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Flocculant Assisted Treatment of Suspended Sidoarjo Mud

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Abstract: This study investigates the use of lime-based flocculants as a treatment method for Sidoarjo mud (LUSI) to improve solid–liquid separation and reduce the environmental impact of its discharge into the Porong River. Several commercial lime-derived flocculants were tested through jar experiments to evaluate their effectiveness in promoting particle aggregation and enhancing settling behavior under conditions similar to the existing treatment pond. The results indicate that a mud-to-water ratio of 1:4 provided the most efficient sedimentation performance, reflected by faster settling rates and clearer supernatant. Among the flocculants examined, differences in chemical composition and particle morphology influenced the degree of aggregation and overall clarity of the treated water. The treatment substantially reduced turbidity and suspended solids, while also lowering chloride levels in the clarified water. These findings suggest that lime-based flocculants are a feasible option for mitigating the environmental burden of LUSI mud disposal by improving separation efficiency.

Keywords: Flocculant; Sidoarjo mud; Particle aggregation; Settling behavior

Introduction

The Sidoarjo hot mudflow (LUSI), which has been erupting continuously since 2006, is not merely a geological phenomenon but also a protracted environmental crisis. Its overflow beyond the containment embankments has contaminated the surrounding areas and threatens the community's sustainability. As a mitigation measure, the government diverts this mud into the sea via the Porong River—a tangible testament to the immense volume of material that must be managed (Pusat Pengendalian Lumpur Sidoarjo 2020). Unfortunately, this solution has given rise to new problems.

The flow of LUSI mud into the Porong River has caused hydrological system dysfunction (Trilita, 2012). The concentration of total suspended solids (TSS) has drastically surged up to 240,448 mg/L (Atmodjo, 2011), far exceeding the ecological threshold of 150 mg/L (Hariyanto, Krisna, Pribadi, Kurniawan, Sukojo, & Taufik, 2017). The high TSS level triggers siltation and changes in the river channel morphology, which significantly reduces its hydraulic capacity (Ali, Ariffin, & Razi, 2017; Saputro, Sisno, & Juwono, 2021; Yanti, Soemitro, Maulana, Satrya, Desa Warnana, & Muntaha, 2023). This condition is alarming, as recent projections warn of the potential for an overtopping disaster by 2032 (Alam, Ansori, & P., 2024).

The root of this problem lies in the physical properties of LUSI mud particles, which are extremely fine and nanoparticle-sized, resulting in a long suspension time and inhibiting natural settling (Handoko, Rifa'i, Yasufuku, & Ishikura, 2015; Plumlee, Casadevall, Wibowo, Rosenbauer, Johnson, Breit, Lowers, Wolf, Hageman, Goldstein, Anthony, Berry, Fey, Meeker, & Morman, 2008). Consequently, the effluent water remains turbid and chemically unbalanced. This condition cannot be effectively overcome by fluctuations in rainwater discharge, leading to continuous sedimentation and contamination (Kure, Winarta, Takeda, Udo, Umeda, Mano, & Tanaka, 2014; Jennerjahn, Jänen, Propp, Adi, & Nugroho, 2013;

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Caesar, Yanuhar, Faqih, Anitasari, Ciptadi, Musa, & Wardani, 2024).

Therefore, an approach is required that can address two crucial problems simultaneously: accelerating the sedimentation of fine particles and improving wastewater quality. This is where flocculant-assisted treatment offers a promising solution. Flocculants work by aggregating fine particles into larger flocs to expedite settling (Pu, Mastoi, Chen, Song, Qiu, & Yang, 2021; Wei, Gao, Ren, Li & Yang, 2018). Their effectiveness has been proven in mud dewatering and hazardous waste treatment, with the ability to accelerate solid-liquid separation and lower contaminant concentrations (Feng, Wan, Deng, Qin, Zhao, Luo, He & Chen, 2020).

Although the fine and moist characteristics of LUSI mud support the potential for flocculant application, its specific effectiveness still requires further study. However, this effort is not only focused on remediation but also opens up opportunities for waste valorization. The processed solids are found to be rich in silica (51.14%) and alumina (14.16%)—a composition equivalent to Class-F fly ash (Triwulan, Ekaputri, & Adiningtyas, 2007). This indicates its potential for utilization as a natural pozzolanic material or a geopolymer precursor in the construction industry.

Based on this description, this research proposes an evaluation of flocculant effectiveness for LUSI mud treatment. The objective is to accelerate sedimentation and improve water effluent quality By integrating aspects of remediation and waste valorization, this research is expected to contribute to sustainable resource management.

Method

This study evaluated the sedimentation behavior of LUSI mud under the influence of various flocculants using a modified jar test procedure. The experiment followed the Indonesian National Standard SNI 19-6449-2000 with specific adjustments to simulate the actual LUSI water discharge treatment system. In standard SNI procedures, mud and water are first combined before flocculant addition. However, infield practice, flocculants are introduced upstream—before complete mixing of LUSI mud and water. Therefore, the sequence in this study was modified to better represent the actual operational conditions at the LUSI discharge site. The primary objective was to assess the performance of four industrial flocculants—Aqua-Nature, SUIMU, MO-1, and BI-1—in promoting particle agglomeration, reducing turbidity, and accelerating mud sedimentation.

The materials used in this study included LUSI mud collected from the Porong River containment area and four commercial flocculants—Aqua-Nature, SUIMU, MO-1, and BI-1 obtained from Japan. These flocculants were chosen based on their chemical characteristics, particularly their high calcium oxide (CaO) and silicon dioxide (SiO_2) contents, which are known to enhance particle aggregation and promote sediment formation in clay-rich suspensions. The chemical compositions of these flocculants, determined through X-ray fluorescence (XRF) analysis, are summarized in Table 1.

Table 1. Flocculant Types and Dosages

Flocculant	CaO (%)	SiO_2 (%)
Aqua-Nature	72.81	19.05
SUIMU	52.64	24.85
MO-1	24.84	37.96
BI-1	67.48	13.65

Each flocculant was tested at its recommended dosage, as provided by the manufacturer, ranging from 300 to 1000 g/m³ (Table 2). Prior to the experiment, predetermined amounts of LUSI mud, flocculant, and water were measured using analytical equipment to ensure precision. The flocculant was first dissolved in water inside a one-liter beaker and homogenized using a magnetic stirrer for one minute. Once the solution became uniform, LUSI mud was gradually added through a funnel to minimize turbulence and maintain consistency between tests.

Table 2. Flocculant Types and Dosages

Flocculant	Dose (g/m³)
Aqua-Nature	1000
SUIMU	500
MO-1	300
BI-1	300

The flocculation process followed a two-stage mixing regime. Rapid mixing was performed at approximately 200 rpm for one minute to achieve even distribution of the flocculant within the suspension, followed by slow mixing at around 40 rpm for two minutes to facilitate the growth and aggregation of flocs. After mixing, the beakers were left undisturbed for 6 hours at room temperature (around 27°C) to allow sedimentation to occur.

Following the settling period, both qualitative and quantitative observations were conducted to evaluate the performance of each flocculant. Visual observations and photographic documentation were used to assess floc size, compactness, and general sedimentation characteristics. Quantitative measurements included turbidity of the supernatant, clarity, and the volume of settled solids.

The overall flow of the experimental procedure is illustrated conceptually as follows: preparation of the flocculant solution, addition of LUSI mud, rapid and slow mixing stages, a 6-hour settling period, and subsequent sampling for analysis of turbidity, settled solids, and floc morphology. This modified jar test design ensured a controlled yet realistic evaluation of flocculant effectiveness under conditions representative of field-scale sedimentation systems.

Results and Discussion

The Effect of Flocculants on LUSI Particle Size

The particle size distribution of the dried LUSI (DL) samples is illustrated in Figure 1. Samples DL2 and DL3 displayed relatively narrow particle size distributions within the 200–500 nm range, whereas DL1 exhibited a broader distribution spanning approximately 100–1100 nm.

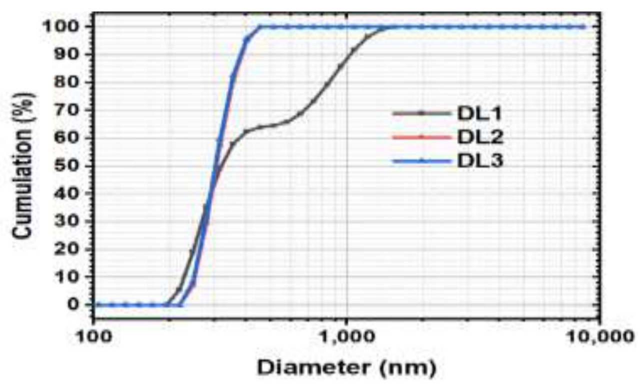

Figure 1 Cumulative DL Particle Size Distribution

These differences are further reflected in the particle size frequency profiles shown in Figure 2. Specifically, samples with a narrower distribution exhibited a single peak, while those with broader distributions presented two distinct peaks, indicating the presence of a more heterogeneous particle population.

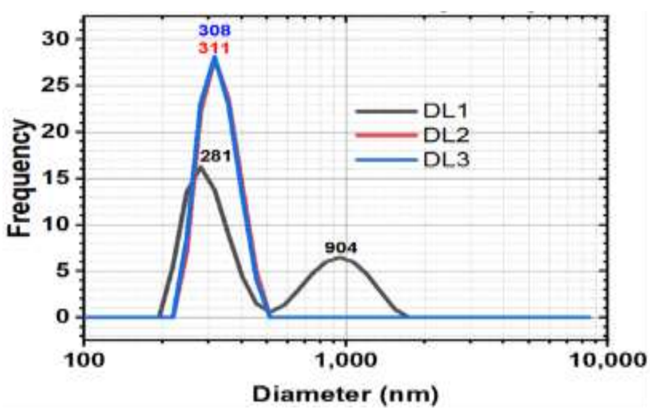

Figure 2. DL Particle Size Frequency

The particle size distribution of the dried flocculated LUSI (DFL) samples is presented in Figure 3. Examination of all three DFL samples reveals a gap-graded distribution, which is characterized by the absence or scarcity of intermediate particle sizes and the simultaneous presence of two distinctly separated particle groups. This pattern suggests the coexistence of two populations within the flocculated material. The first population consists of a smaller fraction of fine particles, most likely representing the primary particles that have undergone partial flocculation but have not yet aggregated into larger clusters. The second, more dominant population corresponds to a significantly larger fraction of particles that have combined into sizable agglomerates as a direct consequence of the flocculation process.

Such a distribution is particularly noteworthy because it demonstrates the effectiveness of the flocculant in bridging and binding finer particles together, thereby producing a substantial increase in the larger particle fraction (Glover, Yan, Jameson, & Biggs, 2000). This bimodal behavior highlights not only the heterogeneity of the treated material but also the structural transformation induced by the flocculation mechanism, where primary colloidal-scale particles are reorganized into larger, more stable aggregates (Zhou, Han, Li & Zhu, 2021). The resulting dual particle populations provide clear evidence of the intended outcome of flocculant application—namely, the reduction of fine, slow-settling particles and the enhancement of larger agglomerates that settle more efficiently.

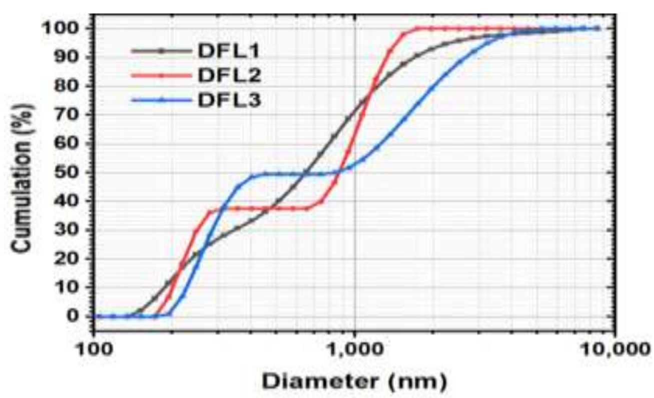

Figure 3. Cumulative DFL Particle Size Distribution

The most noticeable feature in the dried flocculated LUSI (DFL) samples was the appearance of prominent peaks extending well beyond 1000 nm, as illustrated in Figure 4. These peaks provide strong evidence of extensive particle agglomeration that occurred as a direct result of the flocculation process. In comparison to the relatively narrow and uniform distributions observed in the dried LUSI (DL) samples, the DFL samples displayed a markedly broader size spectrum, with the higher particle size peaks representing large, stable aggregates formed from the coalescence of finer particles.

The cumulative distributions further substantiate this observation by confirming the overall increase in both particle heterogeneity and mean particle size across the flocculated samples. Such a shift toward larger particle diameters is consistent with the fundamental mechanism of flocculation, wherein the introduction of a flocculant agent facilitates inter-particle bridging. This bridging reduces the repulsive forces among fine colloidal particles and promotes their aggregation into larger, more compact clusters, commonly referred to as flocs (Seiphoori, Ma, Arratia & Jerolmack, 2020).

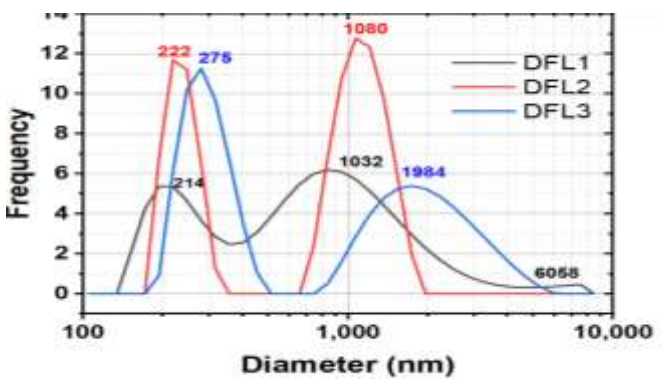

Figure 4. DFL Particle Size Frequency

Importantly, this outcome represents not only the intended but also the expected result of the flocculation process. By converting fine particles, which are typically characterized by slow settling velocities and high suspension stability into larger agglomerates, flocculation enhances sedimentation efficiency and improves the separation of solid and liquid phases. In practical terms, the formation of these larger, more manageable clusters significantly aids in the stabilization of the sediment, thereby demonstrating the effectiveness of the flocculant treatment in modifying LUSI particle behavior.

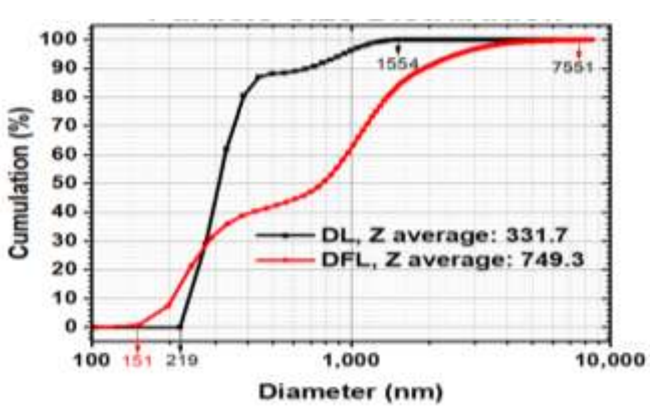

Figure 5 Average Cumulative Particle Size Distribution

A comparative analysis of DL and DFL particle size characteristics is depicted in Figure 5, which shows the average distribution from three replicates. The DFL samples clearly exhibited a broader and more dispersed particle size range compared to DL, a stark contrast to the likely narrower, unimodal distribution of the non-flocculated DL.

The frequency data in Figure 6 confirm that the flocculation process actively promotes the formation of larger particles, as seen in the notable upward and rightward shift of the particle diameter distribution. This indicates not only an increase in the maximum particle size but also a greater proportion of the overall sample existing as these larger agglomerates.

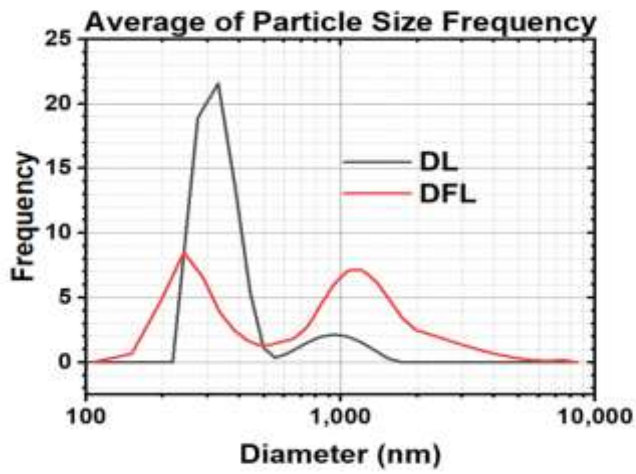

Figure 6 Average of Particle Size Frequency

The observed increase in particle size following flocculant addition can be attributed to the coagulative action of calcium oxide (CaO). Beyond its role in promoting agglomeration, CaO also modifies the Atterberg limits of clay soils by altering inter-particle forces and surface charge interactions. This mechanism is analogous to the behavior reported for biopolymer-based additives such as chitosan, which similarly restructure particle associations and consistency characteristics (Wu, Kannangara, & Zhou, 2024). In this study, the larger particle sizes in DFL corresponded to lower water requirements to reach the plastic limit (PL) and liquid limit (LL), given that particles of the same mass but larger size possess a lower specific surface area and reduced water absorption potential (Arthur, Rehman, Tuller, M., Pouladi, Nørgaard, Moldrup, & de Jonge, 2021; Shimobe & Spagnoli, 2021).

The Effect of Flocculants on LUSI Settling Velocity

The addition of flocculants had a significant impact on both the apparent particle size and sedimentation rate of LUSI mud. Non-flocculated LUSI suspensions exhibited a persistent turbidity due to the dominance of fine-grained, clay-sized particles with diameters typically below 2 µm. These particles—particularly halloysite and smectite—remained suspended in water even after several hours of settling, consistent with previous findings on the colloidal and gel-like behavior of LUSI mud (Fujiyama, Daiki, Ying, & Ekaputri, 2022).

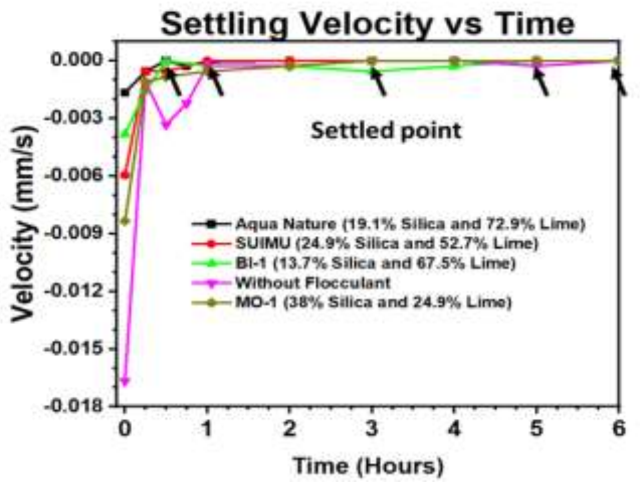

Figure 7. Effect of Flocculant Addition on Settling Velocity within 6 Hours at a ¼ LUSI-to-Water Ratio.

The settling curve results were found through the jar test. A ratio of ¼ LUSI to water was selected as the highest possible, matching the current discharge system. Lower ratios were not used because they would require more water than what is available in the current system. Using more water would depend heavily on the Porong river, which is already used for other industries.

The settling behavior over the first 6 Hours is illustrated in Figure 7. The samples treated with flocculants displayed enhanced settling rates compared to the non-flocculated control. Among them, SUIMU achieved the highest average settling velocity, while Aqua Nature exhibited the lowest.

Excluding Aqua Nature, a trend was observed wherein higher silica content in the flocculants corresponded with greater settling velocities. This finding suggests that silica-rich formulations can increase the agglomeration and sedimentation rate of LUSI particles, which may contribute to reducing the risk of mud overflow during the rainy season.

Although Aqua Nature was applied at the highest dosage, its performance was suboptimal. Visual observations revealed persistent suspended solids, indicating incomplete flocculation. This behavior is attributed to its structural morphology Figure 8 , which displayed a net-like floc structure with relatively large pores. Such morphology enables large particles to be retained while allowing finer particles to pass through and remain suspended, thereby contributing to potential downstream siltation.

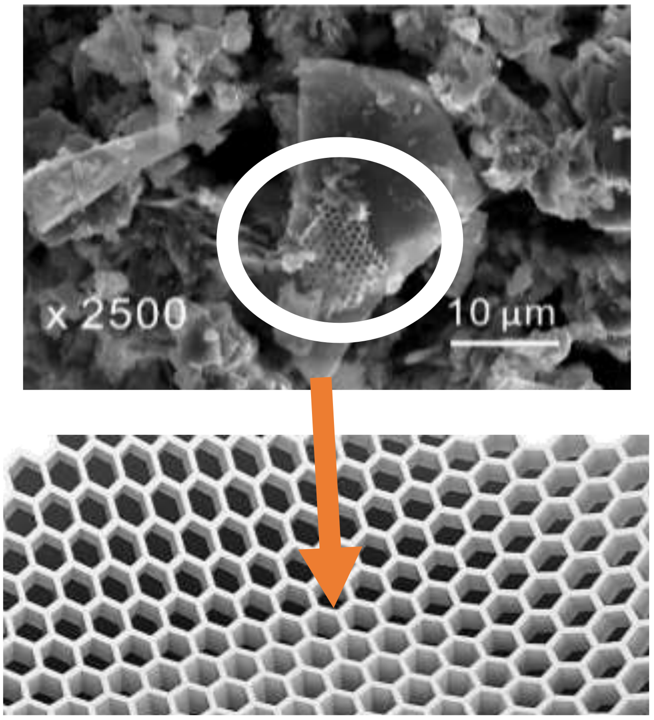

Figure 8 Flocculant Aqua-Nature Morphology Illustration

Conclusion

Flocculant application improved the settling behavior of LUSI mud by enhancing particle aggregation. The process produced compact flocs, indicating effective solid–liquid separation. These results suggest that flocculation offers a practical approach for LUSI mud management and environmental mitigation.

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Concept, C.F.; Investigation, writing—original draft preparation, visualization, T.S.; resources, J.J.E., C.F.; writing—review and editing J.J.E. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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