and 2.56 MPa (28 and 56 day curing periods, respectively) to a strength of 0.06 and 1.19 MPa (28 and 56 day curing periods, respectively) with only a 2% jarosite residue addition, exhibiting an almost tenfold decrease in strength. In both curing periods, the 4 and 8% jarosite addition batches retained almost no strength and were practically failing under their own weight.

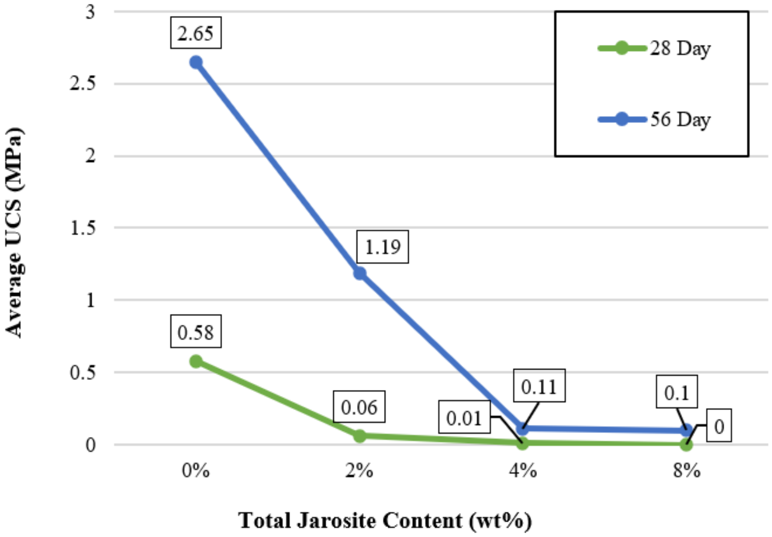

Figure 2. Average UCS versus total jarosite content for Trial Set 1, 25:1 binder content

Contradictory to the lower binder content (25:1) strength loss exhibited with the addition of jarosite residue in Trial Set 1, an unexpected result was noted in the 7 day curing period of Trial Set 2. The batch containing the 0.5% jarosite residue additive slightly improved in strength when compared to the conventional standard (0% jarosite additive) (Figure 3). The subsequent batches with higher jarosite content (1.5 and 2.5%) resulted in a dramatic loss of strength, comparable to the findings from the preliminary Trial Set 1. Future studies are planned to further examine the relationship between jarosite residue additives and strength, and to understand the longer-term effects of jarosite residue addition in the 'body' pour (low binder content) of hydraulic backfill.

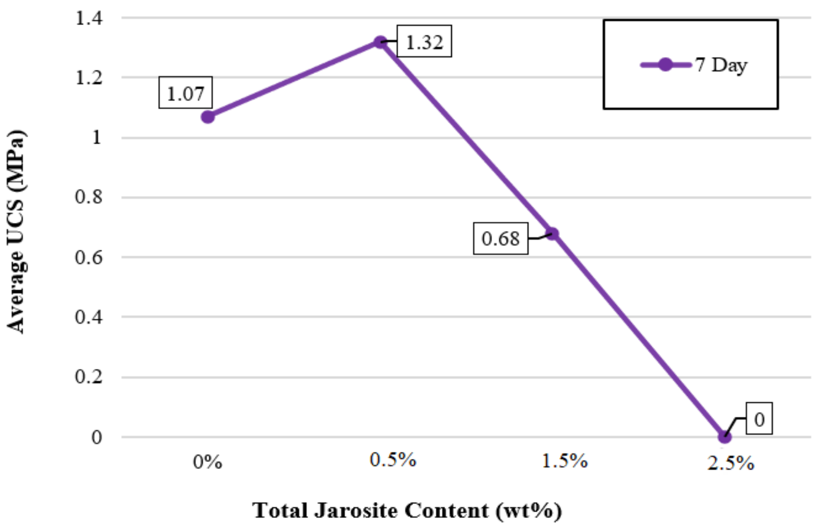

Figure 3. Average UCS versus total jarosite content for Trial Set 2, 25:1 binder content**.**

Laboratory strength determination: high binder content

Curing periods > 56 days have not yet occurred, resulting in a limited number of high binder content sample test results presented in this paper**.** Therefore, this study should again be considered preliminary. The average UCS as a function of total jarosite residue content (wt%) for the higher binder content (15:1) batches of Trial Set 1 can be seen in Figure 4, where an unexpected and positive effect on strength can be observed in both the 28 and 56 day curing periods. Average UCS increases sharply from the conventional standard (0% jarosite residue addition) strength values with only a 2% jarosite residue addition. This phenomenon is extremely obvious in the 56 day curing period results, with strength values almost doubling with a 2% jarosite residue additive when compared to the conventional standard (0% jarosite residue addition)**,** an increase from 3.66 MPa to 7.05 MPa. The other batch prepared with higher jarosite residue contents (8%) resulted in almost no strength in both the 28 and 56 day curing periods, comparable to the lower binder content (25:1) batches.

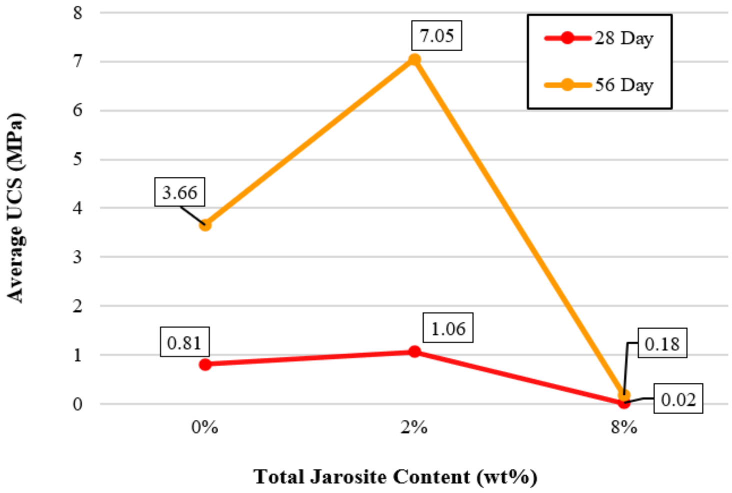

Figure 4. Average UCS versus total jarosite content for Trial Set 1, 15:1 binder content.

The higher (15:1) binder content batches of Trial Set 2 followed a similar trend when compared to the higher binder content batches of Trial Set 1, as the addition of a 0.5% jarosite residue additive also improved the strength of the backfill when compared to the conventional standard (0% jarosite residue addition) (Figure 5). Comparable to the findings from the preliminary Trial Set 1, the batches with higher jarosite residue contents (1.5 and 2.5%) resulted in a significant loss of strength. Future studies are planned to examine the relationship between jarosite residue additives and strength, and to understand the longer-term effects of jarosite residue addition in the 'plug' pour (high binder content) of hydraulic backfill.

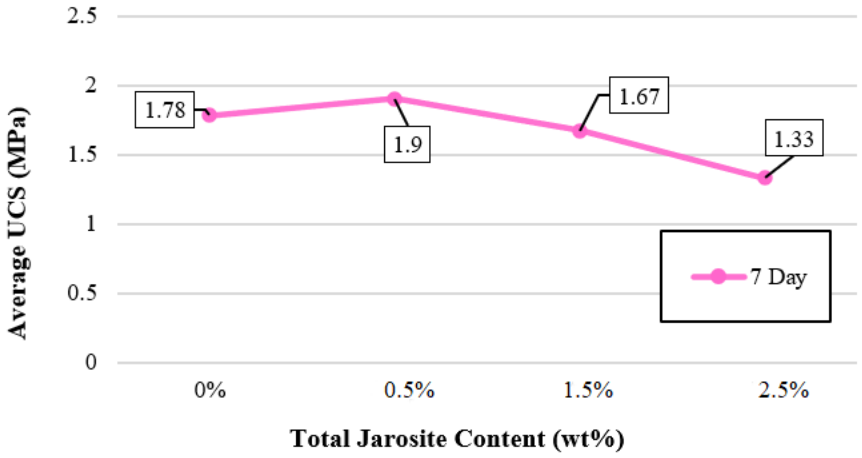

Figure 5. Average UCS versus total jarosite content for Trial Set 2, 15:1 binder content.

From visual inspection of all samples combinations from both Trial sets, it was noted that as jarosite additive content increased, the moisture content of the samples also increased. However, this was not reflected in the moisture content values found through laboratory analysis. It is suspected that the smaller sample portion retained for moisture analysis may not have been representative of the entire sample, as the lower section of the sample likely contained more moisture when compared to the top section. This may be a physical properties effect due to the particle size distribution, or a chemical properties effect due to the addition of the jarosite residue additive. Future studies are planned to investigate this further. It was also noted that the samples with higher jarosite residue content exhibited a visibly lighter associated colouring, which may be due to oxidation during curing. Additionally, small sub-rounded inclusions of highly oxidized material were observed within the 8% jarosite additive samples of Trial Set 1.

Flow properties determination

In February of 2024, after the preparation of each individual raw material mixes of Trial Set 2, a standardized flow cone was used and time of efflux was recorded to provide an initial scope of the effects of jarosite residue addition on flow properties of each mix. All 12 raw material mixes of Trial Set 2 were subjected to two tests using the standardized flow cone.

The average time of efflux as a function of total jarosite residue content (wt%) for all batches of Trial Set 2 can be observed in Figure 6, where no clear trend can be observed. In the lower (25:1) binder content batches, time of efflux increases with 0.5 and 1.5% jarosite residue additions (Mix 4 and 5, respectively), but decreases at 2.5% jarosite residue addition (Mix 6). Similarly, the higher (15:1) binder content batches did not yield conclusive results, as a slight decrease in time of efflux was observed with a 0.5 and 2.5% jarosite residue addition (Mix 10 and Mix 12, respectively), and an increase in the time of efflux was observed with a 1.5% jarosite residue addition (Mix 11).

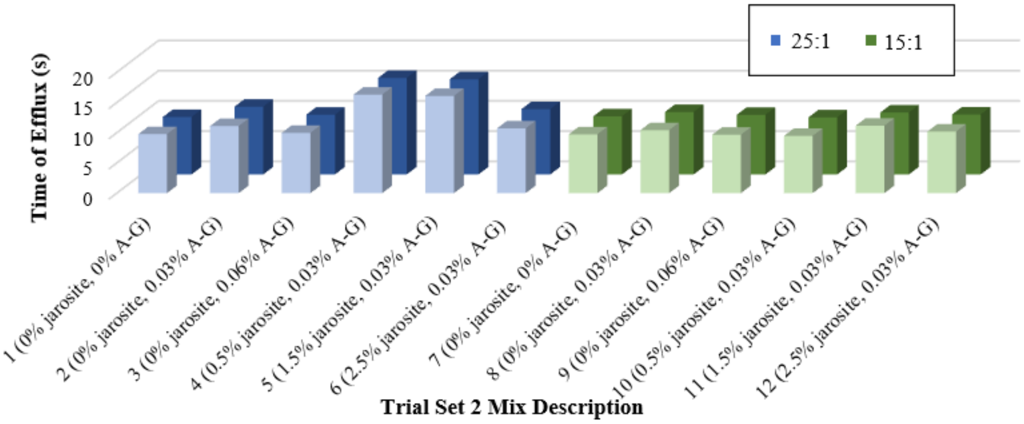

Figure 6. Time of efflux for raw material mixes of Trial Set 2.

Initially, it was believed that these inconclusive results may be caused by variances in the moisture content of the batches in in Trial Set 2, but after analysis of the laboratory determined moisture content of the raw material mixes, there appears to be no correlation between moisture content and average time of efflux (Table 3). Average moisture contents range between 26.83–28.10% and display no correlation to average time of efflux. Further testing is required to determine the effects of additional jarosite on the flowability of backfill.

Table 3. Trial Set 2: Raw material flowability and moisture data.

	Binder wt%	Jarosite wt%	ActiGel wt%	Trial 1 time (s)	Trial 2 time (s)	Moisture Content (%)
Mix 1	3.85 (25:1)	0%	0%	9.77s	9.50s	28.00%
Mix 2		0%	0.03%	11.10s	11.22s	27.14%
Mix 3		0%	0.06%	9.99s	9.89s	28.10%
Mix 4		0.5%	0.03%	16.31s	15.98s	26.83%
Mix 5		1.5%	0.03%	16.09s	15.76s	27.38%
Mix 6		2.5%	0.03%	10.72s	10.81s	27.66%
Mix 7	6.25 (15:1)	0%	0%	9.74s	9.62s	27.93%
Mix 8		0%	0.03%	10.43s	10.34s	27.67%
Mix 9		0%	0.06%	9.67s	9.87s	27.89%
Mix 10		0.5%	0.03%	9.47s	9.45s	27.73%
Mix 11		1.5%	0.03%	11.17s	10.24s	27.32%
Mix 12		2.5%	0.03%	10.20s	9.92s	27.73%

Conclusion

From this initial scoping study on the effects of jarosite residue addition in hydraulic backfill, there appears to be a marked effect on strength. As observed in the lower (25:1) binder content trials, the uniaxial compressive strength was drastically reduced in all samples of Trial Set 1; with a minimal addition of 2% jarosite residue, the strength decreased by almost tenfold. Surprisingly, an increase in UCS was observed with a 0.5% jarosite residue addition in the lower (25:1) binder content batches of Trial Set 2. Another surprising observation was made throughout the higher (15:1) binder content trials of both Trial Set 1 and Trial Set 2, as the addition of a minimum amount of jarosite residue (2 and 0.5%, respectively), slightly increased the strength of the samples**,** with the most noticeable increase in strength observed over the longest curing period to date (56 day curing period of Trial Set 1). However, it should be noted that once the amount of jarosite residue increased beyond these levels, a sharp and almost complete strength depletion was observed. The longer-term effects of jarosite residue addition in hydraulic backfill is yet to be concluded, and further testing and analysis to determine these longer-term effects is planned in the near future. Additional testing and analysis is required to make any conclusions on the effect of jarosite residue additives on the flowability of backfill, as results from this preliminary study were not conclusive.

Further research into the physical and chemical properties (including a chemical analysis of the final products) is planned, along with determinations to discover if there is an ideal jarosite residue content for ensuring the integrity of the backfill. It would also be important to include an investigation into the financial implications in relation the environmental benefits of the jarosite addition in hydraulic backfill. As noted by Singh (2019), jarosite could potentially be considered an alternative binder in some circumstances. Future studies and analysis of data obtained from longer curing periods (56 and 180 days) are planned to explore the varying jarosite additive contents to confirm if it could, in fact, have a positive effect on backfill strength.

This scoping study gives confidence to the authors that addition of jarosite residue in underground backfill may be a viable option for the disposal of bioleaching process residue. The stirred-tank bioleaching process developed by CanmetMINING for recovering nickel and cobalt (both critical for vehicle electrification) results in residue containing jarosite, which as noted in this paper can be severely problematic for long-term disposal. It has been determined through this preliminary study that the disposal of high-jarosite waste from the bioleaching process into the underground mine backfill is a potentially viable option.

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