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EVALUATION OF ACID MINE DRAINAGE NEUTRALIZATION USING CaO AND ALUM

Ridho Yovanda [1*], Audrey Faiza Rosa [2], Finny Marsyah [2], Wiya Elsa Fitri [2], Adewirli Putra [3]

[1] Department of Mining Engineering, Faculty of Engineering, Prabumulih University, South Sumatra, Indonesia.

[2] Department of Public Health, Syedza Saintika University, West Sumatra, Indonesia.

*Email : ridhoyovanda18@gmail.com

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Name : Ridho Yovanda
Affiliation : Faculty of Engineering, Prabumulih Univesity
E-mail : ridhoyovanda18@gmail.com

A B S T R A C T

Acid mine drainage (AMD) is a major environmental issue associated with coal mining activities, characterized by low pH and elevated concentrations of dissolved metals that can degrade water quality and harm aquatic ecosystems. Active treatment using alkaline materials such as quicklime (CaO) combined with coagulants like alum is widely applied to neutralize acidity and reduce metal content. This study aims to evaluate the effectiveness of CaO and alum in improving the pH of acid mine drainage. The research was conducted through a combination of field testing and laboratory analysis. The treatment process involved dosing quicklime and alum into acid mine drainage, followed by periodic pH measurements at inlet and outlet points over a one-month observation period. Data were analyzed using linear regression to determine the relationship between CaO dosage and pH changes. The results showed that the initial pH of acid mine drainage remained acidic, with an average value of 4.43, and increased slightly within the range of 4.43 to 4.76 after treatment. Regression analysis indicated a strong correlation (R^2 = 0.9537$) between CaO dosage and pH increase, suggesting that higher dosages contribute to improved neutralization performance. However,

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the achieved pH values have not yet met the environmental quality standard (pH ≥ 6), indicating that further optimization of treatment dosage and process conditions is required. These findings highlight that while the combination of CaO and alum has potential in neutralizing acid mine drainage, its current application is not yet sufficient to achieve regulatory compliance and improvements in treatment design are necessary.

INTRODUCTION

Acid mine drainage (AMD) is one of the most persistent environmental problems associated with coal mining activities worldwide. It is formed through the oxidation of sulfide minerals, particularly pyrite (FeS_2), when exposed to oxygen and water, producing sulfuric acid and dissolved metals. This process results in water with low pH and high concentrations of potentially toxic elements such as iron (Fe), manganese (Mn), and aluminum (Al), which can significantly degrade surface and groundwater quality. The long-term nature of AMD formation makes it particularly challenging, as it can continue even after mining operations have ceased, posing serious risks to aquatic ecosystems and surrounding communities (Adeniyi et al., 2022; Mukherjee et al., 2024).

In Indonesia, the rapid growth of the coal mining industry has intensified the occurrence of AMD, especially in regions with extensive open-pit mining activities. Poorly managed mine water can lead to severe environmental degradation, including contamination of river systems and disruption of ecological balance (Srivastava & Jha, 2025). Several studies have reported that untreated AMD typically exhibits pH values below 4.5, far below the acceptable environmental standards, and contains elevated levels of dissolved metals that can accumulate in living organisms and cause chronic toxicity (Kusdarini et al., 2026). Therefore, effective management strategies are essential to mitigate its environmental impact and ensure compliance with regulatory standards. Active treatment involves the addition of alkaline chemicals such as calcium oxide (CaO), calcium hydroxide ($Ca(OH)_2$), or sodium hydroxide (NaOH) to neutralize acidity and precipitate dissolved metals. On the other hand, passive treatment systems utilize natural processes, including constructed wetlands and organic substrates, to gradually improve water quality. Among these methods, the use of quicklime (CaO) remains one of the most widely applied techniques due to its high neutralization capacity and relatively fast reaction rate. In addition, alum (aluminum sulfate) is often used as a coagulant to enhance the removal of suspended solids and dissolved metals through coagulation-flocculation processes (Gałuszka, 2025; Otunola & Mhangara, 2024).

Previous studies have demonstrated that calcium oxide (CaO) is effective in increasing pH and facilitating metal precipitation in acid mine drainage (AMD) treatment systems (Seo et al., 2017). In addition, the use of aluminum-based coagulants such as alum has been shown to enhance metal removal efficiency through coagulation and co-precipitation mechanisms (Aleem et al., 2020; Nguegang & Ambushe, 2025). However, most existing studies focus primarily on pH adjustment or adsorption processes separately, with limited investigation into the combined application of CaO and alum, particularly under field conditions (Chen et al., 2022). Furthermore, there is still a lack of quantitative analysis examining the relationship

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between chemical dosage and pH improvement, especially using regression-based approaches to support process optimization (Sadek et al., 2023; Zhao et al., 2024).

Based on these considerations, this study aims to evaluate the neutralization of acid mine drainage using a combination of CaO and alum through field application and laboratory analysis. Specifically, this research focuses on analyzing changes in pH levels before and after treatment, as well as examining the relationship between CaO dosage and pH increase using linear regression analysis. The findings of this study are expected to provide practical insights into the effectiveness of combined chemical treatment for AMD management and contribute to the development of more efficient and optimized treatment strategies in mining operations.

This study provides a field-based evaluation combined with regression analysis, offering a quantitative approach to optimize AMD treatment.

METHODS

This study employed a quantitative experimental approach to evaluate the effectiveness of active treatment using calcium oxide (CaO) and alum in neutralizing acid mine drainage (AMD) (Akhtar, 2022). The research was conducted through a combination of field application and laboratory analysis to obtain both real-condition data and controlled measurement results.

The study was carried out over a one-month observation period. Acid mine drainage samples were collected from a mine water management system and subjected to treatment using CaO and alum. The treatment process began with the pumping of AMD into a treatment basin, where quicklime (CaO) was added as an alkaline agent to increase pH. Alum was subsequently introduced as a coagulant to enhance the aggregation and settling of suspended particles and dissolved metals. The dosing process was conducted gradually to observe the response of pH changes under different treatment conditions (Jones & Cetin, 2017).

The primary parameter measured in this study was pH, which was used as an indicator of acidity and treatment effectiveness. pH measurements were carried out at both inlet (before treatment) and outlet (after treatment) points using a calibrated digital pH meter with an accuracy of ±0.01. Measurements were conducted periodically during the treatment process over the study period to capture variations and trends in pH changes.

To analyze the relationship between CaO dosage and pH increase, a linear regression model was applied. The regression equation was used to determine the correlation between the independent variable (CaO dosage) and the dependent variable (pH value). The strength of the relationship was evaluated using the coefficient of determination (R^2). This analysis aimed to quantify the effectiveness of CaO in increasing pH and to estimate the required dosage to achieve target pH levels in accordance with environmental quality standards (Huang & Yang, 2021).

In addition to field measurements, supporting laboratory tests were conducted to validate the observed pH values and ensure data accuracy. The collected data were then tabulated and analyzed descriptively and statistically to evaluate treatment performance. The results were compared with the environmental quality standards for coal mining wastewater as stipulated in the Decree of the Minister of Environment No. 113 of 2003.

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RESULTS AND DISCUSSION

Characteristics of Acid Mine Drainage Before Treatment

The characterization of acid mine drainage (AMD) prior to treatment indicates that the water was consistently acidic, with an average pH value of 4.43 over a one-month observation period (Figure 1). This condition clearly does not meet the environmental quality standard for coal mining wastewater, which requires a minimum pH of 6. The relatively stable pH value throughout the observation period suggests that acid-generating reactions, particularly the oxidation of sulfide minerals such as pyrite (FeS_2), were continuously occurring in the mining environment.

Under such acidic conditions, the solubility of heavy metals such as iron (Fe), manganese (Mn), and aluminum (Al) increases significantly, enhancing their mobility and potential toxicity in aquatic systems (Mukherjee et al., 2024). This poses serious environmental risks, including water contamination and ecological imbalance. Acid mine drainage is typically characterized by low pH (often between 2 and 5) and elevated concentrations of dissolved metals (Zheng et al., 2023). Furthermore, AMD with pH below 5 can lead to long-term environmental degradation due to persistent acid-generating reactions (Alvarenga et al., 2021).

The persistence of low pH observed in this study indicates that without proper treatment, AMD will continue to degrade water quality. Therefore, active treatment using alkaline materials such as CaO is necessary to neutralize acidity and reduce environmental risks.

Figure 1. Measurement of pH levels of acid mine drainage

Effect of CaO and Alum on pH Changes

The application of quicklime (CaO) and alum in the AMD treatment process resulted in a measurable but limited increase in pH. The observed pH values after treatment ranged from 4.43 to 4.76 (Figure 3). Although this indicates that the treatment contributed to acidity reduction, the increase was not sufficient to reach neutral conditions (pH $\geq$ 6), meaning that the treated water still does not comply with environmental standards.

The treatment process involved the addition of CaO as an alkaline agent followed by alum as a coagulant, as illustrated in Figure 2. The use of alum plays an important role in enhancing the coagulation and flocculation processes, allowing suspended particles and dissolved metals to aggregate and settle more effectively. This process contributes to the clarification of AMD and supports the removal of contaminants that may influence water quality.

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Figure 2. Mixing of Chemical Organic Coagulant Inlet Channel at the experimental location

The increase in pH is primarily attributed to the reaction of CaO with water, forming calcium hydroxide ($Ca(OH)_2$), which releases hydroxide ions (OH^-) that neutralize hydrogen ions (H^+) in acidic water. However, the presence of alum introduces additional chemical interactions. Alum hydrolysis can produce acidic species, which may partially offset the alkalinity generated by CaO. This interaction likely contributed to the relatively small increase in pH observed in this study.

This finding is consistent with previous studies indicating that chemical treatment using alkaline agents can improve pH but may not always achieve optimal results due to competing reactions within the system (Masindi et al., 2017; Pocaan et al., 2025). Similarly, effective neutralization requires precise control of chemical dosage and adequate mixing conditions to ensure complete reactions (Tolonen et al., 2014).

The results suggest that while the combination of CaO and alum has potential for AMD treatment, the effectiveness of this method is highly dependent on operational parameters such as dosage, mixing intensity, and contact time.

This process also enhances the efficiency of metal precipitation, which indirectly supports pH stabilization.

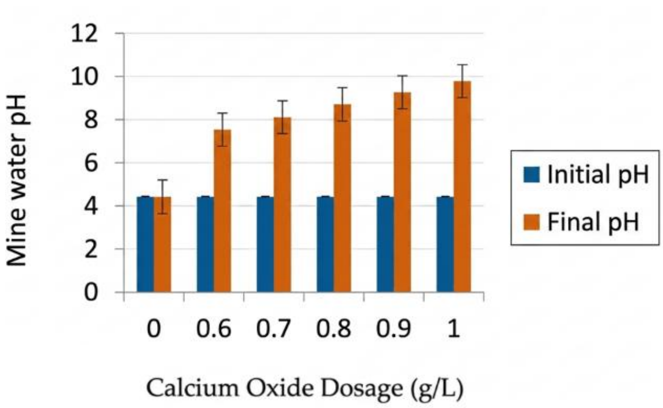

Figure 3. pH changes after adding quicklime (CaO) and alum

Regression Analysis of CaO Dosage and pH Relationship

The relationship between CaO dosage and pH increase was analyzed using linear regression, resulting in the equation:

$$y = 5.7753x + 4.0832$$

Where y represents the pH value and x represents the CaO dosage. The coefficient of determination ($R^2 = 0.9537$) indicates a very strong positive correlation, meaning that approximately 95.37% of the variation in pH can be explained by the variation in CaO dosage.

This strong correlation confirms that CaO plays a significant role in controlling the neutralization process of acid mine drainage (AMD). Increasing the dosage of CaO leads to a proportional increase in pH, which is consistent with the fundamental principles of acid–base reactions (Zhao et al., 2024). Similar findings have been reported in previous studies, where CaO dosage was identified as a key factor influencing AMD treatment efficiency (Othman et al., 2017).

Based on the regression equation, the estimated CaO dosage required to achieve specific pH values can be calculated as follows:

pH = 6 → x = 0.332
pH = 7 → x = 0.505
pH = 8 → x = 0.678
pH = 9 → x = 0.851

These results indicate that higher CaO dosages are required to reach neutral and alkaline conditions. However, within the dosage range applied in this study, the resulting pH values remained below the required standard. This suggests that although the relationship between dosage and pH is strong, the operational dosage range was not sufficient to achieve effective neutralization.

Comparison with Previous Studies

When compared with previous studies, the results of this research show a similar trend but lower effectiveness in achieving the desired pH levels. Previous studies have reported that active treatment using alkaline materials can increase AMD pH to near-neutral levels (pH 6–7) when appropriate dosages and operating conditions are applied (Huang & Yang, 2021; Iakovleva et al., 2015). In contrast, this study achieved a maximum pH of only 4.76, indicating that the treatment conditions were less optimal. This limitation may be associated with insufficient dosage, inadequate mixing, or competing reactions within the system (Turingan et al., 2020).

Furthermore, previous studies have demonstrated that combining active and passive treatment methods can significantly improve acid mine drainage (AMD) quality, including both pH adjustment and metal removal efficiency (Nguegang & Ambushe, 2025; Thisani et al., 2022). These findings suggest that relying solely on chemical treatment may not be sufficient, particularly in systems with high acidity, due to the inherent limitations of single-treatment approaches (Skousen et al., 2017).

In addition, previous studies have highlighted that the effectiveness of acid mine drainage (AMD) treatment is influenced by both pH adjustment and metal removal processes (Davies et al., 2011). The presence of dissolved metals such as iron and aluminum can significantly affect reaction dynamics and buffering capacity, thereby limiting pH increase during neutralization (Kalin et al., 2006; Nordstrom, 2020). This interaction may explain the limited pH improvement observed in this study.

The differences between this study and previous research can be attributed to several factors, including limited CaO dosage, chemical interactions involving alum, variations in AMD composition, and operational conditions such as mixing and contact time.

These findings emphasize that AMD treatment requires site-specific optimization and careful control of process parameters.

Implications for AMD Treatment Optimization

The findings of this study indicate that the use of CaO and alum provides a measurable improvement in AMD pH but has not yet achieved compliance with environmental standards. This highlights the need for further optimization of the treatment process.

Increasing the dosage of CaO is one potential approach to achieve the required pH levels; however, this must be balanced with economic considerations and the potential for increased sludge production. In addition, the role of alum should be carefully evaluated, as its hydrolysis may contribute to acidity under certain conditions.

An integrated treatment approach may offer a more effective solution for acid mine drainage (AMD). Previous studies have demonstrated that combining chemical treatment with additional processes such as sedimentation, filtration, and passive systems can significantly improve overall treatment performance and sustainability (Mokoena et al., 2025; Nguegang & Ambushe, 2025; Raphulu et al., 2024). These integrated systems enhance both pH adjustment and metal removal efficiency by utilizing complementary physical, chemical, and biological processes (Hou et al., 2021; Opitz et al., 2022).

Overall, this study demonstrates that while the combination of CaO and alum has potential in AMD treatment, its current implementation is not yet optimal. Further research and process optimization are required to achieve effective neutralization and compliance with environmental standards.

CONCLUSION

This study evaluated the application of active treatment using calcium oxide (CaO) and alum in neutralizing acid mine drainage (AMD) based on pH improvement. The results showed that the initial AMD condition was strongly acidic, with an average pH value of 4.43, indicating that it did not meet environmental quality standards. The addition of CaO and alum resulted in a measurable increase in pH, with values ranging from 4.43 to 4.76. This indicates that the treatment process contributed to acidity reduction; however, the improvement was not sufficient to achieve the minimum required pH of 6. Therefore, the current treatment conditions cannot yet be considered fully effective in meeting regulatory standards. Regression analysis demonstrated a strong relationship between CaO dosage and pH increase

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(R^2 = 0.9537), confirming that CaO plays a significant role in the neutralization process. Nevertheless, the applied dosage range in this study was not adequate to reach neutral conditions, indicating the need for dosage optimization. Overall, the combination of CaO and alum shows potential for AMD treatment, but further optimization of operational parameters, particularly CaO dosage and treatment conditions, is required to achieve effective neutralization and compliance with environmental standards.

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