Application of the Coagulation Jar Test Method for the Treatment of Coal Wastewater in Industrial Wastewater Management

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Abstract

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The coagulation test for coal wastewater was conducted using the jar test method to evaluate the performance of different coagulants under varying pH and dosage conditions. The coagulants used were $FeCl_3$, $Al_2(SO_4)_3$, and Poly Aluminium Chloride (PAC). The optimal conditions were determined by adjusting the pH (5, 6, 7, and 8) and varying the coagulant dosage at each pH level. The parameters analyzed included turbidity, pH, total suspended solids (TSS), and metal content. Laboratory results indicate that PAC is the most effective coagulant for reducing contaminants in coal wastewater. The optimal coagulation conditions were achieved at pH 8 with a PAC dosage of 1 ppm. The coagulants function by destabilizing colloidal particles, with their efficiency influenced by solubility and pH conditions. $FeCl_3$ and $Al_2(SO_4)_3$, as cationic coagulants, exhibit pH-dependent solubility, significantly lowering the pH of treated water compared to PAC. Conversely, PAC performs optimally in alkaline conditions and induces a smaller pH reduction. Overall, PAC demonstrated superior coagulation performance, achieving turbidity of 2.06 NTU, TSS of 5 mg/L, Fe content of 0.11 mg/L, Mn content of <0.01 mg/L, and Al content of <0.01 mg/L. These findings confirm that PAC is the most effective and efficient coagulant for treating coal wastewater.

1. Introduction

Indonesia is one of the largest coal producers in the world, with an annual production reaching 178.8 million metric tons. Of this amount, approximately 140 million tons are exported, while 38.8 million tons are used for domestic consumption [1, 2]. Indonesia's coal exports contribute significantly to the national economy, particularly in the form of foreign exchange earnings and non-tax state revenues (PNBP). However, alongside the economic benefits gained, the coal mining industry also has negative environmental impacts, particularly related to water, soil, and air pollution [3, 4]. One of the major environmental challenges faced by this industry is the generation of liquid waste, specifically acid mine drainage (AMD), which can lead to water quality degradation and have detrimental effects on aquatic ecosystems and human health [5, 6].

Acid mine drainage (AMD) is formed due to the oxidation reaction of sulfide minerals (such as pyrite, FeS_2) exposed to oxygen and water during mining activities. This reaction produces sulfuric acid and increases the concentration of heavy metal ions such as iron (Fe), manganese (Mn), and aluminum (Al) in wastewater [7]. The presence of AMD with low pH and high metal content can lead to increased toxicity in water bodies, damage aquatic habitats, and contaminate drinking water and agricultural resources in mining areas [8]. Therefore, effective treatment efforts are required to reduce the acidity and heavy metal content in coal wastewater to meet the environmental quality standards set by the government [9].

The treatment methods commonly used for acid mine drainage involve several physical, chemical, and biological techniques. One of the most widely applied methods is the coagulation-flocculation process, a treatment technique that involves the addition of coagulants to accelerate the settling of suspended particles and reduce heavy metal content in wastewater [10]. This process is widely used because it is relatively simple, has lower operational costs compared to other methods, and can be applied on an industrial scale with reasonably high efficiency [11]. However, the effectiveness of the coagulation process heavily depends on several key parameters, such as the type and dosage of coagulants, alkalinity levels, and mixing and settling times. The lack of optimization of these parameters often results in low treatment efficiency, causing pollutant levels in wastewater to exceed the established quality standards [12].

Several previous studies have discussed the treatment of coal wastewater using the coagulation-flocculation method. Research demonstrated that selecting the appropriate type of coagulant can improve sedimentation efficiency by up to 85% in industrial wastewater treatment [12, 13]. Additionally, the importance of optimizing coagulant dosage through the jar test method has been highlighted to enhance treatment efficiency by up to 90% in mine wastewater treatment systems [14].

In Indonesia, coal wastewater treatment units generally use the coagulation-flocculation method, but many still lack optimization in the process. One way to improve the efficiency of this process is by conducting laboratory tests using the jar test method, an experimental technique used to determine the optimal coagulant dosage to achieve the best sedimentation efficiency [15]. This method allows for the evaluation of various process variables, including the type and concentration of coagulants, as well as the most suitable pH conditions for maximum sedimentation[16]. Therefore, this study aims to determine the optimal conditions for coal wastewater treatment using the jar test method, to enhance coagulation efficiency and reduce heavy metal content in wastewater.

The novelty of this study lies in its comprehensive assessment of different coagulants ($FeCl_3$, $Al_2(SO_4)_3$, and PAC) under various pH conditions and dosages, specifically targeting coal wastewater from Indonesian mining operations. Unlike previous studies that focused solely on single coagulant performance, this research provides a comparative analysis of the effectiveness of multiple coagulants in reducing turbidity, total suspended solids (TSS), and heavy metal concentrations. Additionally, the study incorporates optimization strategies tailored to local wastewater characteristics, offering practical insights for improving coal wastewater treatment in Indonesia.

The results of this study are expected to contribute to improving the effectiveness of wastewater treatment in the coal mining industry in Indonesia, as well as serve as a reference for the development of more environmentally friendly and sustainable waste treatment technologies. Furthermore, this research provide practical recommendations for the industry in selecting optimal coagulant dosages to improve sedimentation efficiency, ensuring that the treated wastewater meets applicable environmental standards.

2. Method

This study aims to determine the optimal conditions for the coagulation and flocculation process in the treatment of coal wastewater using the Jar Test method. The research was conducted by comparing the effectiveness of three types of coagulants, namely Ferric Chloride ($FeCl_3$), Aluminum Sulfate ($Al_2(SO_4)_3$), and Poly Aluminium Chloride (PAC), under various pH conditions and coagulant dosages. The observed parameters include total suspended solids (TSS), turbidity, and the final pH of the wastewater after the treatment process.

The research was carried out experimentally in the laboratory using the Jar Test method, with an experimental design that included pH variations of 5, 6, 7, and 8 to determine the effect of acidity on coagulant effectiveness. Additionally, coagulant dosages of 10, 80, 150, and 220 mg/L were tested to determine the optimal dosage for the sedimentation process. Each treatment was performed in triplicate to ensure data accuracy and reduce experimental variability.

2.1 Materials and Equipment

The materials used in this study included artificial coal wastewater samples prepared from coal samples obtained from PT. Quantum Energi in Nagan Raya Regency, Aceh, Indonesia. The coagulants used consisted of $FeCl_3$, which is cationic and effective in removing color and reducing TSS; $Al_2(SO_4)_3$, a conventional coagulant in industrial wastewater treatment; and PAC, which has high efficiency in flocculation. Additionally, supplementary materials such as 0.1 N NaOH were used to adjust the pH, and distilled water was used as a solvent in the dilution process. The filtration medium used was 0.45 µm filter paper for TSS analysis.

The equipment used in this study included a Jar Test apparatus with six impellers, which was used to simulate the coagulation-flocculation process on a laboratory scale. Beaker glasses with capacities of 500 mL and 1000 mL were used as containers for the mixing process, while a pH meter was used to measure the initial and final pH of the wastewater after treatment. Measuring pipettes and bulbs were used for sample collection and coagulant dosage measurement, while an analytical balance was used to measure the mass of chemicals with high precision. An oven was used for drying samples for TSS analysis, and a Buchner funnel and vacuum filtration system were used for filtering suspended solids. Additionally, a desiccator was used to store dried filter paper to prevent moisture absorption.

2.2 Research Procedure

The experimental procedure began with sample preparation, where artificial coal wastewater was prepared using coal obtained from PT. Quantum Energi. The sample was then filtered to remove large particles. The initial pH of the sample was measured using a pH meter and adjusted by adding 0.1 N NaOH. Subsequently, the Jar Test was conducted by placing 500 mL of wastewater sample into six beaker glasses, followed by the addition of coagulants ($FeCl_3$, $Al_2(SO_4)_3$, or PAC) according to the predetermined dosage variations. Rapid mixing was performed at 150 rpm for 2 minutes to ensure homogeneous mixing, followed by slow mixing at 30 rpm for 15 minutes to allow floc formation. After this, the sedimentation process was carried out for 30 minutes.

The results were analyzed by measuring the final pH of the wastewater after treatment. The samples were then filtered using 0.45 µm filter paper for TSS analysis, and turbidity was measured using a turbidimeter. The results of the artificial coal wastewater sample preparation are shown in Figure 1.

Figure 1. Prepared coal wastewater

3. Results and Discussion

In this study, the jar test was conducted using a standard method to determine the effectiveness of coagulants in treating coal wastewater.

3.1 Effect of $FeCl_3$ Coagulant

The effect of $FeCl_3$ coagulant dosage on turbidity at various pH levels is shown in Figure 2. From Figure 2, it can be observed that, based on the jar test analysis results, the optimal dosage of $FeCl_3$ coagulant was found to be 80 ppm. At this dosage, larger flocs were formed compared to other dosage variations. Visually, at different pH levels, the flocs formed were larger and more stable. However, excessive addition of coagulant dosage can cause the wastewater to turn yellowish due to the high presence of metal hydroxide ions. This indicates that determining the appropriate dosage is crucial for optimizing the coagulation process. At dosages below 80 ppm, the flocs formed tended to be smaller, reducing the effectiveness of the sweep floc mechanism in binding colloidal particles.

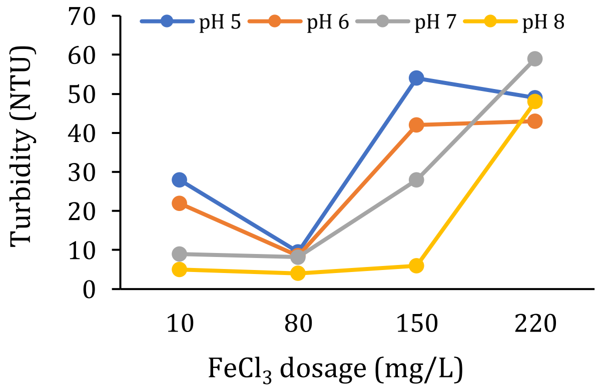

Figure 2. The effect of $FeCl_3$ dosage on turbidity at different pH.

3.2 Effect of Alum Coagulant

The effect of alum coagulant on turbidity is shown in Figure 3. From Figure 3, it can be observed that the optimal dose of alum coagulant is achieved at 150 mg/L, with a similar trend across various pH variations. Unlike $FeCl_3$, the difference in floc size formed at the optimum dose compared to other doses is not clearly visible. However, turbidity test results indicate that the minimum turbidity value is achieved at this dose, suggesting that the dominant mechanism is double-layer compression. The appropriate addition of coagulant dose plays a crucial role in determining the effectiveness of double-layer compression, where metal ions help neutralize colloidal particle charges, thereby facilitating better flocculation.

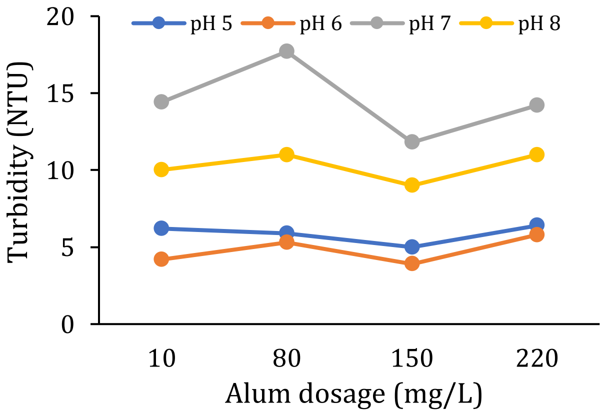

Figure 3. The effect of alum dosage on turbidity at different pH.

3.3 Effect of Poly Aluminum Chloride Coagulant

The effect of Poly Aluminum Chloride (PAC) coagulant on turbidity is shown in Figure 4. From Figure 4, it can be observed that the use of PAC as a coagulant produces more stable results compared to other coagulants. PAC exhibits higher activity and better basicity, preventing a significant decrease in pH. Based on the test results, the optimal PAC dose is 150 ppm, with a working mechanism similar to that of $Al_2(SO_4)_3$ but resulting in larger and more stable flocs. Additionally, the reduction in turbidity at the optimal dose demonstrates its high effectiveness in binding colloidal particles and enhancing the sedimentation process.

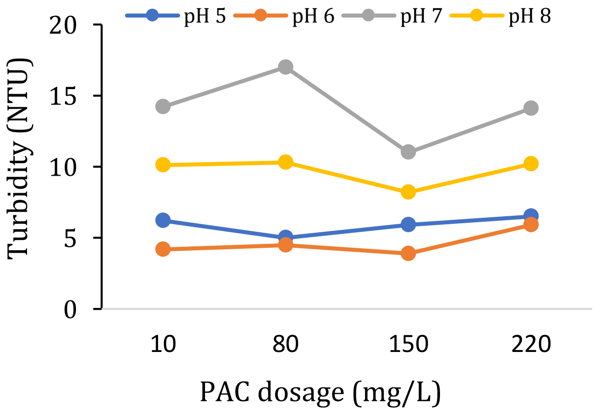

Figure 4. The effect of PAC dosage on turbidity at different pH.

3.4 Analysis of TSS and Metals

The effect of the PAC coagulant on Total Suspended Solids (TSS) is shown in Figure 5. From Figure 5, it can be observed that the TSS analysis indicates a minimum TSS value is achieved at a dose of 80 ppm and pH 8, which corresponds to the condition of minimum turbidity. This finding suggests that the sweep floc mechanism is effective in capturing colloidal particles from wastewater.

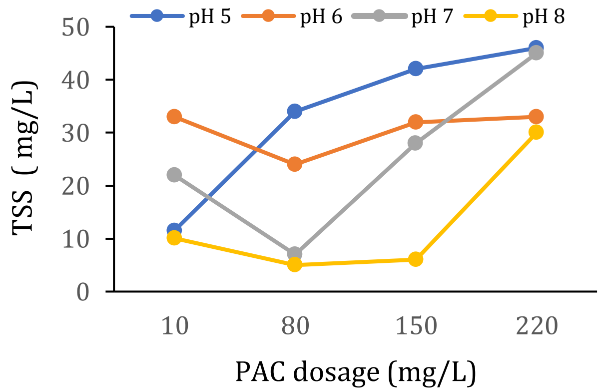

Figure 5. The effect of PAC dosage on total suspended solids (TSS) at different pH.

Analysis of metal content using Atomic Absorption Spectrophotometry (AAS) indicates that under optimal conditions (pH 8 and a dose of 80 ppm), there is a significant reduction in metal concentrations. The test results for metal content are presented in Table 1. From Table 1, it can be observed that the Fe concentration in the initial wastewater, which was 20 mg/L, decreased to 0.39 mg/L after treatment, while the Al concentration, initially 0.76 mg/L, became nearly undetectable (<0.01 mg/L). These results demonstrate that the use of PAC under optimal conditions is highly effective in eliminating metal contaminants from coal wastewater.

Tabel 1. The results of metal content measurement

Sampel	Fe (mg/L)	Mn (mg/L)	Al (mg/L)
Waste water	20	0.38	0.76
pH 8, 80 ppm	0.39	0.19	<0.01
pH 7, 220 ppm	1.32	0.26	20.39

Overall, the research results indicate that among the three coagulants tested, PAC is the most effective in reducing contaminant levels in coal wastewater. In addition to lowering turbidity and metal concentrations, the use of PAC also contributes to reducing sludge volume by 50–90%. Therefore, the treatment method using PAC can serve as a more efficient and environmentally friendly solution for coal wastewater treatment.

4. Conclusion

Based on the research findings and discussion, the following conclusions can be drawn:

The coagulants used in this study have been proven effective for treating coal wastewater.

PAC is the most effective coagulant, with an optimal dose of 150 mg/L. In addition to reducing turbidity, PAC is also effective in lowering Total Suspended Solids (TSS) and heavy metal concentrations in wastewater.

TSS and metal content analysis indicate that at a dose of 80 ppm and pH 8, the minimum TSS value is achieved, and metal concentrations such as Fe and Al are significantly reduced. The Fe concentration decreased from 20 mg/L to 0.39 mg/L, while Al became nearly undetectable (<0.01 mg/L).

Overall, PAC (Poly Aluminum Chloride) is the most effective and efficient coagulant for coal wastewater treatment

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