Experimental Evaluation of Acid Mine Drainage Potential for Cemented Paste Backfill

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Abstract

Safe environmental management of sulfide-bearing tailings material is a significant concern for mining operations. Iron sulfides (mostly pyrite and pyrrhotite) are common in sulfide-bearing mining waste materials. Surface disposal of these waste materials will lead to oxidation in the presence of air and water, eventually generating acid mine drainage (AMD). The utilization of tailings using the cemented paste backfilling method eliminates the necessity of storing most of the tailings on the surface, reducing the environmental footprint. In this study, static and kinetic testing were conducted on the tailings and cemented past backfill mixture to evaluate the potential of acid mine drainage.

From the performed static test on the tailings sample through the Acid-Base Accounting (ABA) method, the results of the net neutralization potential and the ratio of neutralization potential to acid potential show that the tailings material will be acid-generating. An X-Ray diffraction (XRD) test was conducted on the tailings sample for composition analysis. Kinetic tests measure the dynamic performance or reactivity of excavated and exposed materials over time. The column leach testing setup in the laboratory is designed to observe the weekly wet-dry and leaching cycles of cemented paste backfill (CPB) mixtures. The 6-inch diameter by 12-inch long cylindrical PVC columns are filled with CPB materials. The mixture contains tailings, Portland cement, and water. The test set-up was designed following a components matrix, in which six columns contained CPB mixtures and two columns contained tailings only.

The columns are wetted by applying deionized water from the surface, and the leachate water is collected for measurement in a container located at the base. To simulate the drying environment of natural weather, heat lamps at the top are used to ensure sample drying between test solution applications. Typically, the test solution was applied weekly and the leachates were collected every week. For over fifty weeks, the pH and electrical conductivity were measured and analysed weekly on the percolated water for potential AMD evaluation. In the control column, it was observed that the pH value transitioned towards acidic within the first few weeks of measurements. During the initial week of measurements on cemented

columns, the compacted samples showed higher pH values than the uncompacted samples. In the first few weeks, the cemented columns showed pH values around 10 to 12. Then in later weeks, the pH values gradually started to stabilize around 6 to 8.

Introduction

Cemented paste backfill (CPB) is an essential technique in the mining industry that involves using a mixture of tailings, cement, and water to create a solid backfill material. The significance of CPB lies in its capacity to provide support to underground mining operations while simultaneously utilizing mine waste, such as tailings, as a valuable resource. CPB plays a role in preserving the stability of underground openings, preventing ground subsidence, and enhancing overall operational efficiency. While typical concrete has water/cement ratios around 0.5, CPB applications involve higher ratios ranging from 5 to 10. The unconfined compressive strength values vary between 0.05 and 3.5 MPa, which differ from conventional concrete strength levels of 25 to 35 MPa. The properties of tailings are influenced by various factors, including the composition of the original rock, the method used for mineral extraction, and the methods employed for transporting and placing the tailings materials (James et al., 2003). The CPB is generally transported either by gravity or through pumping to fill the desired underground stope (Yilmaz, 2010).

The use of CPB has gained popularity as an alternative method for managing mine waste in Canada and other countries worldwide over the past two decades (Ercikdi et al., 2017). CPB not only has practical benefits but also contributes to environmental mitigation. The inclusion of cement in CPB results in improved strength, decreased permeability, and reduced acid mine drainage (AMD) formation by enhancing the capacity to neutralize acid (Ercikdi et al., 2017). During mining activities, it is possible for minerals in the tailings and binder to undergo oxidation or chemical reactions, resulting in the creation of soluble contaminants. Pyrite is a common sulfide mineral found in mine waste that plays a significant role in AMD. Initially, pyrite undergoes oxidation in the presence of water and molecular oxygen, producing sulfate ions, ferrous ions, and hydrogen ions (Lu et al., 2013).

These contaminants have the potential to affect the quality of water within the mine during operations, and can continue to pose a risk to groundwater and surface water quality even after the mine is closed. Evaluation of potential environmental issues requires characterization of the paste mixture in terms of the mixture's characteristics, such as mineralogy, acid-generating capacity, kinetic reactions and potential for leaching metals is crucial (Benzaazoua et al., 2008). This assessment helps to predict the impact on water quality and ensures proper management strategies are in place.

The use of CPB technology has the ability to decrease the chemical reactivity of tailings and the movement of pollutants by combining and consolidating the tailings with an alkaline substance like cement (MEND, 2006; Kesimal et al., 2005). Although there have been notable advances in integrating sulfide-bearing tailings into CPB systems, the environmental behaviour is still an unexplored area. While numerous studies have examined the mechanical characteristics of CPB, there is limited research on how the chemical reactivity affects the performance of CPB systems (Ouellet et al., 2003). In this study, acid-base accounting test were conducted as a static method to evaluate the potential acid generation and neutralization capacity of the tailings material. Column leach tests were conducted on the cemented past backfill mixture containing variable cement percentage by weight to evaluate the potentiality of acid mine drainage.

Materials and methodology

Tailings properties

Tailings are the waste materials left over after the valuable components have been extracted from ore during the mining or mineral extraction process. They consist of finely ground rock particles, minerals, and water. Tailings are typically deposited in tailings storage facilities or ponds that are designed to contain and manage the waste materials safely. Understanding tailings properties is essential for effective tailings management and addressing environmental considerations.

Tailings, composed of crushed rock, minerals, and water, have varying compositions depending on the processed ore. Tailings typically have a wide range of particle sizes, from fine silt and clay-sized particles to larger sand and gravel-sized particles. As shown in Figure 1, particle size distribution was measured for tailings materials following the standard ASTM C136. The bulk density of the tailings (1.613 gm/cm^3) was measured by following the ASTM C29 on the oven dry tailings sample. The Specific Gravity (2.72) of the tailings samples was determined by following ASTM C128.

Cemented paste backfilling

CPB offers significant advantages in terms of technology, economics, and environmental impact compared to rock and hydraulic fill. It enables a substantial amount of tailings to be returned underground, resulting in reduced space requirements and lower rehabilitation costs. CPB is a customized mixture of unaltered tailings, including fine particles. It typically contains 75 to 85% solids, a hydraulic binder comprising 3 to 9% of the dry paste weight, and sufficient water content for easy transportation. The addition of binder in paste tailings is an essential component to increase the strength and stability. CPB acts as a barrier, preventing water seepage and reducing the formation of acid mine drainage by restricting oxygen diffusion. Portland cement (PC) is widely used as it sets and hardens through chemical reaction with water. When PC comes into contact with water, cement hydration occurs. Throughout the hydration process, the primary components of PC react with water, forming hydration products that contribute to the setting and hardening of concrete. PC is produced by crushing and blending specific quantities of raw materials, such as limestone, clay, and shale.

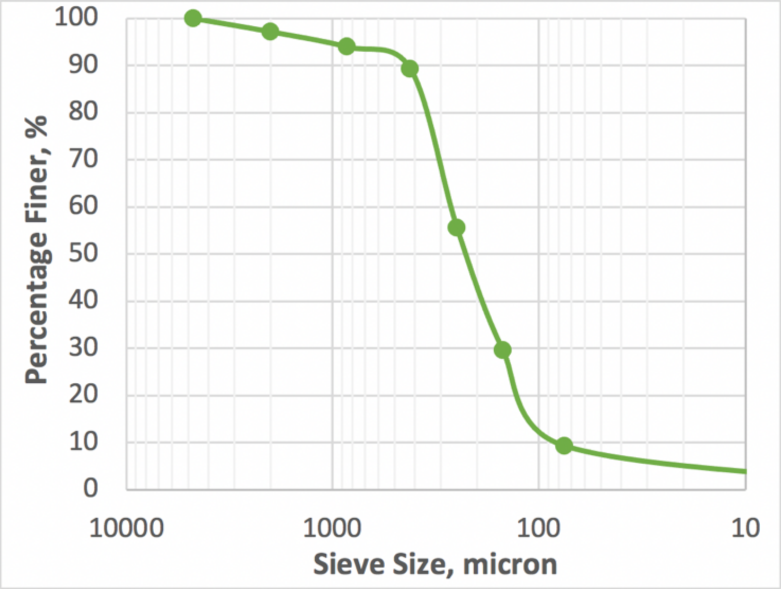


Figure 1: Particle size distribution curve of tailings

Typically, modern PC mainly consists of clinker plus a small quantity of gypsum (3% to 7% wt.), which is used to regulate the initial setting time. Clinker is a vital ingredient that represents about 95% wt. of the PC. Typically, PC and its clinker mainly consist of four oxides: lime (CaO), silica (SiO2), alumina (Al2O3), and iron oxide (Fe2O3) in addition to the minor oxides (Klieger and Lamond, 1994).

AMD prediction approach

To address the environmental concerns related to mining activities, the development of AMD prediction methods is crucial when excavating or exposing significant bedrock. These methods aim to minimize uncertainty, identify potential risks, and facilitate the selection of effective strategies for extraction and waste handling. By providing insights into the behaviour of mining materials and components, the prediction methods also help to identify any potential adverse conditions.

When assessing the potential impacts of AMD and related processes, it is necessary to address several important aspects. Determining the physical and geochemical conditions that facilitate weathering and contaminant transport is necessary. The prediction methods for AMD vary depending on the different phases of mine project development. Typically, chemical, mineralogical, and physical analyses of waste components are performed as part of the initial characterization process.

Static prediction methods

Static tests enable initial assessment of acid-generating components (e.g., sulfides) and acid-consuming components (mainly carbonates) in waste materials. In the AMD studies, a static test is used for analytical methods that evaluate the characteristics and quantities of different components within a sample at a specific moment. Numerous methods for static test analyses are available. One of the widely used static tests in AMD studies is the acid base accounting (ABA) method.

Static tests assume complete reactions of sulfides and carbonates without considering kinetics or chemical equilibria. Moreover, static tests do not offer predictions regarding drainage quality. However, they serve as a quick, cost-effective screening method to determine the preliminary acceptability or unacceptability of water quality. To assess or predict reaction rates and the geochemical evolution accurately, a combination of kinetic tests and static tests is necessary.

Kinetic prediction methods

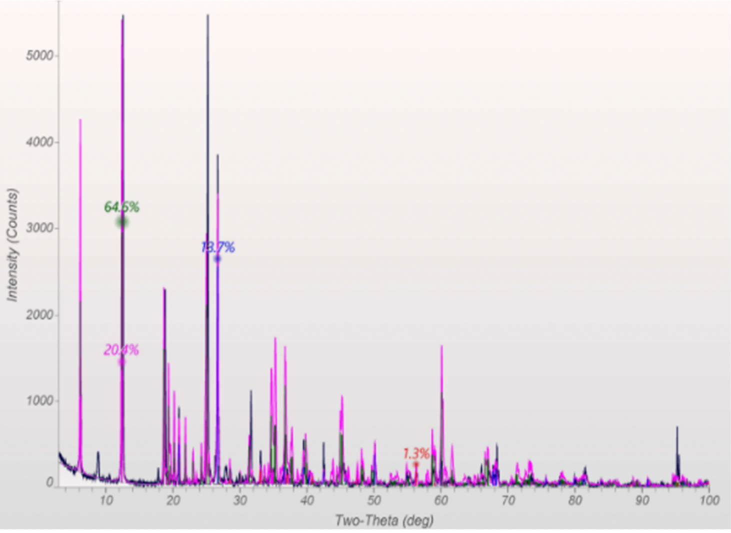
Kinetic tests evaluate the dynamic performance and reactivity of excavated and exposed materials. These tests are usually conducted when static test analysis suggests the potential for AMD generation, or when the results are inconclusive. Prediction testing provides a short-term assessment of a phenomenon that occurs over a longer period. Designing a kinetic prediction test poses challenges as it involves either modelling actual field conditions, which may result in a test duration that is too short, or creating accelerated conditions that may not accurately represent real-world scenarios.

Kinetic prediction tests aim to simulate the long-term processes of acid production and consumption, as well as predict the quality of drainage, in laboratory or field settings. Designing a reliable prediction test for AMD is challenging due to the inability to replicate exact field conditions within a feasible timeframe. Various tests of different types can be employed for kinetic testing, each differing in complexity, duration, cost, and the type of data they can provide. One popular kinetic test approach is the utilization of columns to mimic the weathering of rock or tailings in flooded or percolation leach scenarios.

Experimental analysis

Elemental analysis of tailings

The objective of major element analyses is to identify and measure the total amounts of common mineral forming compounds in a sample. An X-ray diffraction (XRD) test was done on the samples from collected tailings materials and the result is shown in Figure 2. XRD is a scientific technique used to analyze the crystallographic structure and composition of materials. XRD involves directing a beam of X-rays onto a sample, which results in the scattering of X-rays by the crystal lattice of the material. By measuring the angles and intensities of the diffracted X-rays, information about the atomic spacing and arrangement within the sample can be obtained.



Phase ID (4)	Chemical Formula	PDF-#	Wt% (ESD)	DD% (ESD)	RIR	µ
Quartz	SiO_2	98-000-0369	13.7 (?)	15.7 (?)	4.12	91.2
Clinochlore IIb-4	$Mg_{4.54}Al_{0.97}Fe_{0.46}Mn_{0.03}(Si_{2.85}$	98-000-0165	64.6 (?)	64.1 (?)	0.77	111.9
Pyrite	FeS_2	98-000-0363	1.3 (?)	1.8 (?)	3.00	956.9
Chlorite - IIb	MgFeSiAlOOH	98-000-0159	20.4 (?)	18.3 (?)	1.46	267.2

XRF(Wt%): Fe_2O_3=11.5%, MnO_2=0.3%, SO_3=1.8%, SiO_2=40.8%, Al_2O_3=13.9%, MgO=24.0%

Figure 2: XRD results of tailings samples

Acid-base accounting test

The evaluation of acid potential, neutralization potential, the comparative calculation of net neutralization potential (NNP), and the neutralization potential ratio (NPR) is collectively referred to as ABA. ABA encompasses various methods, but the most straightforward approach involves using sulfide-S to calculate acid potential (AP), while the neutralization potential (NP) is determined through a single procedure. They are expressed in comparable and consistent unit kg $CaCO_3$/per tonne of rock or tailings materials. The difference between the two values is termed as the net neutralization potential or Net NP. Table 1 describes the guidelines for interpreting ABA results through the values of NNP and NPR.

$$\text{Net Neutralization Potential (NNP)} = NP - AP \quad (1)$$

$$\text{Neutralization Potential Ratio (NPR)} = NP/AP \quad (2)$$

Acid potential measurement

The AP is determined by analyzing the total sulfur content and calculating AP under the assumption that all sulfur is converted to sulfate, resulting in the production of four moles of H+ per mole of oxidized pyrite. Each mole of sulfur generates two moles of acid, which can be neutralized by 1 mole of calcium carbonate. Consequently, the molar ratio of sulfur to calcium carbonate is 1:1. The AP of the sample, expressed in tonnes of calcium carbonate equivalent per 1,000 tonnes, can be calculated by multiplying the percentage of sulfur by 31.25.

Table 1: Guidelines for interpreting the static test results (US EPA, 2003)

Guidelines from Robertson and Broughton (1992)			
Criteria	**Potentially acid-generating**	**Uncertain behaviour**	**Potentially acid-neutralizing**
NNP	< -20 tonnes/kilotonne	> -20 to < +20 tonnes/kilotonne	> + 20 tonnes/kilotonne
NPR	< 1	1 to 3	>3
Guideline from Price et al. (1997)			
Sulfide-S	**Paste pH**	**NPR**	**Potential for AMD**
Sulfide-S <0.3%	>5.5	–	None
Sulfide-S >0.3%	<5.5	<1	Likely
		1 – 2	Possibly
		2 – 4	Low
		>4	None

Neutralization potential measurements

All materials containing acid-generating minerals like pyrite have the potential to produce acid, but the occurrence of acid rock drainage (ARD) depends on the availability of neutralizing alkalinity. The measurement of neutralization ability is a crucial aspect of drainage chemistry, and the determination of NP through static tests is a significant component of acid-base accounting. To assess NP a recommended procedure is the Sobek et al. (1978) method. In this process, a sample is treated with an excess of standardized hydrochloric acid and heated to ensure complete reaction. A fizz test is conducted to verify that an adequate amount of acid has been added to react with all acid-consuming minerals present. The remaining unreacted acid is then titrated with a standardized base to achieve a pH of 7, allowing for the calculation of the calcium carbonate equivalent of the consumed acid. While the Sobek method is the standard procedure, there are several alternative methods available for measuring laboratory NP, some of which are promoted as being more accurate because they minimize discrepancies between laboratory and field results.

Column leach testing

Column leach tests enable the testing of mine wastes to simulate weathering conditions. A column refers to a structure that contains a mass of materials and allows for the qualitative analysis of water drainage through the sample. It consists of a basin with enclosed sides and a bottom equipped with a drain. The water that seeps through the specimen is collected and analyzed to assess the potential for AMD. As shown in Figure 3, the column leach testing setup is designed to achieve a weekly wet-dry cycle and leaching cycle. The 6 inch × 12 inch cylindrical plastic mould are used as a column. They are made of PVC materials. The cylinders are filled with a mixture of cemented paste backfill materials. The mixture ingredients contain mostly tailings, cement, and water. The CPB mixtures were poured into each cylindrical column up to the height of 6 inches, leaving the rest of the length for pouring in a water solution. There are a total of eight columns, of which six columns are filled with a CPB mixture and the other two column are filled with only tailings, without any binder.

To simulate the drying environment of natural weather, heat lamps were placed to ensure drying of the samples between test solution applications. Throughout the testing duration, the maintained temperature was 21 °C. The bottom part of the columns was perforated with 1 mm-sized mesh to leach the water. The sample were wetted by applying the deionized water from the top of the surface, and the leachate as collected in a container through the funnel at the base. Glass wool filter material was placed inside each funnel to screen any solid substances from the leachate water.

Every week, around 1 litre of deionized water was poured into the columns to percolate through the cemented tailings samples, and the leachates were collected weekly. The internal vibration concept was used as the compaction method to refer the reduction of air content while measuring the AMD potential in CPB mixtures. The test matrix of all eight columns is described in Table 2.

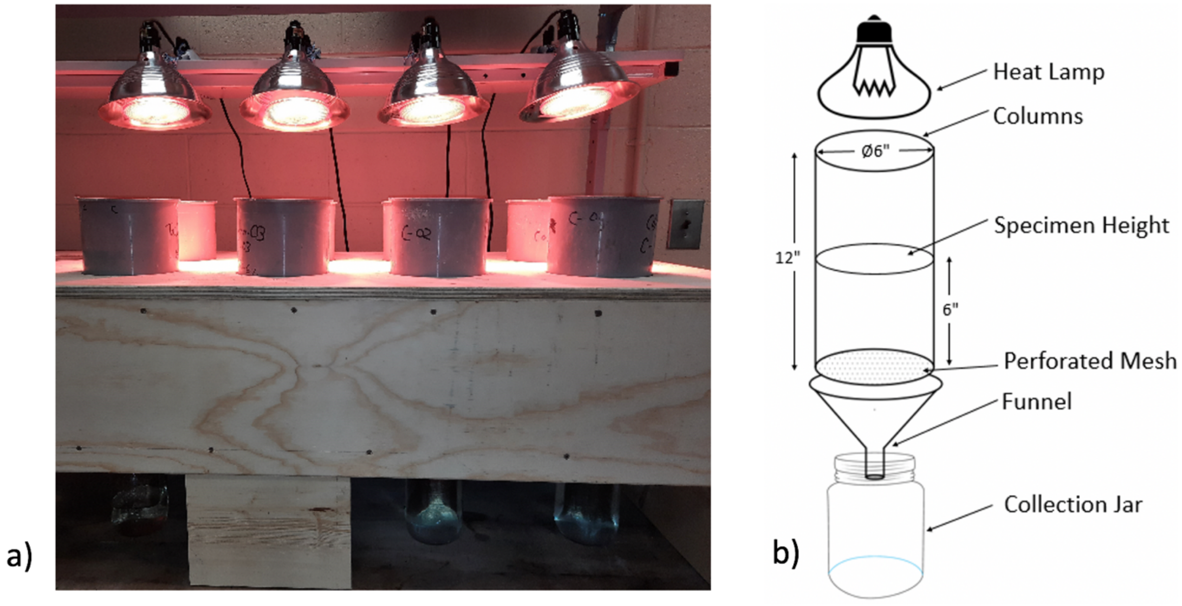


**Figure 3: Experimental set-up of column leach test:
a) Set-up in the laboratory; b) Schematic drawing**

Table 2: Test materials components of column leach test

Compaction	Material components of CPB according to weight percentage			
No vibration (NV)	Column 1 2% Cement 78% Tailings 20% Water	Column 2 4% Cement 76% Tailings 20% Water	Column 3 6% Cement 74% Tailings 20% Water	Column 7 (Controls) Only wet tailings Material 4,800 gm
With vibration (WV)	Column 4 2% Cement 78% Tailings 20% Water	Column 5 4% Cement 76% Tailings 20% Water	Column 6 6% Cement 74% Tailings 20% Water	Column 8 (Controls) Only wet tailings Material 4,800 gm

The pH and electrical conductivity (EC) are measured through a portable waterproof instrument, the ExStik II pH/Conductivity meter. The model of the instrument is Extech EC500 and electrical conductivity is expressed in mS/cm. The EC500 meter features a digital display that shows the pH or EC value, depending on the selected mode. It utilizes a replaceable electrode to measure pH and a built-in conductivity cell for EC measurements. To ensure greater accuracy in measuring EC500 instruments, a Toledo EL20 pH meter was used for pH measurements and a Thermo-scientific A322 portable meter was used to measure conductivity. This enabled the researchers to obtain more comparable and precise results.

Results and discussion

Interpretation of ABA results

The positive Acid Production Potential value of +98.6 kg $CaCO_3$/tonne indicates that the tailings sample has the potential to generate acid when exposed to oxygen and water. This means that there are acid-generating minerals or elements present in the tailings material that could contribute to acid formation. However, the low NP value of 12.4 kg $CaCO_3$/tonne suggests that the tailings contain a limited amount of acid consuming minerals or elements that can neutralize the acid producing capacity. This is further confirmed by the negative Net Neutralization Potential value of -86.1 kg $CaCO_3$/tonne, indicating an overall deficit in acid neutralization. The NPR of 0.1 reveals that the material has a very low ability to neutralize the acid it generates. A ratio below 1 suggests a higher risk of acid generation and a limited capacity for neutralization.

Based on the results in Table 3, it can be interpreted that the material has a significant potential for acid generation, but a very limited ability to neutralize the acid (low NP and negative Net NP). The low NPR value indicates an imbalance in favour of acid generation, implying a high risk of acid formation and associated environmental concerns of acid mine drainage.

Table 3: ABA results of tailings sample

Paste pH	Total sulfur	Sulfate (as S)	Sulfide	Acid Production Potential (AP)	Neutralizing Potential (NP) at pH 8.3	Net NP At pH 8.3	NP/AP
	%	%	%		Kg $CaCO_3$/tonne		
5.9	3.25	0.096	3.15	98.6	12.4	-86.2	0.1

Column leach test results

The percolated leachate water from the column is collected in separate containers each week, after applying a solution (deionized water). The results of the column leach test are presented in Figure 4, following the test matrix described in table 2. In the initial weeks, the pH of the leachate water from both tailings-containing columns ranged from 6 to 8. For columns containing 2%, 4%, and 6% cement, the measured pH on the first week was around 10 to 12. This higher pH indicates the presence of initial hydroxide alkalinity and the subsequent formation of cement hydration products. After 51 weeks of measurements, the pH of the leachate water dropped to less than 4 from the tailings contained columns, indicating significant acid generation. In contrast, the leachate water from all the cemented paste columns maintained a pH value around 6 to 8 even after 51 weeks of measurements, but was around 10 to 12 during the initial weeks.

The influence of compaction on cemented tailings columns was not significantly observed until 51 weeks of measurement. Both compacted and uncompacted columns yielded similar pH value ranges during several weeks of measurements. Specifically, for the 2% cemented tailings columns, the uncompacted samples exhibited pH values ranging from 3 to 5 in the first 10 weeks, while the compacted samples showed values ranging from 6 to 8. The lower percentage of cement content in the cemented paste backfilling mixture resulted in acid generation from those columns. However, from the 10th week until the 50th week of measurement, the pH values measured from the leachate water of those 2% cemented columns remained around 6 to 8.

Electrical conductivity indicates water's capacity to conduct electricity, which is determined by the presence of substances capable of carrying electrical currents. As the concentration of conductive substances increases in water, its conductivity rises. Contaminated water typically exhibits higher conductivity than uncontaminated water. This is attributed to the presence of dissolved metals, sulfates, and hydrogen ions, all of which are capable of conducting an electrical charge. Table 4 provides the range of the EC data in leachates released from the column leach test. The initial EC values in the leachates were higher in the cemented columns, primarily due to the presence of cement components. Throughout the 51 weeks of measurements, the average EC value for these columns ranged between 2 to 3 mS/cm. However, throughout the same duration, the average EC value increased in the un-cemented tailings samples, indicating their acid-generating nature. The average EC values in the leachate water samples from the un-cemented tailings columns were found to be between 4 to 5 mS/cm. This higher EC value suggests the potential generation of acidity in the tailings-containing columns.

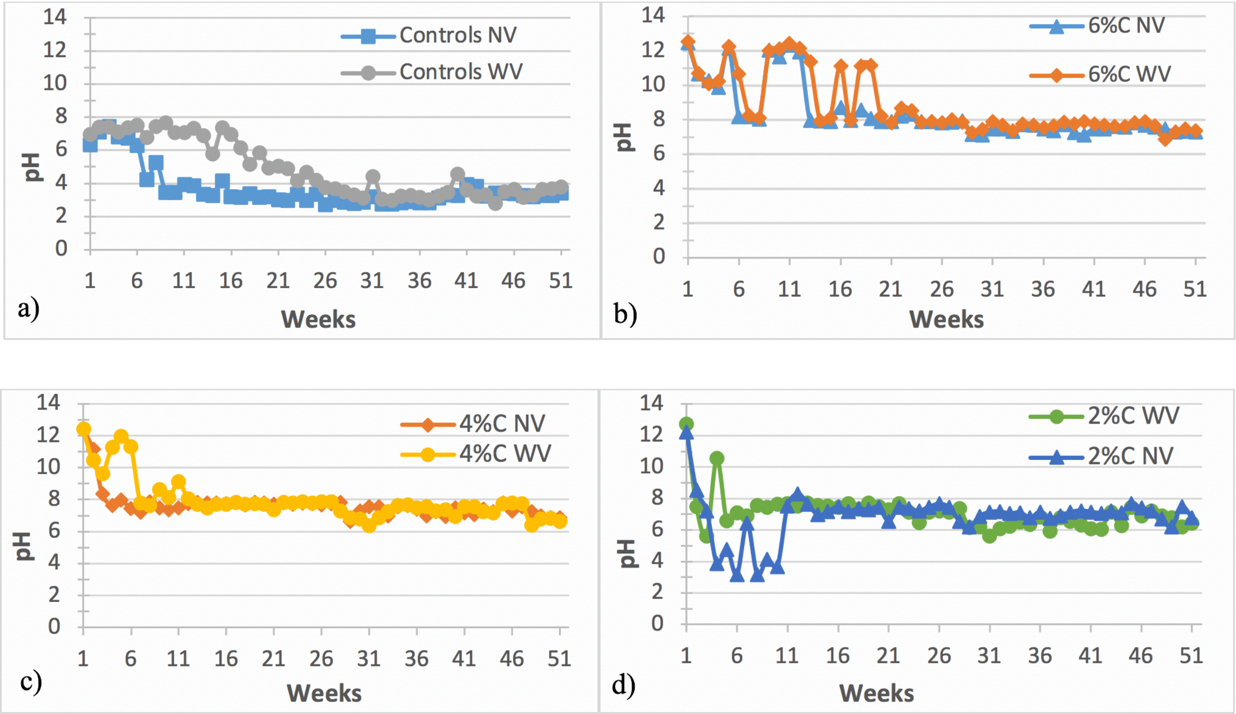


Figure 4: Column leach test results: a) Controls (un-cemented tailings), b) 6% Cemented tailings, c) 4% Cemented tailings d) 2% Cemented tailings

Table 4: Electrical conductivity (mS/cm) measurements data from column leach test

Columns	Weeks	Max.	Min.	Avg.	Std.
C-01	51	8.51	2.12	3.36	1.18
C-02	51	8.05	2.17	3.38	1.1
C-03	51	6.52	1.35	3.16	1.03
C-04	51	8.22	2.05	3.52	1.28
C-05	51	8.42	1.83	3.14	1.22
C-06	51	9.93	1.1	3.11	1.37
C-07	51	7.53	2.78	4.67	1.05
C-08	51	6.64	3.02	4.85	0.89

Conclusion

Storing sulfide tailings underground can be advantageous, potentially providing intimate mixing with alkaline binders and low oxygen conditions during operations. However, the assessment of AMD has emerged as a modern research area due to the growing concern regarding potential groundwater pollution caused by underground waste disposal. The results of the acid-base accounting test indicate that the tailing has a high potentiality of acid generation. Then in the laboratory experiment of the column leach test, the leached water from the cemented tailings sample consistently exhibited a trend of neutral pH values over a period of fifty weeks. Until this period of the study, the range of the measured pH values were around 6 to 8 for the cemented tailings columns. In contrast, the leachate water obtained from the tailings columns showed acidic pH values for the same time duration of measurement. The leachate water from those columns showed the pH values around 3 to 4, indicating an acidic nature. This nature of acid generation from the column leach test of un-cemented tailings confirms the results of acid-base accounting. The addition of cement provides extra neutralization potential to the cemented columns, which leads to the higher pH values compared to the un-cemented columns.

Hence, the utilization of CPB is widely acknowledged as advantageous in mitigating the overall environmental consequences linked to mining activities. CPB helps to minimize the amount of tailings that need to be disposed of on the surface, thus reducing surface impacts by minimizing the required space. Moreover, CPB reduces the presence of free water, leading to a decrease in leachate production. Additionally, the inclusion of cement in CPB offers extra capacity for neutralization and decreases the effective porosity. The challenge in validating laboratory predictions with field verifications lies in the multitude of factors that can impact the results. These factors include changing groundwater flow and quality, the effects of new backfill in neighbouring stopes, and ventilation patterns. To overcome these challenges in a real mine setting, it may be necessary to proceed with more controlled conditions and long-term observation of trends in mine water quality.

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