

Research Article

Technical Evaluation of Fly Ash and Bottom Ash (FABA) Utilization for Acid Mine Drainage Mitigation in Coal Mining Operations

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Abstract: Acid mine drainage (AMD) continues to represent a long-term, technically complex environmental risk in coal mining operations, especially where waste streams are dominated by sulfide-rich, Potentially Acid Forming (PAF) materials. This study critically evaluates fly ash and bottom ash (FABA), a widely available by-product of coal-fired power plants, as an integrated geochemical–geotechnical amendment for AMD control. A detailed analysis approach is used, which includes checking the chemical makeup of materials, doing long-term tests to see how they react with water, and using computer models to predict how they will behave over many years. The findings show that the high amount of calcium oxide in FABA (between 18% and 25%) creates a steady level of alkalinity by dissolving calcium hydroxide. This helps quickly neutralize acidic liquids and causes iron, manganese, and aluminum to form stable hydroxide compounds. When 20% to 30% of FABA is mixed with PAF material, the pH level becomes almost neutral within 10 to 20 weeks, and more than 80% of dissolved metals are reduced. Computer models also show that using FABA as a cover layer that is 0.5 to 1 meter thick can keep the chemical environment stable for 10 years, while untreated PAF sites stay acidic. The results show that FABA works by combining chemical and engineering processes that stop pyrite from reacting and lower the amount of water and oxygen moving through the area. Also, using FABA again helps the environment by turning industrial waste into a cheap, widely usable, and eco-friendly material to deal with acid mine drainage.

Keywords: Acid Mine Drainage (Acid Mine Drainage (AMD); Fly Ash; Bottom Ash; Potentially Acid Forming Materials; Sustainable Remediation.

1. Introduction

Acid Mine Drainage (AMD) is one of the longest-lasting and most harmful environmental problems caused by coal mining, especially in areas where there are a lot of minerals that contain sulfides, like pyrite (FeS₂) [1, 3, 7]. When these minerals react with oxygen and water from the earth, they create acidic water that has harmful metals in it. This kind of water can last for many years and damage rivers, underground water, soil, and the health of ecosystems [1, 4, 8]. Because these chemical reactions continue on their own over time, the ways to fix AMD need to be both strong chemically and able to work well in real-world conditions over a long period [5, 10]. Along with increasing coal power production, Indonesia produces a lot of Fly Ash and Bottom Ash (FABA) as leftovers from burning coal. In the past, FABA was

seen as waste, but now people are starting to think of it as a helpful material for cleaning up mine waste. This is because it contains a lot of alkaline substances, especially calcium oxide (CaO), and it has a fine texture, making it easier to use in engineering projects. [9]. Although some studies have shown that alkaline industrial waste can help neutralize acid, there isn't much information in the global research on how these materials act together in complicated environments that mix water, chemicals, and soil over long periods [2, 9].

Acid Mine Drainage (AMD) is one of the longest-lasting and most harmful problems from coal mining, especially in areas where there are a lot of minerals containing sulfides, like pyrite (FeS₂) [1, 3, 7]. When these minerals mix with water and oxygen, they start a chemical reaction that creates acidic water full of metals. This type of water can last for many years and harms rivers, underground water sources, soil, and the environment as a whole [1, 4, 8]. Because the chemical reactions that cause AMD continue their own, it's important to use methods that work well chemically, are strong in terms of engineering, and can be used reliably over a long time [5, 10]. In Indonesia, as coal-fired power plants grow, a lot of Fly Ash and Bottom Ash (FABA) is produced because of burning coal. In the past, this waste was just disposed of, but now people are looking at FABA as a useful material for cleaning up mine waste. This is because FABA has a high amount of alkali, mainly from calcium oxide (CaO), and its fine texture makes it good for improving the performance of geotechnical systems [9]. Even though some studies have shown that alkaline industrial waste can help neutralize acidity, there isn't much research showing how these materials behave in complex systems involving water chemistry and soil over long periods [2, 9].

This study addresses a gap by using a thorough multi-method approach that combines physical analysis, static geochemical tests, long-term leaching experiments, and hydrogeochemical modeling over decades for waste- rock dumps. These kinds of combined methods are becoming more common in acid mine drainage (AMD) research because they allow for the simultaneous evaluation of chemical balance, water movement paths, and structural changes in potentially acid-forming (PAF) waste areas [2, 4, 5]. A major issue in current research is the limited look into how geochemical and geotechnical processes work together and affect long-term AMD formation. By bringing together lab observations and predictive models, this study offers a full picture of how FABA can be used effectively in mine waste management systems [1, 2, 6]. The results help increase understanding of how to reduce AMD and also offer helpful advice to policymakers, regulators, and industry experts who are trying to find ways to use resources in a sustainable way, fix the land, and keep the environment safe.

1. Materials and methods

1.1. Research Design and Analytical Framework

This study uses a clear and organized method to evaluate how well Fly Ash and Bottom Ash (FABA) can help control Acid Mine Drainage (AMD). The method has four main steps: gathering samples and examining the materials, conducting tests to observe how chemicals behave in still water, carrying out experiments to track how quickly metals are released over time, and using computer models to forecast changes in water chemistry over the long term. This method follows established guidelines, including the Global Acid Rock Drainage (GARD) Guide [5], U.S. EPA standards [6], and acid-base accounting methods from Sobek et al. [6].

1.2. Sampling Strategy and Geological Context

Sampling was carried out in various layers inside the active coal mine pits, focusing on rocks that have different levels of sulfur, which can influence acid production. A method called stratified

composite sampling was used to include changes both up and down the layers as well as side to side in the waste materials [1]. Every sample was collected following steps to prevent contamination and was kept in sealed containers during transport to maintain its chemical properties.

1.3. Physical Characterization of PAF and NAF Materials

The physical process involved drying the material in the air, breaking it into smaller parts, mixing it well, and then keeping it in a dry place. Key aspects like how big the particles were, how tightly they fit together, their natural water content, and how easily water could flow through them were checked. These measurements helped understand how water moves and how oxygen spreads, which are important for creating acid mine drainage [3, 7]. These physical properties also gave important information for testing how reactions happen over time and for making models that show how water and chemicals move through the material.

Table 1. Physical Characteristics of Waste Materials

Parameter	Value	Unit
Particle size range	0.15–20	mm
Bulk density	1.35–1.60	g/cm ³
Moisture content	8–15	%
Permeability	10 ⁻⁴ –10 ⁻⁶	m/s

1.4. Static Geochemical Assessment: Acid–Base Accounting

Static geochemical tests were done to determine if the materials are Potentially Acid Forming (PAF) or Non- Acid Forming (NAF). Tests were done to measure the pH of the paste, the total sulfur in the sample, Net Acid Producing Potential (NAPP), and Net Acid Generation (NAG). These tests used the acid base accounting (ABA) method [6], which gives an initial idea of how much acid each sample might create.

Table 2. Geochemical Properties of PAF–NAF Samples

Sample ID	pH Paste	S-Total (%)	NAPP (kg H ₂ SO ₄ /t)	Classification
PAF-01	3.1	1.90	62	PAF
PAF-02	3.4	2.10	74	PAF
NAF-01	6.8	0.05	-4	NAF
NAF-02	7.2	0.03	-2	NAF

Table 3. Major Oxide Composition of FABA

Oxide	Percentage (%)
SiO ₂	38–45
Al ₂ O ₃	17–22
CaO	18–25
Fe ₂ O ₃	4–7
MgO	1–3
SO ₃	0.5–1.5

1.5. Long-Term Hydrogeochemical Modeling of Waste Rock Dumps

Modeling of Waste Rock Dumps

Researchers did long-term computer simulations to understand how different ways of handling waste might affect the environment over 10 years. They used information about how easily water can move through soil, how much empty space is in the soil, how much water can soak into the ground, and how well the soil can neutralize acid. Different scenarios were tested, including areas where waste was not treated, cover systems made from mixed materials with different thicknesses, and situations with both treated and untreated waste. The results showed how acidity levels, acid-producing ability, and water movement changed over time.

Table 4. Parameters Used for Hydrogeochemical Modeling

Parameter	Value	Unit
Initial permeability	10^{-5}	m/s
Void ratio	0.25–0.40	-
FABA cover thickness	0.25–1.0	m
Blending percentage	10–30	%

2. Results and discussion

This part brings together results from experiments, how fast reactions happen, and models to better understand how Potentially Acid Forming (PAF) materials act when mixed with Fly Ash and Bottom Ash (FABA). The aim is to explain clearly how these materials interact, the chemical changes they cause, and how the whole system changes over time. All the findings are examined to see how they influence controlling acid mine drainage, the long-term behavior of the system, and how effective the treatment is for bigger applications.

2.1. Geochemical Characterization of PAF–NAF Materials

The study of chemical makeup showed a clear difference between PAF and NAF samples. PAF materials had low pH levels in the paste (3.1 to 3.4), high sulfur content (1.90 to 2.25%), and a strong ability to produce acid (62 to 81 kg of sulfuric acid per ton). These results show that PAF waste is likely to create acid when it comes into contact with oxygen and water. On the other hand, NAF samples had very little sulfur (6.5), which supports their category as non-reactive.

Table 5. Geochemical Classification of PAF–NAF Samples

Sample ID	pH Paste	S-Total (%)	NAPP (kg H ₂ SO ₄ /t)	NAG pH	Classification
PAF-01	3.1	1.90	62	3.4	PAF
PAF-02	3.4	2.10	74	2.9	PAF
PAF-03	3.2	2.25	81	3.1	PAF
NAF-01	6.8	0.05	-4	7.3	NAF
NAF-02	7.2	0.03	-2	7.6	NAF

These results provide an important starting point for evaluating how well FABA works. PAF materials that have NAPP values higher than 30 kg H₂SO₄ per ton usually need extra alkaline materials to be added, which means they are good candidates for the strategies discussed in this study.

2.2. Chemical and Mineralogical Characteristics of FABA

The XRF results show that FABA is mainly composed of SiO₂ (38–45%), Al₂O₃ (17–22%), and CaO (18–25%). A significant portion of the CaO helps neutralize acid by reacting quickly with water to form Ca(OH)₂, which releases hydroxyl ions and increases the pH of the system. Smaller amounts of Fe₂O₃ and SO₃ contribute to the formation of other minerals such as iron hydroxides and gypsum.

Table 6. Major Oxide Composition of FABA

Oxide	Percentage (%)
SiO ₂	38–45
Al ₂ O ₃	17–22
CaO	18–25
Fe ₂ O ₃	4–7
MgO	1–3
SO ₃	0.5–1.5

As a result, the mineral makeup of FABA makes it a reactive alkaline substance that can both reduce acidity and help remove metals through hydroxide precipitation.

2.3. Kinetic Column Experiments: pH Trends and Metal Attenuation

The tests on the kinetic columns showed how the chemistry of the leachate changed over time. In the columns without any treatment, the pH dropped quickly from 4.2 to about 2.8 within 10 to 12 weeks, which shows that pyrite was oxidizing faster. However, in the columns where FABA was added, the pH stayed higher. Blends with 20 to 30% FABA reached nearly neutral pH levels within 10 to 20 weeks.

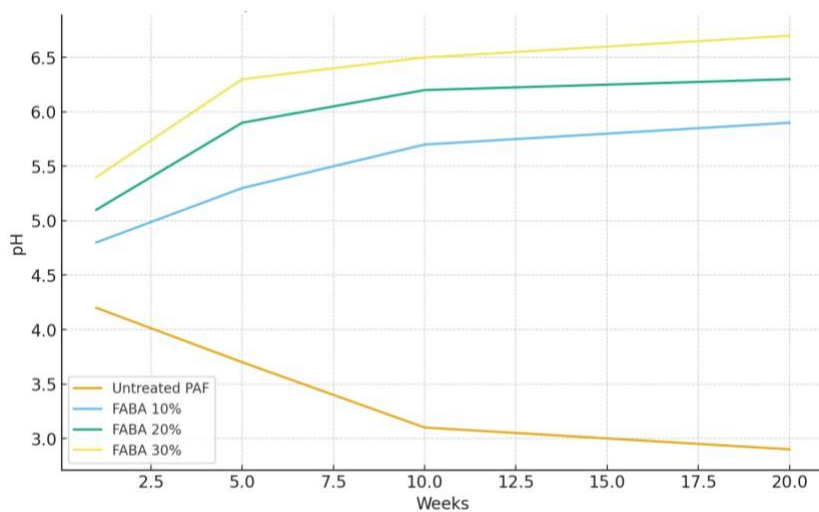


Figure 1. pH Evolution in Kinetic Column Tests

The pattern of metal reduction also supports these findings. Without treatment, the concentrations of dissolved Fe, Mn, and Al increased significantly as pH decreased. However, when 20% FABA was used, the levels of these metals dropped by approximately 80 to 88%, demonstrating that FABA effectively prevents the metals from migrating, mainly because it causes them to form solid deposits regulated by pH.

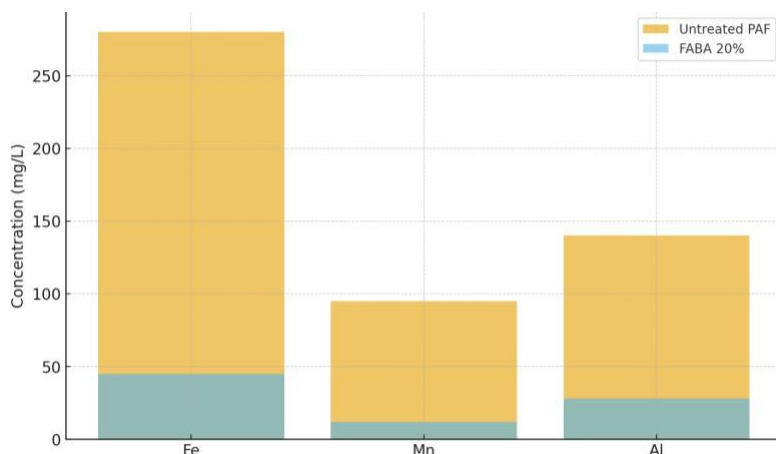


Figure 2. Dissolved Metal Concentrations at Week 20

Overall, these results show that adding FABAs greatly reduces acid production and keeps metals from moving, even when the leaching goes on for a long time.

2.4. Long-Term Hydrogeochemical Modeling

The results from the modeling provide important information about the long-term stability of waste-dump systems that include FABAs. In the case where no treatment is applied, the pH levels stayed below 3 for the entire 10-year simulation, showing that the conditions for ongoing, long-term acid mine drainage (AMD) are still present. However, when FABAs-based cover layers of 0.5 to 1.0 meters thick were used, the pH values increased to a range between 6.2 and 6.8, indicating a stable environment. Additionally, blending FABAs with PAF also showed greatly improved ability to neutralize acidic conditions.

Table 7. Modeled pH Progression Under Different Scenarios (10-Year Horizon)

Year	Untreated PAF	FABAs 0.5 m	FABAs 1.0 m
1	3.5	6.2	6.5
3	3.1	6.4	6.6
5	2.9	6.5	6.7
10	2.8	6.6	6.8

These long-term trends show that FABAs provides more than just immediate benefits for neutralizing acidity; it also helps maintain the stability of the system over time. The fine texture of FABAs reduces how much water and oxygen can enter the material, which slows down the process of sulfide oxidation.

2.5. Integrated Interpretation and Practical Implications

Taken together, these findings show that FABAs serves as a two-in-one solution for reducing AMD. On the chemical side, it quickly and continuously provides alkalinity, helps keep metals from moving into water, and encourages the formation of stable minerals. On the physical side, using FABAs lowers how easily water can flow through the waste, reducing the main causes of AMD. This combination of chemical and physical effects makes FABAs different from traditional neutralizing materials like limestone, which don't affect the physical properties of the waste. From

a practical standpoint, the evidence supports the use of FABA in large- scale AMD management by mixing it with other materials, placing it as a cover, or using a combination of methods. Also, reusing this widely available industrial by-product fits well with the goals of a circular economy and provides a cost-effective, sustainable way to manage mine waste.

3. Discussion

This section gives a summary of the key findings from the geochemical, geotechnical, and hydrogeochemical experiments and models in this study. Its main purpose is to put these results in a broader scientific context and to think critically about how viable it is to use FABA as a complete solution for managing AMD. The discussion focuses on understanding the processes involved, how well they align with other global research, and what practical uses they have for dealing with large-scale mine waste.

3.1. Coupled Geochemical Mechanisms of Alkalinity Release and Metal Immobilization

The ability of FABA to help reduce AMD is influenced by several geochemical processes, primarily because of its high calcium oxide content and reactive aluminosilicate structure. When FABA comes into contact with water, the calcium oxide reacts to form calcium hydroxide, which then breaks down to release hydroxide ions. This increases the pH of the system. As the pH rises, it causes a series of secondary reactions, such as the formation of hydroxides of iron, manganese, and aluminum. These minerals are more stable under nearly neutral pH conditions and help keep metal concentrations in solution low over time. In addition to forming hydroxides, gypsum can also form when sulfate from pyrite oxidation reacts with calcium ions released from the breakdown of FABA. This secondary mineral forms a buffer and locks sulfate into solid form. The fact that high alkalinity lasts for 20 to 40 weeks in column tests shows that FABA continues to dissolve gradually, allowing it to neutralize acidity even as leaching progresses.

3.2. Geotechnical Modifications and Their Influence on AMD Suppression

Besides its chemical role, this study also shows that FABA has important geotechnical benefits. Because of its fine particle size, when mixed with PAF, FABA reduces the size of the small openings in the material, which lowers the overall permeability and limits how much oxygen can enter. Since oxygen is a key factor in the oxidation of sulfides, this physical change slows down the process that creates AMD at the source. Also, the ability of FABA to compact improves the formation of low-permeability zones that stop rainwater from penetrating. These changes in water movement are essential for lowering the amount of water that flows through the waste rock, which in turn reduces the amount of acid and metals that are released. The modeling results suggest that these geotechnical changes provide real, long-term improvements in the stability of waste rock piles.

3.3. Positioning Findings Within Global AMD Mitigation Literature

The results of this study align with a growing body of international research that shows the potential of alkaline industrial by-products in treating acid mine drainage. Earlier work by Hakkou, McCullough, and others has shown that combining neutralization ability with carefully designed cover systems can help maintain environmental stability over time. What makes this study unique is its approach, which brings together real- world data on reaction rates with long-term hydrogeochemical models to create a complete picture of how these systems change over time. Additionally, using FABA as a treatment material supports global goals for sustainable resource

use and the development of a circular economy. In places like Australia, Canada, and the European Union, similar industrial by-products have already been used in restoring mine sites. This study adds to that global conversation by showing, in a specific Indonesian coal mining context, how effective FABA can be in these environments.

3.4. Operational Feasibility and Implementation Pathways

The operational implications of the findings suggest several practical pathways for integrating FABA into AMD management strategies:

1. **Blended Treatment:** Blending 20–30% FABA with PAF materials yields the most consistent improvements in pH and metal attenuation.
2. **Cover Layer Application:** FABA-based cover systems with thicknesses of 0.5–1.0 m provide substantial reductions in infiltration and oxygen diffusion.
3. **Material Handling and Compaction:** Optimal performance requires controlled moisture conditioning and compaction to achieve the intended geotechnical effects.
4. **Long-Term Monitoring:** Although predictive modeling indicates strong stability, periodic monitoring is recommended to detect potential climatic or geochemical perturbations.

These strategies offer scalable, economically viable options that can be integrated into existing mine waste management practices.

3.5. Limitations and Future Research Priorities

Even though the results are promising, there are some important limitations to consider. The composition of FABA can vary between different power plants, which might affect how well it works, so there is a need for standard ways to test and control its quality. Also, while lab experiments offer controlled settings, they can't fully capture the complexity of real-world conditions, such as changes in water levels throughout the year, interactions with living organisms, and the varied structures of waste rock piles. There's still not enough understanding about how secondary minerals evolve over time and how this affects the system's ability to neutralize acidity, and this needs more research. Moving forward, studies should focus on larger field tests, combined geological and chemical modeling, and thorough assessments of ecological risks. These efforts will be crucial for confirming what's observed in the lab, improving predictions about system behavior, and helping create informed policies and regulations for using these methods on a bigger scale.

4. Conclusion

The results of this study have several important implications for national and regional regulators, mining companies, and environmental agencies. First, the proven ability of Fly Ash and Bottom Ash (FABA) to reduce Acid Mine Drainage (AMD) offers a solid scientific foundation for including FABA in official mine closure and reclamation plans. Laws and rules like required AMD risk evaluations, waste management standards, and mine closure rules could clearly include FABA as an approved method for adding alkaline materials and designing cover systems.

Second, using FABA fits well with Indonesia's national focus on a circular economy and improving industrial by-products. Government officials might encourage cooperation between coal power plants and mining firms to build standard supply chains, quality control systems, and shared ways to use FABA. These efforts would help cut down on landfill use, decrease long-term environmental problems, and make mine waste cleanup more cost-effective.

Third, the research shows that FABA can provide stable long-term solutions for

managing AMD. This support can help include FABA-based solutions in environmental impact studies, land use plans after mining ends, and long-term monitoring systems. Regulators could ask mining companies to evaluate the use of FABA in high-risk AMD areas as part of their environmental management strategies. Finally, creating national standards or technical guidelines for testing FABA, how much to use, how to compact it, and how to monitor its performance would help ensure consistent use, protect the environment, and support better decision-making in the mining industry.

This study offers a complete and well-organized evaluation of Fly Ash and Bottom Ash (FABA) as a dual-purpose solution for controlling Acid Mine Drainage (AMD) caused by sulfide-rich waste rock. Using a multi-disciplinary approach that includes geochemical analysis, long-term leaching tests, and long-term hydrogeochemical modeling, the study shows that FABA provides both strong chemical and practical engineering benefits for long-term AMD management.

Geochemically, the high level of calcium oxide (CaO) in FABA creates a lasting alkaline environment by forming and breaking down calcium hydroxide (Ca(OH)₂). This process allows for quick pH balance and supports the formation of stable hydroxide compounds of iron (Fe), manganese (Mn), and aluminum (Al). Experiments using columns show that mixing 20 to 30 percent FABA with potentially acid-forming (PAF) materials consistently raises the pH of leachate to nearly neutral levels within 10 to 20 weeks, while lowering dissolved metal concentrations by more than 80 percent. These results show that FABA can effectively block the acid-producing routes linked to pyrite oxidation. From a geotechnical point of view, the fine texture of FABA reduces permeability and the connection between pores when mixed with PAF materials or used as a cover. These physical changes limit the entry of oxygen and water, which are key factors in acid mine drainage (AMD) formation. Long-term models support these findings by showing that FABA-based cover systems of 0.5 to 1.0 meters keep pH nearly neutral for 10 years, whereas untreated PAF waste sites remain acidic.

Overall, the evidence shows that FABA acts as a helpful material for reducing AMD by tackling both the chemical causes and the physical and water-related factors that keep AMD going. Its ability to do both tasks sets it apart from typical neutralizing agents and makes it more suitable for large-scale mine waste cleanup. At the same time, using FABA in this way also supports broader goals of a circular economy by repurposing a commonly available industrial by-products into a useful environmental resource. Future studies need to look at bigger field tests, more detailed models that mix both geological and chemical factors, and long-term checks on how these systems affect the environment. This will help better understand how FABA works in different climates and types of land. These efforts will be essential for developing regulations, guiding industry use, and supporting national strategies for managing mine waste sustainably.

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