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Research Article

Enhancing Water Retention Capacity and Mechanical Properties of Clay Soils with Bentonite Sand Additives

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Abstract

Clay soils pose significant challenges in civil engineering due to their high plasticity, low shear strength, and sensitivity to moisture variations, necessitating effective stabilization techniques. This study evaluates the impact of bentonite sand addition on the compaction behavior and water retention capacity of clay soils, focusing on changes in maximum dry density and optimum moisture content. Standard Proctor compaction tests, following ASTM D698, were conducted on clay soil samples mixed with 0%, 2%, 4%, and 6% bentonite sand by dry weight. Measurements included physical properties, particle size distribution, maximum dry density, and optimum moisture content. The results demonstrated that bentonite sand addition significantly improved both compaction characteristics and water retention capacity. Maximum dry density increased notably at 2% and 6% bentonite contents, while optimum moisture content rose consistently with higher bentonite percentages. These changes are attributed to the high specific surface area and strong water adsorption capacity of bentonite, enhancing soil particle arrangement and moisture-holding ability. The observed trends align with previous studies, highlighting bentonite's role in modifying soil microstructure and improving mechanical behavior. This study concludes that bentonite sand is an effective and sustainable stabilizer for clay soils, offering enhanced compaction performance and water retention capacity. Its use may contribute to greater soil strength and durability, particularly under moisture-variable conditions. Further research should explore additional strength parameters and validate bentonite's performance under field conditions to optimize its application in geotechnical engineering.

Keywords: Bentonite; Clay; Compaction; Stabilization; Water Retention.

Introduction

The necessity of ensuring adequate soil bearing capacity has long been a fundamental concern in civil engineering practice. Soil materials must possess sufficient strength, stability, and durability to serve as reliable foundations for structures and infrastructures. However, natural soil conditions often present significant variability, particularly in tropical and temperate regions, where moisture fluctuations, particle composition, and inherent mechanical properties

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can compromise soil performance. Among these, clay soils are particularly challenging due to their problematic geotechnical characteristics. The challenges associated with constructing over clay soils and the influence of moisture variation on their mechanical behavior, as well as the methods used to stabilize them, have been extensively documented in the literature.

Clay soils are notorious for their low shear strength, high compressibility, and significant volumetric changes during wetting and drying cycles, characteristics that result in a range of geotechnical problems including excessive settlement, slope instability, and bearing capacity failure [1,2]. For instance, soft clay often experiences differential settlement, adversely affecting the structural performance of highways and roadbeds while posing difficulties in predicting long-term behavior [1]. In addition, swelling and shrinkage behaviors inherent to many types of clay further complicate construction efforts by inducing cracks in pavements and foundations. Such deficiencies necessitate meticulous geotechnical assessment and mitigation strategies, particularly in areas where the soil is subjected to dynamic moisture conditions. Seasonal cycles, characterized by alternating wet and dry periods and, in colder regions, freeze-thaw processes, significantly alter the mechanical behavior of clay soils. Pore water content variations during these cycles lead to changes in strength, stiffness, and volume stability [3,4]. During periods of increased moisture, clay soils tend to lose shear strength, resulting in reduced bearing capacity and greater deformation risks [3]. Conversely, dry conditions cause shrinkage, which induces tensile stresses that manifest as surface fissures, potentially compromising structural integrity [4]. Freeze-thaw cycles can exacerbate these problems by altering microstructural properties and hydraulic behavior, further complicating engineering designs [5].

A critical aspect influencing the mechanical response of clay soils under such variable moisture conditions is their water retention capacity. Water retention capacity describes the ability of a soil to hold water within its structure, which in turn impacts the soil's volume stability, strength, and long-term behavior. Soils with improved water retention are less susceptible to rapid drying and cracking, while also mitigating the abrupt softening that occurs during saturation phases. Thus, enhancing the water retention capacity of clay soils is essential for stabilizing their engineering properties and ensuring their reliability as construction materials, especially in regions prone to significant moisture fluctuations.

The primary research problem stems from the inherent instability of clay soils under variable moisture conditions, which poses considerable challenges to safe and cost-effective construction. Traditional solutions have emphasized soil stabilization techniques to mitigate these geotechnical risks. Historically, stabilization efforts relied on chemical additives such as cement and lime to modify the engineering properties of problematic soils. Cement and lime stabilization methods work by reducing plasticity, enhancing strength, and mitigating the shrink-swell behavior of clay soils [2,6]. These interventions significantly improved soil performance and became the cornerstone of conventional ground improvement practices. However, despite their efficacy, these techniques also raise sustainability concerns due to high energy consumption and carbon emissions associated with the production of cementitious materials.

In response to these limitations, more sustainable stabilization approaches have gained traction. Recent studies highlight the effectiveness of industrial by-products such as steel slag, fly ash, waste foundry sand, and calcium carbide waste in enhancing the mechanical properties of clay soils [7,8]. These materials not only provide technical improvements but also promote environmental sustainability by recycling industrial waste. Additionally, salt-lime stabilization has been explored as an alternative method that enhances compressive strength and durability under mechanical disturbances [2]. These contemporary strategies align stabilization practices with sustainability goals by simultaneously improving soil behavior and minimizing environmental impacts [7].

Chemical stabilization techniques enhance the physical properties of expansive clays by inducing chemical reactions among soil particles. The addition of lime, cement, or other reagents leads to hydration and pozzolanic reactions, forming cementitious compounds such as calcium silicate hydrates (CSH) [9]. These reactions effectively bind clay particles, reduce plasticity, mitigate shrink-swell behavior, and improve overall strength and stiffness. Furthermore, chemical treatments modify the pore structure, thus increasing resistance to moisture-induced volumetric changes. Alternative treatments, such as the use of white soil and sulfuric acid, have demonstrated effectiveness in reducing plasticity and enhancing the mechanical stability of clay soils over time [10].

Among alternative stabilizers, bentonite presents unique advantages compared to traditional agents like lime and cement. Unlike lime and cement, which may cause increased soil brittleness due to rigid pozzolanic bonds, bentonite offers a high specific surface area and intrinsic swelling capacity. These properties enable bentonite to form self-sealing barriers that not only limit water infiltration but also enhance the soil's water retention capacity [11]. By increasing the soil's ability to retain moisture, bentonite treatment reduces the likelihood of sudden shrinkage during dry spells and minimizes the risk of excessive swelling during wet conditions, thus improving volume stability and mechanical resilience. Additionally, bentonite stabilization typically demands less energy for processing and results in a smaller carbon footprint, positioning it as a more environmentally benign option. Under cyclic or dynamic loads, bentonite-treated soils exhibit ductile behavior, enhancing resilience and reducing the risk of cracking compared to lime–cement stabilized matrices [11].

The focus on sustainable and eco-friendly materials has further expanded stabilization research frontiers. Applications of industrial by-products such as basic oxygen furnace (BOF) slag have proven successful in enhancing expansive soil properties, improving bearing capacity while contributing to recycling efforts [12]. Geopolymer mixtures derived from fly ash and bottom ash have shown remarkable potential in improving subgrade performance while reducing environmental waste [13]. Moreover, innovations such as lime sludge activated by sodium chloride offer a novel approach to soil stabilization by utilizing waste products from sugar-cane processing industries, providing both engineering benefits and environmental gains [14]. Such advancements underscore the potential for integrated engineering and sustainability outcomes through the adoption of alternative materials.

Although considerable progress has been made, significant research gaps remain regarding the specific role of bentonite sand in stabilizing clay soils, particularly with respect to its effects on compaction properties such as maximum dry density (MDD), optimum moisture content (OMC), and most importantly, water retention capacity. Previous studies have extensively explored chemical stabilizers and industrial by-products, but empirical data regarding bentonite's effectiveness as a soil stabilizer in tropical clay contexts is relatively sparse. Furthermore, the mechanisms through which bentonite interacts with clay particles under varying moisture conditions and its implications for long-term soil behavior require further investigation.

This study seeks to bridge these gaps by systematically investigating the impact of bentonite sand addition at varying levels (2%, 4%, and 6%) on the compaction properties and water retention capacity of clay soil. By investigating the behavior of clay soils treated with bentonite sand, this research seeks to provide novel insights into an alternative and sustainable stabilization technique. The scope of this study is confined to laboratory-scale evaluations of compaction behavior according to ASTM D698 standards. Findings from this research will contribute to the growing body of knowledge on sustainable ground improvement methods and offer practical recommendations for civil engineering applications where clay soils present significant construction challenges.

Materials and Methods

Materials

The clay soil utilized in this study was collected from Blang Bintang, Aceh Besar. The sampling involved disturbed soil extraction at a depth of approximately 0.5 meters using hand tools. The collected soil samples were stored in bags and transported to the laboratory for further analysis. Prior to testing, the soil was air-dried for 24 hours and then oven-dried at 105°C to remove residual moisture. Following drying, the soil was gently pulverized using a rubber mallet to disaggregate clumps and facilitate the subsequent sieving process through a No. 40 sieve (0.425 mm opening) to ensure uniform particle size distribution.

Initial classification tests confirmed that the native soil was categorized as CH (inorganic clay of high plasticity) according to the Unified Soil Classification System (USCS) and as A-7-5 under the American Association of State Highway and Transportation Officials (AASHTO) system. These classifications indicated a highly plastic, clayey soil type unsuitable for structural support without stabilization. Bentonite is environmentally-friendly material that contains natural mineral. Bentonite sand used in this study was procured from local construction material suppliers. Upon arrival at the laboratory, the bentonite was air-dried and sieved through a No. 200 mesh to obtain a fine material suitable for stabilization purposes. As recommended in previous studies, the bentonite was prepared as a slurry by dispersing it in water before mixing with the clay soil [15]. The slurry method facilitates improved microstructural integration of bentonite within the soil matrix by filling voids and promoting homogeneity, compared to the direct addition of dry powder.

Sample Preparation

In preparation for compaction testing, four groups of soil-bentonite mixtures were prepared with bentonite contents of 0%, 2%, 4%, and 6% by dry weight of soil. Each mixture was thoroughly blended using laboratory mechanical mixers to ensure uniform distribution. Following mixing, the samples were conditioned to equilibrate the moisture content, allowing the bentonite to fully interact with the clay matrix before testing [16]. For each mixture percentage, five identical specimens were prepared, resulting in a total of twenty specimens. This sample distribution enabled a statistically robust analysis of the influence of varying bentonite concentrations on compaction behavior. The specific proportions for each mixture are detailed in **Table 1.**

Table 1. Sample preparation of clay soil-bentonite sand mixture

Bentonite Sand (%)	Soil Weight (gram)	Bentonite Weight (gram)
0	2000	0
2	2000	40
4	2000	80
6	2000	120

Experimental Procedures

Physical property tests were conducted on the untreated clay soil prior to stabilization to establish baseline data essential for evaluating the effects of bentonite sand addition. These tests included specific gravity measurement, determination of the liquid limit (LL) and plastic limit (PL) following standard Atterberg limits procedures, and computation of the plasticity index (PI) as the difference between LL and PL. Additionally, particle size distribution analysis was performed using both sieve and hydrometer methods to characterize the soil's textural composition. The physical properties obtained from these assessments served as critical references for comparing and interpreting the changes induced by the subsequent bentonite stabilization process.

Compaction characteristics were evaluated using the Standard Proctor Test in accordance with ASTM D698. This standardized method involved placing the soil layer-by-layer into a Proctor mold with an internal diameter of 10.15 cm, a height of 11.65 cm, and a weight of 4250 grams, with each layer compacted by 25 blows from a hammer weighing 2.5 kg and dropped from a height of 30.5 cm. Moisture content was carefully controlled through gradual water addition and thorough mixing before compaction to ensure uniformity. The application of a compaction energy of 12,400 ft-lbf/ft^3 (600 kN-m/m^3) ensured consistency and reproducibility of results across different experimental conditions. The resulting compaction curves provided critical data on the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for each soil-bentonite mixture. After compaction, the mold containing the compacted soil was weighed, followed by extrusion of the sample and collection of representative specimens for moisture content determination.

Experimental Design Considerations

The design of this experimental program carefully accounted for the expected nonlinear effects of bentonite addition. As previous studies indicate, small increments of bentonite can enhance water retention and sealing properties, while excessive additions may lead to increased water demand and reduced dry density due to changes in soil fabric and void structure [11]. By systematically varying the bentonite content at 0%, 2%, 4%, and 6%, the study was able to observe the incremental effects on compaction behavior. This design strategy enables identification of an optimal bentonite content that achieves a balance between improved moisture control and mechanical performance, consistent with the approach recommended by Israil [17] and ASTM D698 standards.

Data Analysis

Data analysis focused on interpreting the compaction curves to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for each soil-bentonite mixture. Trends in these parameters were carefully analyzed in relation to the percentage of bentonite added, with particular emphasis on identifying shifts in MDD values, assessing changes in OMC as indicators of the moisture-absorbing capacity of bentonite, and evaluating the correlation between bentonite content and soil workability during compaction. To ensure the robustness and validity of the conclusions, statistical methods, including basic descriptive statistics and trend analysis, were employed, allowing a systematic assessment of the effects of bentonite stabilization across different mixture proportions.

Results

Physical Properties of Untreated Clay Soil

Prior to the addition of bentonite sand, a comprehensive series of laboratory tests was conducted to establish the baseline physical properties of the native clay soil. The specific gravity was determined to be 2.54, indicating a moderate mineral composition typical of fine-grained clays. The liquid limit (LL) was measured at 52.20%, while the plastic limit (PL) was recorded at 18.20%, resulting in a plasticity index (PI) of 34.00%. These values are consistent with the characteristics of highly plastic clays, confirming the soil's classification as CH according to the Unified Soil Classification System a(USCS) and A-7-5 according to the American Association of State Highway and Transportation Officials (AASHTO) classification system.

Sieve analysis indicated that 66.92% of the soil passed through the No. 200 sieve, signifying a predominance of fine particles within the clay size fraction. These findings are consistent with the expectations for highly plastic clays and align with previous observations that such soils are prone to significant volume change and reduced mechanical strength under varying moisture conditions [1,2].

Changes in Particle Size Distribution with Bentonite Addition

The addition of bentonite sand induced notable changes in the particle size distribution (PSD) of the soil (**Table 2**). Furthermore, as can be seen in **Figure 1**, the classification of the soil shifted progressively toward finer textures as the bentonite content increased from 0% to 6%. This transition is attributed to the swelling and delamination behavior of bentonite minerals, particularly montmorillonite, which disaggregate larger soil aggregates and promote finer particle fractions [18].

Table 2. Parameter of classification and sieve analysis of clay soil-bentonite sand mixture

Soil Parameter	Sand Bentonite (%)			
	0%	2%	4%	6%
Sieve pass #200 (%)	66.92	67.21	69.53	71.19
USCS Soil Classification	OH	OH	OH	OH
AASHTO Soil Classification	A-7-5	A-7-5	A-7-5	A-7-5

The increase in fine particles following bentonite incorporation is in agreement with findings from other studies, where hydration and mechanical activation of bentonite led to an observable shift of the PSD curve toward finer particle sizes [19]. These effects contribute to modifications in the soil's permeability, cohesion, and mechanical behavior, aspects critical to engineering applications. Moreover, the observed shift in particle size also aligns with recognized benchmarks established for the classification of stabilized soils, where a movement toward finer size fractions indicates effective dispersion and integration of the stabilizing agent [17,20].

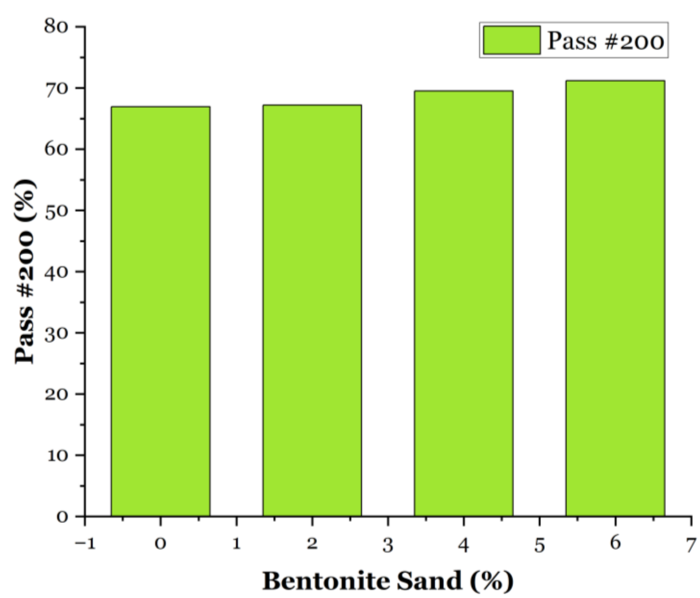

Figure 1. Percentage of passing sieve no. 200 of clay soil-bentonite sand mixture

Compaction Characteristics

The results of the Standard Proctor compaction tests revealed significant changes in the compaction behavior of clay soil following the addition of bentonite sand (**Figure 2**). In terms of Maximum Dry Density (MDD), the untreated clay soil exhibited a value of 1.392 g/cm³. With the addition of 2% bentonite sand, the MDD increased to 1.604 g/cm³, indicating improved particle packing efficiency due to the binding effect of bentonite. However, at 4% bentonite content, the MDD slightly decreased to 1.562 g/cm³, likely resulting from excessive water retention and a corresponding reduction in particle packing. Upon further increasing the bentonite content to 6%, the MDD rose again to 1.640 g/cm³, suggesting a complex, non-linear relationship between bentonite dosage and dry density. These observations are consistent with findings reported by Tan [21] and Khalid [22], who indicated that moderate additions of bentonite either slightly increased or maintained dry density, depending on the native soil's mineralogical composition and the amount of additive used. Overall, the range of MDD changes, approximately 5–10%, aligns with previously documented outcomes for chemically stabilized soils.

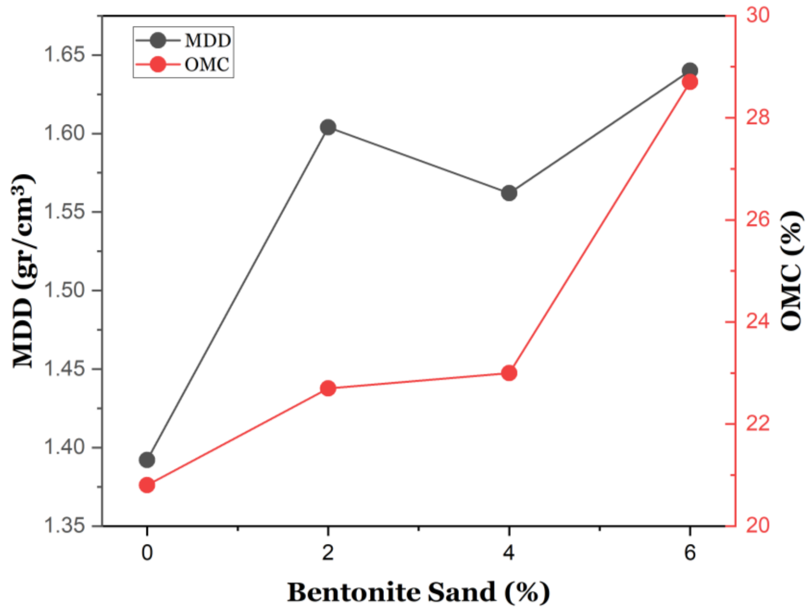

Figure 2. Results of the Standard Proctor compaction of clay soil-bentonite sand mixture

In parallel, the Optimum Moisture Content (OMC) of the clay soil exhibited systematic increases as bentonite sand was incorporated. The untreated soil recorded an OMC of 20.8%, which increased to 22.7% with 2% bentonite, 23.0% with 4% bentonite, and 28.7% with 6% bentonite. This consistent upward trend, as illustrated in Figure 3.3, is directly attributable to the high-water adsorption capacity and expansive nature of bentonite minerals [17,21,23]. The fine particles and large specific surface area of bentonite demand greater water content for effective soil particle lubrication and optimal compaction. As bentonite content increases, more water is absorbed within the soil matrix, necessitating a higher moisture level to achieve maximum density during compaction.

The observed rise in OMC also reflects changes in the soil's water retention capacity, an essential factor in ensuring soil stability under variable moisture conditions. Increased water retention capacity contributes positively to the soil's resistance against drying and shrinkage, particularly in regions subjected to cyclic wetting and drying. However, it is critical to recognize that excessive moisture content may lead to reduced shear strength if not properly managed during field applications.

These findings corroborate previous studies, which consistently noted that even modest additions of bentonite could significantly increase OMC, thereby influencing the energy requirements for compaction and affecting the long-term durability and moisture sensitivity of the stabilized soil [22,23]. Therefore, optimizing bentonite content is vital to achieving a balance between enhanced water retention capacity and maintaining desirable mechanical properties in stabilized clay soils.

Summary of Compaction Behavior Trends

The combined analysis of Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) data suggests a complex yet predictable influence of bentonite on clay soil compaction behavior. Small additions of bentonite, particularly at 2%, significantly enhance dry density while causing only moderate increases in moisture demand, reflecting an optimal balance between particle packing and water retention. At higher bentonite contents (4%–6%), moisture requirements continue to rise, and the impacts on dry density become more variable, highlighting a non-linear response. These observed trends are consistent with bentonite's established mechanisms of action, including its ability to retain water, bind soil particles, and reorganize the microstructure to form a denser, more uniform matrix [15,16]. The data thus indicate that there exists a critical range of bentonite content where beneficial improvements in soil compaction behavior are achievable without substantially compromising dry density or construction efficiency.

The comparative behavior observed in this study aligns well with broader findings regarding the chemical stabilization of clay soils using bentonite and other additives [21,22]. However, the magnitude of changes in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) can vary depending on the soil's mineralogy, initial moisture content, and particle size distribution. Given the characteristics of the Blang Bintang clay, the addition of bentonite effectively improved compaction parameters, supporting its use as a viable stabilizer in moisture-variable tropical climates. The results also highlight the necessity of site-specific laboratory testing before field application, as soil-bentonite interactions are highly influenced by local conditions, consistent with previous studies [18].

Discussion

The addition of bentonite sand to clay soils resulted in significant modifications to their microstructural and mechanical behavior, as observed from the experimental findings. These changes are coherent with existing literature, which has extensively reported the capacity of bentonite to alter the internal structure and performance of soils through its inherent physicochemical properties [24,25]. The observed improvements in maximum dry density (MDD) and optimum moisture content (OMC) in this study reflect a densification mechanism at work, where bentonite particles at lower concentrations effectively occupy the voids between larger soil aggregates. This leads to a more uniform soil fabric and enhances compaction efficiency, consistent with the findings of Nikbakht [26].

As the proportion of bentonite increases, its dominant mineral, montmorillonite, becomes increasingly influential. Montmorillonite's strong water adsorption capacity and swelling behavior promote rearrangement of the soil pore structure, reducing average pore sizes and creating a gel-like framework. This microstructural transition not only enhances particle bonding but also affects the transport properties of the soil, particularly permeability and moisture retention [24],26]. Such phenomena were implicitly observed in the upward shifts in OMC documented in this study, wherein higher moisture levels were necessary to accommodate the increased water-holding capacity induced by bentonite. These outcomes are aligned with prior research indicating that bentonite's microstructural modifications substantially affect the moisture-demand and mechanical response of stabilized soils [17].

The non-linear variation in MDD with different percentages of bentonite further supports the notion that soil-bentonite interactions are complex and dosage-sensitive. At lower bentonite contents, the improved packing density and limited swelling promote higher MDD values. However, as the bentonite content rises to 4%, the increase in interparticle water films and the consequent swelling reduce the compaction efficiency, leading to a slight decline in MDD. Interestingly, at 6% bentonite content, the MDD improved again, suggesting that beyond a certain threshold, the rearranged microstructure and bonding strength contribute positively to dry density. This trend mirrors findings from Tan [21] and Khalid [22], who reported similar dose-dependent behavior in bentonite-stabilized systems.

The enhancements in compaction behavior observed in this study have critical implications for long-term mechanical performance. As reported by Nikbakht [26] and Nu [27], improved MDD and optimal moisture control are positively correlated with increased California Bearing Ratio (CBR), unconfined compressive strength (UCS), and shear strength in bentonite-stabilized soils. Although the present study did not directly measure strength indices, the significant densification and controlled moisture conditions achieved imply a potential for improved load-carrying capacity and deformation resistance. The densification and microstructural tightening induced by bentonite addition are expected to enhance particle interlock, reduce void ratios, and thus improve the soil's ability to withstand applied stresses over time.

Furthermore, the influence of bentonite on the soil’s water retention and permeability properties holds considerable practical importance. In high rainfall or tropical environments where soils are subjected to intense wet-dry cycles, the ability of bentonite to form a homogeneous, low-permeability matrix is critical. By minimizing water infiltration and reducing pore connectivity, bentonite-treated soils offer enhanced resistance to swelling, shrinkage, and structural degradation [17]. These properties are particularly advantageous for applications such as landfill liners, engineered barriers, subgrade stabilization, and other infrastructure subjected to fluctuating moisture regimes.

Field evidence supports the practical durability of bentonite-stabilized soils. Their self-healing characteristics, stemming from the expansive behavior of montmorillonite, enable them to seal minor cracks and defects that may form under mechanical or environmental stress [24]. Consequently, bentonite-treated clays exhibit prolonged service life and reduced maintenance requirements when employed in environments prone to moisture-induced damage. The capacity of bentonite-stabilized soils to resist deformation under cyclic wetting and drying—typical in tropical climates—further validates their use in critical infrastructure, as corroborated by field performance studies [28].

Additionally, the findings of this study underscore the necessity of site-specific evaluation when applying bentonite stabilization techniques. As emphasized in prior research [17], the effectiveness of bentonite varies according to the mineralogical and textural characteristics of the native soil. While the trends observed in this study—such as increases in fine particle fractions, upward shifts in OMC, and MDD modifications—are consistent with broader literature, the magnitude and practical impact of these changes are inherently dependent on local soil properties. Therefore, thorough laboratory characterization remains a prerequisite for the successful design and implementation of bentonite stabilization strategies.

In conclusion, the addition of bentonite sand to clay soils results in substantive microstructural, mechanical, and practical improvements that have been well documented in both this study and previous investigations. The induced changes in compaction behavior, moisture sensitivity, and permeability underscore bentonite’s efficacy as a sustainable soil stabilizer, particularly suited for challenging environmental conditions. The findings reinforce bentonite's potential role in advancing resilient, durable, and environmentally responsible geotechnical solutions for infrastructure development in moisture-variable regions.

Conclusion

This study investigated the effects of bentonite sand addition on the compaction characteristics and water retention capacity of clay soil, with specific attention to changes in maximum dry density (MDD) and optimum moisture content (OMC), by laboratory-scale evaluations of compaction behavior according to ASTM D698 standards. The experimental results demonstrated that the incorporation of bentonite, particularly at 2% and 6% contents, led to significant improvements in MDD, while OMC consistently and systematically increased with higher bentonite additions. These findings are directly attributable to the inherent properties of bentonite, particularly its high specific surface area and strong water adsorption behavior, which alter the soil's microstructure and significantly enhance its water retention capacity.

The discussion of results indicated that bentonite additions promote a more uniform soil fabric, reduce pore sizes, and create a denser particle network, thereby improving both compaction behavior and water retention performance. Furthermore, the study highlighted the potential implications for long-term mechanical performance, suggesting that improved compaction indices and increased water retention capacity are likely correlated with enhanced strength parameters such as California Bearing Ratio (CBR) and unconfined compressive strength (UCS), based on trends observed in the literature. The enhanced sealing properties and reduced permeability associated with bentonite-stabilized soils offer considerable advantages for infrastructure applications, particularly in regions exposed to high rainfall and dynamic moisture conditions.

This research contributes meaningfully to the existing body of knowledge by providing empirical evidence on the performance of bentonite sand as an alternative stabilizer for clay soils, emphasizing its ability to improve water retention capacity alongside mechanical properties. It supports the growing movement toward sustainable soil stabilization techniques by promoting a material that delivers technical benefits while minimizing environmental impacts compared to conventional stabilizers such as cement and lime.

Nonetheless, the study underscores the complexity of soil–bentonite interactions and the necessity for site-specific evaluations. Future research should further explore the influence of bentonite addition on other mechanical properties, such as direct shear strength, unconfined compressive strength, and long-term behavior under cyclic environmental loading. Additionally, field-scale investigations are recommended to validate laboratory findings and optimize the application strategies of bentonite for diverse soil types and climatic conditions. Overall, this study establishes a robust foundation for the expanded use of bentonite in geotechnical engineering practices and highlights its potential role in advancing sustainable and resilient infrastructure development.

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Conflict of Interest

The authors declare no conflicts of interest.

Author Contribution Statement

Jumelia Ardika: Methodology, Writing-Original draft preparation. **Fara Qamara Elmyra:** Software, Writing-Original draft preparation. **Fachri Fachri:** Methodology, Visualization. **Reza Pahlevi Munirwan:** Conceptualization, Validation, Supervision, Writing-Reviewing and Editing. **Yuliana Yuliana:** Software, Writing-Reviewing and Editing. **Siti Mira Maulida:** Data curation, Visualization, Investigation. **Aulia Rahmad:** Data curation, Investigation.

Data Availability Statement

The data used to support the findings of this study are included within the article.

Ethics Approval

Not required.

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