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Long-Term Acid Rock Drainage (ARD) Mitigation in Mining Cemented Tailings under Vibration and Non-Vibration Conditions

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A B S T R A C T

Acid Rock Drainage (ARD) remains a critical environmental challenge in mining, driven by the oxidation of sulphide minerals in mine tailings that can cause long-term acidification and heavy metal release. Effective, sustainable mitigation strategies are essential to minimize ecological impacts and ensure responsible mine closure. This study evaluates the long-term performance of cemented tailings backfill under different cement contents and preparation conditions, with emphasis on vibration-assisted compaction as a potential enhancement. The main objective is to determine whether vibration can improve ARD suppression while reducing cement demand. A 70-week column leach experiment was conducted using tailings blended with 2%, 4%, and 6% Ordinary Portland Cement (OPC) under vibrated (WV) and non-vibrated (NV) conditions. Weekly and biweekly monitoring of pH, electrical conductivity (EC), sulphate, and dissolved metals was carried out, supported by acid-base accounting and mineral analysis. Results show that cement content and vibration both significantly influence ARD behaviour. Vibrated samples maintained more stable neutral pH and lower EC, with 4% OPC + vibration performing as well as or better than 6% OPC without vibration. Control samples with no cement exhibited severe acidification and high EC. These findings highlight vibration-assisted compaction as a cost-effective and environmentally responsible approach for ARD mitigation in underground mining.

التخفيف طويل الأمد لتصريف الصخور الحمضية في مخلفات المناجم التعدينية المعالجة بالإسمنت تحت ظروف الاهتزازوعدم الاهتزاز

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الكلمات المفتاحية:
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مراقبة الرقم الهيدروجيني

الملخص

يُعَدّ تصريف الصخور الحمضية (ARD) من أخطر التحديات البيئية في قطاع التعدين، إذ ينشأ عن أكسدة المعادن الكبريتية في المخلفات التعدينية، مما يؤدي إلى تحمّض طويل الأمد للمياه وإطلاق المعادن الثقيلة. ويُعَدّ تطوير استراتيجيات فعّالة ومستدامة للتخفيف من هذه الظاهرة أمرًا ضروريًا للحد من آثارها البيئية وضمان الإغلاق المسؤول للمناجم. تقيّم هذه الدراسة الأداء طويل الأمد لردم المخلفات الأسمنتي تحت نسب مختلفة من الإسمنت وظروف تحضير متنوعة، مع التركيز على الدمك بالاهتزاز كإضافة محتملة لتعزيز الفعالية. يتمثل الهدف الرئيسي في تحديد ما إذا كان الاهتزاز يُحسّن من كبح ARD مع تقليل الحاجة إلى كميات عالية من الإسمنت. تم

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تنفيذ تجربة ترشيح عمودي استمرت 70 أسبوعًا باستخدام مخلفات ممزوجة بنسبة 2% و4% و6% من أسمنت بورتلاند العادي(**OPC**) ، تحت حالتي الاهتزاز (**WV**) وعدم الاهتزاز .(**NV**) جرى رصد الرقم الهيدروجيني (**pH**) والتوصيلية الكهربائية (**EC**) والكبريتات والمعادن الذائبة أسبوعيًا وكل أسبوعين، مدعومة بتحليل التوازن الحمضي-القاعدي (**ABA**) وفحص التغيرات المعدنية .أظهرت النتائج أن نسبة الإسمنت وتطبيق الاهتزاز لهما تأثير ملحوظ على سلوك **ARD.** فقد حافظت العينات المهزوزة على قيم **pH** أكثر استقرارًا وحيادية، مع انخفاض في قيم**EC** ، حيث أظهرت خلطة 4% إسمنت مع الاهتزاز أداءً مساوياً أو أفضل من خلطة 6% دون اهتزاز. أما العينات غير المعالجة بالإسمنت فقد أظهرت تحمّضًا شديدًا وقيم **EC** مرتفعة. تؤكد هذه النتائج أن الدمك بالاهتزاز يُمثل خيارًا اقتصاديًا وبيئيًا مسؤولاً للتقليل من **ARD** في عمليات التعدين تحت الأرض.

1. Introduction

Acid Rock Drainage (ARD) represents one of the most persistent and environmentally damaging challenges associated with mining activities. When sulphide-bearing minerals such as pyrite (FeS_2) are exposed to oxygen and water, they undergo oxidation reactions that generate sulfuric acid and mobilize dissolved metals. The resulting effluents lead to the acidification of surrounding water bodies, degradation of soils, and long-term ecological harm if unmanaged. Previous studies have highlighted that ARD can continue for decades or even centuries following mine closure, underscoring the urgency of developing reliable methods for its prediction and control [1] [8]).

To evaluate ARD potential, a number of diagnostic and predictive methods have been established and widely applied. Static Acid Base Accounting (ABA) provides estimates of acid-generating and neutralizing capacity, though its simplifying assumptions often limit accuracy [1] [2]. The Net Acid Generation (NAG) test complements ABA by accelerating sulphide oxidation with hydrogen peroxide to directly measure acid formation [3] [4]. Kinetic approaches, such as Column Leach Tests and Humidity Cell Tests (HCT), simulate field-like leaching over extended periods, yielding more realistic predictions of drainage chemistry (Evangelou [5] [6] [7] [8]). In parallel, geochemical modelling tools, such as PHREEQC, allow scenario-based predictions of mineral stability and solution chemistry, though they depend heavily on accurate site-specific data and calibration [9][10]. Each method provides distinct insights into ARD behaviour and collectively supports mine design, permitting, and closure planning.

While prediction tools remain essential, recent research emphasizes the importance of engineered mitigation strategies that simultaneously enhance mine stability and environmental performance. Cemented tailings backfill (CTB) and cemented paste backfill (CPB) are increasingly recognized not only for their role in ground support but also for their capacity to limit sulphide oxidation and reduce contaminant leaching. Parameters such as binder content, particle gradation, curing time, and compaction method strongly influence both geomechanical strength and geochemical containment. In particular, vibration-assisted compaction has been identified as a promising technique to improve material homogeneity, reduce permeability, and promote hydration reactions, suggesting potential benefits for ARD suppression at reduced cement dosages.

Against this background, the present study investigates the long-term ARD behaviour of cemented tailings under vibrated (WV) and non-vibrated (NV) conditions with cement dosages of 2%, 4%, and 6%. A 70-week column leach test was conducted to monitor pH, electrical conductivity (EC), sulphate, and dissolved metal concentrations. By integrating insights from predictive testing and experimental backfill design, this study evaluates whether vibration-assisted preparation can enhance ARD mitigation while reducing binder demand, thereby providing a cost-effective and environmentally responsible solution for underground mining operations.

1.1. ARD Practiced Methods

1.1.1. Static Acid Base Accounting (ABA)

Static Acid Base Accounting (ABA) is a well-established laboratory method used to estimate the acid-generating and neutralizing capacities of mine waste materials. This technique typically involves determining the Acid Potential (AP)-mainly from sulphide content- and the Neutralization Potential (NP), usually from carbonates like calcite ($CaCO_3$) and dolomite ($MgCO_3$). The Net Neutralization Potential (NNP) and Neutralization Potential Ratio (NPR) are then derived to assess whether a sample will produce acid mine drainage or remain neutral over time. ABA testing is rapid and cost-effective, providing preliminary insights within 2-5 days [1]. However, ABA is limited in that it assumes all sulphides will oxidize and all neutralizing minerals will react, which is rarely the case in field conditions. These assumptions can lead to misinterpretation, especially for materials containing non-reactive sulphides or silicate-bound carbonates [2]. Therefore, ABA is often used as a screening tool and should ideally be followed by kinetic testing for long-term prediction.

1.1.2. Net Acid Generation (NAG) Test

The Net Acid Generation (NAG) test complements ABA by offering a direct measurement of acid formation from sulphide oxidation. This method involves oxidizing the sample using hydrogen peroxide (H_2O_2), which rapidly converts sulphides (like pyrite, FeS_2) to sulfuric acid (H_2SO_4). The resulting solution's pH and acidity are then measured to assess whether sufficient neutralizing agents exist in the material. It provides results within 1-2 days and is especially useful for identifying "false negative" risks from ABA [3]. Despite its simplicity, the NAG test does not account for delayed oxidation or field-scale hydrological processes. It is often used alongside ABA for cross-validation. The combination of NAG and ABA has become a regulatory standard in countries such as Australia and Canada for characterizing ARD potential during mine permitting [4].

1.1.3. Column Leach Test

Column leach testing simulates field-like percolation of water through waste rock or tailings over time, making it a powerful method for predicting the actual ARD potential under site-representative conditions. Columns are filled with sample material, irrigated with deionized water or simulated rainfall, and monitored over weeks to months for leachate pH, electrical conductivity (EC), sulphate (SO_4^{2-}), and metal concentrations (e.g., Fe, Al, Zn, Mn). This method is highly suitable for evaluating the effectiveness of mitigation strategies like cement addition [5]. While the test produces more realistic data than ABA or NAG, it is time-consuming and requires careful control of flow rates, temperature, and sample representativeness. Reliable trends may take 2–6 months to emerge, making this method more resource-intensive. However, its ability to capture the interplay of chemical, physical, and hydrological conditions makes it one of the most informative long-term ARD assessment tools [6].

1.1.4. Humidity Cell Test (HCT)

The Humidity Cell Test (HCT) is a kinetic laboratory method designed to evaluate acid generation and metal leaching over an extended period. It consists of weekly wet-dry cycles in a controlled cell that exposes waste rock or tailings to oxidation and simulated rainfall. The leachate is collected weekly and analyzed for pH, EC, sulphate, and dissolved metals. HCT is often required by regulatory bodies because of its rigorous and standardized approach to characterizing long-term ARD risk [7]. Although it provides detailed time-series data, HCT tests typically run for 20 to 40 weeks and are labour- and time-intensive. The main advantage of HCT is its consistency and reproducibility. However, the high cost and long duration can be limiting for smaller operations or early-stage exploration projects. Nonetheless, HCT remains a benchmark method in many mine environmental management plans [8].

1.1.5. Geochemical Modelling (e.g., PHREEQC)

Geochemical modelling, using tools like PHREEQC, is a computational technique that predicts the geochemical behaviour of mine waste systems. By inputting data such as water chemistry, mineralogy, and redox conditions, the model calculates saturation indices, mineral solubility, and potential reaction pathways. This method is particularly useful for scenario analysis, such as predicting the impact of rainfall on tailings or evaluating the long-term performance of cemented paste backfill [9]. While modelling offers great flexibility and cost savings compared to long-term experiments, it relies heavily on accurate, site-specific data and calibration with experimental results. Errors in input assumptions can lead to misleading conclusions. Nonetheless, when used in conjunction with lab tests, geochemical models provide powerful insight into ARD evolution and potential mitigation strategies [10].

1.1.6. DTL_ARD SETUP

Recent research emphasizes the critical link between backfill mixture design and its influence on both mechanical performance and acid generation potential. Specifically, cemented paste backfills (CPB) and cemented tailings backfill (CTB) mixtures have been evaluated not only for their unconfined compressive strength (UCS) but also for their environmental containment capacity. Jamil et al. [11] demonstrated that particle gradation significantly affects UCS, with well-graded mixes outperforming poorly graded ones in long-term strength. Further, the work by Someehneshin et al. [13] and Quan et al. [14] highlighted how binder content, curing time, and internal vibration techniques play a pivotal role in backfill strength development, especially for narrow vein and mining-by-drilling applications. Building on this foundation, the environmental behaviour of backfill materials, especially in terms of ARD potential, is gaining increased attention. Jamil (2023) [12] presented a comprehensive experimental evaluation of CPB's strength alongside its acid mine drainage characteristics, establishing a dual-assessment framework that links geotechnical stability with environmental performance. Likewise, Someehneshin [15] investigated the hydro-geochemical evolution of backfilled stopes and its implications on wellbore stability. These studies collectively emphasize the necessity for integrated testing methodologies that consider both mechanical durability and ARD risk to optimize backfill strategies in underground mining.

Table 1 summarizes ARD measurement methods, including objectives, parameters measured, advantages versus disadvantages, and minimum time required for collecting reliable data.

Table 1: Summary of ARD measurement methods.

Method	Objective	Measurements	Advantages vs. Disadvantages	Minimum Time for Reliable Results	Ref.#
Static Acid Base Accounting (ABA)	Assess acid-generating and neutralizing potential of mine materials	NP, AP, NNP, NPR	**Advantages:** Quick, standardized, low cost. **Disadvantages:** Potential estimation error due to reactivity assumptions	Immediate results; ideally confirmed with long-term tests	[1], [2]
Net Acid Generation Test (NAG)	Quantify acid generation from sulfide oxidation	Net acidity after oxidation	**Advantages:** Simple and fast. **Disadvantages:** Doesn't simulate long-term oxidation	2-3 days with ABA support	[3], [4]
Column Leach Test	Simulate long-term ARD generation in controlled conditions	Leachate pH, EC, (sulfate: SO_4^{2-}), metal concentrations	**Advantages:** Realistic results. **Disadvantages:** Time-intensive, labor-heavy	2-6 months	[5], [6]
Humidity Cell Test (HCT)	Assess ARD generation under oxidizing conditions over time	pH, EC, sulfate, and dissolved metals	**Advantages:** Regulatory approval. **Disadvantages:** Long testing duration	20-40 weeks	[7], [8]
Geochemical Modelling (e.g., PHREEQC)	Predict ARD chemistry and mineral equilibrium	Ion activities, saturation indices, mineral stability	**Advantages:** Predictive modeling. **Disadvantages:** Sensitive to input assumptions	Weeks to months with calibration	[9], [10]

2. Methodology

To evaluate the acid rock drainage (ARD) potential associated with cemented paste backfill materials, a laboratory-based column leach experiment (Figure 1) was designed and executed in a controlled setting AT Drilling Technology Laboratory (DTL).

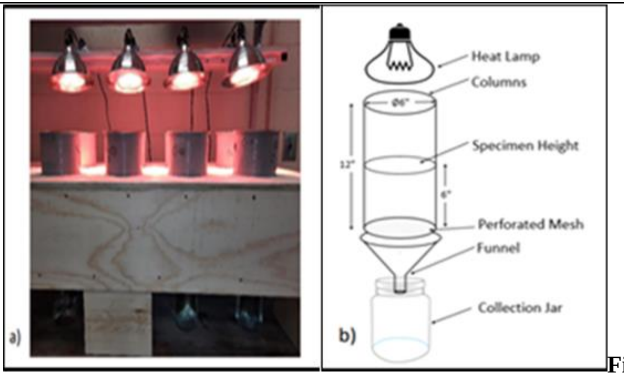

Fig. 1: Experimental set-up of column teach test: a) set-up in the Lab, b) schematic drawing of a single column [11].

The test setup consisted of vertically aligned polycarbonate leaching columns, each filled with backfill samples prepared at varying cement contents (2%, 4%, and 6%) and particle gradations, as guided by Jamil et al. [11] and Jamil [12]. Tailings and binder materials were thoroughly mixed using a mechanical agitator to ensure homogeneity. The prepared backfill mixtures were compacted into columns in three layers, with each layer subjected to gentle vibration to simulate field placement conditions, in line with procedures outlined by Quan et al. [14]. All columns were cured under laboratory conditions for 28 days before initiating leach testing, consistent with industry-standard timelines for backfill strength gain and stabilization.

The ARD set up was initially set up in 2022, and data recording has been collected since then. However, the data presented here shows the data collected since October 2023 to the present for a period of 70 weeks. Data collected before then was reported as indicated in the cited references [11-15].

The leaching experiment extended over a 70-week period, with data collected weekly during the initial 12 weeks and biweekly thereafter. Key monitoring parameters included pH, electrical conductivity (EC), sulphate (SO_4^{2-}), and metal ion concentrations (Fe^{2+}, Zn^{2+}, Cu^{2+}, Mn^{2+}), evaluated using a combination of pH meters, EC probes, and inductively coupled plasma optical emission spectrometry (ICP-OES). The study also incorporated solid-phase sampling at the beginning and end of the testing period to assess changes in mineral composition and cement hydration states. This long-term experimental protocol was adapted from the methodologies described in the theses by Jamil [12] and Someehneshin [15], which emphasized the importance of sustained monitoring to accurately capture the progressive nature of ARD formation and backfill performance under simulated underground conditions.

3. Results and Discussion

The results from the 70-week leach column experiment revealed a clear relationship between binder content and ARD suppression potential. Columns with higher cement content (particularly at 6%) exhibited consistently higher pH levels and lower sulphate and metal ion concentrations, indicating superior acid neutralization capacity. These findings corroborate those of Jamil [12], who reported that CPB mixtures with increased binder fractions buffered acid production more effectively due to the enhanced formation of pozzolanic and hydration reaction products. Moreover, particle gradation played a pivotal role: well-graded mixtures demonstrated more efficient neutralization performance, likely due to reduced permeability and increased physical entrapment of leachates, findings also observed by Jamil et al. [11].

The mechanical properties and geochemical behaviour of the backfill samples showed interdependence. For example, the samples that achieved higher UCS values during initial curing, similar to those reported by Someehneshin et al. [13] and Quan et al. [14], also tended to exhibit lower ARD potential throughout the leach testing phase. This suggests that mechanical strength enhancements through proper mix design and binder optimization not only improve structural performance but also act as a secondary control on fluid transport and acid generation. The outcomes of this study strongly align with the dual-objective research approaches highlighted by Someehneshin [15], reinforcing the need for integrated mechanical-environmental evaluation when designing backfill strategies for modern underground mining systems

3.1. pH Comparison (NV vs WV)

2% Cement

In Figure 2, both NV and WV samples show moderate pH stability over the 70-week period. WV consistently maintained higher and more stable pH values around 7.5-7.6, while NV fluctuated more between 7.1 and 7.4. The enhanced stability in WV samples reflects better buffering, likely due to improved particle bonding and moisture distribution from vibration

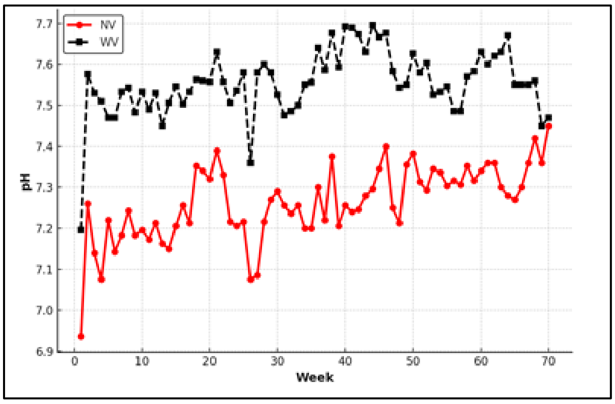

Fig. 2: pH Comparison (NV vs WV) for 2 % cement.

4% Cement

Figure 3 reveals that WV-treated samples maintained pH above 7.4 for most of the test duration, while NV showed noticeable dips in early weeks before stabilizing closer to WV. This suggests that moderate cement content benefits greatly from vibration, which enhances material uniformity and limits acidic channel development.

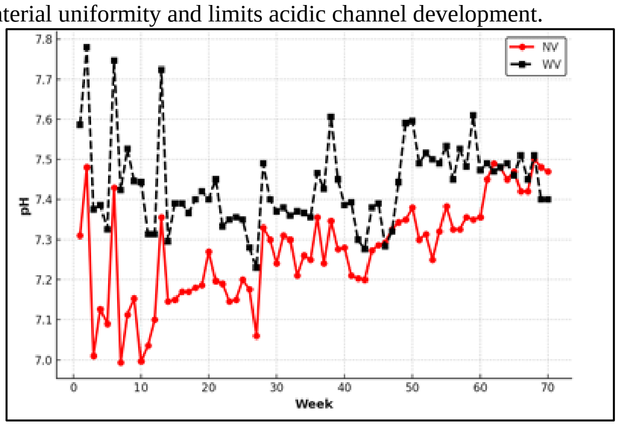

Fig. 3: pH Comparison (NV vs WV) for 4 % cement.

6% Cement

In Figure 4, both NV and WV treatments exhibit pH levels above 7.4. Interestingly, NV slightly outperforms WV in terms of peak values (~8.0), although WV is more consistent over time. This confirms that high cement content provides sufficient neutralizing potential in both cases, but vibration supports long-term chemical equilibrium.

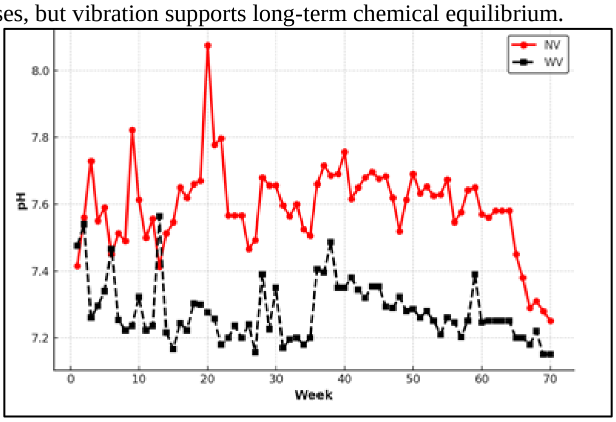

Fig.4: pH Comparison (NV vs WV) for 6 % cement.

Tailings (No Cement)

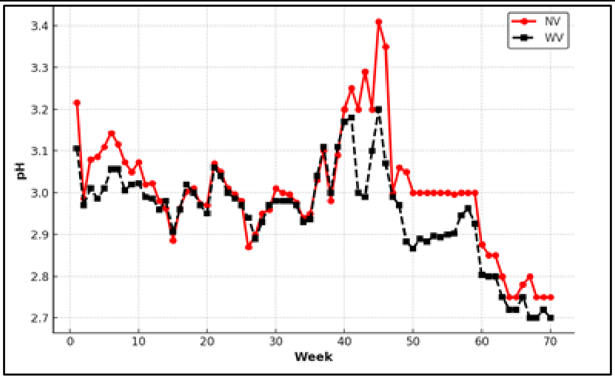

Fig.5: pH Comparison (NV vs WV) for 0% cement, only tailings.

Figure 5 illustrates severe acidification for both NV and WV, with pH values dropping to as low as 2.7 by week 70. WV offers no noticeable advantage. These results confirm that untreated tailings lack buffering capacity and that cement is essential for ARD mitigation, regardless of compaction.

3.2. EC Comparison (NV vs WV)

2% Cement

Figure 6 shows a general decline in EC over time for both NV and WV. However, WV consistently shows lower EC (~1.0 mS/cm), compared to NV (~1.4 mS/cm). This reflects better ion containment in compacted samples, even with minimal binder.

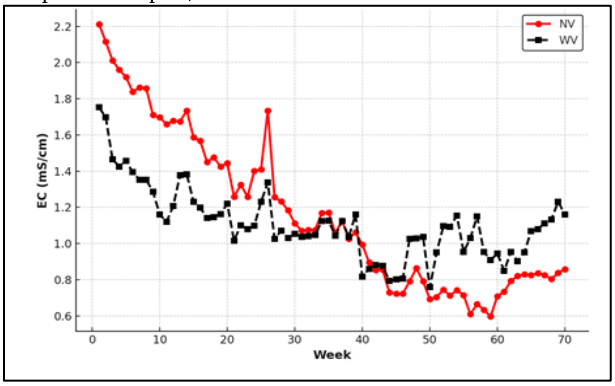

Fig. 6: EC Comparison (NV vs WV) for 2 % cement.

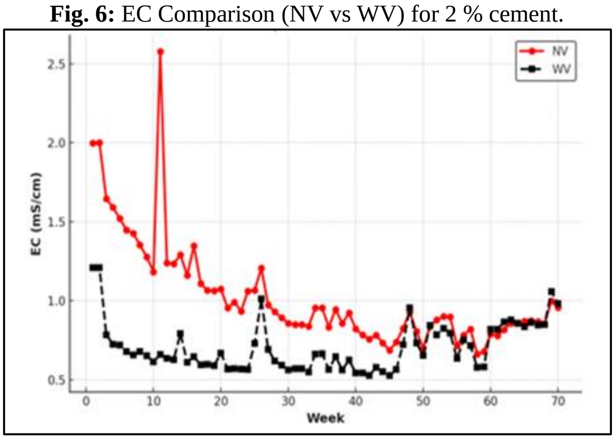

Fig. 7: EC Comparison (NV vs WV) for 4% cement.

4% Cement

In Figure 7, WV samples achieved a strong EC reduction, settling around 0.7-0.9 mS/cm, while NV fluctuated slightly higher. This demonstrates the enhanced performance of moderate cement content when combined with vibration, as compaction reduces permeability and ion migration.

6% Cement

Figure 8 indicates that both NV and WV treatments reduced EC to below 1.0 mS/cm. WV had a smoother and more consistent decline, while NV showed minor early spikes. This suggests that higher binder content ensures effective metal immobilization and ionic stability, especially when vibration assists with internal structure densification.

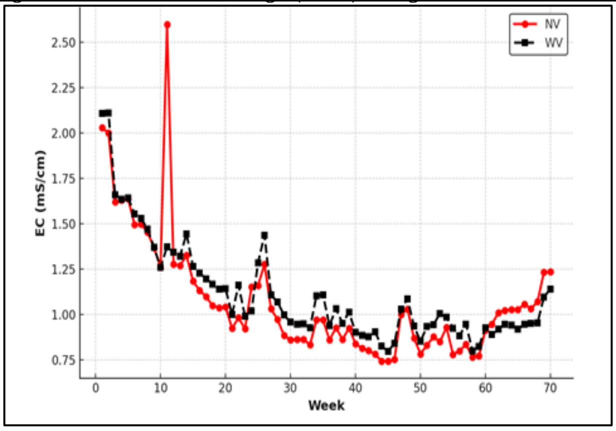

Fig.8: EC Comparison (NV vs WV) for 6 % cement.

Tailings (No Cement)

Figure 9 shows persistently high EC levels (1.5-3.0 mS/cm) in tailings with no cement. WV shows no meaningful reduction compared to NV, confirming that compaction alone does not reduce ionic mobility when no binding agent is present.

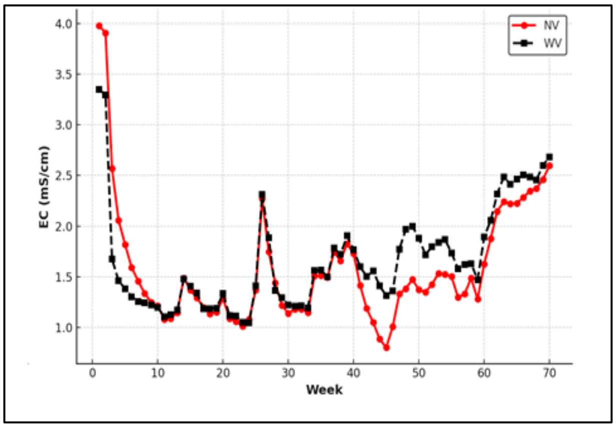

Fig.9: EC Comparison (NV vs WV) 0% cement, only tailings.

3.3. pH Analysis

The long-term pH monitoring of cemented tailings mixtures demonstrates the stabilizing effect of Ordinary Portland Cement (OPC) on acid generation, especially under vibration-assisted placement. For all vibration-treated (WV) samples, even the 2% cement mix was sufficient to maintain a neutral to slightly alkaline environment (pH 7.3-7.6), effectively suppressing Acid Rock Drainage (ARD). In contrast, tailings (without cement) exhibited a sharp and sustained drop in pH to highly acidic levels (~2.7-3.2), confirming their vulnerability to sulphide oxidation. No-vibration (NV) samples also provided reasonable buffering, but required at least 6% cement content to match the pH stability of 4% cement with vibration, highlighting the role of vibration in enhancing compaction, material uniformity, and geochemical containment, as shown in Figure 10.

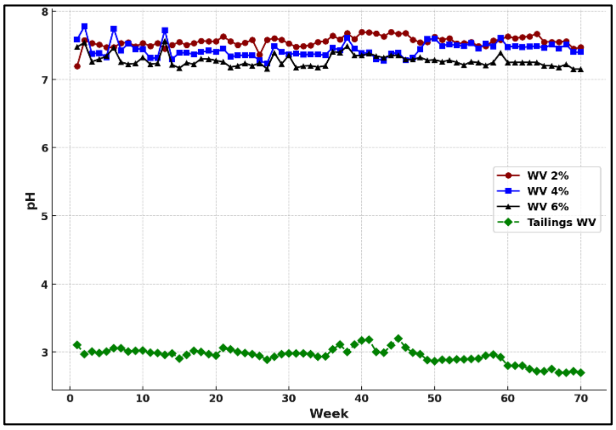

Fig.10: Comparison of pH for 2%, 4 %, and 6 % Cemented vs. Tailings with vibrations (WV).

3.4. EC Analysis

Electrical conductivity (EC), a key indicator of leachate ionic strength and metal mobility, also showed substantial improvement with increased cement content and the use of vibration. Cemented WV columns exhibited significantly lower EC values, consistently ranging from 0.6 to 1.2 mS/cm over the 70-week test period. In contrast, tailings under both WV and NV conditions maintained high EC values above 2.5 mS/cm, indicating ongoing leaching and sulphide oxidation. While NV columns with higher cement (6%) showed improvement, vibration-treated columns achieved comparable or better EC suppression at lower cement contents, especially at 4% OPC, reinforcing the importance of binder activation and physical densification during preparation, as shown in Figure 11.

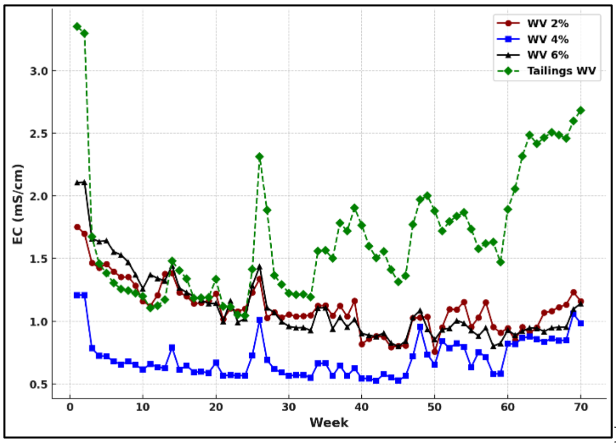

Fig. 11: Comparison of EC for 2%, 4 %, and 6 % Cemented vs. Tailings with vibrations (WV).

3.5. Economic Value of Vibration-Assisted Backfilling

The results shown in Figures 12 and 13 highlight the economic advantage of vibration-assisted backfill preparation in the consideration of both pH and EC data.

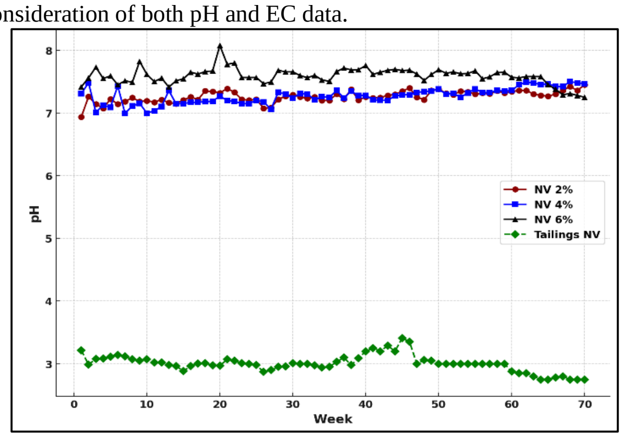

Fig.12: Comparison of pH for 2%, 4%, and 6% Cemented vs. Tailings with no vibrations (NV).

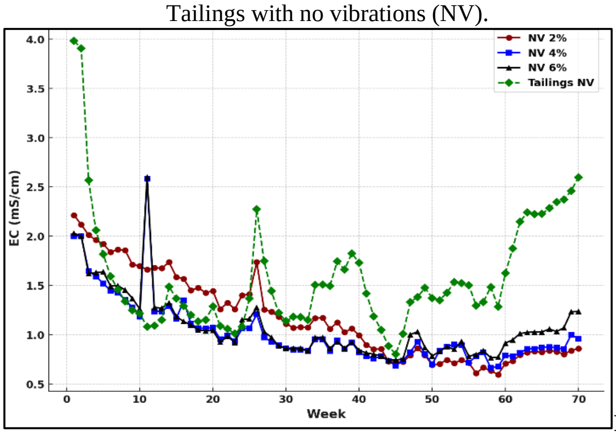

Fig. 13: Comparison of EC for 2%, 4%, and 6% Cemented vs. Tailings with no vibrations (NV).

By enabling effective ARD control with only 4% cement, vibration reduces the need for higher binder percentages (e.g., 6% in NV conditions), which directly translates to material cost savings**.** Additionally, lower cement use allows for higher proportions of tailings reuse, contributing to waste minimization and environmental compliance. This makes vibration not only a technical enhancement but also a cost-effective and sustainable strategy for underground mining operations dealing with ARD risks.

3.6. Acid Base Accounting (ABA) Risk Classification

Table 2 presents a comparative evaluation of acid rock drainage (ARD) behaviour in cemented and uncemented tailings columns, monitored initially in 2022 and again after a 70-week leaching period in 2025. Cemented columns (with 2%, 4%, and 6% cement) consistently maintained alkaline pH values (>7.2) and demonstrated decreasing or stable electrical conductivity (EC), indicating effective long-term neutralization of acidic components. These columns were classified as “Low acid risk” at both time points, confirming the durability of cement amendment for ARD mitigation. In contrast, the uncemented tailings columns (07_NV and 08_WV) exhibited highly acidic conditions from the start (pH < 2.8), which persisted through 2025 despite minor variations.

Table 2: Comparative ARD Assessment: Cemented vs. Uncemented Tailings (2022–2025).

Time	Colum no.	Column ID	pH	EC (mS/cm)	ABA Interpretation
2022 (Initial)	0	01_NV_2%	7.5	1.60	Low acid risk
	1	02_NV_4%	7.5	1.45	Low acid risk
	2	03_NV_6%	7.3	1.21	Low acid risk
	3	04_WV_2%	7.5	1.34	Low acid risk
	4	05_WV_4%	7.4	0.70	Low acid risk
	5	06_WV_6%	7.2	1.21	Low acid risk
	6	07_NV_Tailings	2.8	0.67	High acid risk
	7	08_WV_Tailings	2.7	0.65	High acid risk
2025 (70-Week Average)	0	01_NV_2%	7.3	1.17	Low acid risk
	1	02_NV_4%	7.3	1.02	Low acid risk
	2	03_NV_6%	7.6	1.08	Low acid risk
	3	04_WV_2%	7.6	1.11	Low acid risk
	4	05_WV_4%	7.4	0.71	Low acid risk
	5	06_WV_6%	7.3	1.11	Low acid risk
	6	07_NV_Tailings	3	1.58	High acid risk
	7	08_WV_Tailings	3	1.67	High acid risk

Their EC values increased significantly over time, reflecting ongoing sulphide oxidation and metal leaching. ABA interpretation consistently identified these columns as “High acid risk,” validating the original 2022 risk prediction. Overall, the table underscores the critical role of cement content in suppressing ARD and demonstrates that vibration has minimal influence on ARD behaviour in the absence of cement.

4. Conclusions and Recommendations

This study evaluated the long-term ARD behaviour of cemented and uncemented tailings columns under vibrated (WV) and non-vibrated (NV) conditions using pH and EC monitoring over 70 weeks. Results clearly indicate that cement addition is the primary and most effective factor in ARD mitigation. Cemented columns maintained alkaline pH and stable or declining EC, while uncemented tailings remained strongly acidic with rising EC, confirming the predictions made by ABA analysis in 2022. Although vibration provided marginal benefits in reducing EC in some cemented columns, its effect was not significant in preventing ARD without cement. The findings affirm that binder incorporation, not vibration, is essential for effective ARD control in mine backfill systems. The following points are some specific conclusions and recommendations:

- Cement-treated columns (2%, 4%, 6%) effectively controlled ARD, maintaining pH > 7 and EC < 1.2 mS/cm over 70 weeks.
- Uncemented tailings consistently exhibited low pH (< 3.1) and high EC (> 1.5 mS/cm), confirming their high ARD potential.
- Vibration had a limited influence: It slightly lowered EC in some cemented cases (e.g., 4% WV) but was not effective alone in ARD suppression; however, it shows economic benefits.
- A minimum of 2% cement is sufficient to control ARD under standard conditions; however, 4% cement offers better long-term stability.
- For high-sulphide tailings or critical containment zones, 6% cement is recommended to ensure robust ARD mitigation.
- Mechanical vibration (WV) may be used to improve mixing and structural uniformity, but should not substitute cement for ARD control.
- Cement-free backfill or tailings disposal without stabilization should be strictly avoided, as they fail to suppress acid generation.
- ABA screening should be used in advance to guide binder percentages and ensure materials fall in the NNP > 0, NPR > 2 category for low-risk classification.

5. Nomenclature

ABA	Acid-Base Accounting
AP	Acid Potential
ARD	Acid Rock Drainage
CPB	Cemented Paste Backfill
DTL	Drilling Technology Laboratory
EC	Electrical Conductivity
HCT	Humidity Cell Test
NAG	Net Acid Generation
NNP	Net Neutralization Potential
NP	Neutralization Potential
NPR	Neutralization Potential Ratio
NV	No Vibration
OPC	Ordinary Portland Cement
pH	Potential of Hydrogen
WV	With Vibration

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