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Article

Mitigation of Acid Mine Drainage Using Blended Waste Rock in Near-Equatorial Climates—Geochemical Analysis and Column Leaching Tests

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Abstract: Acid mine drainage (AMD), wherein acidic water is generated from pyrite-containing waste rock, can be mitigated by encapsulating pyritic waste rock with cover materials to restrict the inflow of oxygen and water. However, acidic water inevitably forms during the construction of waste rock dumps before applying cover materials. Considering that the presence of waste rock containing carbonate minerals contributes to acid neutralization, a mixture of carbonate minerals and pyritic waste rock can be utilized to reduce AMD generation before the completion of the cover system as a temporary management strategy. This paper examines waste rock management using blending scenarios. Kinetic NAG and column leaching tests were employed to evaluate the blending ratio necessary to prevent acidic water generation. Geochemical analyses were conducted on rock and leachate samples, including pH and temperature measurements, XRD and XRF analyses, and Ion Chromatography. Consequently, the pH and temperature measurement results obtained during the kinetic NAG test are valuable for expressing the balance between acid generation and acid neutralization by the mixture material. Furthermore, the column leaching test demonstrated that the pH of the leachate remained neutral when the acid generation and acid neutralization reactions were well balanced. Blending waste rocks is an effective method for AMD reduction during the construction of waste rock dumps.

Keywords: acid producing; acid neutralizing; blending; dry cover; encapsulation



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1. Introduction

Acid mine drainage (AMD), a significant environmental issue that has garnered international attention, is characterized by elevated concentrations of metal ions, such as iron, zinc, copper, nickel, arsenic, and cadmium, in mine drainage. This contamination can have detrimental effects on rivers and the surrounding ecosystem. Although remediating polluted water of near-neutral drainage globally requires more extensive efforts, AMD is recognized as one of the major issues to be addressed for mine closure. AMD is considered a long-term problem due to the complex geochemical processes in generating acidic water, making it challenging to halt the reactions once they have commenced. AMD is estimated to persist for hundreds or thousands of years [1,2]. In Japan, AMD generation from closed mines persists and is estimated to last more than one hundred years [3]. The

three primary approaches to addressing AMD issues are collection and treatment, control of sulfide oxidation, and passive remediation techniques, as shown in Figure 1 [4–7]. AMD generated from closed mines is mainly treated through collection and treatment by adding neutralizing agents to the wastewater. However, collection and treatment methods are not economically viable because they require continuous management and maintenance. Therefore, AMD source control, such as sulfide oxidation, is necessary at the early stages of mine development and as part of long-term management after mine closure. AMD is generated in mines from waste rock dumps, tailings dams, and open-pit and underground mine shafts. Due to the higher stripping ratio in open-pit mines, the volume of waste rock is significantly larger, rendering waste rock dumps a primary source of AMD. AMD prevention encompasses various approaches that are primarily aimed at minimizing contributing factors. These factors include oxygen supply, water infiltration and leaching, sulfide mineral availability, and bacteria (associated with biogeochemical processes). Furthermore, prevention methods may involve maximizing the availability of acid-neutralizing minerals or increasing the pH of infiltrated water [8].

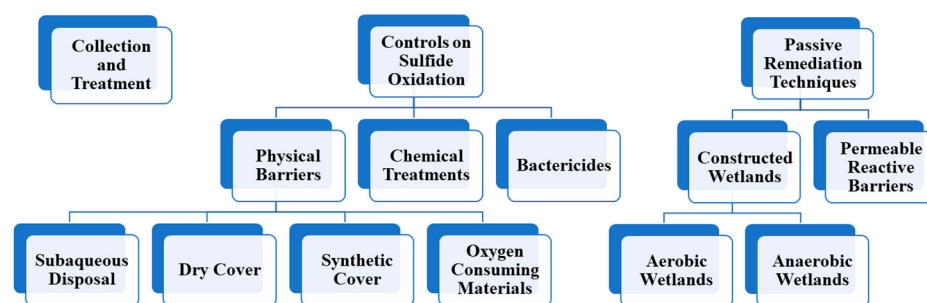


Figure 1. Classification of AMD countermeasures.

Due to its economic viability and adaptability, the dry cover system is a well-established mitigation measure for the acid mine drainage (AMD) problem in operational mines, particularly in waste rock dumps. In this system, waste rocks, the primary source of acidic water generation (potentially acid forming: PAF), are covered with non-acid-forming (NAF) rocks to minimize the influx of oxygen and water into the dump. This approach reduces the potential for sulfide mineral oxidation and mitigates the discharge of acidic water into the surrounding environment. However, several decades may be required to flush out the stored oxidation products that result from exposure to the atmosphere during the construction phase of the dry cover system. Consequently, the collection and treatment of drainage near the waste rock dump are necessary until the water quality improves, although the cover layer significantly reduces residual acidity and metal content. Therefore, it is crucial to investigate methods to mitigate acid water generation during waste rock dump construction. Implementing co-disposal and blending strategies presents a potential solution to address this issue.

Numerous researchers have extensively investigated co-disposal and blending strategies to enhance waste rocks' geotechnical and geochemical properties. This approach is anticipated to mitigate acid mine drainage (AMD) generation through the utilization of alkaline additives. The combination of limestone and sulfidic wastes has been examined to improve leachate quality [9–12]. According to a previous study, incorporating limestone effectively mitigated acid mine drainage (AMD) generation by neutralizing its effects. Furthermore, the reduction in AMD was attributed to the coating of sulfide mineral surfaces and the decrease in permeability resulting from the precipitation of ferric hydroxides and gypsum. Recent investigations have focused on the utilization of by-products and residues. Fly ash, classified as industrial waste, is a commonly employed material for co-disposal and blending due to its alkaline properties. Several researchers have elucidated the applicability of fly ash in enhancing leachate quality within blending and layering scenarios [13–17]. The mechanism for reducing acidic water generation is analogous to that of a limestone

mixture, wherein water quality is enhanced through its neutralization capacity, and the oxidation process is mitigated by microencapsulation. Tailings are also considered a viable material for co-disposal and blending due to their significant potential to minimize the infiltration of water and oxygen into sulfide minerals, which is attributed to their fine particle size. Furthermore, tailings are anticipated to have acid-neutralizing capacity if they contain carbonate minerals. Previous research has demonstrated that a reduction in permeability, an improvement in water retention capacity, and acid neutralization effects were observed after the blending or layering of tailings to minimize acid generation and metal leaching [18–24]. In recent studies, various materials have been investigated for dry covers, including low-permeability neutralized slag, sludge from settling ponds, sewage sludge, residue from pulp production, coal tailings, and municipal food and yard waste [25–30]. Nevertheless, the availability of these materials is occasionally constrained due to the cost and geographical location of the mine. Consequently, the co-disposal and blending of waste rocks is an alternative approach.

The presence of waste rocks with acid-neutralizing capacity has been confirmed at mine sites [31–34]. Consequently, the co-disposal and blending of waste rocks possessing acid-neutralizing capacity with potentially acid-forming (PAF) materials can effectively suppress acid water generation when these rocks are combined in an appropriate mixture ratio. The enhancement of the geochemical properties of waste rock through blending was substantiated by static test results [35]. A waste rock classification system for the design of waste rock dumps, including blending, was proposed. This system, termed the Triple Characterization Criteria (TCC), comprises the neutralizing potential ratio (NPR), acid generation (NAG pH), and the modal mineralogy weathering index (MMWI) [36,37]. However, assessing the balance between acid-producing and acid-neutralizing processes in blending waste rocks remains challenging.

This investigation focuses on blending waste rocks containing carbonate minerals with waste rocks containing pyrite to mitigate acid water generation until the construction of the cover layer. The equilibrium between acid production and neutralization was examined using kinetic NAG and column leaching tests in various blending scenarios.

2. Materials and Methods

2.1. Static Geochemical Analysis

Three mudstone samples (WRD-1, WRD-2, and WRD-3) were obtained from a waste rock dump in the Kyaukpahto gold mine, Myanmar's first open-pit gold mine.

X-ray diffraction (XRD) analysis and X-ray Fluorescence (XRF) analysis were conducted to investigate the mineral and elemental compositions of the samples. A Rigaku RINT 2000 instrument was utilized in the XRD analysis to confirm the mineral content under the following conditions: radiation $\text{CuK}\alpha$, operating voltage 40 kV, current 26 mA, divergence slide 1 deg, anti-scatter 1 deg, receiving slit 0.3 mm, step scanning 0.050° , scan speed $2.000^\circ/\text{min}$, and scan range $2.000\text{--}65.000^\circ$. The XRF analysis was performed using a Rigaku RIX 3100 instrument. The static geochemical approach is widely adopted to evaluate rocks' acid-producing/acid-neutralizing potential. This study also employed standard static methods to investigate the geochemical properties of the waste rocks. Geochemical analyses were conducted according to the standards proposed by AMIRA [38]. These included a paste pH test, a Net Acid Generating (NAG) test, and an Acid–Base Accounting (ABA) test. In the paste pH test, rock samples were dissolved in deionized water following pulverization. The change in pH was recorded as the paste pH after 12 h of the dissolution process. In the NAG test, rock samples were subjected to a forced oxidation process using hydrogen peroxide. The samples' potential for acid production was quantified based on the change in pH, which is reported as the NAG pH after the dissolution process. Although NAG pH does not reflect all acid consumption, as some silicate minerals require long-term dissolution, it can indicate the acid generated by the sample after acid production and consumption. The balance between the acid-producing capacity and neutralization potential of rock samples was calculated based on the Maximum Potential Acidity (MPA)

and acid-neutralizing capacity (ANC) in the ABA test [39]. Maximum Potential Acidity (MPA) was calculated based on the sulfur content, whereas acid-neutralizing capacity (ANC) was determined through titration. The percentage of sulfur was ascertained from the X-ray Fluorescence (XRF) analysis results. The balance value was calculated as Net Acid-Producing Potential (NAPP). This value serves as an indicator of the acid-producing capacity of rocks during mining operations. Based on the MPA and ANC results, NAPP was calculated using the acid–base balance calculation method from the formula $\text{NAPP (kg H}_2\text{SO}_4/\text{t}) = \text{MPA} - \text{ANC}$. Rock was classified as potentially acid-forming (PAF) if $\text{NAG pH} \leq 4.5$ and $\text{NAPP} \geq 0 \text{ kg H}_2\text{SO}_4$, while it was classified as non-acid-forming (NAF) if $\text{NAG pH} \geq 4.5$ and $\text{NAPP} \leq 0 \text{ kg H}_2\text{SO}_4$ [40]. Rock types not classified as PAF or NAF were classified as uncertain (UC).

2.2. Kinetic NAG Test

The kinetic NAG test is a modified version of the NAG test that includes monitoring the temperature and pH during the procedure. According to Miller et al. (1997) [40], the kinetic NAG test can indicate lag times and oxidation rates similar to those of leach columns. Previous researchers conducted kinetic NAG tests to predict leach column lag times [41]. They confirmed that the kinetic NAG test is helpful in providing complementary data to predict lag times in column leaching tests, although it did not replace column leach tests due to certain limitations: varying reaction rates in sulfide minerals, armoring or encapsulation of sulfide minerals in column leaching tests, and differing durations of acid-buffering reactions. During the kinetic NAG test, acid-producing and acid-neutralizing reactions can also be quantified by measuring the variations in temperature and pH during the reaction between hydrogen peroxide and a rock sample over time. Furthermore, excessive oxidation of sulfides may be detected through temperature monitoring, as samples containing sulfides typically exhibit a temperature increase throughout the NAG test, which is attributed to the exothermic reaction of sulfide oxidation. Kinetic NAG tests were conducted to analyze and compare the formation of acidic water when the waste rocks were blended. The WRD-1 sample was blended with WRD-2 and WRD-3 at mixing ratios ranging from 20% to 80% by weight. A 2.5 g sample consisting of particles less than 75 μm in size was placed into a 500 mL beaker. Subsequently, 250 mL of hydrogen peroxide solution with a concentration of 15% was added to the beaker. A thermocouple (SUS316; Chino Corp., Tokyo, Japan) and pH meter (WM-32P; DKK-TOA Corp., Tokyo, Japan) were inserted into the beaker. The temperature and pH were continuously monitored and recorded for 12 h. Data were collected at one-minute intervals using a data recorder (GL220; GRAPHTEC, Yokohama, Japan).

2.3. Column Leaching Test

The concept of the column leaching test is illustrated in Figure 2. Columns with a diameter of 41 mm and height of 80 mm were utilized in the column leaching experiment. This column was equipped with filter paper and glass beads positioned at the base of the sample. Six columns were established with a blending layer of waste rocks, and three control columns were used. The particle size diameters of the samples ranged from 1 mm to 2 mm. Each column was filled with 30 mL of deionized water from the top. The leachate accumulated near the base of the column. After the water flow, the columns underwent a drying procedure in the laboratory, simulating the climate of near-equatorial sites. This procedure involved exposing them to light for 6 h daily for 5 days. The aforementioned process was repeated for 10 cycles. The water collected in each cycle was analyzed for pH, major anions, and cations after passing through 0.45 μm filters using Ion Chromatography (930 Compact IC Flex; Metrohm).

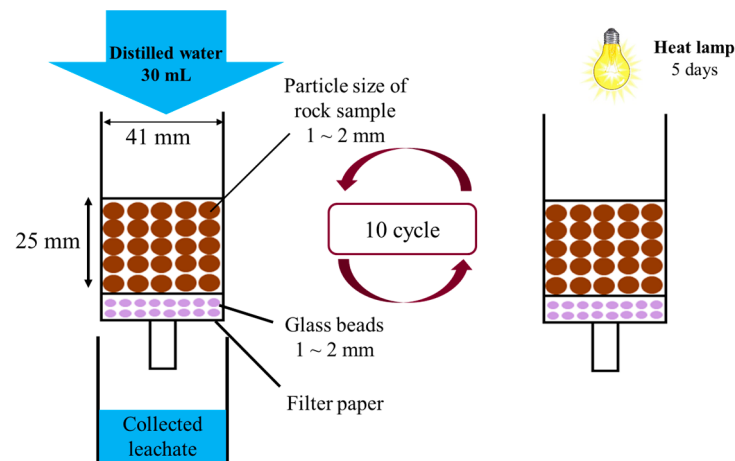


Figure 2. An outline of the column leaching test.

3. Results and Discussion

3.1. Geochemical Properties of Rock Sample

Figure 3a–c present the XRD analysis results. X-ray diffraction analysis confirmed the presence of quartz (SiO_2), illite ($\text{K}_{0.6}\text{Al}_{12}(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$), and kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) in all rock samples. Calcite and dolomite were identified as carbonate minerals in WRD-1. Conversely, pyrite was detected as a sulfide mineral in WRD-2 and WRD-3. Based on the XRD analysis, pyrite, dolomite, and calcite play significant roles in the rapid dissolution process. This is attributed to the low reactivity of quartz, illite, and kaolinite. The results of XRF analysis for the major elements are presented in Table 1. The analysis revealed that the materials exhibited substantial enrichment in silica (SiO_2), alumina (Al_2O_3), iron oxide (FeO), K_2O , MgO , CaO , and sulfur. It was also observed that WRD-1 contained a considerably higher quantity of alkali components. Furthermore, the sulfur content of WRD-3 was elevated (1.64%).

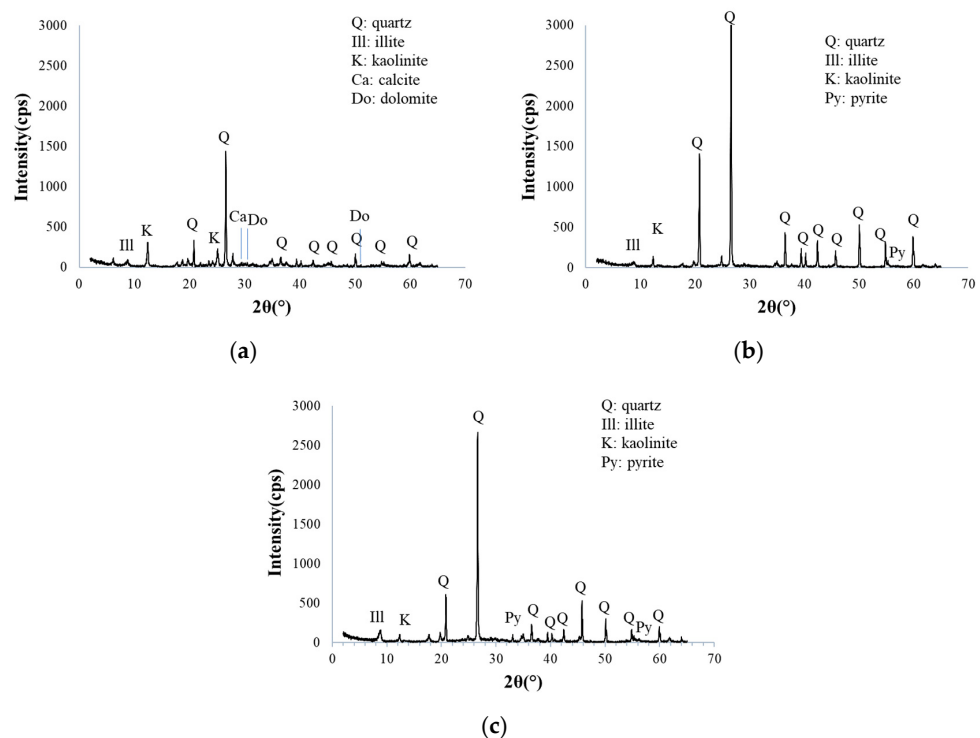


Figure 3. Results of XRD analysis: (a) WRD-1; (b) WRD-2; (c) WRD-3.

Table 1. Elemental composition from XRF analysis.

Sample	SiO ₂ (%)	Al ₂ O ₃ (%)	FeO (%)	MnO (%)	K ₂ O (%)	MgO (%)	CaO (%)	S (%)
WRD-1	57.74	17.54	7.18	0.12	3.34	5.30	1.22	0.14
WRD-2	85.34	7.53	0.73	0.00	1.69	0.71	0.04	0.51
WRD-3	71.91	13.99	2.35	0.01	3.39	0.85	0.06	1.64

Table 2 demonstrates that WRD-1 exhibited a NAG pH of 7.8 and a negative NAPP, indicating its classification as NAF. Furthermore, the negative NAPP value suggests that the sample possesses acid-neutralizing capacity. This characteristic is attributed to the presence of carbonate minerals, which function as buffers against acidity. Conversely, WRD-2 and WRD-3 were classified as PAF due to their NAG pH values below 4.5 and positive NAPP. WRD-3 displayed lower paste pH and NAG pH values and a higher NAPP than WRD-2, indicating a greater acid-producing potential. This enhanced acid-producing capacity can be attributed to the elevated sulfur content of WRD-3 (1.64%), as evidenced by the elemental composition values obtained from XRF analysis. Table 3 presents the NAPP calculation results for specific mixture ratios. NAPP decreases with an increasing WRD-1 mixture ratio. Sufficient neutralizing effects can be anticipated when blending waste rocks containing acid-buffering minerals.

Table 2. Static geochemical evaluation for rock classification.

Sample	Paste pH	NAG pH	S Mass (%)	MPA *	ANC *	NAPP *	Classification
WRD-1	8.5	7.8	0.14	4.1	19.3	−15.2	NAF
WRD-2	4.3	3.6	0.51	15.7	−2.2	17.9	PAF
WRD-3	3.3	2.4	1.64	50.1	−10.6	60.7	PAF

* in kg H₂SO₄/ton; MPA: Maximum Potential Acidity; ANC: acid-neutralizing capacity; NAPP: Net Acid Potential Production; NAG: Net Acid Generating. Calculation: MPA = Total S% * 30.6; NAPP = MPA − ANC. Classification: NAF: NAG pH ≥ 4.5 and NAPP ≤ 0; PAF: NAG pH < 4.5 and NAPP > 0; PAF: potentially acid forming; NAF: non-acid forming; UC: Uncertain.

Table 3. NAPP calculation with different mixture ratios of waste rocks.

Sample	WRD-1 (%)	WRD-2 (%)	WRD-3 (%)	NAPP (kg H ₂ SO ₄ /ton)
1	100	0	0	−15.2
2	60	40	0	−1.9
3	40	60	0	4.7
4	20	80	0	11.3
5	0	100	0	17.9
6	80	0	20	0.0
7	60	0	40	15.2
8	40	0	60	30.4
9	0	0	100	60.7

3.2. Evaluation of the Balance of Acid-Producing/Acid-Neutralizing Reaction with the Kinetic NAG Test

Figures 4 and 5 illustrate the results of the kinetic NAG test, demonstrating the variations in pH and temperature over time. The findings indicate that the initial pH and the pH after 720 min decreased as the mixture ratio of WRD-2 and WRD-3 increased. This phenomenon can be attributed to the insufficient acid-neutralizing reactions with carbonate mineral dissolution compared to the acid-producing reaction with sulfide oxidation. During the kinetic NAG test, the pH exhibited a consistent upward trend, ultimately approaching a neutral value when the NAPP was negative (−1.9 kg H₂SO₄/ton), as depicted in Figure 4a. This observation suggests that the carbonate minerals possess a greater capacity

to neutralize acid than the acid generated by the oxidation reaction of sulfide minerals. Consequently, blending waste rock with sufficient acid-neutralizing capacity may prevent acidic water generation. As shown in Figure 4a–c, no significant temperature changes were observed. However, for WRD-2 = 100% (Figure 4d), the pH rapidly became acidic at the onset of the experiment, accompanied by a temperature increase due to the oxidation of sulfide minerals. This result indicates that temperature changes can be observed when substantial oxidation reactions with sulfide minerals occur.

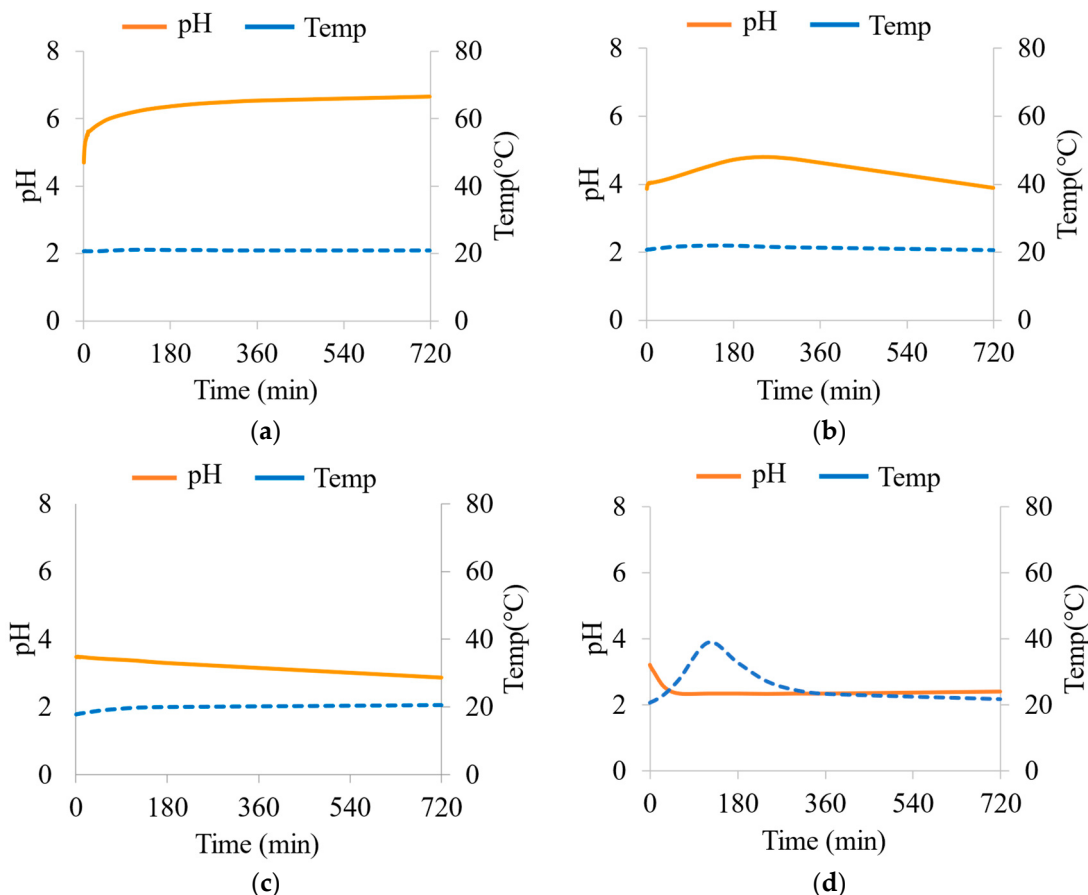


Figure 4. Results of the kinetic NAG test for a mixture of WRD-1 and WRD-2: (a) WRD-2 = 40%; (b) WRD-2 = 60%; (c) WRD-2 = 80%; (d) WRD-2 = 100%.

As illustrated in Figure 5a, the pH reached neutrality. At the same time, the initial phase of the test exhibited an acidic pH, indicating that the acid-neutralizing reaction occurred after the acid-producing reaction. Furthermore, the acid-neutralizing reaction surpassed the acid-producing reaction due to the NAPP of the mixture sample being 0 kg H_2SO_4 /ton. As demonstrated in Figure 5a,b, the pH decreased as the WRD-2 mixture ratio increased, whereas no significant variations in temperature were observed. Figure 5c,d depict a substantial temperature increase, as shown in Figure 4d, suggesting that the acid-neutralizing reaction was insufficient to counteract the acid-producing reaction. Moreover, the maximum temperature and the timing of the temperature rise differ: the 100% WRD-3 sample exhibits the highest maximum temperature and experiences a rapid temperature increase. This indicates that blending waste rock with an acid-neutralizing capacity can mitigate the oxidation reaction rate. Additionally, a significant quantity of sulfide minerals contributed to the oxidation reaction in WRD-3, as evidenced by its higher sulfur content than WRD-2.

These results indicate that the kinetic NAG test can effectively measure the equilibrium between acid-producing and acid-neutralizing reactions. Furthermore, significant

acid-producing reactions in materials with insufficient acid-neutralizing capacity can be identified by detecting temperature increases during the test procedure.

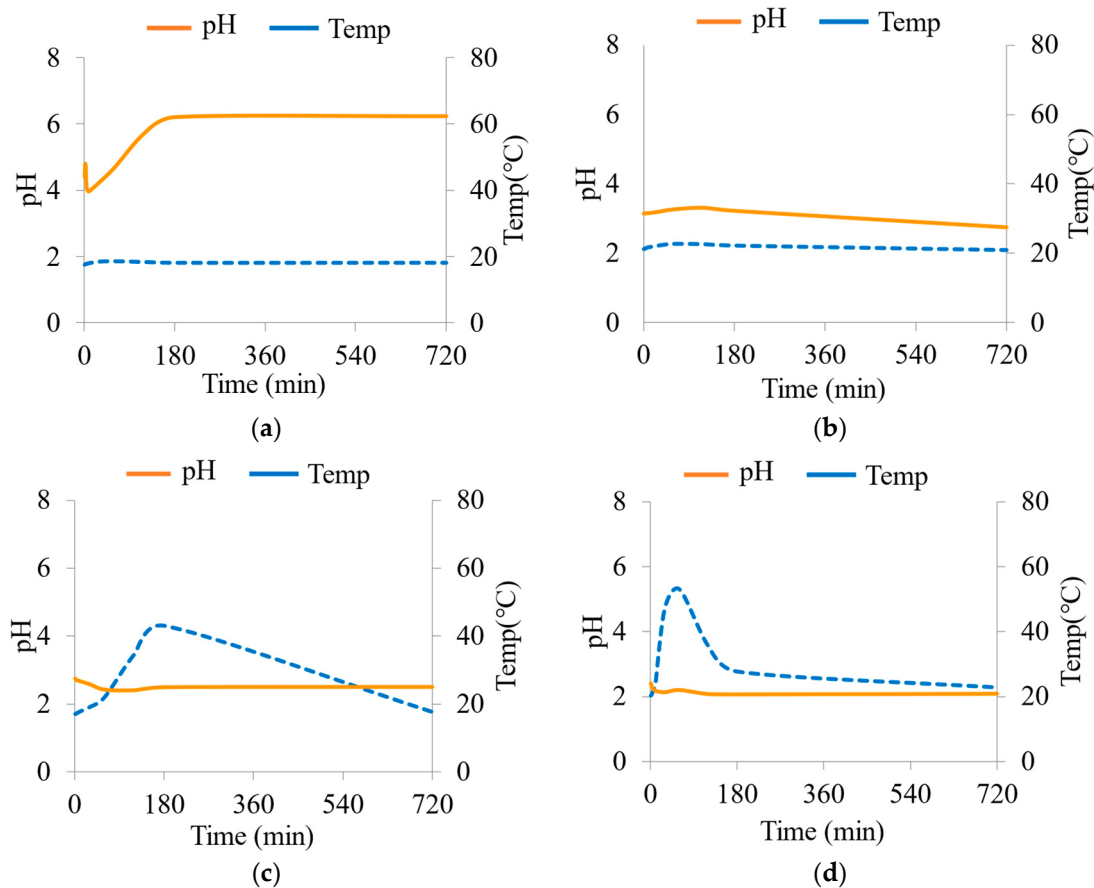


Figure 5. Results of the kinetic NAG test for a mixture of WRD-1 and WRD-3: (a) WRD-3 = 20%; (b) WRD-3 = 40%; (c) WRD-3 = 60%; (d) WRD-3 = 100%.

3.3. Demonstration of Leaching Behavior from Blending Waste Rocks

Figure 6a,b illustrate the pH results of the column leaching tests. Low pH was observed during the initial leaching test when PAF material was blended. These occurrences were attributed to the initial conditions of materials exposed to the atmosphere and humidity, resulting in the oxidation of sulfide minerals. The WRD-1 sample (WRD-2 and WRD-3 = 0%) exhibited a neutral pH throughout the experiment, whereas the 100% WRD-2 and WRD-3 samples demonstrated acidic conditions at pH = 4, even after 10 cycles. As depicted in Figure 6a, the pH decreased with an increased blending ratio of WRD-2. However, the pH approached neutrality after 10 cycles, although the duration required for the pH to increase varied. Alterations potentially influence these conditions in the column's geochemical reactions of carbonate minerals. The availability of neutralizing minerals such as calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) influenced the oxidation mechanism and water quality. Neutralization reactions occurred due to acidity: i.e., calcite and dolomite dissolved due to decreased pH. Previous research has observed a similar tendency, although the study examined a multi-layering system [42]. The remediation of pH was slower when the blending ratio of WRD-2 was larger. This can be attributed to the time required for the acid-neutralizing reaction to overcome the acid generation caused by the oxidation of sulfide minerals. Figure 6b demonstrates a gradual decrease in pH with an increase in the blending ratio of WRD-3. The pH was also lower than that of the sample blended with WRD-2; specifically, the pH of the leachate remained acidic throughout the experiment

when WRD-3 was blended at 60%. This is attributed to the higher sulfur content in the WRD-3 sample, resulting in more frequent sulfide oxidation than the WRD-2 sample.

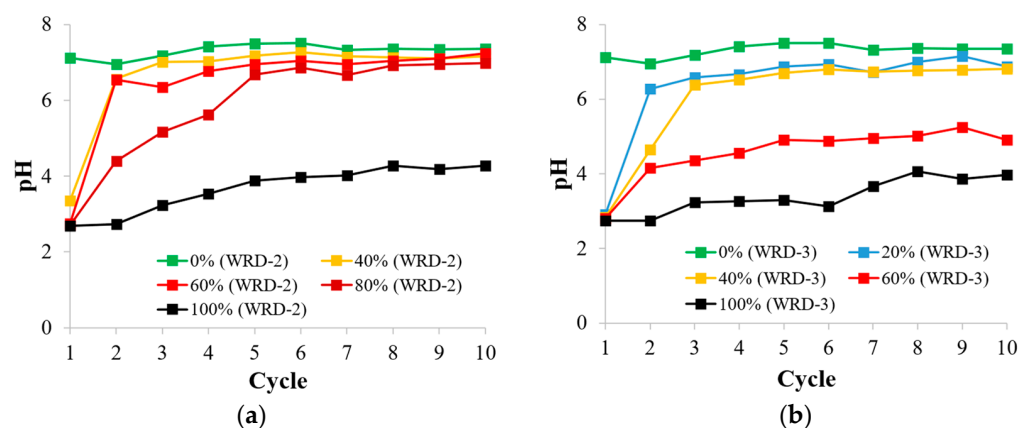


Figure 6. Results of pH in the column leaching test: (a) WRD-2; (b) WRD-3.

Table 4 presents the SO_4^{2-} and cation concentrations in the leachate. The leachate from cycles 2 and 6 was selected for water analysis to examine the reaction in the initial and equilibrium stages, considering the pH of the leachate in the column leaching test. The water quality of the leachate from blending samples is influenced by sulfur and carbonate minerals, which neutralize the acidity. Assuming that the oxidation of sulfide minerals is predominant in the production of acidic water, SO_4^{2-} can serve as an indicator of acid-producing reactions. Furthermore, the dissolution of cations reflects the results of the acid-neutralizing reaction of carbonate minerals. Since Ca^{2+} and Mg^{2+} are the primary ions, most acid-neutralizing reactions were attributed to the dissolution of calcite and dolomite contained in WRD-1. WRD-3 exhibited higher SO_4^{2-} dissolution than WRD-2 in cycles 2 and 6. This was attributed to the higher sulfur content in WRD-3. The dissolution of SO_4^{2-} generally demonstrated an upward trend with increasing mixture ratios of WRD-2 and WRD-3, with the exceptions of WRD-2 = 80% and WRD-3 = 60%. In these exceptional cases, the water flow path in the sample may have been affected by the dissolution of ions. As this test was conducted with free draining from the top of the column, it is plausible that the heterogeneity in the sample caused the water to flow preferentially into the channel formed by repeated dry and wet cycles. In such instances, the quantity of SO_4^{2-} ions eluted would have been reduced because the ions were primarily dissolved around the channel through the water flow path. An alternative explanation is that the fine grains produced by weathering of the sample may have encapsulated the sulfide minerals, thereby inhibiting the acid generation reaction. The dissolution of cations was correlated with the concentration of SO_4^{2-} . This correlation indicates that the acid-neutralizing reaction was enhanced when the acid-producing reaction was intensified.

Figure 7a,b show the oxidation–neutralization curve plotted with SO_4^{2-} and the sum of Ca^{2+} , Mg^{2+} , Na^+ , and K^+ in meq/L (charge of ions) [43]. This curve represents the geochemical evolution of the acid to neutralize the element-produced ratios [44,45], indicating that the acid-neutralizing reaction is in equilibrium with the acid-producing reaction if the plot is close to the 1:1 line. In the analysis of the leachate from cycles 2 and 6, as presented in Figure 7a, the WRD-2 = 40% and WRD-2 = 60% samples exhibit a balanced composition of cations ($\text{Na}^+ + \text{Mg}^{2+} + \text{Ca}^{2+} + \text{K}^+$) and SO_4^{2-} , irrespective of the cycle. However, in the WRD-2 = 80% sample, the quantity of SO_4^{2-} eluted exceeded that of cations in cycle 2, although SO_4^{2-} and cation concentrations were equilibrated in cycle 6 when the pH was neutral. Notably, the NAPP value at WRD-2 = 80% was 11.3 kg H_2SO_4 /ton, higher than those of the other samples. Consequently, the acid-neutralizing reaction rate was delayed for the blended sample with positive NAPP. Blended samples with negative and slightly positive NAPP (WRD-2 = 40% and 60%) demonstrated sufficient

capacity to elevate the pH to neutral in the initial stage. This indicates that these samples possess a high acid-neutralizing capacity against acid generation.

Table 4. Anion and cation concentrations in the leachate.

Sample	Cycle 2					Cycle 6				
	SO ₄ ^{2−} (mg/L)	Na ⁺ (mg/L)	K ⁺ (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	SO ₄ ^{2−} (mg/L)	Na ⁺ (mg/L)	K ⁺ (mg/L)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)
WRD-1	82.1	4.1	3.8	19.4	0.4	7.0	0.3	2.5	22.8	3.8
WRD-2 = 40%	532.8	0.7	4.4	198.4	19.7	87.6	0.0	0.0	52.1	4.9
WRD-2 = 60%	1273.2	2.2	0.0	423.2	56.7	271.4	0.0	0.0	104.0	8.2
WRD-2 = 80%	917.0	0.0	0.0	265.0	30.6	138.3	0.0	2.0	56.3	3.4
WRD-2 = 100%	4651.0	0.0	0.0	124.5	16.5	121.6	0.0	0.0	7.8	1.2
WRD-3 = 20%	833.2	1.0	4.8	290.4	40.3	443.5	0.0	2.6	168.7	15.6
WRD-3 = 40%	1591.0	0.0	0.0	520.5	67.5	1044.8	0.0	0.0	399.6	24.1
WRD-3 = 60%	871.7	0.0	0.0	137.4	32.3	391.9	0.0	0.0	103.5	14.0
WRD-3 = 100%	9851.5	0.0	0.0	35.0	108.0	1091.1	0.0	0.0	0.0	0.0

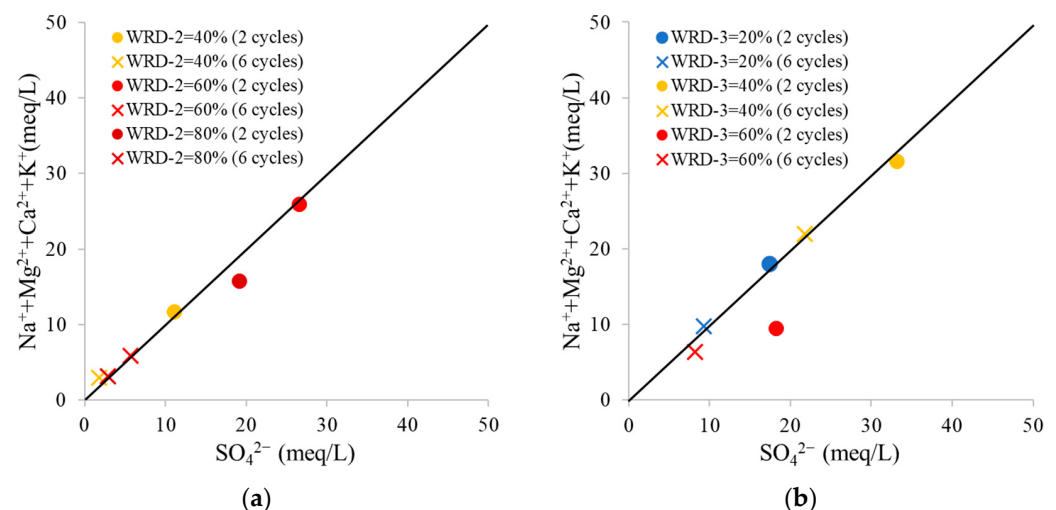


Figure 7. Oxidation–neutralization balance: (a) WRD-2; (b) WRD-3.

An analysis of the leachate from cycles 2 and 6, as depicted in Figure 7b, indicates that the WRD-3 = 60% sample eluted a greater quantity of SO₄^{2−} than cations, irrespective of the cycle. This outcome is consistent with the pH of the leachate. SO₄^{2−} and cations were equilibrated in both cycles 2 and 6 in the WRD-3 = 20% sample, which exhibited a neutral pH in the initial stage of the column leaching test. The WRD-3 = 40% sample demonstrated greater SO₄^{2−} dissolution than cations in cycle 2 when the pH was acidic. However, in the cycle 6, SO₄^{2−} and cations were equilibrated. The WRD-3 = 60% sample consistently exhibited an acidic pH, demonstrating 30.4 kg H₂SO₄/ton NAPP. NAPP was significantly higher than in the other samples, indicating that the leachate's acid neutralization capacity was insufficient, resulting in an acidic pH. Moreover, the WRD-3 = 60% sample increased the temperature due to the oxidation reaction of sulfide minerals in the kinetic NAG test. This finding suggests the potential to identify cases where sufficient acid neutralization is not anticipated due to significant oxidation reactions from PAF materials. In the WRD-3 = 20% sample with 0 kg H₂SO₄/ton NAPP, the pH of the leachate improved to neutral from the initial stage.

These results make mitigating acid water generation by blending waste rocks feasible. The proportion of waste rock can be determined by using NAPP as a benchmark. During this experiment, the pH of the leachate was neutral within 10 cycles, even in the sample with a positive NAPP value. This may be attributed to decreased rates of oxidation processes due to the armoring of sulfide minerals by fine particles resulting from rock weathering

processes and salt formation from oxidation processes. However, it has also been noted that AMD can rapidly coat and encapsulate the carbonate mineral, rendering it inert. Therefore, the armoring/encapsulation effects of sulfide and carbonate minerals on AMD mitigation require further investigation, including examining changes in geochemical properties over time.

4. Conclusions

This study utilized the kinetic NAG test and column leaching test to investigate the mitigation of acid water generation by blending waste rocks containing pyrite and waste rocks containing carbonate minerals. The kinetic NAG test confirmed the acid-neutralizing effect of carbonate minerals and the temperature increase due to the oxidation reaction of sulfide minerals, indicating its potential as an index for determining the optimal blending ratio of waste rock to inhibit acidic water generation. Furthermore, the test demonstrated the ability to identify significant PAF oxidation reactions and cases where acid neutralization is unlikely. The column leaching test revealed that pH levels improved to neutral when acid production and acid neutralization were balanced. Additionally, the study elucidated that blending waste rocks containing minerals with acid-neutralizing properties, such as carbonate minerals, can effectively suppress acidic water generation resulting from the oxidation of sulfide minerals. The blending ratio of waste rock can be determined using NAPP as a benchmark. Further research is necessary to assess the acid production–acid neutralization balance of blended waste rocks, including the consideration of armoring/encapsulation of sulfide minerals and carbonate minerals.

5. Patents

Not applicable.

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