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Correlation of Methylene Blue Value with the Behavior of Natural and Stabilized Expansive Soils

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Abstract

This study investigates the expansive nature of soils from various regions in Indonesia, focusing on their natural and post-stabilization characteristics. The research aims to bridge the gap in understanding the relationship between Methylene Blue Value (MBV) and soil expansivity, both in natural and stabilized states. Soil samples were systematically collected from seven locations across three Indonesian islands and subjected to a range of laboratory tests, including X-ray diffraction analysis, to determine their properties and mineral composition. Compaction and swell tests were conducted to establish Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), as well as swell pressure and free swell parameters. The study further explored soil improvement techniques using cement and lime stabilizers at varying concentrations from 5% to 15%. The results indicated that both cement and lime significantly reduce swell pressure and free swell, with a 15% additive concentration being optimal for mitigation. The analysis revealed a strong correlation between MBV and soil expansivity, with higher MBV values indicating greater expansivity. Regression analysis showed a non-linear relationship between MBV and swell pressure, explaining 97.8% of the variation in swell pressure. Additionally, a linear relationship between MBV and the expansive mineral content was identified, suggesting that the Methylene Blue Test can serve as a cost-effective and rapid substitute for identifying expansive minerals in the soil. The findings highlight the reliability of MBV as an indicator of soil behavior and its potential application in predicting soil expansivity.

Keywords: Expansive Mineral; Methylene Blue Value; Swell Pressure; Free Swell; Cement and Lime Stabilization.

1. Introduction

Expansive soils present significant challenges to infrastructure both in Indonesia and worldwide due to their susceptibility to substantial volume changes in response to variations in water content [1-4]. This volumetric instability frequently leads to severe damage, particularly to lightweight structures such as foundations, retaining walls, road pavements, airports, and riverbanks [5–8]. A critical issue arises when the swell pressure exceeds the load-bearing capacity of foundations, resulting in undesirable uplift and structural instability [5, 9, 10]. The economic impacts of expansive soil are substantial. Annual repair costs due to soil-related damage are estimated at $300 million in the UK and billions globally, with the United States alone incurring costs exceeding $15 billion annually by 2012 [2, 11]. These figures highlight the urgency of developing effective methods to identify and mitigate expansive soil behavior.

Fundamentally, swelling occurs when water infiltrates and separates clay particles, increasing their volume [5, 12]. In unsaturated soils, this phenomenon is influenced by soil mineralogy, water content, and environmental conditions.

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When swelling is constrained, such as beneath a structural load, multidirectional swell pressures develop, often leading to damage [7, 13]. These pressures are particularly concerning in soils with high swelling potential, emphasizing the need for accurate identification and mitigation strategies.

Numerous studies have focused on identifying expansive soils and quantifying their expansion characteristics [14–16]. Traditional methods such as X-ray diffraction (XRD) and electron microscopy provide valuable insights but are resource-intensive and time-consuming [7, 17]. While some researchers have explored empirical correlations between soil properties and expansivity [18–20], these approaches often lack accuracy and are limited to preliminary evaluations. Further empirical correlations can be seen in the mentioned study [21]. Consequently, there is a pressing need for affordable, practical, and reliable methods to assess soil expansivity, particularly in regions like Indonesia, where expansive soils are prevalent.

The Methylene Blue Value (MBV) test offers a promising solution. This simple and practical method eliminates the need for specialized equipment, making it suitable for assessing clay mineral content during preliminary investigations [22–24]. The test measures the cation exchange capacity (CEC) and specific surface area of soil, which are strongly correlated with soil expansivity [25–28]. Previous studies have used MBV to assess soil properties such as plasticity index and swelling potential [24, 29, 30]. However, it is also challenging to establish new correlations related to the Methylene Blue (MB) test in this context. While MB has been widely used as a geotechnical parameter [28, 31–33], its application has primarily been limited to estimating cation exchange capacity (CEC), with little exploration of its broader potential in soil characterization. The most recent methylene blue correlation studies are dated back to 2020 [24, 30, 34–36].

Beyond initial soil identification, assessing soil expansivity requires further evaluation. Once a soil is classified as expansive, two possible courses of action arise: relocating the project or implementing soil stabilization measures. However, stabilization efforts are often conducted without adequately measuring the degree of swelling, making it difficult to assess their effectiveness. While lime and cement are well-established stabilizers for mitigating soil expansivity [37, 38], their interactions with specific mineral compositions remain insufficiently understood. Recent studies have attempted to evaluate stabilization effectiveness using the Methylene Blue Value (MBV) [39, 40], but these efforts are constrained by limited datasets and do not fully account for the variability of expansive soils in Indonesia. Moreover, research on the consistency and reliability of MBV correlations for stabilized soils remains scarce, which is crucial for validating its broader applicability in engineering practice.

This study aims to address critical gaps in the application of the MBV test for stabilized soils, which have often been overlooked in existing research. Specifically, this research focuses on Indonesian soils, emphasizing their diverse mineral compositions and varying degrees of expansivity, which remain underexplored. Additionally, this research seeks to develop and validate correlation models that link MBV to key expansive soil parameters, such as swell pressure and free swell, to enhance the predictive capabilities and practical applicability of MBV in geotechnical engineering applications.

The methodology of this study involved a systematic approach to soil sampling, laboratory testing, and stabilization processes. Soil samples were collected from seven distinct locations across three Indonesian islands, representing diverse geological conditions. The samples were characterized through laboratory tests, including grain size distribution, Atterberg limits, and X-ray diffraction (XRD) analysis, to determine their fundamental properties and mineral compositions. Compaction and swell tests were conducted to evaluate the natural soils' Maximum Dry Density (MDD), Optimum Moisture Content (OMC), and expansive characteristics, following ASTM standards. For soil improvement, lime and cement were employed as stabilizers at varying dosages. The MBV test, based on BS EN 933-9, was used to determine the soil's ion absorption capacity and its correlation with expansive soil parameters.

2. Material and Methods

2.1. Soil Sampling and Characterization

The investigation began with a systematic soil sampling method at seven distinct locations across three islands in Indonesia (Figure 1). The samples were collected by removing the surface soil to depths ranging from 20 to 50 cm, and then acquiring the immediate sub-surface soil from beneath the stripped layer (Figure 2). To ensure sufficient material for various subsequent laboratory tests, a minimum of 100 kg of soil samples was taken from each location. The soil samples were named after their respective sites: Cisomang, Sadang, Buma Binungan, Tanjung Redeb, Morowali A-B, Morowali C-D, and Gedebage.

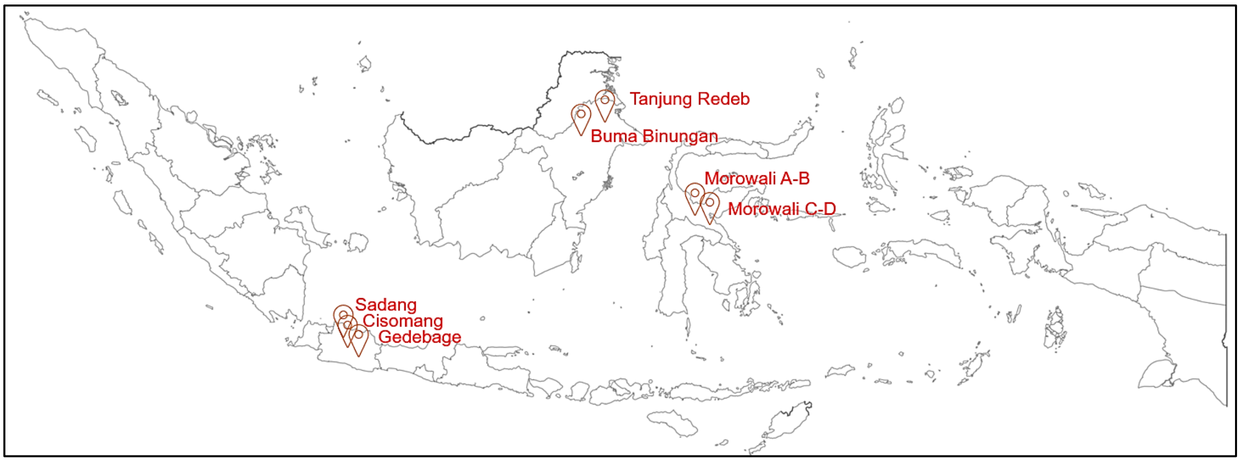


Figure 1. Samples' location

Figure 2. The Sadang sample size condition

Figure 3 presents the preliminary visual inspections results, showing that all samples were classified as clay. Five samples exhibited a grayish color, while the Morowali A-B and C-D samples had a reddish hue. Notably, the Cisomang and Sadang samples displayed distinct characteristics; the Cisomang sample originated from a riverbed, while the Sadang sample obtained from high-altitude mountain deposits.

Figure 3. Visual appearance of the seven soil samples

Laboratory tests were conducted to characterize the fundamental properties of the soil samples. These tests included grain size distribution, specific gravity, and Atterberg limits. Subsequently, the samples were categorized according to the Unified Soil Classification System (USCS), identifying different soil categories for each sample. The mineral composition of the samples was determined using X-ray diffraction (XRD) analysis [17]. For this analysis, the soil samples were ground as finely as possible and analyzed using Rigaku Smartlab XRD equipment. Quantitative XRD analysis was performed using the Reference Intensity Ratio (RIR) method [41–43].

2.2. Compaction and Swell Tests

Compaction tests were conducted on the samples to determine their maximum dry density (MDD) and optimum moisture content (OMC). These tests followed the standard procedures outlined in ASTM D698, using a 4-inch mold. Compaction Method A was selected based on the soil's compliance with the specified grading criteria. The values obtained under natural conditions served as important benchmarks for subsequent assessments of the soil samples. Specifically, the OMC condition was chosen for further swell testing.

Swell tests were conducted after determining the soil properties. These tests adhered to ASTM D4546 Method A, using a conventional oedometer. For these tests, the soil samples were prepared following the standard one-dimensional consolidation test routine. The procedure involved applying pressure, starting at 1 kPa, prior to inundating the samples. Dial readings were recorded at designated intervals, ranging from 0.5 minutes to 72 hours. This testing yielded two critical parameters: free swell, representing the percentage of expansion resulting from water absorption at 1 kPa, and swell pressure, denoting the minimum pressure required to prevent any expansion of the soil.

2.3. Soil Improvement

Soil samples identified as expansive underwent improvement procedures using cement and lime. Cement and lime are stabilizers recognized in their effectiveness in mitigating the expansive nature of soil [37, 38, 44-46]. These materials enhance soil properties through cation exchange and flocculation-agglomeration. The stabilization of expansive soils using lime and cement is based on chemical reactions that improve soil properties by altering their in structure, composition, and bonding. These reactions primarily include cation exchange, flocculation-agglomeration, and pozzolanic processes, which significantly reduce soil expansivity and enhance its engineering performance.

2.3.1. Lime Stabilization Reactions

When lime (CaO or $Ca(OH)_2$) is added to expansive soils, it reacts with the water present in the soil to produce calcium hydroxide (slaked lime):

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} \tag{1}$$

The calcium ions (Ca^{2+}) released by lime displace monovalent cations (e.g.,Na^+) from the clay surface through cation exchange. This process neutralizes the negative charges on clay particles, reducing their ability to attract water and thus mitigating swelling:

$$2\,Na^+ + Clay + Ca(OH)_2 \rightarrow Ca^{2+} + Clay + 2Na^+ + OH^- \tag{2}$$

Additionally, lime causes the fine clay particles to aggregate into larger particles (flocculation-agglomeration), improving soil structure and reducing plasticity. Over time, a pozzolanic reaction occurs as calcium hydroxide reacts with silica (SiO_2) and alumina (Al_2O_3) in the soil, forming cementitious compounds such as calcium silicate hydrate (C−S−H) and calcium aluminate hydrate (C−A−H):

$$\begin{aligned} Ca(OH)_2 + SiO_2 &\rightarrow C - S - H \\ Ca(OH)_2 + Al_2O_3 &\rightarrow C - A - H \end{aligned} \tag{3}$$

These reactions increase soil strength and durability while reducing swelling potential.

2.3.2. Cement Stabilization Reactions

Cement stabilization involves hydration and pozzolanic reactions, which are similar to those in lime stabilization but occur more rapidly due to the presence of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) in cement. Upon hydration, these compounds form calcium silicate hydrate (C−S−H) and calcium hydroxide:

$$\begin{aligned} 2C_3S + 6H_2O &\rightarrow 3CaO \cdot 2SiO_2 + 3H_2O + 3Ca(OH)_2 \\ 2C_2S + 4H_2O &\rightarrow 3CaO \cdot 2SiO_2 + 3H_2O + Ca(OH)_2 \end{aligned} \tag{4}$$

The calcium hydroxide produced then participates in secondary pozzolanic reactions with silica and alumina from the soil, as shown in the lime stabilization process. This dual mechanism—hydration and pozzolanic activity—contributes to the rapid development of strength and reduction in soil expansivity.

Various studies have utilized different types of cement and lime, each with varied content, without a singular prescribed dosage [37, 38, 44-46]. Specific for expansive soils, Al-Gharbawi et al. [47] and Ouendi & Zentar [48] used cement and lime content ranging from 5% to 9%, resulting in significant reduction in free swell (65%) and swell pressure (76%). The same trends are found by Phanikumar & Ramanjaneya Raju (2020) [37] whose used 0-6% lime and 0-20% cement content.

In this study, ordinary Portland Cement Type I and CaO (lime) were used as stabilizers. The content of cement and lime was systematically varied at 5%, 10%, and 15% by weight of the soil. These contents are selected to ensure economic feasibility for the field work in Indonesia.

Each soil sample was then thoroughly mixed and compacted with an energy level of 1 ec, following the ASTM D698 Method A compaction standard. The same set of tests conducted on the natural soils was then applied to these stabilized samples to assess the effectiveness of the improvement procedures.

2.4. Methylene Blue Test

The Methylene Blue test assesses the ion absorption capacity of soil by determining the quantity of methylene blue required to saturate the surface area of clay particles. The amount of methylene blue absorbed is directly proportional to the ability of the clay to absorb water. This test is based on the chemical titration reaction between the free cationic methylene blue ($C_{16}H_{18}N_3S^+$) obtained by dissolving methylene blue in water and the exchangeable anions in the clay soil (OH^-).

$$C_{16}H_{18}N_3SCl + Al_2Si_2O_5(OH)_4 \longrightarrow C_{16}H_{18}N_3S(OH)_4 + Al_2Si_2O_5Cl \quad (5)$$

Clay particles with larger specific surface areas and higher negative charges have a greater capacity for cation exchange, thereby adsorbing more methylene blue.

In this study, the Methylene Blue test was conducted based on the British Standard, BS EN933-9 (2022). The Methylene Blue (MB) solution was prepared by dissolving 10 ± 0.1 g of methylene blue powder in 1 L of distilled water. This mixture was stirred at room temperature for one hour in a beaker. The soil solution was prepared by mixing 7.5 g (or 30 g for larger samples) of the soil, passed through a No. 40 sieve, with 50 ml (or 200 ml for 30 g of soil) of distilled water. This mixture was agitated at 700 RPM for 5 minutes. This step is important as it ensures the particle sizes of the samples tested are in roughly the same conditions. Different treatments on sample preparation may result in different MBV [48].

Subsequently, 5 mL of the MB solution was added to the dispersed soil solution. A drop of this dyed suspension was then placed on filter paper using a pipette, forming a stain with a solid color in the center surrounded by a colorless wet zone. This addition of MB solution continued until a positive test result was achieved: the formation of a halo, indicated by a light blue ring in the wet zone, as detailed in Figure 4. The complete Methylene Blue test procedure is illustrated in Figure 5. The MBV is then determined using the following formula:

$$MBV = \frac{V_{MB\ added}}{W_{soil}} \quad (6)$$

For tests using methylene blue solution with a concentration of 10 g/L.

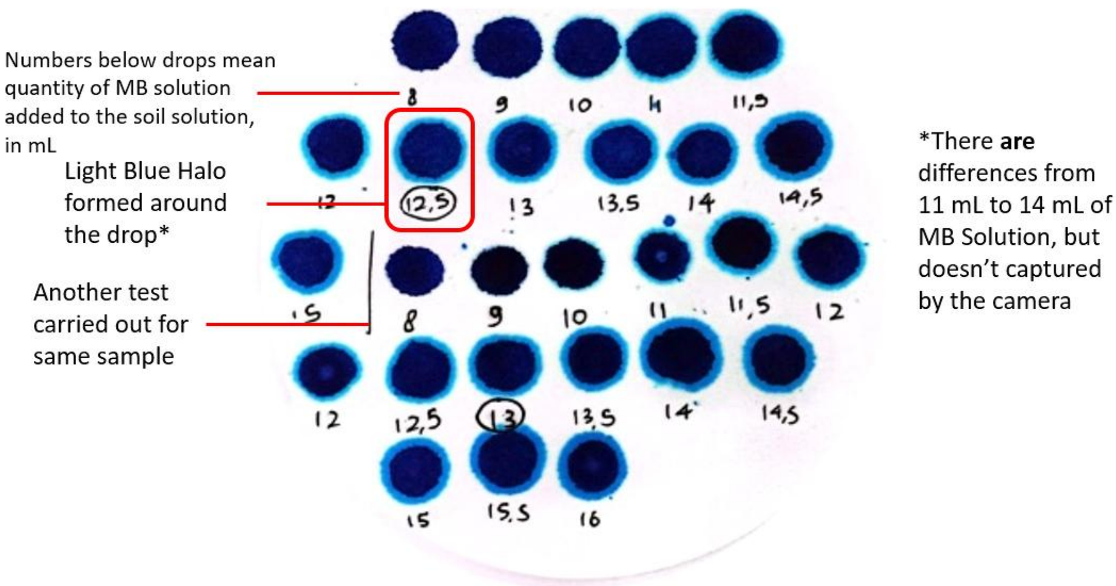


Figure 4. Light blue halo formed in the wet zone of the methylene blue drop

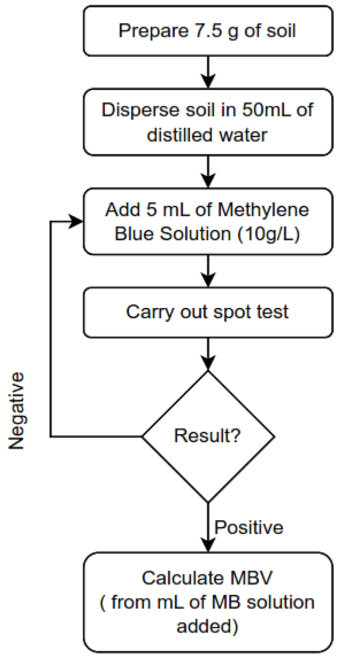


Figure 5. Methylene blue test procedure

3. Results and Discussion

3.1. Soil Properties and Mineral Contents

The soil samples obtained from seven different locations in Indonesia exhibited diverse natural characteristics. Table 1 presents the results of laboratory tests conducted under natural conditions for these soil samples. All samples displayed very high fine content. While most had a liquid limit (LL) greater than 50, the Morowali samples stood out with low LL and plasticity index (PI) values, classifying them differently from the others.

Table 1. Results of soil properties laboratory test under natural condition

Sample Name	Cisomang	Sadang	Buma Binungan	Marowali A-B	Marowali C-D	Tanjung Redeb	Gedebage
Location	West Bandung Regency, West Java	Purwakarta Regency, West Java	Berau Regency, East Kalimantan	Marowali Regency, Central Sulawesi	Marowali Regency, Central Sulawesi	Berau Regency, East Kalimantan	Bandung City, West Java
USCS Classification	MH	CH	MH	CL	CL	MH	CH
Gs	2.71	2.72	2.67	2.60	2.60	2.48	2.54
Fine Content	90.28	96.96	93.11	90.62	90.14	92.72	94.83
LL	64.62	78.00	66.57	30.07	23.22	57.98	85.41
PL	32.57	24.45	53.28	16.78	16.88	47.52	37.32
PI	32.05	53.55	13.29	13.29	6.34	10.46	48.09
OMC (%)	16.25	35.00	46.84	12.89	13.12	55.22	37.50
$\gamma_{dry,max}$ (kN/m^3)	17.78	13.16	11.42	17.69	18.35	10.52	12.13

According to Casagrande's chart, shown in Figure 1, the Morowali samples fall into the CL category, while the Sadang, Gedebage, and Cisomang samples belong to the CH category. The remaining samples are classified as MH. Figure 6 further illustrates the significant variations between these soil samples.

Figure 7 presents the results of the XRD test, showcasing the mineral types and contents of each soil sample. The primary clay minerals identified include Muscovite and Kaolinite. Other minerals identified include quartz, cordierite, and albite. To improve clarity, minerals with minor content not directly related to expansivity are grouped under the 'Others' category. Despite its lack of direct correlation with soil expansivity, quartz retains a separate category due to its abundance.

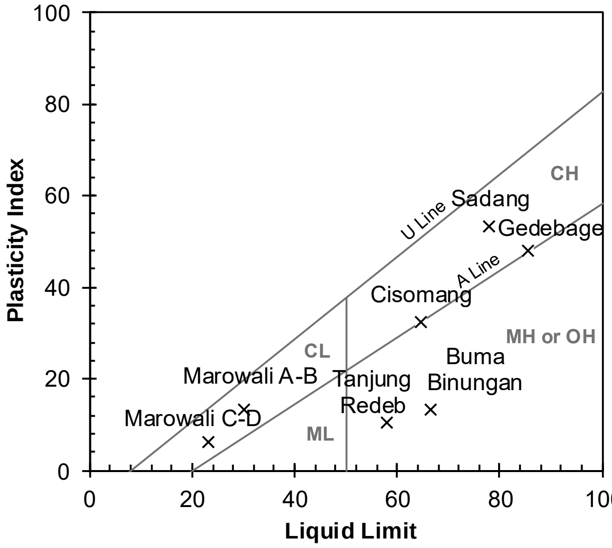


Figure 6. Casagrande chart for samples

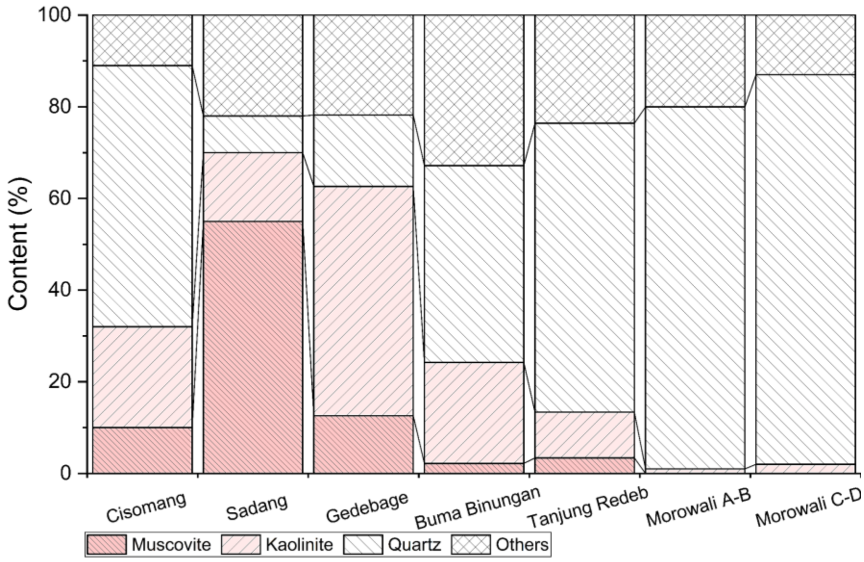


Figure 7. Mineral content from XRD test for each sample

Muscovite is known for its high cation exchange capacity [6], unlike kaolinite. CEC measures the ability of a clay mineral to attract and retain water molecules. Due to its high exchange capacity, muscovite retains more water, thereby increasing soil expansivity.

To facilitate differentiation among clay minerals, represented in Figure 7 using a thin red color with striped (or crossed) patterns. The variation in thin red and solid red colors indicates the level of expansiveness of the mineral. It is noted in some literature that kaolinite is not considered an expansive mineral [6, 7].

Figure 7 reveals that the Sadang and Gedebage samples exhibit the highest and second-highest content of clay minerals. The Buma Binungan, Cisomang, and Tanjung Redeb samples contain considerable amounts of such minerals. The Morowali A-B and Morowali C-D samples contain very low expansive mineral content. These results align with the visual observation in Figure 3 and the soil properties presented in Table 1. The variation in mineral content among the samples highlights the diverse characteristics of Indonesia's expansive soils, which are influenced by their geographical and geological contexts.

The Cisomang, Sadang, and Gedebage samples, located in West Java, contain the highest concentrations of Muscovite mineral. In contrast, the Buma Binungan and Tanjung Redeb samples from East Kalimantan have lower Muscovite content but still contain other clay minerals that contribute to their expansive nature. The Morowali A-B and Morowali C-D samples, however, exhibit very low expansive mineral content, which aligns with their classification based on liquid limit and plasticity index. This diversity in mineral composition ensures that the subsequent analyses adequately represent the diverse soil conditions found across Indonesia.

As an additional note, there is a specific potential misidentification regarding the use of XRD for clay mineral identification between montmorillonite and muscovite. Three factors contribute to misidentification are similar layer structures of clay mineral, peak broadening in Montmorillonite and Preferred Orientation. Both montmorillonite and muscovite share a 2:1 layer structure [49], which can result in overlapping peaks in their XRD patterns. Montmorillonite often produces broad, diffuse peaks due to its variable interlayer spacing, influenced by water and exchangeable cations. If not carefully interpreted, these broad peaks can resemble the sharper peaks of muscovite. Additionally, clay minerals tend to align during sample preparation, causing preferred orientation effects. This can enhance certain peaks while diminishing others, potentially leading to confusion.

3.2. Expansive Behavior under Natural Conditions

Table 2 presents the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the soil samples under natural conditions, as determined by compaction tests. The results indicate that the Morowali A-B and Morowali C-D samples conform to the typical compaction values for clay and sand as defined by ASTM D-698. In contrast, samples from Sadang, Buma Binungan, Gedebage, and Tanjung Redeb exhibit compaction parameters that deviate from typical values. The OMC for these samples ranges from 35.00% to 55.22%, which is higher than the typical range, while the MDD is lower, ranging from 11.42 to 13.16 kN/m³. These values indicate that these samples consist of soft to medium clay.

Table 2. Results of Soil compaction and swelling Laboratory Tests under Natural Conditions

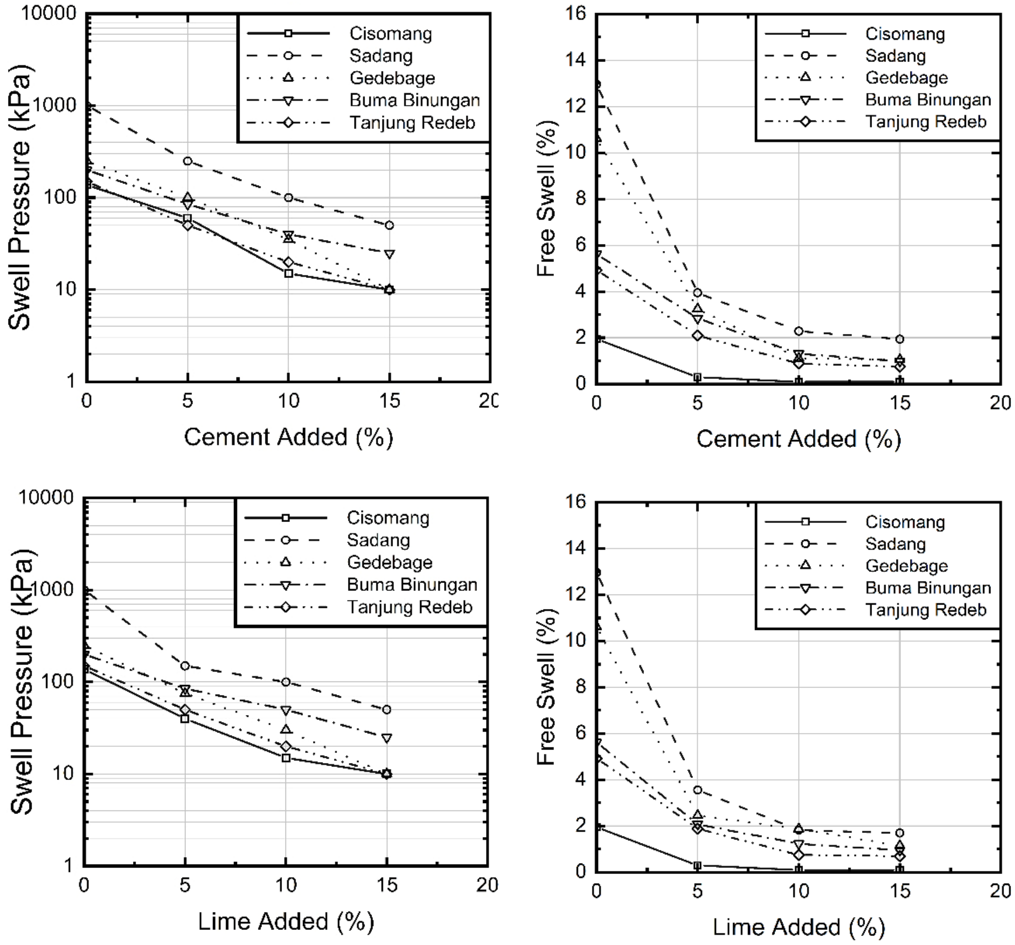
Sample Name	Cisomang	Sadang	Buma Binungan	Marowali A-B	Marowali C-D	Tanjung Redeb	Gedebage
OMC (%)	16.25	35.00	46.84	12.89	13.12	55.22	37.50
$\gamma_{dry,max}$ (kN/m^3)	17.78	13.16	11.42	17.69	18.35	10.52	12.13
σ_s (kPa)	137.00	1000.00	200.00	25.00	25.00	150.00	250.00
Free Swell (%)	1.94	12.97	5.62	0.97	1.10	4.93	10.62
Expansivity	Moderate	Very High	Moderate	Low	Low	Moderate	High
MBV	12.63	32.37	11.40	2.13	1.98	10.24	16.50

Table 2 also summarizes the findings related to the expansive properties of the soil samples. The Morowali A-B and Morowali C-D samples displayed low expansiveness, with a free swell of approximately 1%, a swell pressure of 25 kPa, and free swell values of 0.97 and 1.10, respectively. These values align with the expected range for non-expansive soils, which have swell pressures lower than 50 kPa [5]. In contrast, the remaining samples exhibited significant expansive behavior. For instance, the Cisomang soil demonstrated a swell pressure of 137 kPa, while the Sadang soil exhibited an exceptionally high swell pressure of up to 1000 kPa. According to Chen's classification [5], as noted in the 'Expansivity' row of Table 2, the Cisomang, Buma Binungan, Tanjung Redeb, Gedebage, and Sadang samples demonstrate moderate to very high levels of expansivity, classifying them as expansive soils. From this, it can be concluded that the soil samples used in this study cover all categories of expansive soils described by Chen [5].

The observed expansive properties correspond closely with the mineral content. For example, the non-expansive Morowali A-B and Morowali C-D samples show minimal content of potentially expansive minerals. On the other hand, samples exhibiting high-swelling characteristics, such as Sadang and Gedebage, reveal a higher content of potentially expansive minerals. However, some discrepancies exist. The Cisomang sample, with its higher muscovite content, should theoretically exhibit greater expansiveness compared to the Tanjung Redeb sample, which contains only 3% muscovite. This discrepancy may be attributed to the unique geological processes at the riverbed site of the Cisomang sample, leading to the formation of clay minerals other than muscovite that were later identified by XRD as muscovite [50].

3.3. Expansive Behavior after Soil Improvements

Figures 8-a and 8-b present the swelling test results, depicting the swell pressure and free swell of the improved soil samples. The top panels show the results of cement-treated soils, while the bottom panels display those of lime-treated soils, with different soil samples distinguished by their dot and line patterns. These figures reveal a clear trend: both swell pressure and free swell parameters decrease with increasing concentrations of cement or lime. A noticeable reduction in these parameters is evident even with only a 5% addition of cement or lime, and this trend continues up to a 15% addition.



(a) (b)

Figure 8. Swell test result in soil parameters (a) swell pressure, and (b) free swell

Converting the swell pressure data to a logarithmic scale reveals a consistent log-linear relationship between the level of additive and the logarithm of swell pressure across all samples, as shown in Figure 8-a. The free swell parameter, as shown in Figure 8-b, also exhibits a significant decrease following the addition of 5% cement or lime. These results indicate that lime is as effective as cement in reducing free swell values at the same concentration level. Furthermore, the most substantial reductions in swell parameters were observed in samples that initially exhibited high free swell values. For example, the Sadang samples experienced a more significant reduction in swelling than the Cisomang samples at the same additive concentration.

Based on these findings, a 15% additive concentration may represent the optimal level for mitigating both swell pressure and free swell development. This concentration resulted in a reduction of swell pressure below 50 kPa, with the exception of the Sadang sample, classifying it as non-expansive soil according to Chen's classification [5]. The decline in the free swell curve tends to plateau at this point, implying a diminishing marginal benefit from further additive increments beyond 15%. Moreover, the considerable variability in swelling parameters across the samples (ranging from 137 kPa to 1000 kPa for swell pressure) supports this statement.

These findings align with previous research on the use of lime and cement in improving expansive soils. Al-Gharbawi et al. [47] tested a single type of soil and found a significant decrease (up to 70%) in swell pressure and free swell when lime or cement stabilizers were added. Smaida et al. [51] also observed similar results using different swell parameters, such as swelling potential (ASTM D4546-90). They found that the addition of lime or cement reduced the swell characteristics of the soil. Süt Ünver et al. [52] obtained similar results using Esenboga Clay, observing a significant decrease in the swell up to 30%, at 9% lime addition.

One notable observation from this dataset is the development of a non-linear relationship between the addition of lime and cement and the resulting swell parameters. Note that previous studies [47, 52] identified a linear correlation in their studies. This difference may be attributed to the extended investigation, which includes lime content levels up to 15%, potentially influencing the observed relationship. Furthermore, this study includes a broader range of soil expansivity, offering more comprehensive insights. These findings highlight the unique non-linear effects of higher additive concentrations, which were not covered by previous research [51], enhancing the understanding of soil stabilization dynamics.

3.4. Relationship Between Methylene Blue Value (MBV) and Soil Expansivity

The analysis of the expansivity and MBV results for the samples provides valuable insights into their soil characteristics. The MBV test results for natural soil are shown in Table 2. For example, the Sadang sample, which exhibits very high expansivity, has the highest MBV of 32.37. Conversely, the Morowali A-B and Morowali C-D samples, which have low expansivity, show the lowest MBV values of 2.13 and 1.98, respectively. Similar to swell parameters, the MBV values obtained from soil samples exhibit a wide distribution, indicating that the high variation in MBV can holistically represent the relationship between MBV and swelling parameters.

Figure 9 presents the results of the Methylene Blue test after soil improvements. The top panel displays the results of cement-treated soils, while the bottom panel shows the results of lime-treated soils, with each graph showing MBV on the y-axis. Similar to the swelling characteristics observed in the swell test, the Figure demonstrates that MBVs decrease with increasing concentrations of cement or lime stabilizers. The MBVs show a progressive decline, starting from a 5% addition and continuing up to a 15% addition of cement or lime. The pattern observed in Figure 9 closely parallels the one in Figure 8, with significant reductions noted even at the 5% addition level, and the trend persisting up to the 15% addition.

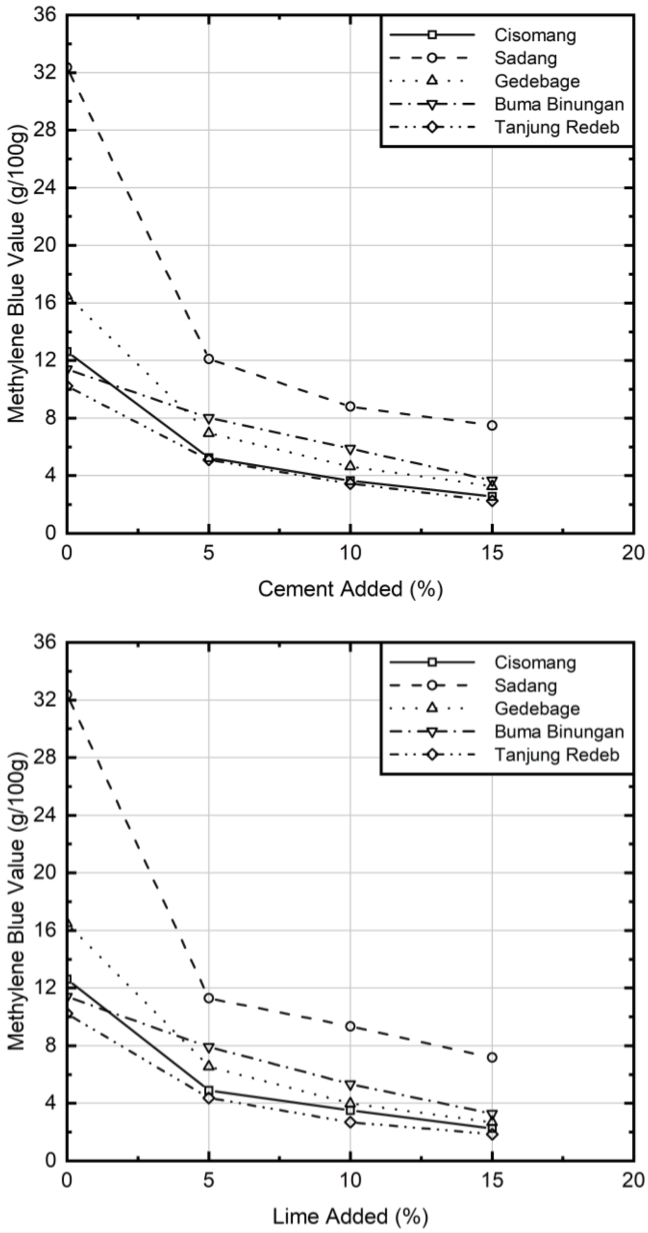


Figure 9. Methylene Blue Test result

These results imply a relationship between expansivity and MBV, where greater expansivity correlates with higher MBV values. This finding highlights the reliability of MBV in assessing soil expansivity potential and its reaction to moisture fluctuations. A similar phenomenon was observed by Süt Ünver et al. [52], who employed lime for soil improvement and measured its MBV. They found that with lime addition, the MBV value decreases proportionally to the lime content increment. Among the studies reviewed, only this study addresses MBV in relation to the addition of lime. The significance of the present study in further elucidating soil stabilization dynamics and establishing MBV as a practical and effective tool for soil identification.

By examining the similarity of patterns and relationships between Figures 8 and 9, a regression analysis was conducted to quantify the relationship between MBV and swell parameters. A non-linear regression formula was applied to establish the relationship model:

$$Sp = a(MBV)^b \tag{7}$$

In this model, Sp represents the swell pressure, while a and b are the model coefficients obtained from empirical data. Figure 10 shows a regression analysis representing the relationship between MBV and swell pressure, with MBV on the horizontal axis and swell pressure on the vertical axis. Each point represents one data point, with different shapes indicating the location and color indicating the condition of the soil, whether natural or improved. This non-linear approach was chosen due to the observed non-linear pattern evident in the data, as visualized in Figure 10.

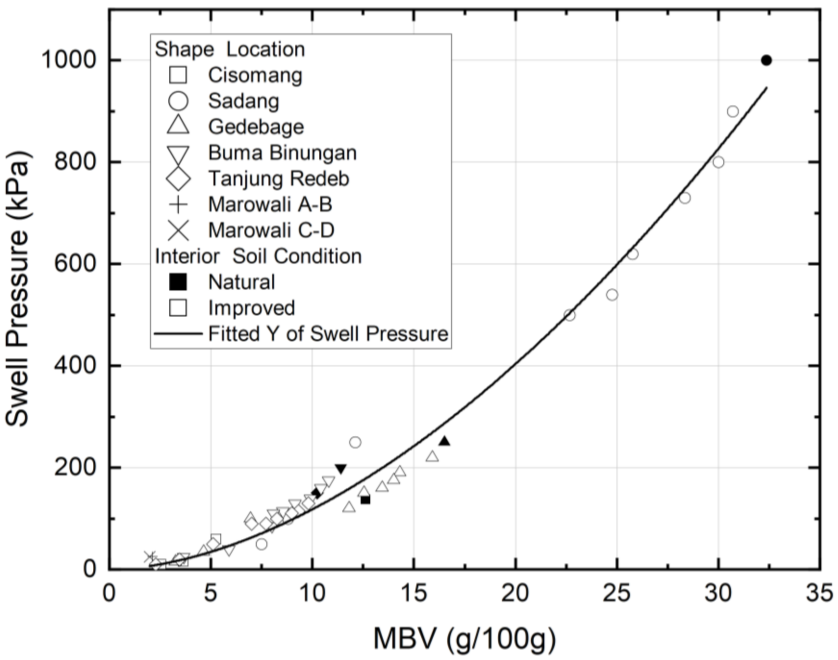


Figure 10. Regression Line for Swell pressure vs. MBV

The regression was fitted using least squares estimators to produce a relationship model between swell pressure and MBV, as shown in equation below and in Figure 10 as the 'Fitted Y of Swell Pressure' line:

$$Sp = 1.698\ MBV^{1.819} \tag{8}$$

The R^2 value was found to be 0.978, suggesting that MBV can explain approximately 97.8% of the variation in swell pressure. This finding underscores the utility of MBV as a valuable tool for identifying expansive soils and assessing their expansiveness level. It is important to note that this proposed model applies within the tested ranges of 0–32 for MBV and 0–1000 kPa for 1-D swell pressure. Beyond these ranges, the prediction accuracy of the proposed model may decrease. The variance within the defined ranges is found to be below 5%, indicating a small regression error. The results of this regression are also based on a sufficient amount of data, with more than 25 samples.

Several previous studies, such as those by Mahedi et al. [46] and Yukselen & Kaya [26], also measured swelling potential. In general, these studies indicate that the swelling potential of soil can be determined using the MB test method. Furthermore, Forouzan [36], develop regression using MBV as one of the parameters used for predicting, which has positive correlations to swelling pressure. However, there is one study stating that swelling pressure has weak negative correlations to MBV (R=-0.06) [53]. Nevertheless, there is still a lack of research linking MBV and swell pressure for soils with varying characteristics, both in their natural and improved conditions. This study addresses this gap by providing a detailed analysis of this relationship.

It is important to consider the high R^2 values observed in this research. This may be attributed to the wide range of data, which includes several outliers. The presence of these outliers, the Sadang samples, in both natural and improved conditions, likely contributes to the exceptionally high correlation results.

It should be noted that this high correlation result applies to remolded soil under OMC conditions. However, swell pressure is not solely determined by a single parameter (such as clay mineral content, CEC, or SSA) but is also influenced by other factors. Parameters that represent actual field conditions, such as initial void ratio, dry density, and natural moisture content, significantly affect the magnitude of swelling that occurs [21].

3.5. Relationship Between Methylene Blue Value (MBV) and Expansive Clay Mineral Content

An important relationship can also be observed between the MBV and the content of expansive clay minerals (Figure 11). A linear regression analysis, utilizing the MBV of natural soils and their mineral content, demonstrates a strong linear relationship, with an R-square value exceeding 0.93. This finding indicates a potential correlation between the mineral content of soils and their level of expansiveness. These results suggest that the Methylene Blue test may also serve as a cost-effective and rapid substitute for identifying expansive minerals in soil. From a theoretical perspective, the MB test measures cation exchange capacity (CEC) [26, 54], which is directly related to the expansive properties of the soil [55, 56]. The clay mineral content shown in Figure 11 is the sum of various clay minerals, each contributing to cation exchange capacity and expansiveness to varying degrees [13]. Despite these promising results, further validation of this relationship is required due to the limited scope of available natural data. The dataset used for this regression analysis is limited to seven samples, with significant gaps between data points.

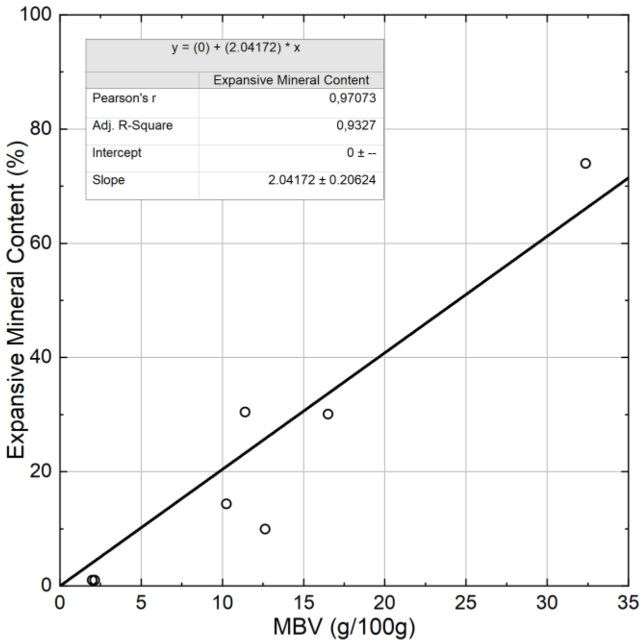


Figure 11. Expansive Mineral Content vs. Methylene Blue Value Regression

4. Conclusions

This study has provided valuable insights into the expansive nature of soils with different mineral contents from different regions in Indonesia, analyzing their properties both in natural states and after stabilization. The key findings are summarized as follows:

- The expansive behavior of soils under natural conditions correlates closely with their mineralogical composition. Non-expansive samples like Morowali A-B and Morowali C-D exhibited minimal content of expansive minerals. In contrast, samples with high-swelling characteristics, such as Sadang and Gedebage, displayed higher content of expansive minerals.
- The addition of cement and lime significantly reduces both swell pressure and free swell. Even a 5% concentration of stabilizers effectively decreased soil expansivity. A 15% additive concentration appears to be optimal for reducing both swell pressure and free swell development, as indicated by the convergence of the free swell curve. Additionally, lime proved to be as effective as cement in reducing free swell values at equivalent concentration levels.
- The Methylene Blue test results corroborated the findings of the swelling tests, showing a decline in MBV with increasing stabilizer concentrations. The strong correlation between MBV and soil expansiveness (R^2=0.978) underscores MBV as a reliable indicator of soil behavior. This emphasizes its potential to predict soil expansive behavior in a practical way.

- A notable linear relationship was observed between MBV and the content of expansive minerals ($R^2 > 0.93$), suggesting that the Methylene Blue test can serve as a cost-effective and rapid method for identifying expansive minerals in the soil. While MBV cannot directly estimate mineral content, it can help indicate the presence of expansive clay minerals.

Given the limited scope of available natural data, the findings of this study are constrained by the tested ranges of MBV and swell pressures, highlighting the need for further validation of the established relationships. Future studies could build upon this work by exploring a broader range of soil samples and incorporating additional soil stabilization methods. Moreover, while lime and cement proved effective as stabilization methods, their environmental impact underscores the necessity of exploring more sustainable alternatives. Despite these limitations, this study makes a substantial contribution to geotechnical engineering by enhancing the understanding of expansive soils with varying characteristics. It also provides practical insights for identifying and mitigating soil expansion, ultimately supporting improved stabilization practices.

5. Declarations

5.1. Author Contributions

Conceptualization, H.N. and D.A.; methodology, H.N.; software, M.F.A.; validation, H.N. and D.A.; formal analysis, H.N.; investigation, M.F.A.; resources, M.F.A.; data curation, M.F.A.; writing—original draft preparation, H.N.; writing—review and editing, D.A.; visualization, M.F.A.; supervision, H.N.; project administration, M.F.A.; funding acquisition, H.N. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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