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Investigation of the Effects of Two Different Biopolymers on the Strength Parameters of Silty Soil

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Anahtar Kelimeler

Biyopolimer
Zemin iyileştirme
Xanthan gum
Guar gum
Çapraz bağlanma

Graphical/Tabular Abstract (Grafik Özet)

This study investigates the effects of Xanthan Gum and Guar Gum biopolymers combined with $CaCl_2$ on the strength parameters of silty soil. UCS and shear strength tests were performed at various curing times. Results showed that biopolymers, particularly Guar Gum, significantly enhance long-term soil strength. / Bu çalışma, Xanthan Gum ve Guar Gum biyopolimerlerinin $CaCl_2$ ile birlikte kullanılarak siltli zeminin dayanım parametrelerine etkisini araştırmıştır. Deneyler, farklı kür sürelerinde UCS ve kayma mukavemeti testleriyle gerçekleştirilmiştir. Sonuçlar, biyopolimerlerin özellikle Guar Gum'un uzun vadeli dayanımı artırdığını göstermiştir.

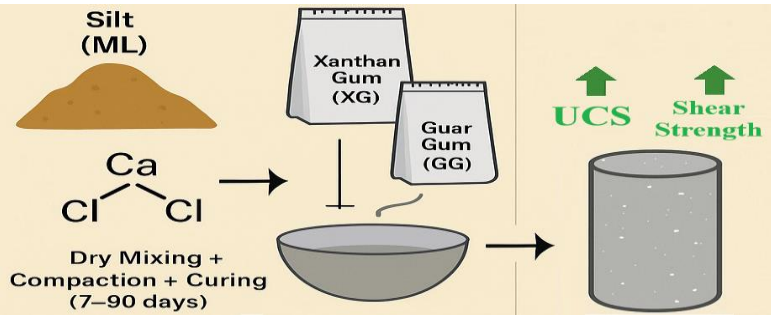

Figure A: *Experimental process /* ***Şekil A:*** *Deneysel süreç*

Highlights (Önemli noktalar)

- *Xanthan Gum ve Guar Gum; siltli zemin stabilizasyonu için, sabit miktarda (%0,5) $CaCl_2$ içeriğinde kullanıldı. / Xanthan Gum and Guar Gum were used for silty soil stabilization at constant amount (%0.5) of CaCl2 content.*
- *Guar Gum, Xanthan Gum'a göre uzun vadede daha yüksek dayanım sağladı. / Guar Gum provided superior long-term strength gains compared to Xanthan Gum.*
- *En iyi performans için optimum biyopolimer oranı %0,5 belirlendi. Aşırı biyopolimer kullanımı, aşırı jel oluşumu nedeniyle UCS değerini düşürdü. / Optimal biopolymer content was determined as 0.5% for best performance. Excessive biopolymer content reduced UCS due to over-gelation effects.*

Aim (Amaç): *Investigate the effects of Xanthan Gum and Guar Gum biopolymers, used in combination with constant amount of Calcium Chloride, on the strength parameters soil and to determine the optimum biopolymer content. / Xanthan Gum ve Guar Gum biyopolimerlerinin, sabit oranda Kalsiyum Klorür ile birlikte kullanıldığında zeminin dayanım parametreleri üzerindeki etkilerini araştırmak ve optimum biyopolimer oranını belirlemektir.*

Originality (Özgünlük): *The effects of Xanthan and Guar Gum with $CaCl_2$ on silty soil strength, focusing on long-term curing and optimal biopolymer content. / Xanthan ve Guar Gum'un $CaCl_2$ ile siltli zemindeki etkilerini, uzun süreli kürleme ve optimum biyopolimer oranına odaklanarak özgün biçimde incelenmektedir.*

Results (Bulgular): *Xanthan Gum improved short-term strength, while Guar Gum enhanced long-term strength of silty soil. The optimum biopolymer content was determined as 0.5%. / Xanthan Gum'un kısa vadede, Guar Gum'un ise uzun vadede zemin dayanımını artırmıştır. Optimum biyopolimer oranı %0,5 bulunmuştur.*

Conclusion (Sonuç): *Xanthan Gum and Guar Gum biopolymers, when combined with $CaCl_2$, significantly improve the strength of silty soil. Guar Gum showed superior performance in long-term strength. The optimum biopolymer content was found to be 0.5%, as higher contents reduced strength. / Xanthan Gum ve Guar Gum biyopolimerlerinin, $CaCl_2$ ile birlikte kullanıldığında siltli zeminin dayanımını önemli ölçüde artırabilir. Özellikle Guar Gum, uzun vadeli dayanımda üstün performans sergilemiştir. Optimum biyopolimer oranı %0,5 olup, daha yüksek oranlar dayanımı düşürmüştür.*

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Abstract

Soil improvement methods are commonly employed to enhance the load-bearing capacity of weak soils. Due to environmental concerns, traditional additives like lime and cement are increasingly being replaced by more sustainable alternatives. Recently, biopolymers have gained attention as environmentally friendly options for soil stabilization. However, studies on combining biopolymers with supplementary additives to enhance the strength of the bonds formed between the soil and biopolymers are scarce. This study investigates the effects of using Guar Gum and Xanthan Gum biopolymers in combination with Calcium Chloride ($CaCl_2$) on the strength parameters of silty soil. Biopolymers are known to form gel-like structures between soil particles, increasing strength. At the same time, Calcium Chloride interacts with the carboxyl groups of biopolymers, creating cross-linkages that further improve soil strength. In this research, biopolymers and Calcium Chloride were combined with silty soil and subjected to 7,28,56 and 90 days of curing. Unconfined compressive strength (UCS) and direct shear tests were conducted, and the results were compared with reference samples. Changes in internal friction angle and cohesion were also analyzed based on different biopolymer ratios. The results demonstrated significant improvements in the strength of long-term cured samples, with Calcium Chloride enhancing the cross-linking effect of biopolymers. These findings suggest that biopolymers, in combination with Calcium Chloride, can be effective in environmentally friendly soil stabilization projects.

İki Farklı Biyopolimerin Siltli Zemin Dayanım Parametreleri Üzerindeki Etkilerinin Araştırılması

Makale Bilgisi

Araştırma makalesi
Başvuru: 29/01/2025
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Öz

Zemin iyileştirme yöntemleri zayıf zeminlerin taşıma gücünü artırmak için yaygın olarak kullanılır. Çevresel kaygılar nedeniyle kireç ve çimento gibi geleneksel katkı maddeleri, yerini giderek daha sürdürülebilir alternatiflere bırakmaktadır. Son zamanlarda, biyopolimerler zemin iyileştirme amacıyla, çevre dostu seçenekler olarak dikkat çekmektedir. Ancak, zemin ve biyopolimer arasında oluşan bağların mukavemetini artırmak için biyopolimerleri ek maddelerle birleştirme konusundaki çalışmalar nadirdir. Bu çalışma, Guar Gum ve Xanthan Gum biyopolimerlerinin kalsiyum klorür ($CaCl_2$) ile birlikte kullanılmasının siltli zeminin mukavemet parametreleri üzerindeki etkilerini araştırmaktadır. Biyopolimerlerin zemin matrisi arasında jel benzeri yapılar oluşturarak mukavemeti artırdığı bilinmektedir. Aynı zamanda kalsiyum klorür, biyopolimerlerin karboksil gruplarıyla etkileşime girerek zemin mukavemetini daha da artıran çapraz bağlar oluşturur. Bu çalışmada, biyopolimerler ve kalsiyum klorür siltli zeminle birleştirilerek 7,28,56 ve 90 günlük kürlemeye tabi tutulmuştur. Kürlenen numunelerin serbest basınç ve kayma mukavemetleri, referans numune ile karşılaştırılmıştır. İçsel sürtünme açısı ve kohezyondaki değişiklikler de farklı biyopolimer oranlarına göre analiz edilmiştir. Sonuçlar, kalsiyum klorürün biyopolimerlerin çapraz bağlama etkisini artırmasıyla uzun süreli kürlenmiş numunelerin mukavemetinde önemli iyileştirmeler olduğunu göstermiştir. Bu bulgular, biyopolimerlerin kalsiyum klorürle birlikte çevre dostu zemin stabilizasyon projelerinde etkili olabileceğini ortaya koymaktadır.

1. INTRODUCTION (GİRİŞ)

Soil improvement is one of the primary engineering applications used to increase the shear strength and stability properties [1]. Weak soils can negatively affect the load-bearing capacity of structures, making soil improvement methods crucial for the safety and longevity of construction projects [2].

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While chemical stabilizers such as cement and lime have traditionally been used in soil stabilization, they pose environmental sustainability concerns [3–7]. As a result, natural and eco-friendly alternatives are increasingly preferred [8–12].

Biopolymers have emerged as an environmentally friendly alternative to traditional soil stabilization methods, such as lime and cement, demonstrating significant potential in improving the strength parameters of silty soils. Xanthan gum (XG), guar gum (GG), and agar gum (AG) are among the biopolymers extensively studied for their ability to enhance soil strength [13]. Biopolymers from natural sources offer sustainable and environmentally friendly alternatives for soil improvement projects [14]. Biopolymers like Guar Gum and Xanthan Gum form gel-like structures when combined with water, creating bonds between soil particles and thus improving soil strength [15–18]. These biopolymers present sustainable and eco-friendly solutions, particularly in fine-grained soils, where their high water retention capacity enhances soil strength by forming gel-like structures between soil particles [13,19–21]. The addition of XG to highly plastic silty soils in the Brahmaputra Valley resulted in a fourfold increase in unconfined compressive strength (UCS) while maintaining low thermal conductivity and moderate abrasiveness, highlighting its effectiveness in enhancing soil strength for temporary infrastructure applications [22].

Similarly, the application of XG in low-plasticity silty soils showed significant improvements in both tensile and compressive strength, with its effectiveness influenced by the presence of fine particles such as kaolin in the soil matrix [23]. Although a reduction in the effective friction angle was observed in granular soils, the shear strength was still enhanced due to increased effective cohesion, as evidenced by biopolymer treatment [24]. Additionally, guar gum (GG) has been shown to improve the stiffness and strength of clay soils by forming viscous gels and hydrogen bonds, which progressively enhance the soil’s modulus of stiffness over time [25]. In the Kuttanad region, the application of XG and GG led to a substantial increase in UCS and a decrease in optimum moisture content, emphasizing their potential to improve the mechanical properties of silty and clayey soils [26]. Despite these promising results, the durability of biopolymer-treated soils under extreme weather conditions, such as wet-dry and freeze-thaw cycles, remains a concern. These conditions can lead to strength degradation due to water adsorption and dilution of the biopolymer matrix [27].

The literature shows that various studies have examined the effects of biopolymers on soil. In a study by Muguda et al. [28], the unconfined compressive strength of clay and sand soils improved by Guar Gum was measured, showing a 110% increase in clay and approximately 85% in sand compared to reference samples. Similarly, [14] improved the strength of wind-eroded sandy soils using Xanthan Gum, reducing wind erosion by approximately 40%. Kavazanjian et al. [29] reported a 60% reduction in erosion using Xanthan Gum. Additionally, Soldo et al. [30] observed that Xanthan Gum and Guar Gum increased cohesion in clay soils by over 150%. In conclusion, biopolymers represent a sustainable and effective tool for enhancing the strength parameters of silty soils. However, further research is required to optimize their application and ensure long-term durability under varying environmental conditions [17,31]. In addition to these studies, the relationship between various biopolymers and soil strength parameters has been extensively investigated in the literature [32–45]. However, these studies are generally limited to examining the effect of a single biopolymer [46].

The effect of biopolymers is enhanced by specific amounts of various cross-linking agents in the environment, allowing them to form hydrogen bonds with the matrix they are introduced into [27,28]. The required amount of cross-linking agent varies depending on the type of biopolymer used, the cross-linking agent itself, and the characteristics of the medium in which they are incorporated [20,47–50]. If an optimum bonding structure is desired, the cross-link agent ratio should be higher than the biopolymer content when forming ionic bonds (e.g., Alginate, Pectin, Carrageenan), but equal to or lower than the biopolymer when forming covalent or physical bonds (e.g., Xanthan Gum, Guar Gum, Chitosan), as excessive cross-link agent can disrupt the gel matrix and polymer network, alter water absorption capacity, increase brittleness, and lead to chemical precipitation, ultimately compromising mechanical stability [51–59]. In terms of biopolymer content, the literature indicates that the optimal ratio for different biopolymers and soil types generally ranges between 0.5% and 3% [32,48,50,60–63].

This study conducted unconfined compressive strength (UCS) tests on soil specimens containing different types and proportions of biopolymers. They were subjected to curing periods of 7, 28, 56, and 90 days to determine their compressive strength. Additionally, direct shear tests (DST) were performed on specimens cured for 28 days to evaluate the effects of biopolymers and $CaCl_2$ on the internal friction angle, cohesion, and shear strength parameters compared to the reference soil specimen.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Material (Materyal)

The materials used in this study can be categorized into three groups: soil, biopolymer, and stabilizing agent. The silty material used in this study was obtained from the Taşköprü district of Kastamonu province. It is a yellow-colored, low-plasticity silt (classified as ML). The graduation curve obtained by sieve analysis of the soil sample is shown in Figure 1 (The gradation curve of the biopolymers was drawn according to the information received from the manufacturer since the biopolymers gelled the mixture liquid during the hydrometer analysis).

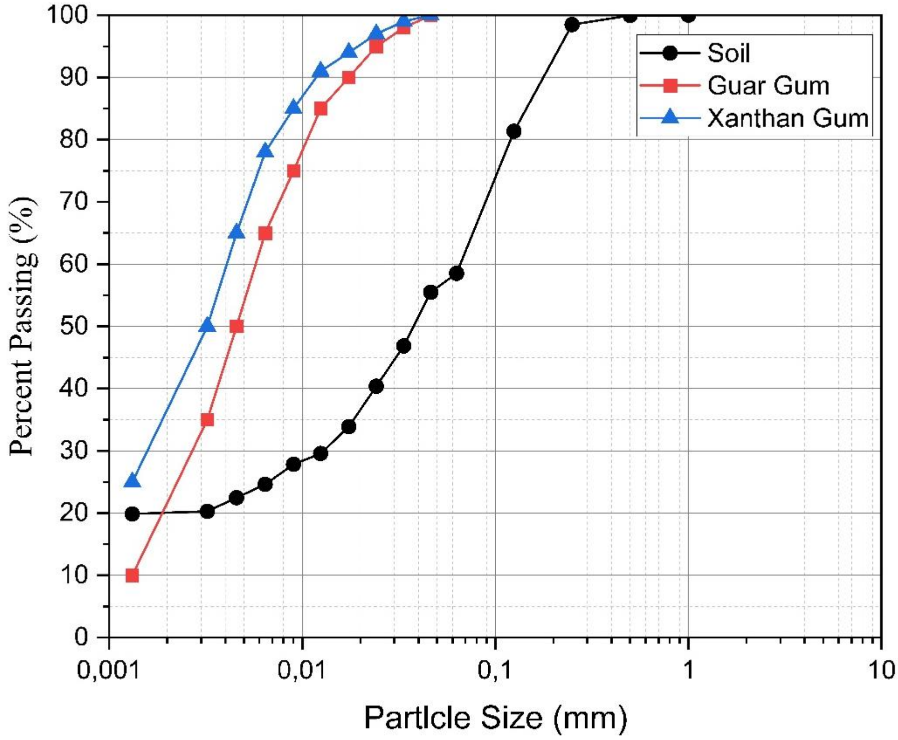

Figure 1. Grain size distribution curve (Dane boyutu dağılımı)

Other geotechnical properties of silt and the ASTM standards used to determine them are given in Table 1. After being brought to the laboratory, the silt was oven-dried at 105°C for 24 hours. The dried material was then ground and sieved through a No. 40 sieve (0.425 mm) before being used in the experiments. Casagrande apparatus was used to determine the Liquid Limit values.

Table 1. Properties of the ML (ML'nin özellikleri)

Property	Unit	Value	Relative Standard
Silt Content	%	46,6	ASTM D7928-17 [64]
Clay Content	%	19,9	ASTM D7928-17 [64]
Sand Content	%	33,5	ASTM D6913-04 [65]
Specific Gravity (G_s)	-	2,69	ASTM D854-14 [66]
Liquid Limit	%	31,84	ASTM D4318-17 [64]
Plastic Limit	%	22,54	ASTM D4318-17 [64]
Plasticity Index (PI)	%	9,3	ASTM D4318-17 [64]

Two different biopolymers were used in this study. The first is Xanthan Gum, coded as E415, which is natural biopolymer extracted from the bacterium Xanthomonas campestris, has a high water retention capacity, a pH range of 6-8, and is white. The second biopolymer is Guar Gum, derived from the Guar plant, coded as E412, with a high water retention capacity, a pH range of 5.5-7, and is yellowish-white. Images of the biopolymers are shown in Figure 2.

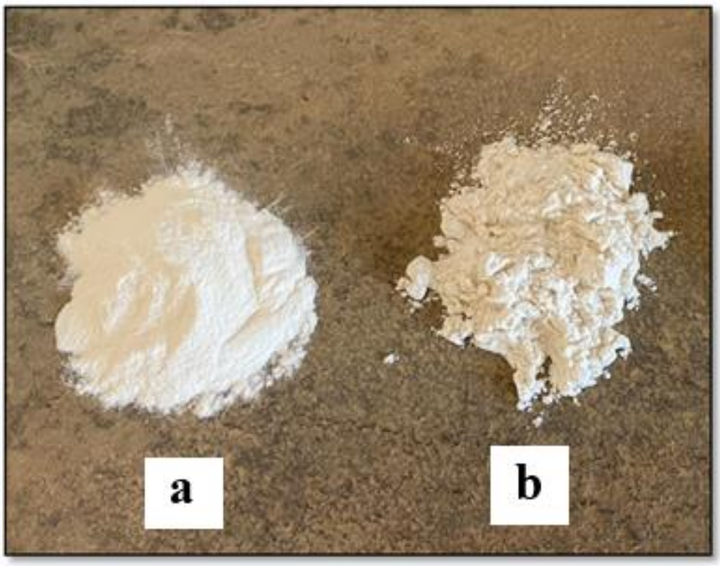

Figure 2. Biopolymers: Xanthan Gum (a) and Guar Gum (b) (Biyopolimerler: Xanthan Gum (a) ve Guar Gum (b))

Biopolymers transform into a gel form when in contact with water, filling soil voids and creating bonds between soil particles. This process reinforces the soil. Unlike previous research, this study investigated the behavior of biopolymers in the presence of calcium ions. Calcium ions interact with the carboxyl groups of biopolymers, such as xanthan gum and guar gum, forming cross-links. This process tightens the chemical bonds between biopolymers, forming a more robust gel matrix. Calcium-containing compounds, such as Calcium Chloride, create cross-links within the gel structures of biopolymers, enhancing the durability and stability of the gel [14,21,27,67,68].

This study used high-purity Calcium Chloride ($CaCl_2$), chemically coded as E509, to facilitate cross-linking with the biopolymers (Figure 3). Calcium Chloride was selected as the cross-linking agent due to its availability, low cost, and excellent solubility in water. When dissolved, Calcium Chloride undergoes an exothermic reaction, dissociating into calcium (Ca^{2+}) and chloride (Cl^{-}) ions. The free calcium ions form strong bonds with the carboxyl groups of the biopolymers, thereby reinforcing the bonds created by the biopolymers [46,68].

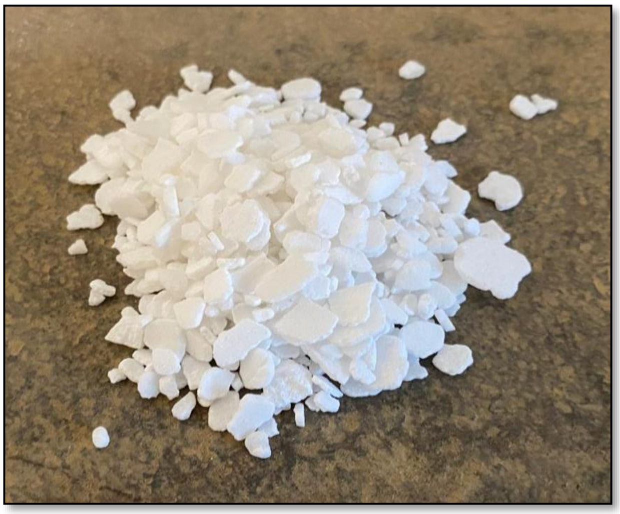

Figure 3. Calcium chloride (Kalsiyum klorür)

2.2. Method (Metod)

In soil improvement studies, the optimum biopolymer ratio typically ranges between 0.5% and 3%, depending on factors such as the type of biopolymer used and soil characteristics [48,60,61]. However, it has been reported that this ratio may decrease when a cross-linking agent is used [46]. Accordingly, in the experimental design of this study, Xanthan Gum (XG) and Guar Gum (GG) biopolymers were incorporated at 0.5%, 1%, and 1.5% by the dry weight of the soil. Based on the literature findings presented in the introduction and by the recommendation that the amount of cross-linking agent should be lower than the biopolymer content when using physically binding biopolymers such as Xanthan Gum and Guar Gum [28,51–56,69–71], the amount of $CaCl_2$, which was used as a cross-linking agent, was set at a constant 0.5% for all mixtures (except the Reference Mixture), equal to the lowest biopolymer percentage (Table 2).

All samples were prepared using the dry mixing method. CaCl2 was ground into powder and subsequently mixed with the biopolymer. The initial water content of the soil was determined as 1.16%. The optimum water content for each mixture used in the experiments was individually determined to ensure the most suitable conditions for UCS and DST tests (Figure 4 and Table 2). In this context, the Proctor test was conducted following the ASTM D698 [72] standard to determine the optimum moisture content for each mixture separately. This test identified the maximum dry unit weight and the corresponding optimum moisture content, and the samples were subsequently compacted into molds based on these values [14,25,42].

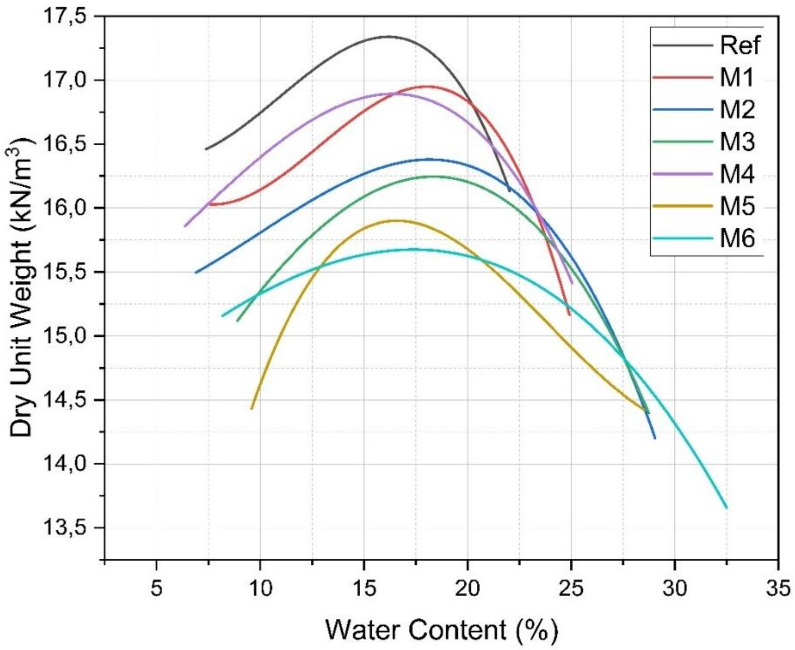

Figure 4. Optimum moisture content values of the mixtures (Karışımların optimum su muhtevası değerleri)

To ensure a homogeneous blend, the mixture was stirred first at low speed and then at high speed for an extended period before being promptly molded. Specimen preparation was carried out using a Harvard Miniature Proctor compaction mold. To achieve the equivalent compaction energy of the Standard Proctor test as specified in ASTM D698 [72], cylindrical specimens with a diameter of 5 cm and a height of 10 cm were compacted in three layers, with 15 blows applied. The compaction was performed using a 2.5 kg rammer dropped from a height of 30 cm. The samples were then wrapped in plastic film and placed in desiccators for 7, 28, 56 and 90 days. UCS test was performed on the samples at these curing times, and the DST test was also applied at the end of the 28-day curing period. All of these experiments were performed on two samples, and the average of the experimental results is shown in the graphs. The experimental design is summarized in Table 2.

Table 2. Experimental Scheme (Deney şablonu)

		Reference	M1	M2	M3	M4	M5	M6
$CaCl_2$ (%)*		0	0,5	0,5	0,5	0,5	0,5	0,5
Xanthan Gum (%)*		0	0,5	1	1,5	0	0	0
Guar Gum (%)*		0	0	0	0	0,5	1	1,5
Optimum Water Content (%)		17,34	16,95	16,38	16,25	16,89	15,95	15,68
Curing Durations	**UCS**	7, 28, 56, 90	7, 28, 56, 90	7, 28, 56, 90	7, 28, 56, 90	7, 28, 56, 90	7, 28, 56, 90	7, 28, 56, 90
	DST	28	28	28	28	28	28	28

*****by dry weight of soil

UCS test was carried out on samples cured in a desiccator for 7, 28, 56, and 90 days (Figure 5). For the UCS test, cylindrical samples with a diameter of 50 mm and a height of 100 mm, free of hairline cracks, were prepared. During the test, to provide precise and accurate results, changes in sample height and applied load were measured using LVDTs with real-time data recorded by a computer (Figure 6.a). The load-displacement curve was drawn from the recorded data, and the peak values of this curve were taken as the unconfined compressive strength (ASTM D2166 / D2166M-16 [73]). The loading speed was set to 1 mm/min for the UCS test.

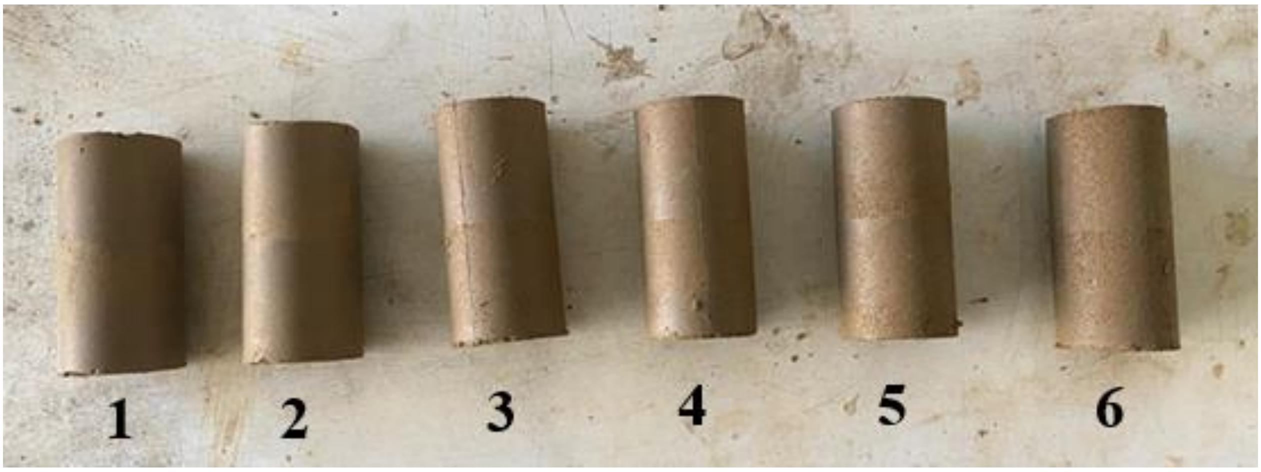

Figure 5. Specimens 1, 2, 3, 4, 5, and 6 from left to right (Soldan sağa doğru 1,2,3,4,5 ve 6 numaralı karışımlar)

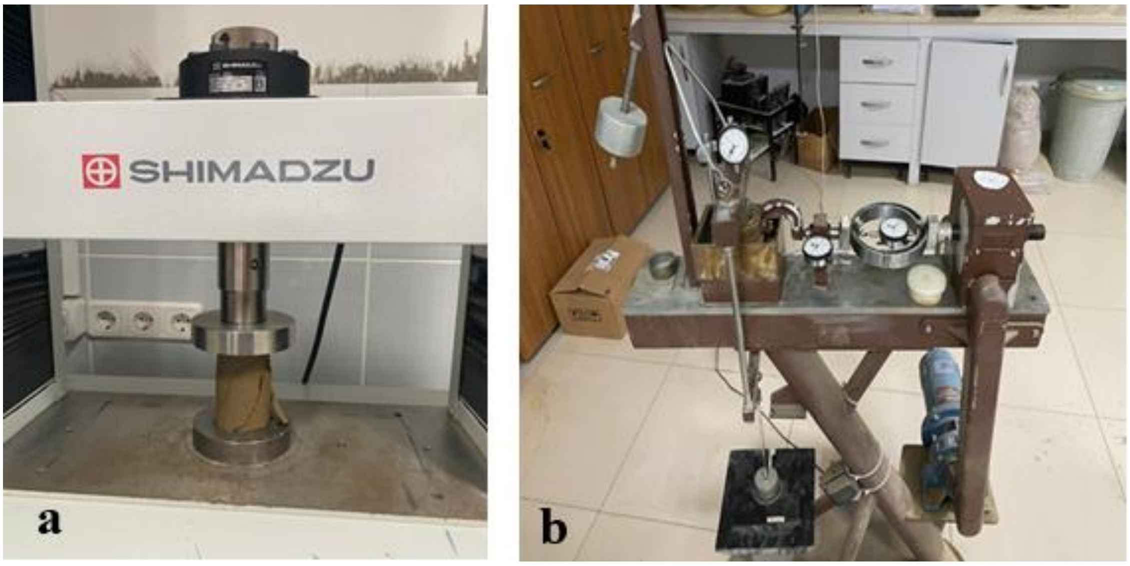

Figure 6. Unconfined compressive strength (UCS) test (a) and Direct Shear Test (b) (Serbest basınç (UCS) deneyi (a) ve kesme kutusu deneyi (b))

DST was performed on samples cured in a dryer for 28 days to determine cohesion (c), internal friction angle (ϕ), and shear strength by ASTM D3080/D3080M-11 [74]. During this test, 50, 100, and 150 kPa normal stresses were applied to the samples at a deformation speed of 0.8 mm/min (Figure 6.b).

3. RESULTS (BULGULAR)

3.1. Unconfined Compressive Strength (UCS) Results (Serbest Basınç Deneyi (UCS) Sonuçları)

The UCS values of the soil specimens prepared with 0.5%, 1%, and 1.5% Xanthan Gum and Guar Gum, along with 0.5% $CaCl_2$ by the dry weight of the soil, are presented in Figure 7. Figure 8 illustrates a graphical comparison of these values. For the reference soil specimens, UCS values at 7, 28, 56, and 90 days of curing were measured as 502, 508, 511.2, and 512.4 kPa, respectively. The increase in UCS for the reference soil specimens containing only $CaCl_2$ did not exceed 2%. Based on this, an average UCS value of 508.25 kPa was considered a baseline for comparison with other mixtures.

According to these results, M1 exhibited the highest compressive strength at 7 and 28 days, while M4 achieved the highest strength at 56 and 90 days of curing. The unconfined compressive strength of M1, which contains 0.5% Xanthan Gum, reached 790.92 kPa at 7 days and 987.57 kPa at 28 days. On the other hand, the UCS of M4, which contains 0.5% Guar Gum, was 2040.11 kPa at 56 days, making it the highest among all mixtures. However, M3 and M6, which contained 1.5% biopolymer, generally exhibited lower compressive strength values. This suggests that excessive gel formation negatively affects particle bonding, reducing strength [57–59]. At the end of the 90-day curing period, M4 achieved the highest UCS value of 3871.51 kPa, confirming the superior long-term performance of Guar Gum in soil stabilization.

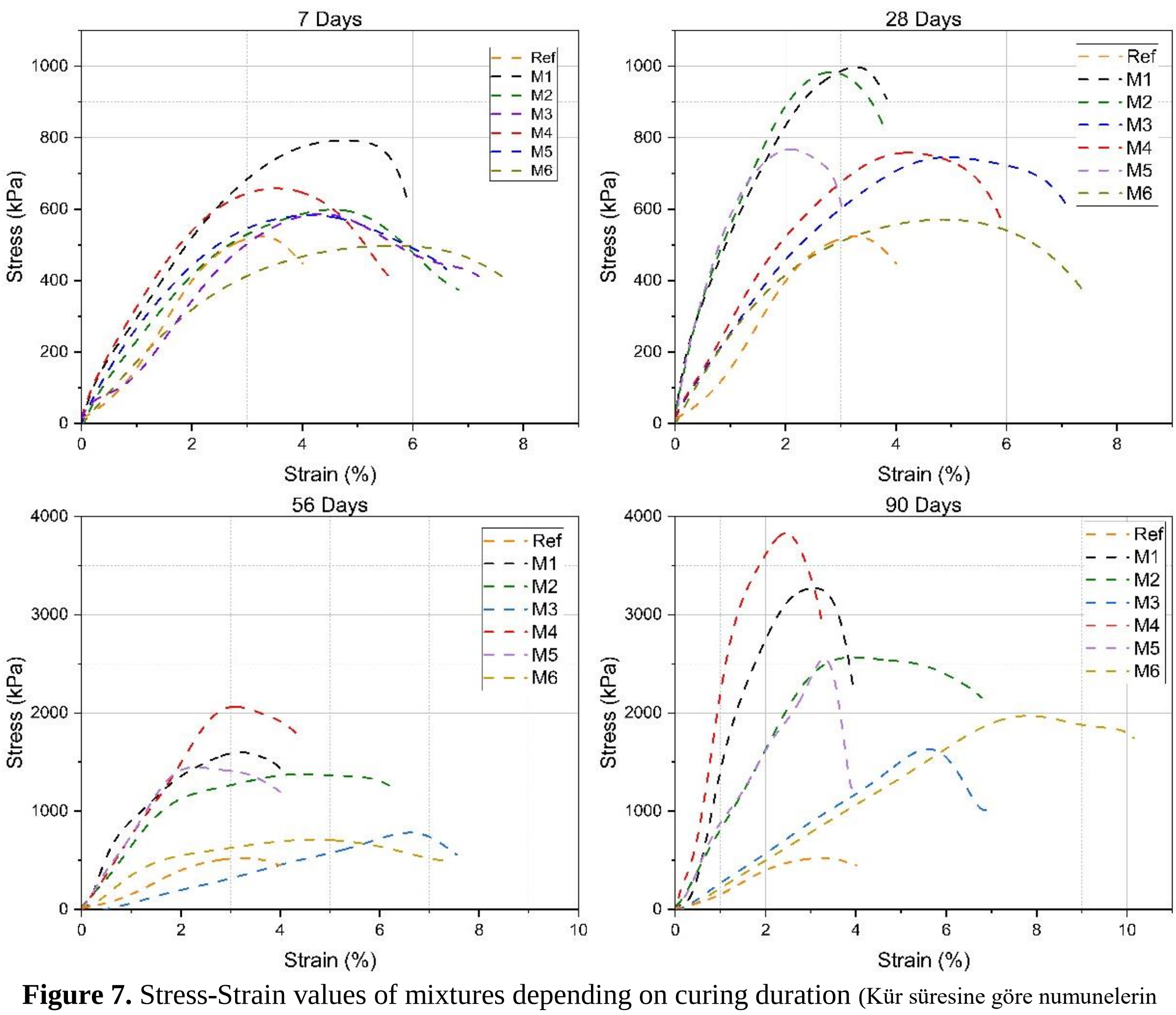

Figure 7. Stress-Strain values of mixtures depending on curing duration (Kür süresine göre numunelerin gerilme-gerinim değerleri)

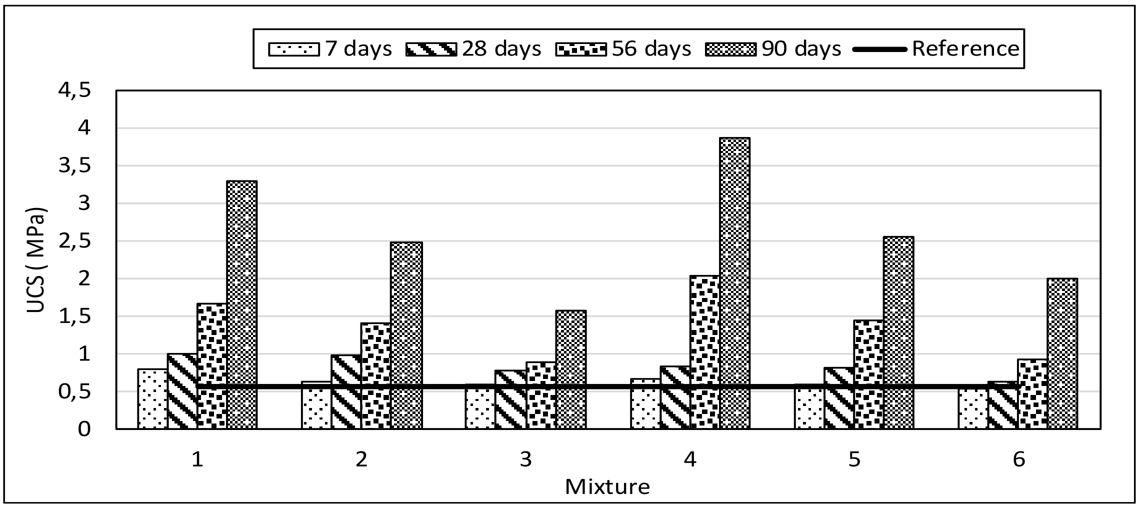

Figure 8. UCS values for 7, 28, 56 and 90 days of curing based on mixture numbers (7, 28, 56 ve 90 günlük kür sürelerine göre numunelerin serbest basınç dayanım değerleri)

The percentage change in unconfined compressive strength (UCS) values of the mixtures compared to the reference sample, depending on the curing duration, is presented in Figure 9. The UCS increase percentages of Xanthan Gum-containing specimens (1, 2, and 3) compared to the reference sample were 43.75%, 13.89%, and 7.63% after 7 days of curing, and 79.49%, 76.04%, and 39.28% after 28 days of curing, respectively. For Guar Gum specimens (4, 5, and 6), the UCS increase percentages after 7 days of curing were 20.07% and 5.97%, while the UCS of specimen 6 decreased by 4.59% compared to the reference sample. After 28 days of curing, the UCS values of Guar Gum specimens increased by 50.29%, 47.74%, and 14.65%, respectively. When the 56-day and 90-day curing periods are examined, it can be observed that Guar Gum-containing mixtures exhibited a more significant long-term increase in UCS values compared to Xanthan Gum-containing mixtures. At the end of the 90-day curing period, the highest UCS improvement was recorded in Mixture 4, where UCS increased by approximately 604% compared to the reference sample. Additionally, it was noted that as the biopolymer content increased, the UCS improvement rate decreased for both biopolymers. Furthermore, as the curing duration increased, the rate of strength improvement in the mixtures also showed an increasing trend.

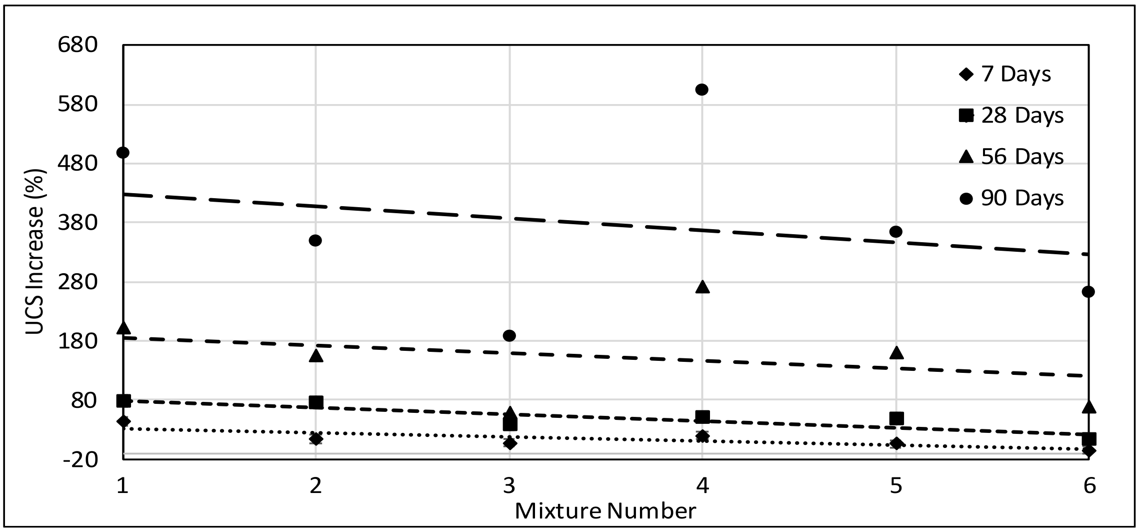

Figure 9. UCS value increase compared to the reference sample based on curing duration and mixture numbers (Karışım numaralarına göre serbest basınç dayanımı artış miktarları)

According to the UCS test results, all mixtures that achieved the highest UCS values contained 0.5% biopolymer. Additionally, the optimum biopolymer ratio remained at 0.5% for 7, 28, 56, and 90-day curing periods, suggesting that the presence of the cross-linking agent may have reduced the optimal biopolymer content. When the biopolymer ratio exceeded this threshold, excessive gel formation tendencies negatively affected soil strength, reducing UCS [26]. This trend was particularly evident in the 90-day UCS results, where an inverse relationship between biopolymer content and strength was observed across all curing periods. As the biopolymer content increased, the overall strength of the soil specimens declined, confirming that 0.5% is the optimal biopolymer dosage for this soil type.

Soil specimens treated with Xanthan Gum achieved their maximum strength at 7 and 28 days of curing, while those treated with Guar Gum reached their highest strength at 56 and 90 days. The literature indicates that Guar Gum's hydrogen bonding and gelation properties exhibit long-term effectiveness compared to Xanthan Gum, which explains why Xanthan Gum primarily enhances short-term strength, whereas Guar Gum contributes more significantly to long-term strength development [46,49,75,76]. In this regard, the findings of this study are consistent with the literature.

Figure 10 presents the Secant Modulus (E_{50}) values for each mixture. The data indicate that all biopolymer-treated mixtures exhibited an increase in E_{50} compared to the reference sample, with the highest value of 221 MPa recorded in M4 at 90 days of curing. Additionally, M1, which exhibited the highest UCS at 7 and 28 days, and M4, which showed the highest UCS at 56 and 90 days, demonstrated a significant increase in Secant Modulus compared to the reference sample. The silt soil used in this study exhibited a particularly low Secant Modulus, with the reference sample recording only 18.2 MPa. This indicates that the soil is highly susceptible to large deformations under applied loads, exhibiting low stiffness and load-bearing capacity, making it more flexible and highly sensitive to deformation [79–81]. While biopolymer modification resulted in substantial improvements in Secant Modulus, this confirms that biopolymers contribute to increasing the rigidity and load-bearing capacity of the soil [23,80,81]. Although a higher Secant Modulus does not always correspond to the highest UCS value [77], it was observed in this study that mixtures exceeding the optimal biopolymer ratio of 0.5% exhibited relatively inconsistent Secant Modulus values, further emphasizing the importance of maintaining an optimal biopolymer dosage (Figure 9). The maximum increase in Secant Modulus was approximately 1200%, and previous studies have also reported that biopolymer stabilization can lead to similar improvements in Secant Modulus [47,48,77,78].

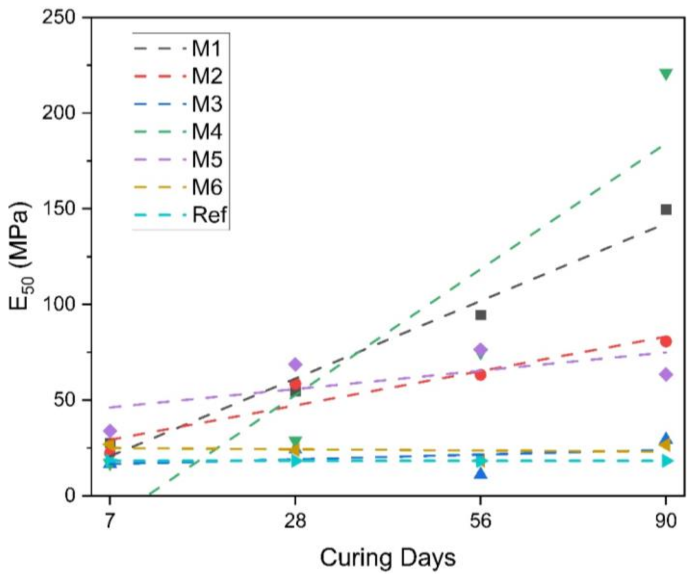

Figure 10. Secant Modulus (E_{50}) Values of the Mixtures Based on Curing Duration (Kür süresine bağlı Sekant Modülü (E_{50}) değerleri)

3.2. Direct Shear Test (DST) Results (Kesme Kutusu Deney Sonuçları)

The direct shear test results obtained in this study indicate that, under 50 kPa normal stress, the shear strength values for the reference sample and mixtures 1, 2, 3, 4, 5, and 6 were 44.02, 70.23, 66.77, 61.33, 88.03, 54.40, and 54.90 kPa, respectively. Under 100 kPa normal stress, these values increased to 68.25, 108.80, 91.49, 82.10, 96.93, 79.13, and 80.61 kPa, respectively. At 150 kPa normal stress, the shear strength values were measured as 93.97, 148.37, 122.16, 105.84, 112.76, 108.31, and 106.83 kPa, respectively. The experimental results are presented in Figure 11, while the corresponding graphical representations are provided in Figure 12.

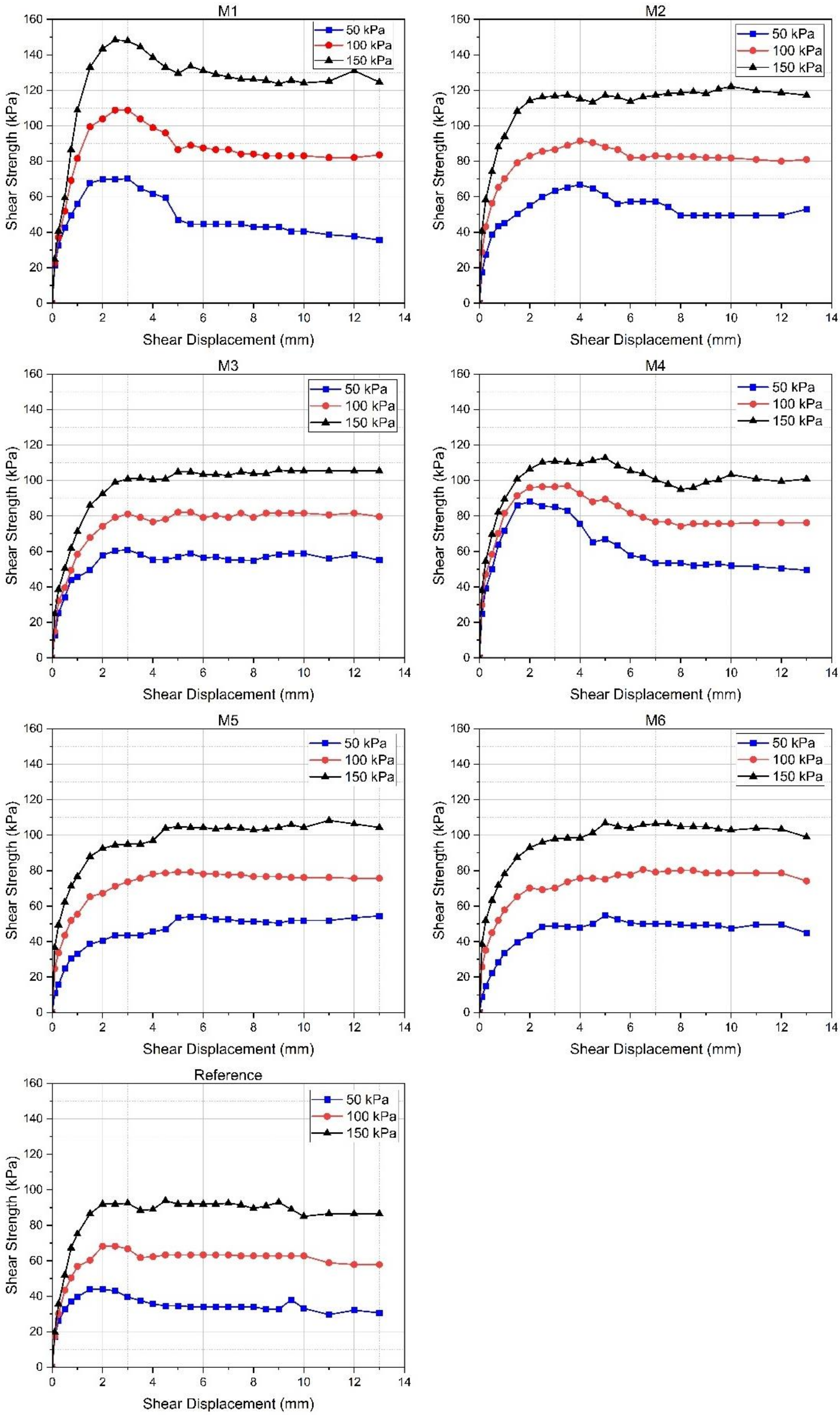

Figure 11. DST Test Results of the Mixtures (Karışımların kesme kutusu deney sonuçları)

Shear strength values were evaluated under 50, 100, and 150 kPa normal stresses. The highest shear strength under 50 kPa normal stress was measured as 88.03 kPa in Mixture 4. Under 100 kPa normal stress, the highest value was recorded in Mixture 1 at 108.80 kPa, whereas under 150 kPa normal stress, the maximum shear strength reached 148.37 kPa in Mixture 1. These results suggest that Xanthan Gum provides higher shear strength, particularly under higher normal stress conditions, whereas Guar Gum performs better at lower stress levels [24,83].

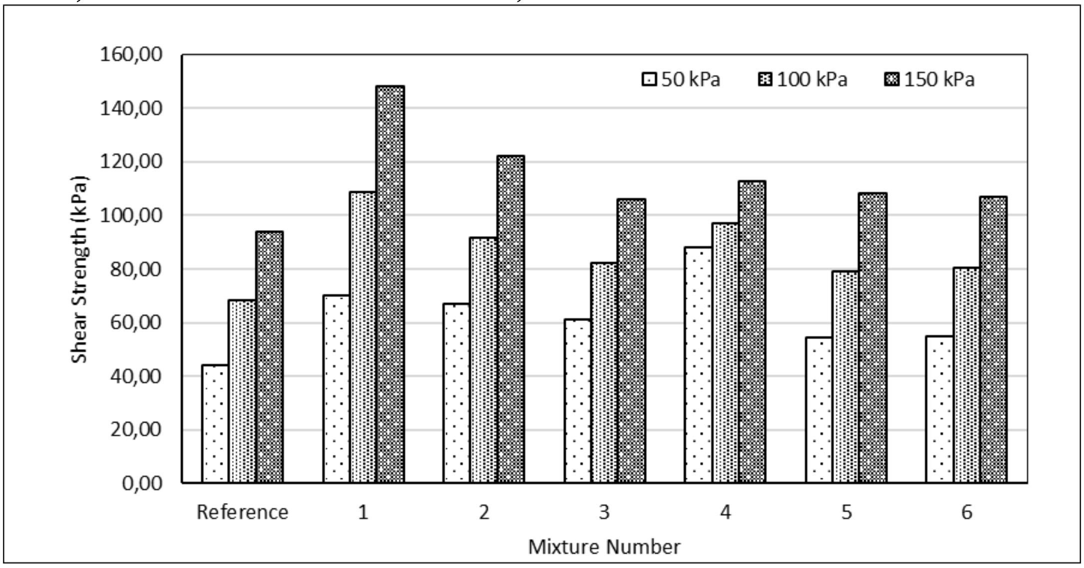

Figure 12. Variation of Shear Strength Based on Mixture Number (Karışım numarasına göre kayma mukavemeti değişimi)

Figure 13 and 14 illustrating the internal friction angle (ϕ) and cohesion values obtained from the direct shear test are presented in Figures 9 and 10. According to the results, the internal friction angle of the reference sample was 18.79°, while the internal friction angles of the other mixtures were measured as 26.5°, 38°, 29°, 12.5°, 13.9°, 28.3°, and 27.4°, respectively. Similarly, the cohesion value of the reference sample was 18.79 kPa, whereas the cohesion values for the other mixtures were 30.99 kPa, 38.01 kPa, 67.51 kPa, 74.51 kPa, 26.71 kPa, and 28.85 kPa, respectively. It is well known that the use of biopolymers in different proportions leads to varying integrated structures within the soil matrix, preventing a linear trend in their effects, and consequently, shear strength values do not always exhibit a consistent increase [46,48,84].

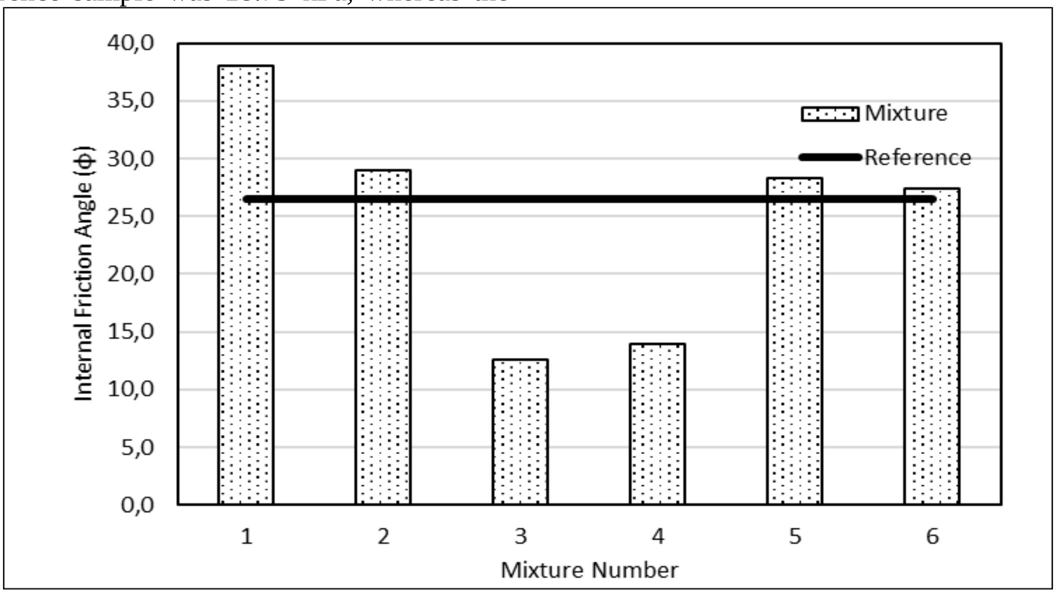

Figure 13. Variation of Internal Friction Angle Based on Mixture Numbers (Karışım numarasına göre içsel sürtünme açısı değişimi)

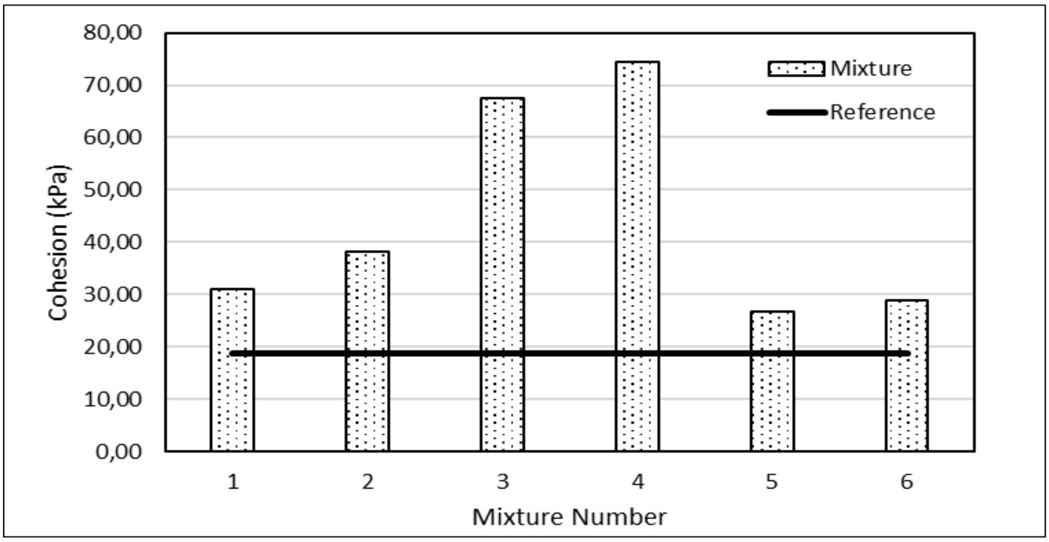

Figure 14. Variation of Cohesion Based on Mixture Numbers (Karışım numarasına göre kohezyon değişimi)

Regarding internal friction angle and cohesion, the reference sample exhibited an internal friction angle of 18.79° and a cohesion value of 18.79 kPa. The highest internal friction angle was observed in Mixture 1 at 38°, while the lowest value was recorded in Mixture 4 at 12.5°. Conversely, the highest cohesion value was obtained in Mixture 4 at 74.51 kPa, whereas the lowest was measured in Mixture 5 at 26.71 kPa. These findings indicate that Guar Gum improves cohesion by strengthening interparticle bonding, whereas Xanthan Gum enhances the internal friction angle, improving shear resistance. Similar to these results, previous studies have reported that the addition of Xanthan Gum and Guar Gum to the soil does not result in a linear increase or decrease in shear parameters; instead, variations in internal friction angle and cohesion values depend on the specific biopolymer mixture ratio [17,85].

Overall, mixtures containing 0.5% biopolymer provided optimal cohesion and shear strength stabilization. When the biopolymer content was increased to 1.5%, UCS values decreased by 7.63% to 39.28%, indicating that excessive biopolymer content led to over-gelation, which reduced soil strength [26,86]. These results highlight the importance of optimizing biopolymer dosage and emphasize the need for further investigation of its long-term effects on various soil types [87,88].

4. CONCLUSIONS (SONUÇLAR)

- This study evaluated the effects of Xanthan Gum and Guar Gum biopolymers on the strength parameters of silty soil in the presence of a constant $CaCl_2$ concentration (0.5%). The role of biopolymer additives in soil stabilization was analyzed by comparing unconfined compressive strength (UCS), shear strength, internal friction angle, and cohesion values.
- In terms of unconfined compressive strength (UCS), the highest values were obtained in Xanthan Gum mixtures at 7 and 28 days of curing (790.92 kPa and 987.57 kPa, respectively), while the highest values at 56 and 90 days were recorded in Guar Gum mixtures (2040.11 kPa and 3871.51 kPa, respectively). The biopolymer ratio in all mixtures with the highest strength is 0.5%. Additionally, biopolymer and CaCl2 increased the secant modulus (E50) values for all cure times and mixtures compared to the reference sample.
- For shear strength, the highest values under 50, 100, and 150 kPa normal stresses were measured as 88.03 kPa (Guar Gum), 108.80 kPa (Xanthan Gum), and 148.37 kPa (Xanthan Gum), respectively.
- When internal friction angle and cohesion values were compared, the highest internal friction angle was recorded as 38° (Xanthan Gum), while the lowest was 12.5° (Guar Gum). The highest cohesion value was 74.51 kPa (Guar Gum), while the lowest was 26.71 kPa (Guar Gum).
- When the biopolymer content was increased to 1.5%, UCS values decreased by 7.63% to 39.28%. Biopolymer additives can be considered an effective stabilization method for improving the strength of silty soils when applied at optimal ratios. While Xanthan Gum provides rapid, short-term stabilization, Guar Gum improves long-term strength.

5. FUTURE WORK AND RECOMMENDATIONS (GELECEK ÇALIŞMA VE ÖNERİLER)

Calcium Chloride was used at a fixed ratio of 0.5% in all mixtures (excluding the reference sample). Notably, the maximum strength was achieved when the amount of biopolymer matched the Calcium Chloride content at 0.5%. The behavior of these mixtures under varying Calcium Chloride ratios should be investigated. The effects of increasing Calcium Chloride and biopolymer contents on strength should also be examined. The influence of Calcium Chloride alone on the performance of biopolymers should be further studied. Therefore, future studies are recommended to investigate the effect of using Calcium Chloride at varying proportions or not using it at all on the strength properties.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Halil Oğuzhan KARA*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

***Mehmet Uğur YILMAZOĞLU*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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