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A STUDY ON THE INFLUENCE OF LOCUST BEAN GUM ON THE SWELLING BEHAVIOR OF CLAY SOILS WITH DIFFERENT PLASTICITY

Ahmet Talha GEZGİN *

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Abstract: Swelling clays cause severe engineering issues due to moisture-induced volume changes. This study experimentally investigates how locust bean gum (LBG), which is a sustainable biopolymer, affects the swelling behavior of kaolin-bentonite mixtures with varying plasticity levels. One-dimensional oedometer tests were conducted on medium- and high-plasticity clay mixtures to evaluate the impact of LBG concentration and mixing water temperature on swelling potential and swelling pressure. Results reveal that LBG effectively mitigates swelling, especially in highly plastic clays. At room temperature, a 2% LBG treatment reduced swelling potential and pressure by 79% and 68%, respectively. Notably, increasing the mixing water temperature to 60 °C further enhanced these reductions to 95% and 90%, respectively. In contrast, treating medium-plasticity clays with LBG completely neutralized the swelling tendency, resulting in immediate settlement under low vertical stress. This behavioral difference indicates that the settlement in medium-plasticity clays is driven by biopolymer-induced structural flocculation, whereas the swelling suppression in high-plasticity clays is governed by a hydrogel network that physically restricts clay hydration. Ultimately, this study demonstrates that soil plasticity and preparation temperature are critical factors for optimizing sustainable soil stabilization using biopolymers.

Keywords: Biopolymers, Locust bean gum, Clay plasticity, Swelling potential, Swelling pressure, Sustainable soil improvement

Farklı Plastisiteye Sahip Kil Zeminlerin Şişme Davranışına Keçiboynuzu Sakızının Etkisi Üzerine Bir Araştırma

Öz: Şişen kil zeminler, suyla temas ettiklerinde gösterdikleri yüksek hacimsel değişimler nedeniyle ciddi mühendislik sorunları yaratmaktadır. Bu çalışmada, sürdürülebilir ve doğal bir biyopolimer olan keçiboynuzu sakızının (LBG), farklı plastisiteye sahip kaolen-bentonit karışımlarının şişme davranışı üzerindeki etkileri deneysel olarak incelenmiştir. Orta ve yüksek plastisiteli kil karışımları üzerinde tek boyutlu ödometre deneyleri yapılarak, biyopolimer oranının ve karışım suyunun sıcaklığının şişme potansiyeli ile şişme basıncı üzerindeki etkileri değerlendirilmiştir. Sonuçlar, LBG'nin özellikle yüksek plastisiteli killerde şişmeyi başarılı bir şekilde baskıladığını göstermiştir. Oda sıcaklığında %2 LBG ilavesi, şişme potansiyelini %79, şişme basıncını ise %68 oranında düşürmüştür. Biyopolimer çözeltisinin 60 °C'de su ile hazırlanması durumunda ise bu iyileşme oranları sırasıyla %95 ve %90 seviyelerine çıkmıştır. Öte yandan, orta plastisiteli karışımlarda LBG ilavesi şişme eğilimini tamamen ortadan kaldırmış ve numunenin düşük düşey gerilme altında oturmasına neden olmuştur. Bu mekanik farklılık; orta plastisiteli killerdeki oturmanın biyopolimer kaynaklı flokülasyondan (yumaklaşma), yüksek plastisiteli killerdeki şişme direncinin ise kilin su almasını fiziksel olarak engelleyen hidrojel ağından kaynaklandığını göstermektedir. Elde edilen bulgular, biyopolimer tabanlı sürdürülebilir zemin iyileştirme uygulamalarında zemin plastisitesinin ve hazırlama koşullarının ne denli kritik bir rol oynadığını vurgulamaktadır.

Anahtar Kelimeler: Biyopolimerler, Keçiboynuzu sakızı, Kil plastisitesi, Şişme potansiyeli, Şişme basıncı, Sürdürülebilir zemin iyileştirme

* ahmettalhagezgin@uludag.edu.tr, Bursa Uludağ University, Engineering Faculty, Department of Civil Engineering, Görükle Campus, 16059, Nilüfer, Bursa, Türkiye

1. INTRODUCTION

Swelling clay soils exhibit significant volume changes when in contact with water due to their high content of active clay minerals. This behavior is particularly associated with changes in the crystal structure of layered clay minerals, such as montmorillonite. Interlayer water adsorption and hydration of exchangeable cations cause this process, which begins at the microscale, to be observed as swelling behavior at the macroscale (Mitchell & Soga, 2005; Nelson & Miller, 1992). Volume increases in swelling soils lead to serious engineering problems such as loss of bearing capacity, differential settlements, and damage to superstructure elements. Such problems pose significant risks, particularly for lightweight structures, road pavements, and infrastructure systems (Dave & Siddiqui, 2020; L. Jones et al., 2020; L. D. Jones & Jefferson, 2023). Therefore, understanding and controlling the behavior of swelling-prone soils has long been an important research topic in geotechnical engineering.

Chemical stabilization materials, such as cement and lime, are widely used to improve the performance of swelling-prone soils. These additives react with clay minerals to induce flocculation, agglomeration, and cementation, thereby making the soil structure more rigid and less sensitive to volume changes (Barman & Dash, 2022). Nevertheless, these methods also result in negative environmental impacts such as high energy consumption and carbon emissions. Furthermore, the permanent alteration of soil pH by chemical additives and their potential adverse effects on groundwater quality constitute significant disadvantages of these methods from a sustainability perspective (Benghazi et al., 2024; Jaiswal et al., 2024; Mohammed et al., 2023).

These environmental issues have increased interest in sustainable and environmentally friendly soil improvement methods in recent years. Biopolymers stand out as alternative improvement materials because they are obtained from renewable sources, are biodegradable, and do not leave harmful residues in the environment (Chang et al., 2016, 2020; Fatehi et al., 2021). While this biodegradable nature significantly reduces the carbon footprint compared to traditional stabilizers, it also implies that the treated soil matrix will be susceptible to biological degradation over time (Gezgin & Ercan, 2026; Sasar et al., 2024; Vydehi & Moghal, 2022). Consequently, biopolymer treatment is particularly advantageous for temporary engineering applications (e.g., temporary excavation support or short-term access roads), whereas its long-term performance in permanent structures requires careful consideration of aging and durability (Chang et al., 2020; Fatehi et al., 2021). Biopolymers used in geotechnical engineering applications are classified into various categories based on their origin and chemical structure. The most commonly used biopolymers in the literature include microbial-derived polysaccharides (e.g., xanthan gum), plant-derived polysaccharides (e.g., guar gum and starch derivatives), and animal-based biopolymers (e.g., casein and chitosan) (Chang et al., 2020; Ilman & Balkis, 2023).

A review of current studies shows that biopolymers have the potential to be used in geotechnical engineering applications across all soil types (Gezgin & Ercan, 2026). Some have examined the effects of biopolymers on strength, stiffness, permeability, and deformation properties by forming a binding network among cohesionless soil particles (Bouazza et al., 2009; A F Cabalar et al., 2017; Chen et al., 2013; Khatami & O'Kelly, 2013; Lee et al., 2019). On the other hand, most studies on the use of biopolymers in cohesive clay soils have focused on strength and stiffness (Ali Firat Cabalar et al., 2018; Cheng & Geng, 2023; Judge et al., 2022; Weng et al., 2023). Behaviors related to volume change, such as swelling and consolidation settlement, have been addressed in a limited number of studies (Joga & Varaprasad, 2019; Kwon et al., 2023).

Locust bean gum (LBG) was chosen as the biopolymer additive in this study. LBG is a plant-derived, galactomannan-based polysaccharide known for its high viscosity-forming capacity and strong interaction with water (Prajapati, Jani, Moradiya, Randeria, Nagar, et al., 2013; Prakash & Kumar, 2023). However, the use of LBG in geotechnical engineering applications is represented by a limited number of studies in the literature (Cheng & Geng, 2023; Kurt Albayrak et al., 2026; Shen et al., 2025). Most existing studies have focused on more common biopolymers such as xanthan gum and guar gum (Anandha Kumar et al., 2023; Bagheri et al., 2023; Bozyigit et al., 2021; Chang et al., 2015; Dehghan et al., 2019; Hamza et al., 2023; Kwon et al., 2023; Sulaiman et al., 2022). The effects of LBG on the behavior of clay soils, particularly those associated with volume changes, have not been sufficiently investigated. This situation makes the investigation of locust bean gum's behavior in swelling-prone clay soils a current and original research topic.

Another critical yet overlooked factor in biopolymer applications is that not only the type and concentration of the biopolymer but also the preparation conditions of the biopolymer solution may affect soil behavior. The literature suggests that as temperature increases, the solubility of biopolymers increases, allowing more homogeneous solutions to be obtained (Gezgin & Ercan, 2026; Mudgil et al., 2014). Although only a limited number of findings suggest that application-dependent parameters, such as mixture water temperature, may affect the biopolymer–clay interaction and, consequently, the swelling behavior, very few studies have systematically investigated this effect.

Among the various biopolymers investigated for soil improvement, locust bean gum has attracted increasing attention due to its biodegradable nature, low environmental impact, and galactomannan-based molecular structure. Unlike ionic or highly reactive polymers, locust bean gum primarily interacts with soil via water retention and hydrogen bonding, mechanisms particularly relevant for swelling control in clay soils. While biopolymers such as xanthan gum and guar gum have been widely studied, existing research has predominantly focused on enhancing strength and stiffness. In contrast, the influence of locust bean gum on swelling behavior, especially in relation to soil plasticity and preparation conditions, remains relatively underexplored. Accordingly, locust bean gum was selected in this study to address this specific gap and to evaluate its potential for environmentally sustainable swelling mitigation in clay soils.

Despite the growing interest in biopolymer-based soil improvement, significant gaps remain in the current literature: the vast majority of research focuses on strength and stiffness rather than volume change (swelling), locust bean gum (LBG) remains largely unexplored compared to other common biopolymers, and the coupled effects of inherent soil plasticity and biopolymer preparation temperature on swelling mitigation lack systematic investigation. To bridge these specific gaps, this study experimentally investigates the effects of the locust bean gum biopolymer on the swelling behavior of kaolin–bentonite-based clay soils with varying plasticity levels. The influence of biopolymer content and mixing water temperature on swelling potential and swelling pressure is systematically evaluated using oedometer tests. By explicitly considering soil plasticity as a governing parameter, the study clarifies how biopolymer treatment alters volume change behavior in clays with contrasting swelling tendencies.

Building on the identified gaps in the existing literature, the experimental program was intentionally designed as a controlled comparative study focused on swelling behavior rather than on strength or stiffness improvement. By limiting the number of variables and maintaining consistent sample preparation and testing conditions, the study isolates the role of soil plasticity and preparation conditions in governing swelling response. Within this defined scope, the findings provide new insights into the conditions under which locust bean gum can be effectively used to mitigate swelling behavior in clay soils and contribute to the limited literature on biopolymer-based, environmentally sustainable soil improvement techniques.

2. MATERIALS AND METHODS

2.1. Soil Characterization

In this study, clay soils with varying plasticity were prepared from kaolin and bentonite. Based on the chemical analysis, the bentonite used is inherently a calcium-based (Ca) bentonite, and the detailed chemical compositions of both the kaolin and bentonite clays are presented in Table 1. In the experimental studies, mixtures containing pure kaolin (100% kaolin), 75% kaolin–25% bentonite, and 25% kaolin–75% bentonite were used. The kaolin used has a low to medium plasticity, while bentonite is a clay mineral with high plasticity and significant swelling potential. These mixtures were selected to enable a comparative study of the effects of biopolymer addition in soils with varying plasticity.

The specific gravity (Gs) of the soils was determined according to ASTM D854. Consistency limit tests were performed in accordance with the ASTM D4318 standard using the Casagrande method for the liquid limit. Plastic limit values were determined using the same standard, and the plasticity index (PI) was calculated from the liquid limit (LL) and plastic limit (PL). The test stages for determining the index properties of the soils are presented in Figure 1. Using the obtained index properties, the soils were classified according to the Unified Soil Classification System (USCS) plasticity diagram.

Table 1. Chemical composition of the kaolin and bentonite clays used in this study

Parameter / Oxide	Kaolin (%)	Bentonite (%)
Silica (SiO_2)	70.0	55.17
Alumina (Al_2O_3)	18.0	16.84
Iron Oxide (Fe_2O_3)	0.8	9.50
Calcium Oxide (CaO)	0.6	3.24
Magnesium Oxide (MgO)	0.4	1.95
Sodium Oxide (Na_2O)	-	1.92
Potassium Oxide (K_2O)	-	0.62
Titanium Dioxide (TiO_2)	0.4	1.38
Loss on Ignition (LOI)	-	8.40

2.2. Preparation of Biopolymer-Amended Soil Samples

Locust bean gum (LBG), a natural and biodegradable polysaccharide, was used as the biopolymer additive in this study. The biopolymer was commercially available and used as a powder in the experimental studies (Figure 2a). Locust bean gum is a plant-derived galactomannan polysaccharide obtained from the seeds of Ceratonia siliqua. Chemically, it consists of a linear backbone of (1→4)-linked β-D-mannopyranosyl units with single (1→6)-linked α-D-galactopyranosyl branches, typically presenting a mannose-to-galactose (M:G) ratio of about 4:1. Furthermore, its macromolecular structure contains abundant hydrophilic hydroxyl (-OH) groups. It is widely used in food, pharmaceutical, and industrial applications due to its high water-binding capacity and viscosity-enhancing properties driven by these specific chemical characteristics. The chemical structure and physicochemical characteristics of locust bean gum, including its typical molecular weight range and rheological behavior, have been extensively documented in the literature (Prajapati, Jani, Moradiya, Randeria, & Nagar, 2013; Prakash & Kumar, 2023). In the present study, a commercially available locust bean gum was used, and the investigation focused on its macroscopic influence on the swelling behavior of clay soils rather than on detailed biopolymer characterization.

The LBG content was determined to be 0.5%, 1.0%, 1.5%, and 2.0% of the dry base weight (i.e., percentage by oven-dry mass of soil solids). These specific dosage levels were selected based on a comprehensive review of existing biopolymer-based soil improvement literature, which indicates that highly viscous, polysaccharide-based biopolymers (such as xanthan, guar, and locust bean gums) are remarkably effective at low concentrations, typically yielding optimum performance between 0.5% and 2.0% by dry weight (Chang et al., 2020; Gezgin & Ercan, 2026). Furthermore, preliminary mixing trials conducted in this study confirmed that LBG contents exceeding 2.0% result in excessive hydrogel formation. This rapid gelation significantly hinders the workability and homogeneous mixing of the highly plastic clay matrix. Finally, keeping the maximum dosage at 2.0% ensures that the treatment remains economically and logistically viable compared to traditional mass-stabilization techniques (Kiran et al., 2025; Smith et al., 2023).

The biopolymer solutions were prepared by adding LBG at the given ratios to the mixing water. For each specimen, the required mass of dry soil was first defined, and the total mixing water was then calculated to achieve the target initial water content (see below); the LBG mass was computed as a percentage of this dry soil mass and dissolved within the pre-calculated mixing water.

The solutions were stirred with a magnetic stirrer until a homogeneous structure was obtained (Figure 2b). To investigate the effect of mixing water temperature, some samples were prepared at room temperature (approximately 25 °C), while others were prepared using water at 60 °C. The temperature of 60 °C was selected as a practical upper temperature that enhances the dissolution and dispersion of galactomannan-based biopolymers in water without inducing thermal degradation, thereby enabling a clearer assessment of temperature-dependent preparation effects (Barak & Mudgil, 2014). From a practical engineering perspective, highlighting this temperature dependence is highly significant. In large-scale field applications, such as deep soil mixing or grouting, utilizing mobile boilers or heated mixing tanks to thermally activate the biopolymer slurry ensures complete polymer hydration. This maximizes treatment efficacy, enabling targeted suppression of swelling at lower, more economical biopolymer dosages.

The prepared biopolymer solutions were mechanically mixed with the clay material using a mechanical mixer to achieve a homogeneous mixture (Figure 2c). All oedometer samples were prepared at the plastic limit water content corresponding to the relevant soil type. In this study, the plastic limit (PL) was adopted as the target initial water content for specimen preparation (w = PL) to provide comparable initial consistency and sufficient workability across mixtures with different plasticity levels. Preparing specimens near the liquid limit may result in excessive initial softening, whereas optimum water content is typically associated with compaction-based studies; therefore, PL was considered a more appropriate reference state for the present swelling-focused oedometer program. Accordingly, the total water content of each specimen (including the water used to dissolve LBG) was adjusted to match the PL of the corresponding soil mixture, ensuring consistent initial water content across untreated and treated specimens. Given the soil's moldable, paste-like consistency at the plastic limit, the specimens were not subjected to high-energy dynamic or heavy static compaction. Instead, the prepared mixtures were carefully placed into the standard oedometer rings using manual compaction (light tamping) to ensure the rings were completely and uniformly filled without entrapping air voids. Because the initial water content (PL) naturally varied depending on the specific kaolin–bentonite ratio, the initial bulk density of each individual specimen was precisely determined by measuring the mass of the manually compacted soil within the known volume of the oedometer ring prior to the curing process.

The prepared clay material with the biopolymer additive was placed in standard oedometer molds; the masses of the specimens were measured, and the pre-test preparation was completed (Figure 2d). After preparation, the specimens were tightly sealed with stretch film and cured for 28 days at a controlled room temperature (approximately 20 ± 2 °C). This specific 28-day curing duration was deliberately selected to ensure that the primary biopolymer hydration and matrix stabilization processes were largely completed. This prevents significant ongoing curing from interfering with the long-term swelling behavior observed during the test. During this period, the sealed specimens were stored in a desiccator to provide a constant-humidity environment, minimizing any unintended moisture loss or gain from ambient humidity and preserving the target initial water content until the oedometer test (Figures 2e-f).

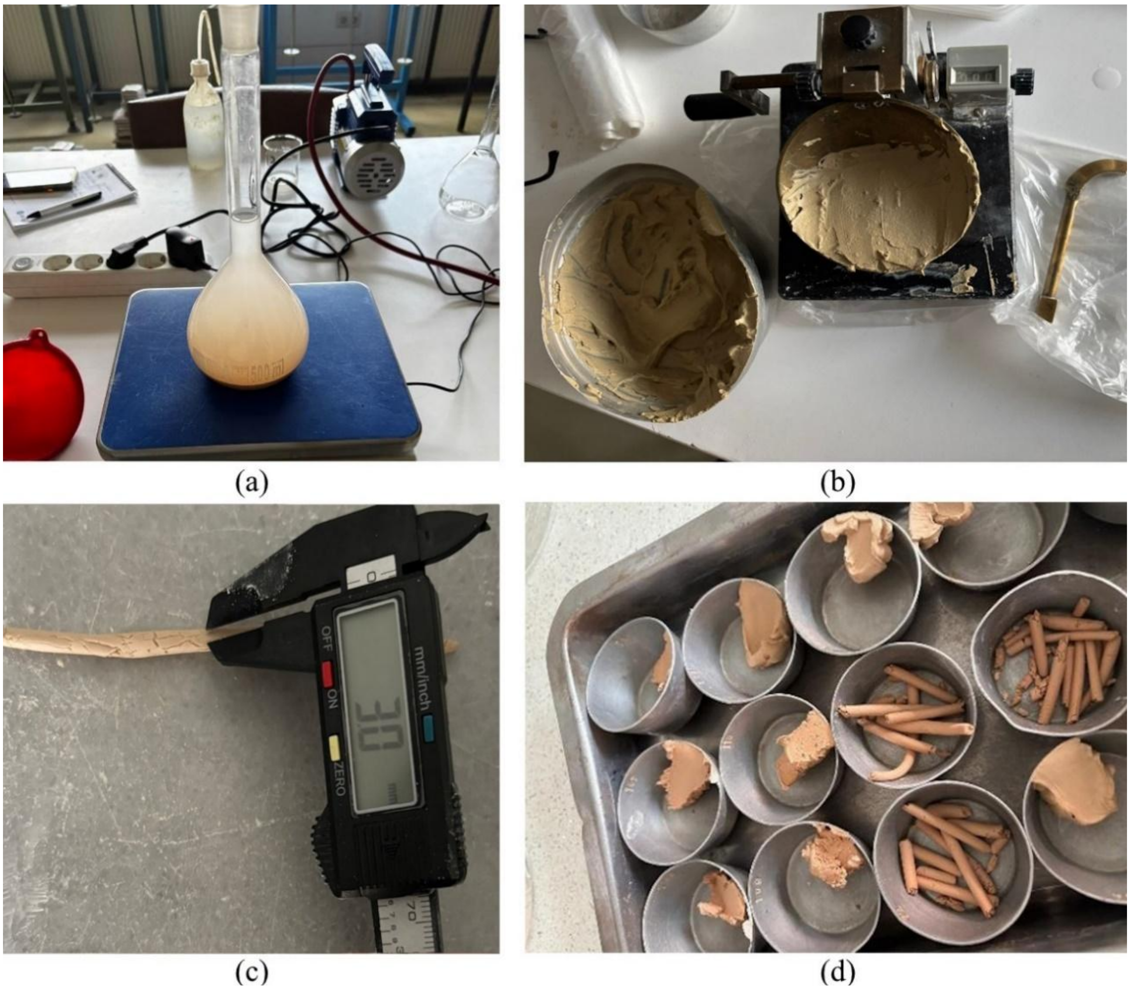


Figure 1:

Key stages of the soil characterization process performed in this study: (a) preparation of clay mixtures with controlled kaolin–bentonite ratios, (b) determination of the liquid limit using the Casagrande apparatus, (c) determination of the plastic limit, and (d) evaluation of the index properties for soil classification according to the Unified Soil Classification System (USCS).

2.3. Swelling Tests

The swelling behavior of the samples was determined using one-dimensional oedometer tests. The tests were conducted in accordance with ASTM D4546. The sample preparation and placement stages for the oedometer tests are presented in Figure 2. The specimens were placed between porous stone and filter paper (Figure 2a), prepared for the loading system (Figure 2b), and the test process was initiated. After being placed in the oedometer cell, the specimens were inundated with water to allow swelling under controlled boundary conditions. An initial seating pressure of 5 kPa was then applied to ensure proper contact between the specimen and the loading system. The specimens were allowed to complete their swelling under this stress level. The swelling phase was considered complete when vertical deformation ceased, defined as the specimen height remaining constant for a continuous 24-hour period. The subsequent loading stages were initiated only after this equilibrium condition was reached. After swelling was complete, the specimens were subjected to increasing vertical stress levels. Loading levels were increased from 12.5 kPa to 25, 50, and 100 kPa, and deformations were monitored for 24 hours at each level (Figure 2c). The swelling potential was calculated using the vertical unit deformations occurring under 5 kPa vertical stress. The swelling pressure was quantitatively defined as the vertical stress required to compress the swollen specimen back to its initial height (i.e., reaching a net zero vertical strain, $\Delta H/H_0 = 0$) during the incremental loading phase. The swelling behaviors of the specimens were comparatively evaluated using the obtained deformation–stress relationships. All oedometer tests were performed under carefully controlled and identical laboratory conditions to ensure repeatability, including consistent sample preparation, curing environment, loading sequence, and deformation measurement procedures. The deformation–stress responses presented in this study represent typical, reproducible behaviors observed under each test condition. The experimental results were evaluated primarily through comparative trend analysis rather than statistical characterization, as the study focused on assessing relative changes in swelling behavior associated with soil plasticity and biopolymer treatment.

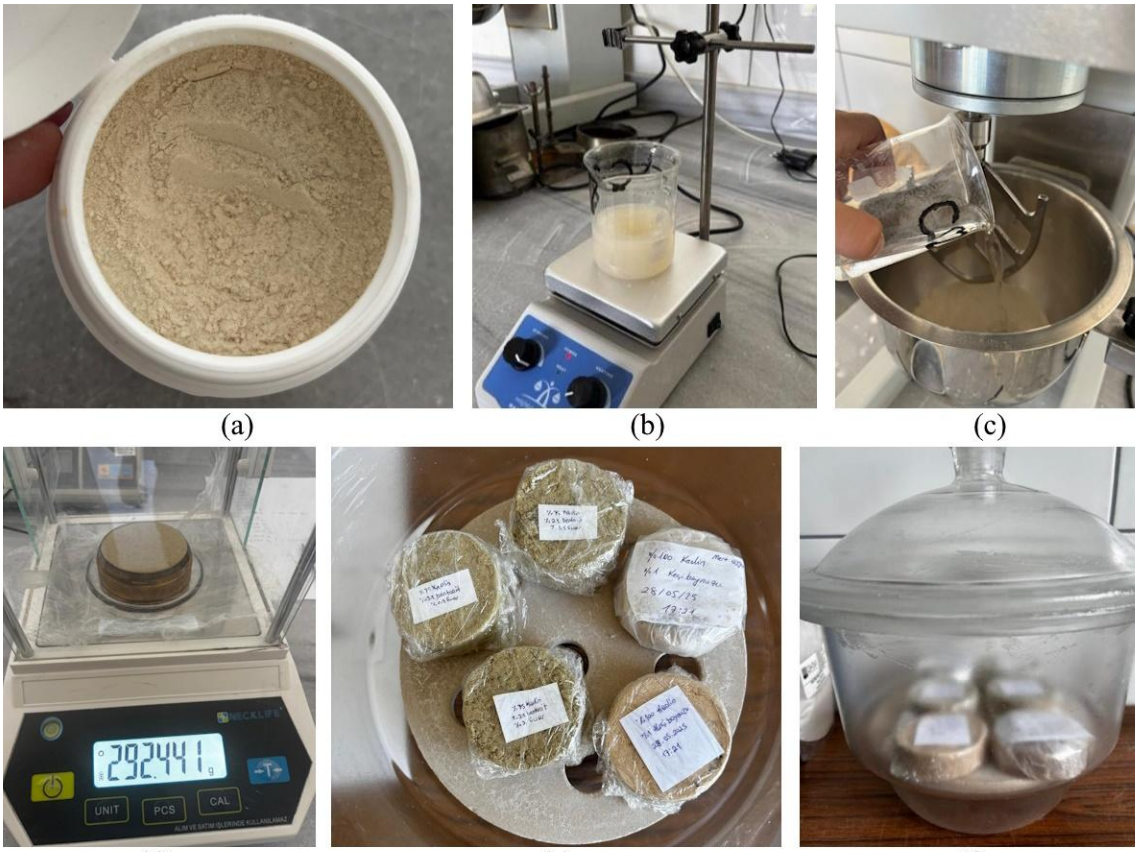
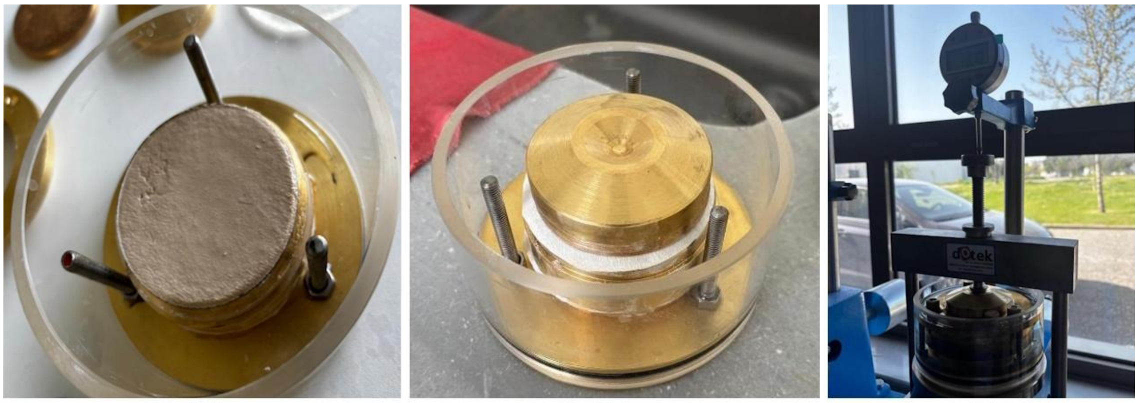


Figure 2:

Preparation and curing stages of locust bean gum (LBG)-treated clay samples: (a) locust bean gum powder, (b) preparation of biopolymer solution using magnetic stirring, (c) mechanical mixing of clay and biopolymer solution to achieve homogeneity, (d) placement of the mixture into the oedometer mold, (e) specimen preparation prior to testing, and (f) controlled curing of specimens in a desiccator.



(a) (b) (c)

Figure 3:

Sample placement and loading stages of the oedometer test: (a) positioning of the specimen between porous stones and filter papers, (b) assembly of the oedometer cell within the loading frame, and (c) monitoring of vertical deformation during incremental loading.

3. RESULTS AND DISCUSSION

This section presents and discusses the swelling behavior of clay soils with different plasticity characteristics under the influence of biopolymer additives, based on experimental results. First, the index properties of the soils were evaluated, followed by an investigation of the effects of biopolymer content and mixing water temperature on the swelling behavior of medium and high-plasticity clay mixtures. The findings were interpreted using strain–stress relationships.

The findings presented in this study are discussed within the defined scope of the experimental program. The results reveal systematic trends in swelling potential and swelling pressure as functions of soil plasticity, biopolymer content, and mixing water temperature, rather than providing a fully generalized description of biopolymer–clay interactions. While a broader experimental framework could further refine these observations, the controlled approach adopted here allows the primary governing factors to be identified without the confounding effects of additional variables. Accordingly, the swelling responses reported are considered representative trends reflecting systematic differences between untreated and treated clay mixtures.

Before discussing the detailed swelling responses, it should be noted that the mechanistic interpretations presented in this study are based on observed macroscopic behavior and supported by findings reported in the literature, rather than on direct microstructural evidence. While microstructural techniques such as SEM, XRD, or FTIR could provide valuable insight into the nature of biopolymer–clay interactions, the present study focuses on the behavioral response of treated clay soils under controlled loading conditions. Accordingly, the proposed mechanisms should be regarded as plausible explanations that warrant further investigation through dedicated microstructural analyses.

3.1. Soil Characterization

The specific gravity and consistency limits of the soils used in the study are given in Table 2. A significant increase in liquid limit and plasticity index values was observed with increasing bentonite content. Pure kaolin fell within the low-medium plasticity range, while kaolin-bentonite mixtures exhibited higher plasticity characteristics. The highest plasticity values were obtained in the bentonite-dominant mixture.

Specific gravity values were higher in samples with a high kaolin content. A modest decrease in Gs values was observed with increasing bentonite content. This trend is consistent with the mineralogical properties of the clay minerals used.

The index properties obtained clearly demonstrated the plasticity difference required for swelling tests. Due to the low plasticity and limited swelling potential of the pure kaolin sample, the effects of biopolymer addition on the swelling behavior were not evaluated for this soil. Pure bentonite was excluded from the study due to its excessive plasticity, difficulties in sample preparation, and insufficient representation of natural soil conditions. Therefore, the evaluation of swelling behavior focused on kaolin–bentonite mixtures.

Table 2. Physical and index properties and USCS classifications of the tested soils

Soil Type	Gs (-)	LL (%)	PL (%)	PI (%)	Plasticity Level	USCS Class
%100 Kaolin	2.69	46.1	32.0	14.1	Low (LL < 50)	ML
%75 Kaolin – %25 Bentonite	2.64	77.5	33.5	44.0	High (LL > 50)	CH
%25 Kaolin – %75 Bentonite	2.54	171.2	59.3	111.9	Extremely high (LL ≫ 50)	CH

3.2. Swelling Behavior of Medium Plasticity Clay Mixture

The stress–strain relationship of the untreated sample of the medium plasticity clay mixture is presented in Figure 4. The untreated sample exhibited a distinct swelling behavior at low stress levels. The swelling potential and swelling pressure could be determined for this sample.

No swelling behavior was observed below 5 kPa in the biopolymer-modified specimens. Therefore, the stress–strain curves for these specimens are not included in Figure 4. Because the deformation mechanisms differ, the settlement responses of biopolymer-treated samples are presented separately in Figures 5 and 6 to facilitate clearer interpretation.

Figure 5 shows the settlement amounts at low stress levels as the biopolymer content increases. The settlement amount increased with increasing biopolymer content up to 1%, then decreased at higher contents under the initial low stress level (i.e., the 5 kPa seating pressure). Because the primary focus of this experimental program was to evaluate swelling potential, the tests for these specific samples were terminated at this stage without applying higher stress increments. This transition from minor swelling to net settlement indicates that the biopolymer effectively neutralizes the bentonite fraction's swelling potential. Once the upward swelling force is suppressed, the soft clay matrix—prepared at the Plastic Limit—is no longer able to counteract the 5 kPa seating load upon inundation, leading to a net downward movement.

However, as expected, if higher stress levels were applied, this settlement would increase significantly. Under elevated vertical stresses, the biopolymer-induced open and flocculated clay fabric would yield and collapse, leading to progressive consolidation of the soil matrix. This non-linear settlement behavior observed in the medium-plasticity clay can be attributed to the competing mechanisms of fabric modification and hydrogel pore-filling. At lower concentrations ($\leq 1\%$), the interaction between LBG and clay particles likely induces flocculation, generating a more open, porous initial micro-fabric that readily undergoes structural collapse and particle rearrangement under the 5 kPa seating stress. Conversely, at higher concentrations ($> 1\%$), the excess biopolymer forms a highly viscous, continuous hydrogel network that occupies the inter-particle void spaces. This pore-filling effect, combined with enhanced polymer-particle cross-linking, significantly increases the overall stiffness of the soil matrix, thereby resisting compression and reducing the settlement. This threshold behavior is consistent with trends reported in the literature for other polysaccharide biopolymers, such as xanthan gum, in which an optimal polymer concentration governs the transition from fabric flocculation to matrix stiffening.

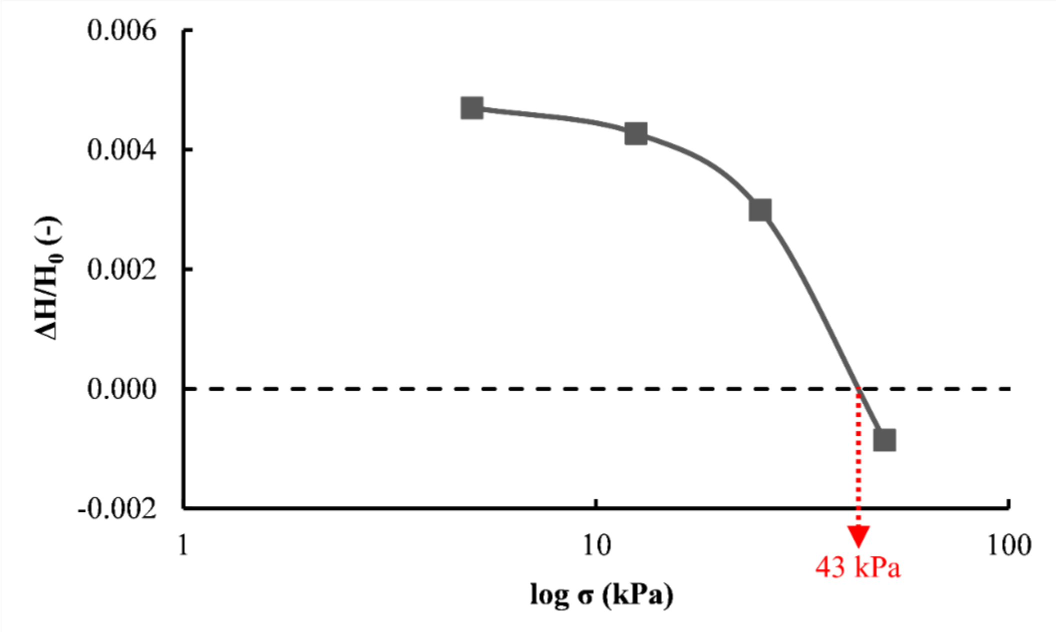


Figure 4:

Stress–strain response of the untreated clay mixture with 75% kaolin and 25% bentonite obtained from oedometer tests.

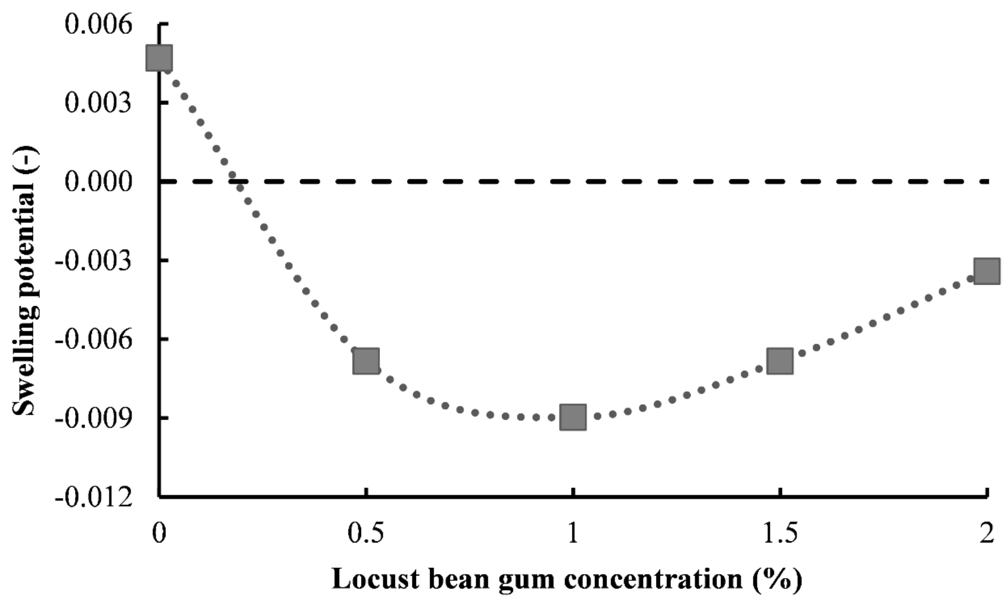


Figure 5:

Settlement behavior of the 75% kaolin–25% bentonite clay mixture treated with different locust bean gum (LBG) contents under low vertical stress levels.

Figure 6 shows the effect of mixing water temperature at a constant biopolymer content. It was observed that the settlement amount increased in samples prepared at higher temperatures.

However, this finding is insufficient to draw general conclusions about consolidation behavior. These observations indicate that the response of the medium-plasticity clay mixture cannot be explained solely by swelling suppression and requires further discussion of its underlying deformation mechanisms. The settlement observed at low stress levels in biopolymer-treated medium-plasticity clay mixtures suggests a behavioral mechanism distinct from swelling suppression. While locust bean gum limits swelling by restricting clay–water interaction, the applied vertical stress may induce a gradual rearrangement of the clay–biopolymer matrix during the initial loading stage. This microstructural reorganization, potentially associated with biopolymer-induced flocculation or particle bridging, can reasonably result in temporary soil fabric densification and manifest as settlement under low stress levels.

It is important to note that the present study does not aim to characterize consolidation behavior or long-term deformation. Accordingly, the observed settlement should be interpreted as an initial structural adjustment rather than as conventional consolidation. Since the main objective of this study was to evaluate swelling behavior, further investigation over extended loading durations would be required to fully elucidate it.

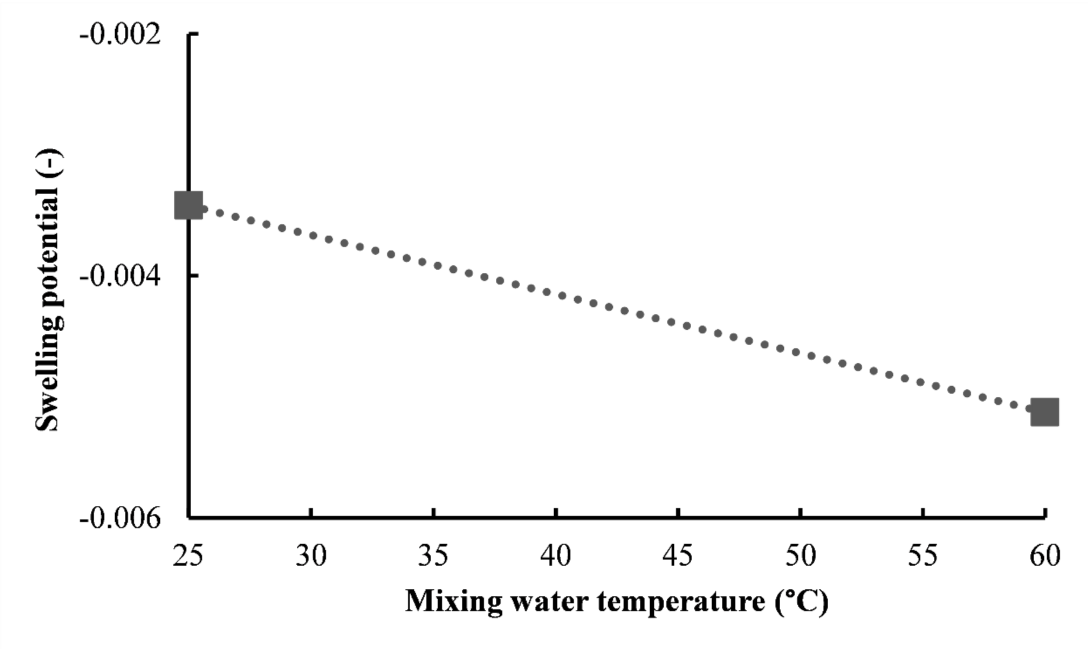


Figure 6:

Effect of mixture water temperature on the settlement response of the 75% kaolin–25% bentonite clay mixture treated with 2% locust bean gum (LBG).

3.3. Swelling Behavior of High Plasticity Clay Mixture

In contrast to the behavior observed in the medium-plasticity clay mixture, the swelling response of the high-plasticity clay mixture is governed by markedly different mechanisms, driven by its higher bentonite content and greater water affinity. The following results and discussion focus on how increased plasticity influences swelling potential, swelling pressure, and the effectiveness of biopolymer treatment. The stress–strain curves for the high-plasticity clay mixture are presented in Figure 7. The untreated sample exhibited a significant swelling potential and high swelling pressure. In the biopolymer-modified specimens, the curves shifted downward and to the left as the biopolymer content increased. This trend corresponds to a decrease in swelling potential and swelling pressure.

Figure 8 directly shows the change in swelling potential and swelling pressure with biopolymer content. A regular decrease in both parameters was observed with increasing biopolymer content. The recorded swelling pressure for the untreated high-plasticity mixture was approximately 150 kPa. Although this represents a significant increase compared to the medium-plasticity mixture, it remains within a moderate range considering the 75% bentonite content. This behavior is primarily attributed to the mineralogical characteristics of the bentonite used, which is identified as a Calcium (Ca)-bentonite (CaO: 3.24% vs. Na2O: 1.92%). Ca-bentonites are known to exhibit lower swelling intensity than Sodium (Na)-bentonites due to their smaller diffuse double layers. Furthermore, since the specimens were prepared at their Plastic Limit (PL), the relatively high initial hydration level and low initial matric suction naturally restricted the magnitude of the swelling pressure generated during inundation.

Figure 9 indicates the effect of the mixture water temperature at a constant biopolymer content. Samples prepared at higher temperatures exhibited lower swelling potential and swelling pressure values. This indicates that the biopolymer–clay interaction is sensitive to preparation conditions. However, additional experimental studies are needed to fully elucidate the mechanism of this effect.

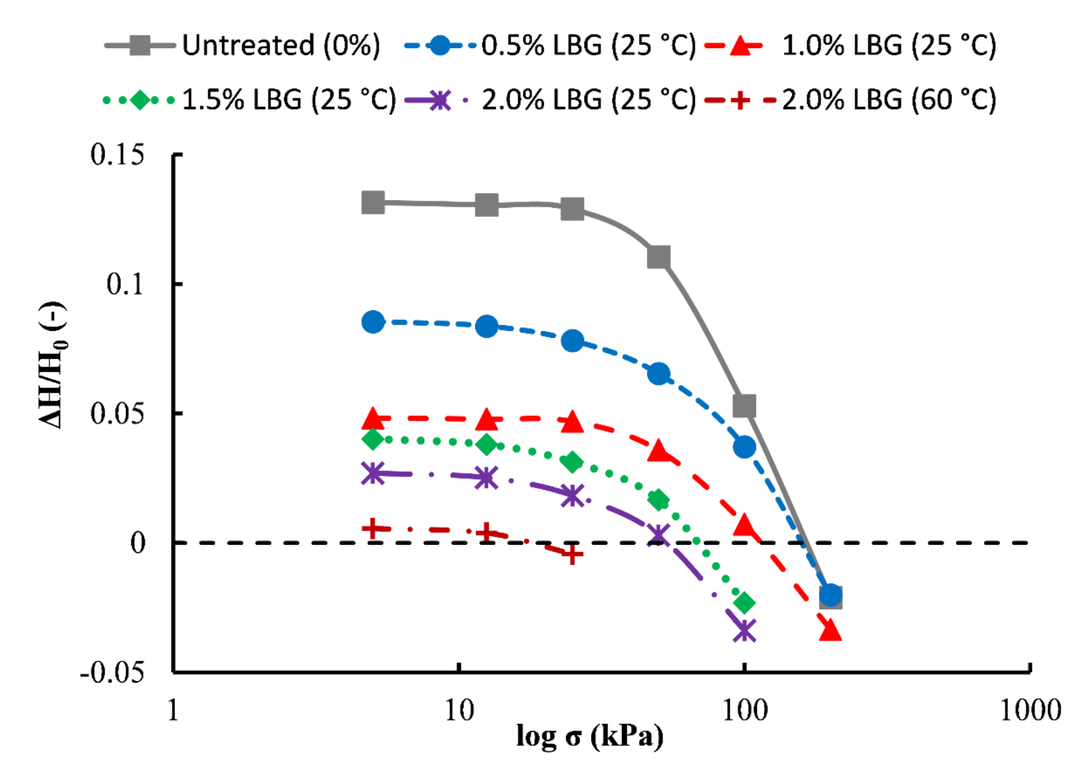


Figure 7:

Stress–strain responses of untreated and locust bean gum (LBG)-treated clay mixtures with 25% kaolin and 75% bentonite obtained from oedometer tests.

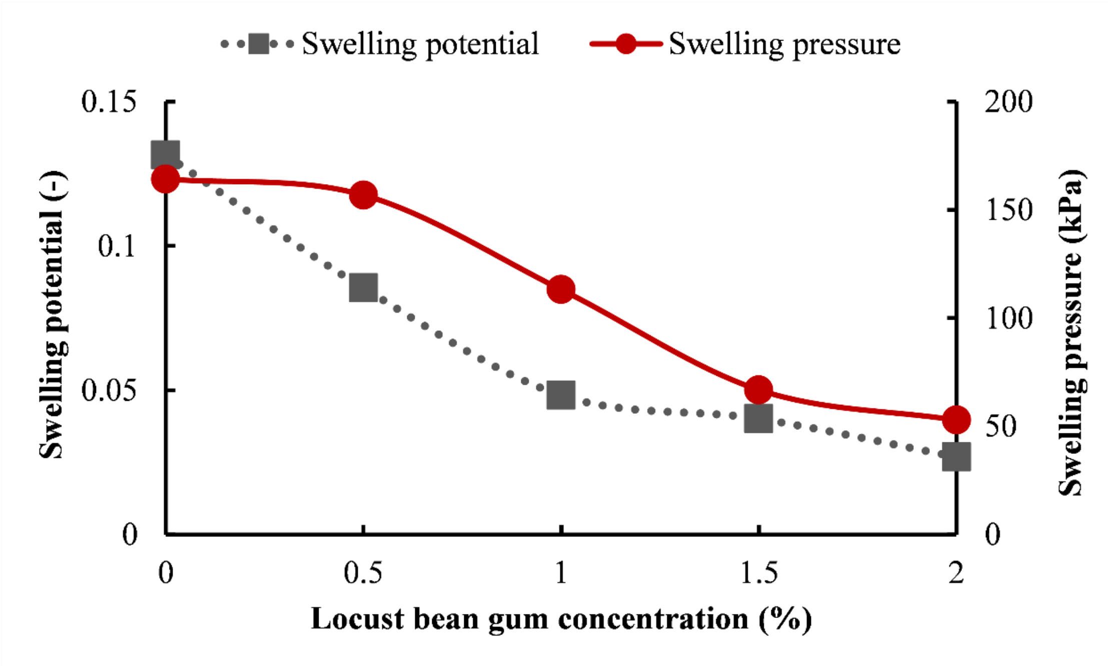


Figure 8:

Variation of swelling potential and swelling pressure with locust bean gum (LBG) content for the 25% kaolin–75% bentonite clay mixture.

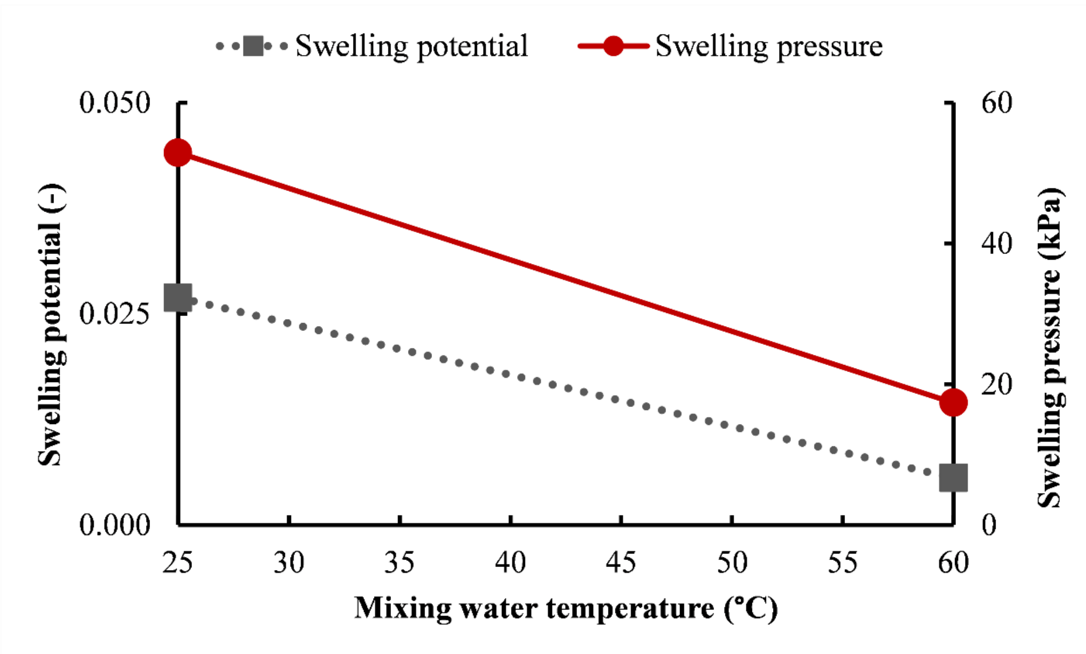


Figure 9:

Effect of mixture water temperature on swelling potential and swelling pressure of the 25% kaolin–75% bentonite clay mixture treated with 2% locust bean gum (LBG).

3.4. Clay–Biopolymer Interaction and Stabilization Mechanism

The stabilization of kaolin–bentonite mixtures using Locust Bean Gum (LBG) is governed by physicochemical interactions rather than primary covalent chemical bonding. LBG, a non-ionic galactomannan, features a high density of hydroxyl ($-OH$) functional groups along its macromolecular chain. These groups facilitate hydrogen bonding with the silanol ($Si - OH$) and aluminol ($Al - OH$) groups on the edges and surfaces of clay minerals. The primary interaction can be represented by the following hydrogen bonding mechanism:

$$Clay - OH + LBG - OH \rightarrow Clay - O \cdots H - O - LBG + H_2O \tag{1}$$

The holistic stabilization achieved in this study can be synthesized through three synergistic mechanisms that explain the observed macro-mechanical behaviors:

- Adsorption and Coating (The Barrier Effect): LBG chains adsorb onto the clay surfaces, creating a physical 'biopolymer coating.' This layer acts as a protective barrier, significantly reducing the thickness of the diffuse double layer (DDL) and impeding the hydration of expansive smectite minerals, thereby directly explaining the reduction in swelling potential.
- Flocculation and Bridging (The Fabric Effect): Long biopolymer chains simultaneously attach to multiple clay particles, acting as 'bridges.' This leads to a more open, flocculated initial structure. This explains why, at lower concentrations, the soil matrix yields and undergoes settlement under the 5 kPa seating load once the swelling potential is neutralized.
- Hydrogel Matrix and Pore-Filling (The Stiffening Effect): Upon hydration, LBG forms a viscous hydrogel that fills the inter-particle voids. This pore-filling effect, combined with enhanced polymer-particle cross-linking at higher concentrations, provides physical resistance against compression and swelling pressure alike.

3.5. Mechanistic Interpretation and Synthesis

To move beyond a descriptive presentation of the results, the following discussion interprets the observed trends by linking swelling behavior to soil plasticity, clay mineralogy, and biopolymer chemistry. The reduction in swelling potential and swelling pressure observed in biopolymer-treated clay mixtures can be attributed to a combination of interacting mechanisms governed by soil plasticity, clay mineralogy, and biopolymer chemistry. Locust bean gum is a highly hydrophilic, galactomannan-based polysaccharide capable of retaining a substantial amount of water within its polymeric network. By binding free pore water, the biopolymer reduces the water available for interlayer hydration of expansive clay minerals, thereby suppressing swelling. In addition, biopolymer chains may partially coat clay particle surfaces and occupy pore spaces, reducing effective pore connectivity and restricting water ingress into the clay fabric. Together, these effects modify soil–water interaction pathways and constrain swelling-induced deformation.

The effectiveness of biopolymer treatment is strongly governed by soil plasticity and associated mineralogical composition. High-plasticity clay mixtures, characterized by higher bentonite content, larger specific surface area, and greater water affinity, contain a higher proportion of expansive clay minerals and provide more attachment sites for biopolymer attachment. As a result, the influence of locust bean gum on swelling behavior becomes more pronounced with increasing plasticity, which is consistent with the experimental observations reported in this study. In contrast, medium-plasticity clay mixtures exhibit fewer active interaction sites, leading to effective swelling suppression accompanied by initial structural rearrangement under low stress levels rather than pronounced swelling deformation.

Beyond these general mechanisms, the preparation conditions of the biopolymer solution play a critical role in determining the efficiency of swelling suppression. The enhanced reduction in swelling observed in samples prepared with elevated mixing water temperature can be interpreted in terms of temperature-dependent biopolymer behavior. Higher temperatures improve the solubility and dispersion of galactomannan-based polysaccharides, resulting in a more homogeneous polymer solution and greater chain expansion in water. Improved dissolution facilitates more uniform distribution of the biopolymer within the clay matrix, enhances water-binding capacity, and increases the likelihood of interaction between polymer chains and clay particle surfaces. Although direct rheological measurements were not conducted in this study, this interpretation is consistent with well-established findings on the temperature-dependent solubility and hydration behavior of biopolymers.

The swelling behavior observed in locust bean gum–treated clay soils is broadly consistent with trends reported for other biopolymers, such as xanthan gum and guar gum, which have been shown to suppress swelling through polymer–water interaction and partial coating of clay particle surfaces. Previous studies indicate that these biopolymers are particularly effective in high-plasticity soils, where the formation of a viscous polymer network restricts water ingress into the clay fabric. In this context, the present results demonstrate that locust bean gum exhibits a swelling suppression mechanism comparable to those of xanthan and guar gums, while showing a pronounced dependence on soil plasticity and preparation conditions. These findings collectively highlight that swelling control through biopolymer treatment is governed by the coupled effects of soil plasticity, clay mineralogy, and the physicochemical characteristics of the biopolymer, and position locust bean gum as a viable alternative for swelling mitigation when preparation conditions are carefully controlled.

In addition to soil plasticity and mineralogical composition, biopolymer–clay interactions are influenced by physicochemical parameters such as cation exchange capacity, specific surface area, pore-fluid chemistry, and pH. While these parameters were not explicitly quantified in the present study, their combined effects are inherently linked to clay mineralogy and plasticity, which were systematically controlled. A detailed investigation of these physicochemical factors would provide further insight into the underlying interaction mechanisms and represent an important direction for future research.

3.6. Economic and Environmental Feasibility

The practical applicability of biopolymers in geotechnical engineering is often evaluated based on their cost-effectiveness relative to traditional stabilizers such as cement and lime. While the unit market price of Locust Bean Gum (LBG) is higher than that of conventional additives, its economic viability is supported by several factors, as highlighted in recent literature (Gezgin & Ercan, 2026). First, the dosage efficiency of LBG is significantly higher; effective swelling mitigation and fabric stabilization are achieved at concentrations as low as 0.5–1.0% by weight. In contrast, traditional chemical stabilization typically requires 5–10% additive content, which bridges the gap in total material expenditure.

Second, the environmental cost of traditional stabilizers must be considered. Cement production is responsible for approximately 5–8% of global CO_2 emissions. As carbon taxes and environmental regulations become more stringent, the carbon-neutral nature of LBG offers a long-term economic advantage by reducing environmental mitigation costs throughout a project’s life cycle.

Furthermore, the low dosage requirements translate into reduced logistics, transportation, and storage costs. Unlike cement, which can lead to brittle failure and alter soil pH, LBG-treated soils exhibit a more ductile response without compromising environmental health. Therefore, when evaluated through the lens of sustainable geotechnics, LBG treatment represents a cost-effective and eco-friendly alternative for managing expansive soils in modern infrastructure projects.

4. CONCLUSION

This study experimentally investigated the effects of the locust bean gum biopolymer on the swelling behavior of clay soils with varying plasticity. Quantitative evaluation of oedometer test results demonstrated that the effectiveness of biopolymer treatment is strongly governed by soil plasticity and preparation conditions. Based on the experimental findings, the following key conclusions can be drawn:

- Evaluations revealed that the plasticity level and swelling potential of clay soils increased significantly with increasing bentonite content.
- In the medium-plasticity clay mixture, the biopolymer additive suppressed swelling and induced settlement at low stress levels. This settlement response is interpreted as an initial structural adjustment of the clay–biopolymer matrix rather than as conventional consolidation. Accordingly, the observed settlement behavior and swelling suppression are governed by distinct mechanisms.
- In the highly plastic clay mixture, the biopolymer additive was found to significantly reduce the swelling potential and swelling pressure. At a biopolymer content of 2%, swelling potential and swelling pressure were reduced by approximately 79% and 68%, respectively, at room temperature. Furthermore, it was determined that increasing the mixture water temperature further reduced swelling behavior, even at a constant biopolymer content. When the biopolymer solution was prepared using water at 60 °C, the reductions in swelling potential and swelling pressure increased to approximately 95% and 90%, respectively.

Overall, the findings indicate that biopolymer addition offers an environmentally friendly and sustainable alternative for improving expansive clay soils, particularly those with high plasticity. However, the effectiveness of the treatment is strongly dependent on design variables such as biopolymer content and mixing water temperature, which must be carefully controlled in engineering practice.

The present study focuses on short-term swelling behavior under controlled laboratory conditions. Future research should aim to extend these findings by systematically investigating time-dependent and environmental effects. In particular, studies incorporating curing time, aging, long-term loading conditions, and environmental cycles (such as wetting–drying and temperature fluctuations) are needed to evaluate the durability and post-treatment deformation behavior of biopolymer-treated soils. Furthermore, integrating physicochemical and microstructural analyses (e.g., SEM, XRD, FTIR, cation exchange capacity, and pore-fluid chemistry) would provide deeper insight into the underlying biopolymer–clay interaction mechanisms and support broader implementation of these mitigation techniques in the field.

CONFLICT OF INTEREST

The author declares that there is no known conflict of interest and no financial or personal relationships with any institution, organization, or individual that could have influenced the work reported in this study.

AUTHOR CONTRIBUTIONS

Ahmet Talha Gezgin: Conceptualization, methodology, data collection, formal analysis, interpretation of results, writing—original draft preparation, writing—review and editing, and approving the final version of the manuscript.

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