Settling Characteristics and Treatment Strategies for Open-Cast Coal Mine Water in South Sumatra, Indonesia

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Abstract

This research investigates the efficacy of sedimentation ponds in treating mine water contaminated with suspended solids (SS). The study focuses on the design parameters of these ponds, highlighting the limitations of Stokes' law and emphasizing the importance of site-specific data. Experimental settling tests were conducted on six water samples, evaluating pH, ORP, TSS, and concentrations of iron and manganese. The results reveal that water with high acidity (pH 3.16–4.05) can naturally eliminate up to 57.4% of suspended solids within a 50-minute period. In contrast, water with neutral pH requires chemical coagulation, with dosages ranging from 20 to 200 mg/L. Following coagulation, additional settling tests were employed to establish detention time and overflow rates through the use of iso-removal curves.

Keywords: Mine water, sediment pond, settling test, suspended solid, iso-removal curve

Introduction

The management of coal mine water in Indonesia presents unique challenges due to the country's high precipitation levels. Indonesia experiences intense rainfall, with maximum daily amounts reaching 377 mm (Lubis *et al*. 2022). This substantial precipitation contributes to significant water inflow into sediment ponds, which serve as mine water treatment facilities, with peak inflows of up to 2000 L/s (Hasan *et al*. 2024). Moreover, the prevalent use of open-pit mining in Indonesia's coal industry exposes overburden and waste rock directly to rainwater, heightening the risk of adverse environmental consequences, particularly water quality deterioration (Abfertiawan *et al*. 2016).

In Indonesia, mine water typically exhibits acidic properties or high turbidity. Acid Mine Drainage (AMD) results from the interaction of sulfide minerals in overburden or waste rock with oxygen and water, producing acidic water (Abfertiawan *et al*. 2020). Additionally, the presence of colloidal clay minerals often renders mine water turbid, elevating Total Suspended Solids (TSS) concentrations (Abfertiawan *et al*. 2024). While comprehensive mine water characterization is crucial for determining optimal treatment methods, practical constraints often limit the design and monitoring of treatment systems to two primary parameters: pH and TSS. Turbid water is frequently presumed to have high TSS, prompting immediate treatment with coagulants like aluminum sulfate. However, mine water particles can be categorized as suspended or settleable solids, potentially settling naturally without chemical additives. This misconception may lead to excessive chemical use and inflated operational expenses.

The design of sediment ponds, critical for treating mine water containing suspended solids (SS), presents another challenge. These facilities are typically designed based on

Stokes' law, which assumes specific particle settling velocities or gravities. However, actual particle characteristics vary by location, and finer sediments (<2 μm) often deviate from Stokes' law due to inter-particle interactions. Consequently, site-specific designs require additional data on particle size and settling velocity. This study aims to develop a comprehensive framework for designing sediment ponds suitable for various types of coal mine water in Indonesia's South Sumatra region. By incorporating detailed particle characterization and settling behavior analysis, the research seeks to enhance coal mine water treatment efficiency and effectiveness, thereby mitigating environmental impacts and optimizing operational sustainability.

Methods

An analysis of water samples was undertaken to elucidate their physicochemical characteristics, encompassing pH, conductivity, oxidation-reduction potential (ORP), total dissolved solids (TDS), total suspended solids (TSS), and metal concentrations (Fe and Mn, in both total and dissolved forms). The Water Quality Laboratory at ITB conducted the examination, which revealed three principal water quality issues: (1) acidity (pH <6), (2) elevated turbidity (TSS >100 mg/L), and (3) a simultaneous occurrence of both conditions (pH <6 and TSS >100 mg/L). A stepwise treatment protocol was employed, contingent upon TSS concentrations. When TSS surpassed 100 mg/L, type 1 sedimentation was implemented to promote gravitational settling of discrete particles. Conversely, for TSS values ≤100 mg/L, this sedimentation step was bypassed, and the process advanced directly to jar testing using lime (CaO) for optimal dosage determination.

The sedimentation behavior of discrete particles was investigated using a Type 1 sedimentation test. This experiment employed a 7.5 L water sample in a 100 cm-high settling test column. Prior to testing, the sample underwent homogenization. Measurements were recorded at 10-minute intervals for a duration of 60 minutes, at a depth of 95 cm from the water surface. Gravimetric analysis was utilized to determine TSS concentrations, enabling the assessment of particle settling characteristics. Concurrently, a jar test was conducted using four beaker glasses, each containing varying coagulant dosages. The procedure involved a rapid mixing phase at 120 rpm for 1 minute, followed by slow mixing at 60 rpm for 10 minutes, and a 10-minute settling period. Subsequently, the supernatant was analyzed for TSS, pH, TDS, conductivity, and ORP to identify the optimal coagulant dosage. A Type 2 sedimentation test was performed to examine the settling dynamics of flocculent particles post-chemical addition. This test utilized an 8.5 L sample in a 115 cm-high column. Single sampling was conducted from five ports, positioned 20 cm apart, over a 90-minute period. The TSS removal efficiency was evaluated using overflow rate (VO) and total removal fraction (RT). Isoremoval graphs were employed to visualize TSS removal efficiency across time and depth. pH analysis was performed using a pH meter, while TSS and TDS analyses were conducted using gravimetric methods in accordance with APHA Methods 2540 Solids. Iron concentration was determined following APHA 3500 Fe B – Iron by Phenanthroline,

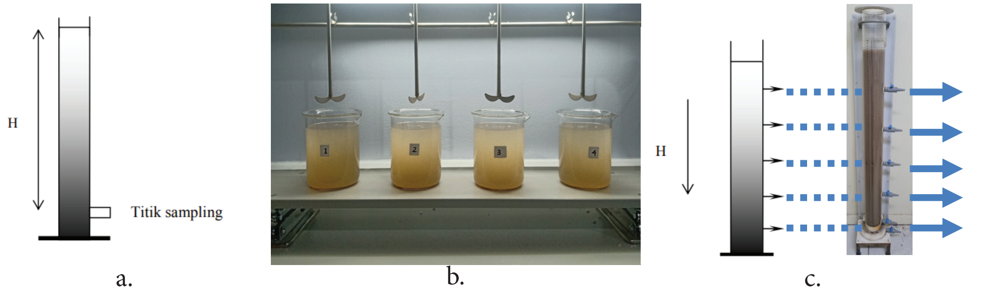

__Figure 1__ Illustration of (a) type 1 of sedimentation test, (b) jar test, and (c) type 2 of sedimentation test.

Table 1 Initial characterization of mine water.

No	Sample	pH	ORP (mv)	Conductivity (µS/cm)	TSS (mg/L)	Total Fe (mg/L)	Dissolved Fe (mg/L)	Total Mn (mg/L)	Dissolved Mn (mg/L)
1	A 02	5.73	274	1261	4	3.00	0.20	9.74	2.18
2	A 03	6.46	204	795.2	167.5	3.56	0.29	8.12	1.70
3	A 12	7.22	207	1576	865	37.94	4.38	9.52	1.25
4	B 02	6.45	222	761.9	252.5	4.34	0.66	6.77	2.18
5	B 04	4.05	375	1452	103.25	9.82	0.86	15.36	7.50
6	B 07	3.16	431	2130	259.5	5.72	1.63	14.74	11.70

and manganese concentration was quantified based on APHA 3500 Mn B – Manganese in Water by Persulfate and Spectrophotometry.

Results and Discussion

The mining water samples were collected using the grab sampling method, where samples were taken at a single point in time. The data presented in Table 1 represent the results of the mining water collected directly, without any prior sedimentation or treatment at the sedimentation pond inlet.

Mine water treatment encompasses three principal phases: sedimentation of discrete particles, optimization of coagulant dosage through jar testing, and sedimentation of flocculent particles. The concentration of suspended solids serves as a crucial indicator in evaluating water quality, as excessive levels of Total Suspended Solids (TSS) can obstruct the penetration of sunlight required for photosynthetic processes in aquatic flora. This obstruction may lead to a reduction in dissolved oxygen (DO) concentrations, creating an inhospitable environment for aquatic biota. Furthermore, elevated TSS levels contribute to increased surface water temperatures through the absorption of solar energy, exacerbating the depletion of DO due to the diminished solubility of oxygen in warmer water. Consequently, the elimination of suspended solids from wastewater prior to discharge is imperative to minimize detrimental environmental effects and preserve the balance of aquatic ecosystems. Initial characterization tests of the mine water samples reveal three distinct classifications: those exhibiting acidic pH, those with high turbidity, and those demonstrating a combination of both acidic pH and high turbidity (Table 2).

Type 1 sedimentation refers to the settling of discrete particles that settle independently without interacting with other particles or requiring chemical coagulants. Therefore, type 1 sedimentation tests were conducted only on samples with high turbidity (TSS > 100 mg/L), as well as those characterized by both acidic pH and high turbidity. In contrast, samples with only acidic pH issues generally had lower turbidity (TSS < 100 mg/L), making type 1 sedimentation

Table 2 Classification of mine water conditions, removal from type 1 of sedimentation, jar test results, calculation of sediment pond dimension through type 2 of sedimentation.

No	Classification	Sample Name	Removal from Discrete Settling (%)	Chemical Agent	Optimum Dosage (mg/L)
1	Acidic pH (pH <6)	A 02		Lime	14
2	High Turbidity (TSS >100 mg/L)	A 03	5.3%	Al2(SO4)3	20
3		A 12	0%		200
4		B 02	18.1%		200
5	Combination of both factors (pH <6 and TSS > 100 mg/L)	B 04	53.5%	Lime	140
6		B 07	57.4%		260

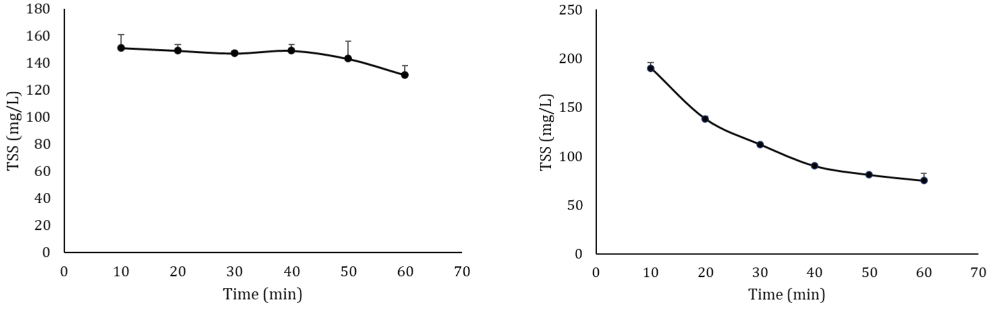

Figure 2 *Variation in TSS concentration over settling time in type 1 of sedimentation (discrete particle) for: a. sample with high turbidity (A03) and b. sample with acidic pH and high turbidity (B07) .*

unnecessary. Fig. 2 presents the variation in TSS concentration over the settling period for samples with high turbidity (A03) and those with both acidic pH and high turbidity (B07), providing critical insights into the effectiveness of the sedimentation process in improving water quality.

The results of type 1 sedimentation for the six mine water samples are presented in Table 2. Based on Fig. 2a, the type 1 sedimentation results indicate that sample A03 contains highly stable colloidal particles, making natural gravitational settling ineffective. Table 2 shows that samples with high turbidity issues had an average removal efficiency of less than 20%, suggesting the presence of stable colloidal particles that require further treatment for destabilization to enhance sedimentation and facilitate effective removal. In contrast, samples with both acidic pH and high turbidity exhibited an average removal efficiency above 50%. This is attributed to the acidic nature of mine water, which is rich in iron ions. These ions act as natural destabilizing agents for negatively charged colloidal particles, leading to the formation of larger flocs that settle more easily. This observation aligns with the study by (Dyestiana *et al.* 2023) which investigated the effects of mixing acid mine drainage with suspended solid-laden water. This study found that water with both acidic pH and high turbidity had a zeta potential exceeding -10 mV (ranging from -5 to -10 mV) at a volumetric mixing ratio of 1:1. It is well established that for optimal coagulation, the zeta potential of a solution should surpass -10 mV, approaching the isoelectric point near 0 (Kumar and Dixit 2017). The type 1 sedimentation results suggest that natural gravitational settling can be effectively utilized for samples with both high turbidity and acidic pH, minimizing the need for chemical additives. This advantage can be utilized in the design of pre-sedimentation ponds before the coagulation process to reduce chemical consumption.

The jar test was performed to determine the optimal dosage of chemical additives required for effective treatment. The primary chemicals used in this process were coagulants, which facilitate the aggregation of colloidal particles into larger flocs that can settle more efficiently. Colloidal particles are extremely small and do not settle naturally by gravity, necessitating the addition of coagulants to enhance the coagulation and sedimentation process. Additionally, pH-neutralizing agents were added to samples with acidic pH to induce chemical precipitation and increase pH levels. The key parameters analyzed in the jar test were TSS and pH levels. In this study, lime was utilized for pH neutralization, while aluminium sulfate served as the primary coagulant. The water samples with both acidic pH and high turbidity issues contains particles that naturally tend to settle through gravitational sedimentation. Therefore, the primary treatment focus is pH neutralization using lime to comply with regulatory standards. The results of the jar test, along with the chemical agent and consumption, are shown in Table 2.

Type 2 sedimentation evaluates the behavior of flocculated particles following

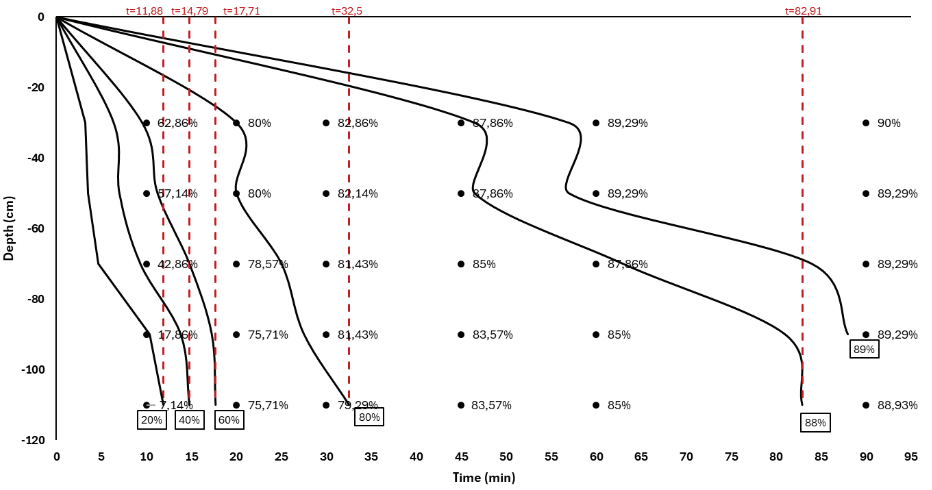

Figure 3 Iso-removal graph for sample A03 with a target efficiency of 82.14% (achieving the water quality standard of 100 mg/L TSS concentration).

chemical treatment. In high-turbidity water, are formed through the coagulation process, whereas in acidic water, precipitates are generated as a result of pH neutralization. This test involves sampling from five different ports at varying depths within the sedimentation tank. Samples are collected at different time intervals to observe the settling dynamics, which are then used to determine the overflow rate (vO) and total removal fraction (RT). The TSS concentration data obtained from the test is converted into percentage removal values. The determination of RT and VO is performed using an isoremoval graph, which illustrates the relationship between TSS removal efficiency, settling time, and sampling depth. Interpolation is applied to the plotted data points, allowing for the construction of a removal percentage curve. Fig. 3 illustrates an example of an iso-removal graph for sample A03. From this analysis, the relationship between overflow rate, detention time, and removal efficiency was determined, as shown in Fig. 4. In the case of sample A03, a removal efficiency of 82.14% is required to meet the water quality standard, ensuring that the TSS concentration does not exceed 100 mg/L.

The overflow rate and detention time values for a specific target removal percentage were determined. These values were then adjusted using a scale-up factor of 1.75 for detention time and 0.65 for overflow *rate* (Reynolds and Richards 1996). The adjusted detention time and overflow rate were then used to determine the pond dimensions using a formula, where A

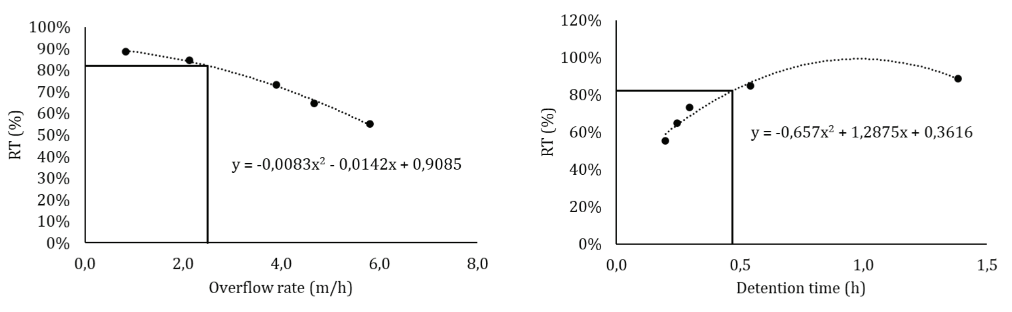

Figure 4 The correlation between: (a) overflow rate and (b) detention time with the total solids removal fraction.

denotes the cross-sectional area (m²), Q represents the flow rate (m³/h), v_0 is the overflow rate (m/h), H indicates the depth (m), and td is the detention time (h). The calculated sediment pond dimensions are summarized in Table 3.

$$A = \frac{Q}{v_0}\ ;\ H = \frac{Q \times td}{A}$$

From Table 3, a noticeable difference can be observed between the calculated sediment pond dimensions (column test) and the actual conditions (Stoke's law). This difference is due to variations in the calculation approach between the column test and Stokes' law, which was initially used in the sediment pond design. A widely used method for estimating theoretical settling velocity is Stokes' law, which assumes that particles are spherical in shape and smooth. However, coal mine water in Indonesia typically contains high levels of clay, which is the primary contributor of high TSS concentrations. Clay particles are often needle-shaped, plate-shaped, or flaky, which makes Stokes' law unsuitable for accurate predictions and giving incorrect results. Moreover, interactions between particles and flocculation occur due to the introduction of coagulants or precipitation resulting from pH neutralization in coal mine water treatment. When chemical agents such as coagulants or pH neutralizers are added, particles tend to bind with oppositely charged particles, forming larger aggregates that increase the settling velocity. On the other hand, Stokes' law assumes that particles settle freely without interacting with others (Ogolo *et al.* 2024). These factors highlight the need for iterative adjustments to sediment pond design based on the actual characteristics of mine water in the field rather than relying solely on Stokes' law assumptions during the initial mine plan. This approach improves the efficiency of chemical usage and enhances the operational evaluation of the sediment pond. Fig. 5 illustrates a guideline for selecting treatment methods or evaluating existing sediment pond designs using two key parameters: pH and TSS. These parameters are critical in coal mining water management, as they represent some of the most common challenges encountered by coal mining companies in Indonesia.

Conclusion

In Indonesia, pH and TSS are the most commonly observed and monitored parameters in coal mine water. However, a proper understanding of these two parameters is crucial for selecting the most effective and efficient treatment method. Not all turbid water contains suspended solids that require coagulants; some may consist of settleable solids that can naturally settle due to gravity and reducing the need for chemical usage. This can be verified through a simple field experiment using a settling test column following the Type 1

Table 3 *Calculation results of the sediment pond and the actual dimensions of the sediment pond.*

No	Sample		Removal TSS target (%)	t_d (h)	v_0 (m/h)	Existing Mine Water Discharge (m3/h)	Sediment pond dimension (Calc)		Sediment pond dimension (Act)	
							Cross sectional area (m²)	Depth (m)	Cross sectional area (m²)	Depth (m)
1	Acidic pH	A 02	55%	0.25	10.23	4680	458	2.6	3765	3
2	High Turbidity	A 03	82.14%	0.82	1.63	26640	16344	1.5	13496	2
3		A 12	99.29%	0.86	0.57	243360	426947	0.5	24268	3
4		B 02	96.57%	0.30	1.69	6480	4873	0.5	1547	5
5	Acidic pH and High Turbidity	B 04	95.33%	0.37	1.01	116640	115486	1.5	35308	6
6		B 07	87.44%	0.26	3.30	580680	175964	1	14821	3

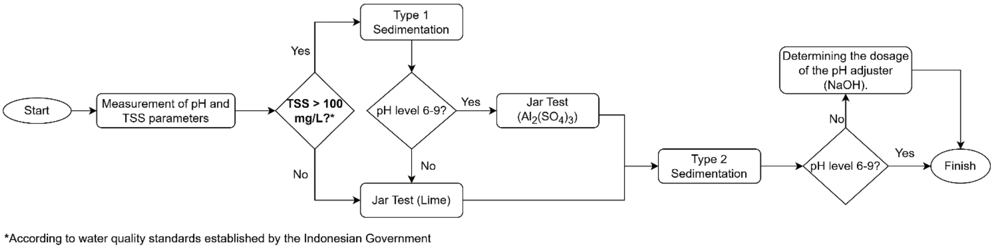

Figure 5 Guideline for selecting treatment methods and evaluating sediment pond design.

sedimentation procedure, which is relatively easy to perform in the field. Additionally, choosing the right chemical treatment – whether coagulants or pH-neutralizing agents – requires compatibility testing with the mine water characteristics. This can be conducted through a jar test procedure to determine the most optimum dosage. The results of the jar test are then applied in the type 2 sedimentation procedure, which serves as a basis for evaluating the design of existing sedimentation ponds. Unlike Stokes' law, which assumes free-settling particles to determine settling velocity, the type 2 sedimentation method considers real mine water conditions in the field without relying on theoretical assumptions. These steps are expected to provide valuable insights for decision-making, optimizing chemical usage, and improving the management of coal mine water treatment in Indonesia, particularly in optimizing sediment pond operations.

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