

CUKUROVA UNIVERSITY  
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

---

**Improvement of Geotechnical Properties of Clayey Soil Using  
Biopolymer and Ferrochromium Slag Additives**

---

**Mustafa Yasin ÇETİN**

*Civil Engineering Department*

July 2024

**CUKUROVA UNIVERSITY**  
**INSTITUTE OF NATURAL AND APPLIED SCIENCES**

**MSc THESIS APPROVAL**

---

**Improvement of Geotechnical Properties of Clayey Soil Using  
Biopolymer and Ferrochromium Slag Additives**

---

**Mustafa Yasin ÇETİN**

*Civil Engineering Department*

This Master's Thesis was evaluated by the following Jury Members on .../.../..... and was approved by unanimity / majority of votes.

Jury : Doç. Dr. Baki BAĞRIAÇIK (Advisor) .....

: Prof. Dr. Abdulazim YILDIZ .....

: Doç. Dr. Bahadır OK .....

**This Thesis was written in the Department of Civil Engineering, Institute of Natural and Applied Sciences.**

**Thesis Number:**

**Prof. Dr. Sadık DİNÇER**  
**Director**  
**Institute of Natural and Applied Sciences**

**Note:** The usage of the presented specific declarations, tables, figures, and photographs either in this thesis or in any other reference without citation is subject to "The law of Arts and Intellectual Products" number of 5846 of Turkish Republic

## CONTENTS

ABSTRACT.....	I
ÖZ.....	II
GENİŞLETİLMİŞ ÖZET .....	III
LIST OF TABLES .....	VI
ACKNOWLEDGEMENTS .....	VII
LIST OF FIGURES .....	VIII
SYMBOLS AND ABBREVIATIONS .....	X
1. INTRODUCTION .....	1
2. PRELIMINARY WORK .....	3
2.1. Soil Improvement with Bio-Based Substances .....	3
2.2. Soil Improvement with Biopolymer Additives .....	4
2.3. Soil Improvement Additives and Freeze-Thaw Cycles .....	5
2.4. Soil Improvement with Ferrochromium Additives .....	6
2.5. Soil Improvement with Mixing Methods .....	7
3. MATERIAL AND METHOD .....	9
3.1. Materials .....	9
3.1.1. Natural Clay Soil.....	9
3.1.2. Ferrochromium Slag .....	9
3.1.3. Agar Gum.....	10
3.2. Methods.....	10
3.2.1. Soil Classification .....	11
3.2.2. Atterberg Limits.....	11
3.2.3. Compaction Test (Standard Proctor).....	11
3.2.4. Unconfined Compressive Strength Test.....	12
3.2.5. Direct Shear Test.....	12
3.2.6. Mixing Method .....	13
3.2.7. Freeze-Thaw Cycles.....	13
4. RESULTS AND DISCUSSIONS .....	15
4.1. Atterberg Limits.....	15
4.2. Soil Classification .....	16
4.3. Compaction Test (Standard Proctor).....	18
4.4. Unconfined Compressive Strength Test .....	19
4.4.1. Natural Clay Soil.....	19
4.4.2. Biopolymer Additive.....	20
4.4.3. Ferrochromium Slag Additive.....	21

4.4.4. Biopolymer and Ferrochromium Mixture Additive .....	22
4.4.5. Freeze-Thaw Performance .....	23
4.5. Direct Shear Test.....	25
4.5.1. Natural Clay Soil.....	26
4.5.2. Biopolymer Additive.....	27
4.5.3. Ferrochromium Slag Additive.....	31
4.5.4. Biopolymer and Ferrochromium Mixture Additive .....	33
4.5.5. Freeze-Thaw Performance .....	36
4.6. Microscopic Analysis.....	43
5. CONCLUSIONS.....	45
REFERENCES .....	49
CURRICULUM VITAE.....	59



---

**Improvement of Geotechnical Properties of Clayey Soil Using  
Biopolymer and Ferrochromium Slag Additives**

---

Mustafa Yasin ÇETİN

*Advisor: Doç. Dr. Baki BAĞRIAÇIK*

*Department of Civil Engineering*

**ABSTRACT**

In this study, geotechnical properties of a clay soil and its mixtures with different proportions of biopolymer (Agar Gum, AG) (0.75%, 0.85%, 1%, and 1.15%) and ferrochromium slag (FS) (0.25%, 0.50%, 0.75%, and 1%) having various curing periods (1, 7, 14, 21, and 28 days) were studied through a series of soil mechanical tests to investigate possibilities to improve its inadequate plasticity, strength, compaction and consolidation characteristics. The clayey soil, named as Handere clay, is present throughout the northern parts of Adana city where extensive settlement projects are now underway especially after the two devastating earthquakes on February 6th, 2023. Laboratory testing such as Atterberg Limits, Compaction, Unconfined Compression strength, and Direct Shear test were performed. The results revealed that both AG and FS improved the geotechnical engineering properties of the clay soil, considerably.

**Keywords:** Clayey soil, Soil Improvement, Biopolymers, Ferrochromium Slag, Engineering Properties,

---

**Killi Zeminlerin Geoteknik Özelliklerinin Biyopolimer ve  
Ferrokrom Katkısı Kullanılarak İyileştirilmesi**

---

Mustafa Yasin ÇETİN

*Danışman: Doç. Dr. Baki BAĞRIAÇIK*

*İnşaat Mühendisliği Anabilim Dalı*

**ÖZ**

Bu çalışmada, farklı oranlarda biyopolimer (Agar Gum, AG) (%0.75, %0.85, %1 ve %1.15) ve ferrokrom cürufu (FS) (%0.25, %0.50, %0.75 ve %1) ile karıştırılmış bir kil zeminin çeşitli kür sürelerine (1, 7, 14, 21 ve 28 gün) sahip geoteknik özellikleri, yetersiz plastisite, mukavemet, sıkışma ve konsolidasyon özelliklerini iyileştirme olasılıklarını araştırmak için bir dizi zemin mekaniği testi ile incelenmiştir. Handere kili olarak sınıflandırılan kil zemin, özellikle 6 Şubat 2023'te meydana gelen iki yıkıcı depremden sonra Adana şehrinin kuzey kısımlarında geniş yerleşim projelerinin devam ettiği bölgelerde bulunmaktadır. Atterberg Limitleri, Kompaksiyon, Serbest Basınç Dayanımı ve Direkt Kesme Deneyi gibi laboratuvar testleri yapılmıştır. Sonuçlar, hem AG hem de FS'nin kil zeminin geoteknik mühendislik özelliklerini önemli ölçüde iyileştirdiğini ortaya koymuştur.

**Anahtar Kelimeler:** Killi Zemin, Zemin İyileştirme, Biyopolimer, Ferrokrom Cürufu, Mühendislik Özellikleri,

## GENİŞLETİLMİŞ ÖZET

Mühendislik açısından zemin, anakaya üzerinde bulunan, gevşek, tutturulmamış, kayaların ufalanıp parçalanmasıyla meydana gelen değişik boyuttaki mineral, organik materyal ve sediman topluluğudur. Zeminler yeryuvarını oluşturan kayaların, fiziksel ve kimyasal ayrışmalar sonucunda ufalanıp parçalanması ve bu parçaların taşınım veya çökmesi sonucunda oluşurlar (Holtz et al., 1981). Zemini oluşturan taneler arasındaki boşluklar ya da gözenekler sıvı (genellikle su) ve/veya hava içerir. Zeminler jeolojik süreç boyunca, kayaç döngüsünün bir parçası olarak, kayaç tiplerinin (magmatik kayaçlar, tortul kayaçlar, başkalaşım kayaçları) kimyasal, fiziksel ve biyolojik aşınması, birikmesi ve yer değiştirmesi ile meydana gelmiştir.

Zemin karmaşık yapılara sahiptir. Bu durum zeminlerin bazı fiziksel yönlerini ön plana çıkarmaktadır. Bunların başında taşıma gücü ve oturma miktarı gelmektedir. Ayrıca zeminlerin şişme potansiyeli, geçirimsizliği, don direnci, sıvılaşma potansiyeli, deprem yükleri altındaki davranışı zeminlerin diğer önemli kriterleridir. Zemin ile etkileşimi kaçınılmaz olan, toprak üzerine veya içine inşa edilen yapıların projelendirilmesinde ve uygulamasında, zeminin fiziksel özellikleri başta olmak üzere her türlü özelliğin ve tüm yönlerin dikkate alınması vazgeçilmez bir koşuldur.

Bu zemin özelliklerinden önemli bir yere sahip olan kesme ya da kayma direnci, zemin davranışını belirlemede kritik bir role sahiptir. Zeminin bu yöndeki yeterliliği, inşaata uygun bölgelerin gittikçe azaldığı günümüzde, normal şartlar altında yapı inşasının güç olduğu bölgelerin durumunu anlamamız için iyi bilinmesi gereken bir unsurdur. Kaymaya karşı mukavemeti artırılan bir zemin deprem, sel, rüzgâr gibi doğal unsurlara ve altyapı çalışmaları gibi beşerî unsurlara karşı önemli bir direnç elde etmiş olur. Bu bakımdan zeminlerin kayma direncinin iyileştirilmesi inşaat endüstrisi için ilgileneilmesi ve araştırılması gereken bir alandır.

Zeminlerin genel mukavemet özelliklerini iyileştirmek için literatürde kapsamlı çalışmalar bulunmaktadır. Birçok fiziksel, kimyasal ve biyolojik yöntem ve bunların ortak kullanımı gibi çözüm metotları incelenmiş ve ilgi çekici gelişmeler kayda geçmiştir. Bilimin doğası gereği kümülatif ilerleme sağlandığından her çalışma kendinden önceki çalışmalarla dayanak bulmaktadır. Bu durumun bir sonucu olarak bir önceki önerilen metodun eksikleri sonraki çalışmalar ile giderilmeye çalışılmaktadır.

Bu çalışmanın başlangıç noktasını oluşturan zemin iyileştirme metodu ferrokrom katkısıdır. Ferrokrom, krom ve demirin birleşmesiyle oluşan bir alaşımdır. Krom, metalürji, kimya ve refrakter sanayinin temel elementlerinden biridir. Krom metalinin ekonomik olarak üretilebildiği tek mineral ise kromittir. Krom, ayrıca bitkiler ve canlılar için de önemli bir eser elementtir. Ancak, konsantrasyonu belirli bir seviyenin üzerine çıktığında zararlı olabilir. (Kartal et al., 2003) Kromun bitkiler ve canlılar üzerindeki etkisi, kimyasal formuna ve canlının büyüklüğüne göre değişir. Kromun aşırı alımı veya maruziyeti, karaciğer, böbrek, sinir sistemi ve kan hücreleri üzerinde olumsuz etkilere neden olabilir.

Ferrokrom ile daha önce yapılan çalışmalarda özellikle ulaşım amaçlı tasarlanan yapılarda kullanılan malzemelerin iyileştirilmesi amaçlanmıştır. Bu çalışmaların sonucunda ise malzeme özelliklerinde kayda değer iyileştirmeler gözlenmiştir. Ancak yol üst yapısında kullanılması büyük ölçüde bir sorun teşkil etmezken doğal haldeki zemine karıştırılarak zemin özelliklerinin iyileştirilmeye çalışılması daha önce bahsedildiği gibi ciddi bir problem olasılığı doğurmaktadır. Bunun sebebi ise ferrokromun normal hali ile ekosisteme zarar verebilecek potansiyele sahip olmasıdır. Ağır metal bileşenleri, doğal sistemleri sekteye uğratma özelliğine sahiptir. Bu çalışmanın ilgilendiği sorun ise bu durumun önlenmesi ve ferrokromun olumsuz etkilerinin zemin iyileştirme için kullanımında en aza indirilmesidir.

Bu durumun çözümü için ise zemin iyileştirme uygulamaları için birçok farklı şekilde araştırılmış olan biyopolimer katkısı bu çalışmanın önerdiği çözümdür. Biyopolimerler, doğal veya sentetik olarak üretilen, tekrarlayan birimlerden oluşan uzun zincirli moleküllerdir. Biyopolimerlerin zemin iyileştirmede kullanılması, zeminin mühendislik özelliklerini iyileştirmek ve çevreye zarar vermemek için bir alternatif yöntemdir. Biyopolimerlerin zemin iyileştirmede kullanılması, zeminin yoğunluğunu, kesme mukavemetini, geçirgenliğini ve drenaj kapasitesini artırabilir. Ayrıca, biyopolimerlerin zemin iyileştirmede kullanılması, zeminin sıvılaşma riskini azaltabilir.

Biyopolimerin viskoz yapısı ferrokrom katkısının çevresinde yalıtıcı bir katman oluşturarak doğaya zararlı olabilecek etkilerinin ortaya çıkmasını engellemektedir. Ayrıca zemin iskeletinde de kesme mukavemetini iyileştirici bir etki oluşturmaktadır. Biyopolimer ile zemin iyileştirme yöntemleri de literatürde geniş bir alana sahiptir. Birçok farklı zemin türüne ve koşuluna adapte edilebilmesinin yanı sıra malzeme yapısı gereği ekosisteme önemli bir negatif etki oluşturmamaktadır.

Bu çalışmanın amacı, ferrokrom katkılı zeminlerin kesme mukavemetini iyileştirmek için biyopolimer kullanımının etkinliğini araştırmaktır. Bu amaçla, farklı ferrokrom ve biyopolimer oranlarına sahip zemin numuneleri hazırlanmış ve doğrudan kesme deneyine tabi tutulmuştur. Deney sonuçlarına göre, biyopolimer ve ferrokrom katkılı zeminlerin kesme mukavemeti parametreleri (içsel sürtünme açısı ve kohezyon) doğal kil zemine göre artmıştır. Ayrıca, biyopolimer ve ferrokrom oranlarının artması ile kesme mukavemetinin de arttığı gözlenmiştir. Bu sonuçlar, biyopolimer ve ferrokrom katkısının zeminlerin kesme mukavemetini iyileştirmede etkili bir yöntem olduğunu göstermektedir. Bu sonuçlar, özellikle taşıma gücü, oturma miktarı, şişme potansiyeli, geçirimsizlik, don direnci, sıvılaşma potansiyeli ve deprem yükleri altındaki davranışı gibi kriterler açısından zeminlerin iyileştirilmesi gereken durumlarda kullanılabilir. Bu çalışmanın sonuçları, ayrıca biyopolimer ve ferrokrom katkısının çevreye zararlı olmayan ve ekonomik bir yöntem olduğunu da göstermektedir. Bu nedenle, bu çalışmanın sonuçları, zemin mühendisliği, inşaat mühendisliği, yol mühendisliği, altyapı mühendisliği gibi alanlarda faydalı olabilir.

Deney sonuçları, biyopolimerin ferrokrom katkıli zeminlerin kesme mukavemetini artirdigini ve ferrokromun çevresel etkilerini azalttigini göstermiştir. Bu çalıřma, biyopolimerin zemin iyileřtirme uygulamalarında potansiyel bir malzeme olduğunu ortaya koymuřtur.

Çalıřma kapsamında yapılan deneyler Çukurova üniversitesi, Mühendislik fakültesi, İnřaat mühendislięi Bölümü Geoteknik laboratuvarında ASTM standartlarına uygun olarak yürütölmüřtür.



## LIST OF TABLES

Table 4.1 LL, PL and PI values for different AG mixture ratios. ....	15
Table 4.2 LL, PL and PI values for different FC mixture ratios. ....	16
Table 4.3 Specific gravity test results .....	16
Table 4.4 Soil classification results summary for the natural clayey soil. ....	18
Table 4.5 Proctor Test results for the natural clayey soil.....	18
Table 4.6 OWC and Dry Unit Weight values for different AG mixture ratios. ....	18
Table 4.7 OWC and Dry Unit Weight values for different FC mixture ratios. ....	18
Table 4.8 Direct shear test results of the natural clay soil.....	26
Table 4.9 Shear test results of sample mixed with optimum 1% Agar Gum biopolymer additive at various curing days. ....	28
Table 4.10 Shear test results of samples mixed with optimum various Agar Gum biopolymer additive.....	29
Table 4.11 Shear test results of sample mixed with optimum 1% Ferrochromium slag additive... 32	
Table 4.12 Shear test results of sample mixed with both optimum 1% Agar Gum biopolymer and Ferrochromium slag additive at various curing days. ....	34
Table 4.13 Shear test results of samples mixed with Agar Gum biopolymer additive at various mixing ratios. ....	36
Table 4.14 Shear test results of sample mixed with optimum 1% Agar Gum biopolymer additive at various freeze-thaw cycles. ....	37
Table 4.15 Shear test results of sample mixed with optimum 1% Ferrochromium slag additive at various freeze-thaw cycles. ....	39
Table 4.16 Shear test results of sample mixed with both optimum 1% Agar Gum biopolymer and Ferrochromium slag additive at various freeze-thaw cycles. ....	41

## ACKNOWLEDGEMENTS

I express my heartfelt gratitude to Assistant Professor Dr. Baki BAĞRIAÇIK for his unwavering commitment to this research and his invaluable guidance. I extend my warm greetings and sincere thanks to the members of the thesis committee: Associate Professor Dr. Baki BAĞRIAÇIK, Professor Dr. Abdulazim YILDIZ, and Associate Professor Dr. Bahadır OK. Additionally, I am deeply appreciative of the Department of Civil Engineering and the entire teaching staff for their support. Lastly, I offer special thanks to my wonderful family—my father, mother, and sister—for their boundless encouragement throughout this thesis and my educational journey.



## LIST OF FIGURES

Figure 3.1. Location of the sampling area. The image is taken from Google Earth. ....	9
Figure 4.1. Liquid Limit chart for the natural clayey soil. ....	15
Figure 4.2. Gradation curves for the clay soil. ....	17
Figure 4.3. Plasticity Chart marked with Atterberg test results for the natural clayey soil.....	17
Figure 4.4. UCS stress-strain curve of the natural clay soil.....	19
Figure 4.5. UCS stress-strain curves of the natural clay soil mixed with various percentages of AG at 21 days of curing.....	21
Figure 4.6. UCS stress-strain curves of natural clay soil mixed with optimum 1% of Agar Gum biopolymer at various curing times. ....	21
Figure 4.7. UCS stress-strain curves of the natural clay soil mixed with various percentages of Ferrochromium slag additive. ....	22
Figure 4.8. UCS stress-strain curves of the natural clay soil mixed with optimum 1% of Agar Gum biopolymer and 1% Ferrochromium slag additive at various curing times. ....	23
Figure 4.9. UCS stress-strain curves of the natural clay soil mixed with optimum 1% of Agar Gum biopolymer at various freeze-thaw cycles.....	24
Figure 4.10. UCS stress-strain curves of the natural clay soil mixed with optimum 1% Ferrochromium slag additive at various freeze-thaw cycles.....	25
Figure 4.11. UCS stress-strain curves of the natural clay soil mixed with both optimum 1% Ferrochromium slag additive and 1% Agar Gum biopolymer at various freeze-thaw cycles .....	25
Figure 4.12. Failure envelope of the natural clay soil.....	27
Figure 4.13. Failure envelope of the soil mixed with optimum 1% Agar Gum biopolymer additive. ....	28
Figure 4.14 The relationship between Internal Friction Angles ( $\phi$ ) and curing time. ....	29
Figure 4.15. The relationship between Cohesion (c) and curing time. ....	29
Figure 4.16. Failure envelope of the samples mixed with Agar Gum biopolymer at various ratios. .....	30
Figure 4.17. Comparison between Internal Friction Angle ( $\phi$ ) values by various AG mixing ratios. ....	30
Figure 4.18. Comparison between Cohesion (c) values by various AG mixing ratios. ....	31
Figure 4.19. Failure envelope of the soil mixed with optimum 1% Ferrochromium slag additive. .....	32
Figure 4.20. Failure envelope of the samples mixed with Ferrochromium Slag additive at various ratios. ....	32

Figure 4.21. Comparison between Internal Friction Angle ( $\phi$ ) values by various FC mixing ratios. ....	33
Figure 4.22. Comparison between Cohesion (c) values by various FC mixing ratios. ....	33
Figure 4.23. Failure envelope of the soil mixed with both optimum 1% Agar Gum biopolymer and 1% Ferrochromium slag additive. ....	35
Figure 4.24. Comparison between Internal Friction Angle ( $\phi$ ) values by curing days. ....	35
Figure 4.25. Comparison between Cohesion (c) values by curing days. ....	36
Figure 4.26. Failure envelopes of sample mixed with optimum 1% Agar Gum biopolymer additive at various freeze-thaw cycles. ....	38
Figure 4.27. Comparison between Internal Friction Angles ( $\phi$ ) by freeze-thaw cycles. ....	38
Figure 4.28. Comparison between Cohesion (c) values by freeze-thaw cycles. ....	39
Figure 4.29. Failure envelopes of sample mixed with optimum 1% Ferrochromium slag additive at various freeze-thaw cycles. ....	40
Figure 4.30. Comparison between Internal Friction Angles ( $\phi$ ) by freeze-thaw cycles. ....	40
Figure 4.31. Comparison between Cohesion (c) values by freeze-thaw cycles. ....	41
Figure 4.32. Failure envelopes of sample mixed with both optimum 1% Agar Gum biopolymer and Ferrochromium slag additive at various freeze-thaw cycles. ....	42
Figure 4.33. Comparison between Internal Friction Angles ( $\phi$ ) by freeze-thaw cycles. ....	42
Figure 4.34. Comparison between Cohesion (c) values by freeze-thaw cycles. ....	43
Figure 4.35. The microscopic views of (a) FS grain surrounded by silt grains and clay domains not treated with AG, (b) a close-up view of the exact FS grain, (c) a general view of the sample with both FS and AG admixtures together, (d) a close-up view of FS and AG admixtures together, (e) FS grain partially coated with AG, and (f) a clay domain coated with AG. Notice the uncoated (a,b), coated (d), and partially coated (e) nature of the FS grains surrounded by other constituents. FS: Ferrochromium Slag, S: silt, C: clay domain. Photo lengths: (a) 1.5 mm, (b,f) 1 mm, (c,e) 5 mm, and (d) 3 mm. ....	44

## **SYMBOLS AND ABBREVIATIONS**

ASTM:	American Society for Testing Materials
LL:	Liquid Limits
PL:	Plasticity limit
PI:	Plasticity index
O.W.C:	Optimum Water Content
PD:	Density of dry soil
UCS:	Unconfined Compression Strength
N.S:	Natural Soil
ND:	Maximum natural density
DD:	Maximum dry density
CS:	Clayey soil
AG:	Agar Gum
FC, FS:	Ferrochromium Slag
BR:	Biopolymer Ratio
FR:	Ferrochromium Slag Ratio

## 1. INTRODUCTION

Soil, in an engineering sense, is the relatively loose agglomerate of mineral and organic materials and sediments found above the bedrock. Soils form by first physical and chemical weathering of the rocks forming the Earth's crust, and then deposition of these distinct size grains as weathering products in-situ or transported (Holtz et al., 1981). Structures of all types (buildings, bridges, highways, retaining walls, etc.) rest directly on, in, or against soil; therefore, proper analysis of soil and design of foundations are necessary to ensure that these structures remain safe and free of undue settling, tilting and collapse (Liu & Evett, 1992). Soil has a porous structure and contains water that is partially or fully integrated with the soil particles. These two elements form a soil profile together with the soil particles. Soil has complex structures that bring some physical aspects of soil to the foreground. Among these aspects are bearing capacity and settlement amount. In addition, swelling potential, permeability, frost resistance, liquefaction potential, and behavior under earthquake loads are other important criteria for soils. In the design and implementation of structures that are built on or into the soil, which interact with the soil inevitably, it is essential to consider all kinds of properties and aspects of the soil, especially its physical properties. One of the important properties of soil that affects its behavior is shear resistance. The adequacy of soil in this aspect is important for understanding the situation of regions where construction is difficult under normal conditions, as the suitable areas for construction decrease day by day. A soil with increased shear resistance obtains significant resistance against natural elements such as earthquakes, floods, wind, and human elements such as infrastructure works. Therefore, improving the shear resistance of soils is an area that needs to be interested in and researched for the construction industry.

There are comprehensive studies in the literature to improve the general strength properties of soils. Various solution methods such as physical, chemical, and biological methods and their combined use have been examined and interesting developments have been recorded. As a result of the nature of science, cumulative progress has been achieved, so each study finds its basis in previous studies. As a result of this situation, an attempt has been made to eliminate the shortcomings of the previously proposed method with subsequent studies. The starting point of this study is the soil improvement method with FeCr addition. FeCr is an alloy formed by combining chromium and iron. Chromium is one of the basic elements of metallurgy, chemistry, and refractory industry. The only mineral that chromium metal can be economically produced is chromite. Chromium is also an important trace element for plants and living beings. However, it can be harmful when its concentration exceeds a certain level. The effect of chromium on plants and living beings varies depending on its chemical form and the size of the organism. Excessive intake or exposure to chromium can cause adverse effects on the liver, kidney, nervous system, and blood cells.

In earlier studies with FeCr additives, it was aimed at improving the materials used for transportation purposes. As a result of these studies, significant improvements were seen in material

properties. However, while it does not pose a major problem when used in road superstructure, mixing it with natural soil in order to improve soil properties creates a serious possibility of problems as mentioned before. The reason for this is that the FeCr has the potential to harm the environment and human health by releasing toxic chromium compounds into the soil and groundwater, especially under acidic conditions. Therefore, it is important to investigate the effects of FeCr addition on the soil properties and the potential environmental risks.

Though there are extensive studies on clay soil improvement using Agar Gum biopolymer (AG), there are limited studies on Ferrochromium Slag (FS) used for clayey soil improvement, and there are no studies utilizing both of them together; even though they have both separately demonstrated significant enhancements in geotechnical and environmental properties. Also, there is no comprehensive study on mitigating the negative effects of chemical soil additives without sacrificing much of their effectiveness on soil improvement by using these ingredients in tandem with organic bio-friendly admixtures (Çetin et al., 2024).

In this study, plasticity, shear strength, compaction and consolidation characteristics of a clay soil were investigated by adding different percentages of FeCr alongside with biopolymer. The soil samples were subjected to various tests such as compaction, Atterberg limits, unconfined compression, and direct shear. Samples with different combinations of the FeCr and biopolymer additives were also subjected to four different freeze-thaw cycles. The results were compared with each other and those of the untreated soil to find the optimum combination of biopolymer and FeCr content.

The main aim of this study was to evaluate the feasibility and efficiency of using FeCr in tandem with AG biopolymer as a soil stabilizer for clay soils. The specific goals were:

- Determine the optimum FeCr and biopolymer mixture content for maximum shear resistance.
- Evaluate the impact of FeCr addition on soil properties.
- Mitigate environmental risks associated with FeCr.
- Identify optimal use cases for these mixtures.
- Observe behavior under freeze-thaw conditions.
- Compare performance with standalone Ferrochromium and biopolymers.

## **2. PRELIMINARY WORK**

### **2.1. Soil Improvement with Bio-Based Substances**

Kushwaha et al. (2018), aimed to investigate the effects of using Eko Soil (ES) enzyme as a stabilizer for a soil with poor geotechnical properties, and to evaluate its suitability for highway embankment construction. The ES enzyme was an effective stabilizer that improved the geotechnical properties of the expansive soil, such as the Atterberg's limits, the plasticity index (PI), the unconfined compressive strength (UCS) and the California bearing ratio (CBR). The paper conducted laboratory tests on the expansive soil treated with different dosages of ES enzyme, from 1% to 6% by volume of water. The PI test results showed that the optimum dosage of ES enzyme was 4%. The paper then performed compaction tests on the expansive soil with different ES enzyme dosages and determined their optimum moisture content (OMC) and maximum dry density (MDD). Using the OMC values, the paper prepared UCS and CBR samples and cured them for 7, 28, 45 and 90 days. The paper found that the geotechnical properties of the expansive soil stabilized with 4% ES enzyme were significantly enhanced after 28 days of curing. The CBR and UCS values increased by 347% and 334%, respectively, compared to the untreated soil.

P. Agarwal, (2014) investigates the effect of a bio-enzyme called Terrazyme on the unconfined compressive strength of black cotton soil, which is a type of expansive soil with poor engineering properties. The paper describes the materials, procedures, and results of the laboratory tests conducted on the soil samples treated with different dosages of Terrazyme for different curing periods. The paper presents the data in tables and graphs and analyzes the trends and variations. Study concludes that the optimum dosage of Terrazyme for improving the unconfined compressive strength of black cotton soil is 1ml per 5kg of soil, and that the stabilization with Terrazyme results in significant increase in strength, reduction in permeability, and enhancement of weather resistance and load bearing capacity of the soil.

Almajed et al., (2021) elucidates innovative approaches aimed at fortifying and purifying soil through the utilization of minute living entities known as microbes and enzymes. Microbes and enzymes, akin to adept assistants, possess remarkable capabilities. Certain varieties can even catalyze the formation of a distinctive rock known as calcite, characterized by its lustrous and white appearance. The ensuing adhesion of calcite to soil results in heightened solidity and reduced permeability. The study delineates two methodologies for leveraging microbes and enzymes in the production of calcite within the soil. The first method, denoted as MICP (Microbial-Induced Calcite Precipitation), involves microbes generating the urease enzyme. Urease, in turn, catalyzes the conversion of urea into ammonia and carbon dioxide. The subsequent interaction of these gases with water and calcium culminates in the formation of calcite. The second method, termed EICP (Enzyme-Induced Calcite Precipitation), circumvents the use of microbes, relying directly on the urease enzyme to instigate calcite production. Both methodologies exhibit the capacity to enhance soil

strength, rigidity, and resilience to water and seismic activity. Furthermore, the investigation expounds upon the merits and demerits of these methodologies, considering their applicability to diverse soil types and scenarios. Factors such as the requisite quantity of calcite for optimal fortification, the natural presence of microbes or enzymes in different soils, and the potential contamination with hazardous substances, including heavy metals, are discussed. Notably, these methodologies present a means to mitigate or ameliorate such contaminants. The study also scrutinizes the challenges and limitations inherent in these techniques, offering insights into potential enhancements and synergistic combinations with other methods to bolster their efficacy and sustainability.

Arabani & Shalchian (2023), presents a comprehensive review of the use of bio-based substances for soil stabilization, which is a technique of enhancing the soil performance by using biological additives. The paper evaluates the biochemical effects of diverse types of bio-stabilizers, such as microorganisms, enzymes, and polymers, on various soils. The paper also describes the biochemical processes of bio-stabilization and the factors that affect its efficiency. The paper gives guidelines for choosing the optimal type and dosage of bio-stabilizers depending on the soil type. The paper shows that some bio-stabilizers can greatly increase the strength and decrease the permeability, compressibility, and shrinkage of soil by forming bonds between soil particles. The paper also highlights the role of temperature, curing time, and soil pH in bio-stabilization.

## **2.2. Soil Improvement with Biopolymer Additives**

There are numerous studies that investigate the effects of the biopolymers on soils with poor engineering properties. Below, there are some studies that capture the main ideas that made their way into this study.

Fatehi et al. (2018), investigated the effects of adding biopolymers from milk, namely sodium caseinate and casein, on the stabilization of dune sand. They employed an unconfined compression test to measure the compressive strength of the sand-biopolymer mixtures with different proportions and curing times. They found that the strength increased with the increase of biopolymer content and curing time, indicating that the biopolymers improved the cohesion and bonding of the sand particles. They also examined the influence of temperature on the strength and found that the optimal temperature range was up to 60°C, beyond which the strength decreased due to the degradation of the biopolymers. To further evaluate the properties of the stabilized sand, they performed other tests, such as direct shear test to measure the shear strength, leaching test to measure the environmental impact, and California bearing ratio (CBR) test to measure the bearing capacity. They also used Scanning Electron Microscopy (SEM) to observe the microstructure of the sand-biopolymer mixtures and to understand the mechanism of stabilization. They concluded that biopolymers from milk are effective and eco-friendly additives for soil stabilization and can be used as alternatives to conventional materials such as cement and chemical polymers.

Dehghan et al. (2019), explored various methods and materials for improving and stabilizing soil. They conducted several tests, such as consolidation, compaction, unconsolidated undrained triaxial and permeability tests, on collapsible soils that were stabilized with two types of biopolymers (XG and GG). They used different ratios of biopolymers and different curing times to examine their physical and mechanical effects on the soil. They also used scanning electron microscopy (SEM) to see the changes in the soil morphology due to biopolymers. The test results showed that the permeability and the maximum dry density of the soil decreased with the biopolymers, and that the stress-strain curve was influenced by the curing time and the amount of biopolymer. The SEM results revealed the interaction between the biopolymers and the fine-grained soil particles. The authors concluded that XG and GG stabilization could enhance the mechanical properties of fine-grained collapsible soil and supply an eco-friendly and economical alternative to conventional soil additives.

### **2.3. Soil Improvement Additives and Freeze-Thaw Cycles**

Ok & and Bagriacik (2022), inducted an experimental study to explore the feasibility of using Guar Gum (GG), a biopolymer, as an additive for stabilizing cohesive soil. They mixed the soil with different amounts of GG (1%, 2%, and 3% by weight) and prepared cylindrical specimens. They then subjected the specimens to different curing times and different numbers of freeze-thaw cycles (1, 3, 5, and 10) to simulate the environmental conditions in cold regions. They performed unconfined compression strength (UCS) and swelling pressure tests on the specimens to evaluate the effects of GG on the mechanical properties of the soil. They found that GG increased strength and decreased the swelling pressure of the soil, showing that GG improved the cohesion and bonding of the soil particles and reduced their susceptibility to frost damage. They also found that the effects of GG were influenced by the proportion of biopolymer, the curing time, and the number of freeze-thaw cycles. They come to the conclusion that GG could be a useful additive for improving cohesive soil in cold regions.

Bağrıaçık et al. (2021), held an experimental study to explore the feasibility of using *Bacillus Sp.*, a bacterium that produces calcium carbonate in the soil, as an additive for stabilizing clay soils. They mixed two types of clay soils, high plasticity clay (CH) and sandy clay (SC), with *Bacillus Sp.* and prepared cylindrical specimens. They then subjected the specimens to different numbers of freeze-thaw cycles (1, 3, 5, and 10) to simulate the environmental conditions in cold regions. They performed unconfined compression strength (UCS) and swelling pressure tests on the specimens to evaluate the effects of *Bacillus Sp.* on the mechanical properties of the soils. They found that *Bacillus Sp.* increased strength and decreased the swelling pressure of both types of soils, indicating that *Bacillus Sp.* improved the cohesion and bonding of the soil particles and reduced their susceptibility to frost damage. They also found that the effects of *Bacillus Sp.* were influenced by the type of soil,

the proportion of bacterium, and the number of freeze-thaw cycles. Their results indicated that *Bacillus Sp.* could be a useful additive for improving clay soils in cold regions.

Mahmutoğlu & Bağrıaçık (2020), conducted a study to explore the feasibility of using glass waste sludge (GWS), a by-product of glass production, and cement (CMT) as additives for stabilizing clay soil under freeze-thaw cycles. They mixed the soil with different proportions of GWS and CMT and prepared cylindrical specimens. They then exposed the specimens to different numbers of freeze-thaw cycles (1, 3, 5, and 10) to simulate the environmental conditions in cold regions. They performed unconfined compression strength (UCS) and consolidation tests on the specimens to evaluate the effects of GWS and CMT on the mechanical properties of the soil. They found that GWS improved the stability, strength, and consolidation behavior of the clay soil under freeze-thaw cycles. They also found that CMT enhanced these improvements further by increasing the cementation and bonding of the soil particles. This study found that GWS and CMT could be useful additives for improving clay soil in cold regions.

#### **2.4. Soil Improvement with Ferrochromium Additives**

Patla et al. (2021), conducted an experimental study to investigate how ferrochrome slag, a waste material from the steel industry, can enhance the performance of silty soil (ML). They used ferrochrome slag that was sieved to a size range of 1.0 to 4.75 mm and mixed it with the soil in various proportions, from 10% to 60% by weight. They then performed two types of tests to evaluate the strength of the soil-slag mixtures: triaxial test, which measures the resistance to shear stress under different confining pressures, and CBR test, which measures the bearing capacity of the soil under a standard load. They compared the results of these tests with those of the pure soil and pure slag samples. They discovered that the optimal mixture was 50% soil and 50% slag, which showed the maximum improvement of strength compared to the other mixtures. This implies that ferrochrome slag can be a useful additive for stabilizing silty soil and increasing its suitability for engineering applications.

Şentürk, (2019), dedicated to investigating the viability of utilizing blast furnace slag, an output of the annual 7.8 million tons of iron and steel production in this country, for this purpose. The blast furnace slag was sourced from Kardemir A.Ş., while a bentonite soil sample was acquired from Geoplas company.

The experimental design involved incorporating blast furnace slag into bentonite at varying proportions (5%, 10%, 15%, and 20% by weight) and conducting experiments at intervals of 1, 7, 14, and 28 days of the curing period. Initial experiments involved compressing samples using the standard Proctor technique, followed by compaction testing to ascertain water content and dry unit weights. Consistency limits of liquid and plastic test specimens were determined through shear box and free pressure tests, evaluating changes in ground cohesion and shear strength with specific water content and weight proportions. Swelling tests were additionally conducted to observe changes in

the swelling characteristics of bentonite soil with increasing blast furnace slag rates in the prepared samples. The outcomes of the experiments revealed a decrease in liquid limit values, a reduction in internal friction angle, and an increase in cohesion and free pressure strengths over the curing time and blast furnace slag ratio in the mixture. Conversely, swelling pressure decreased with the curing time and blast furnace slag ratio in the mixture.

## **2.5. Soil Improvement with Mixing Methods**

Caraşca (2016), summarizes the research on soil improvement using the mixing method, which is a way of enhancing the physical and mechanical properties of clay soils by adding varied materials to them. The mixing method is an eco-friendly technique that has been widely used around the world for various construction projects. The research aims to understand how the soil behavior changes after stabilization and to provide accurate design criteria for the mixing process. The research uses experimental data from previous studies that tested manufactured soils stabilized with cement for both sandy and clay soils. The tests included flexion strength, density, porosity, unconfined compressive strength, dynamic modulus, and scanning electron microscopy (SEM) images. The research shows that the mixing method can improve the soil properties significantly and offers a better alternative to some conventional materials such as cement and chemical polymers.



### 3. MATERIAL AND METHOD

#### 3.1. Materials

##### 3.1.1. Natural Clay Soil

In this study, clay soil (CS) samples were collected from various locations in Adana, Turkey, to investigate their geotechnical and geochemical properties. The samples underwent classification according to the Unified Soil Classification System (USCS) criteria, which relies on the widely used ASTM Standard D 2487 for soil identification and description. Key parameters such as the liquid limit, plastic limit, and plasticity index were determined using the standard procedures outlined in ASTM D 4318. These parameters play a crucial role in evaluating soil behavior and consistency.

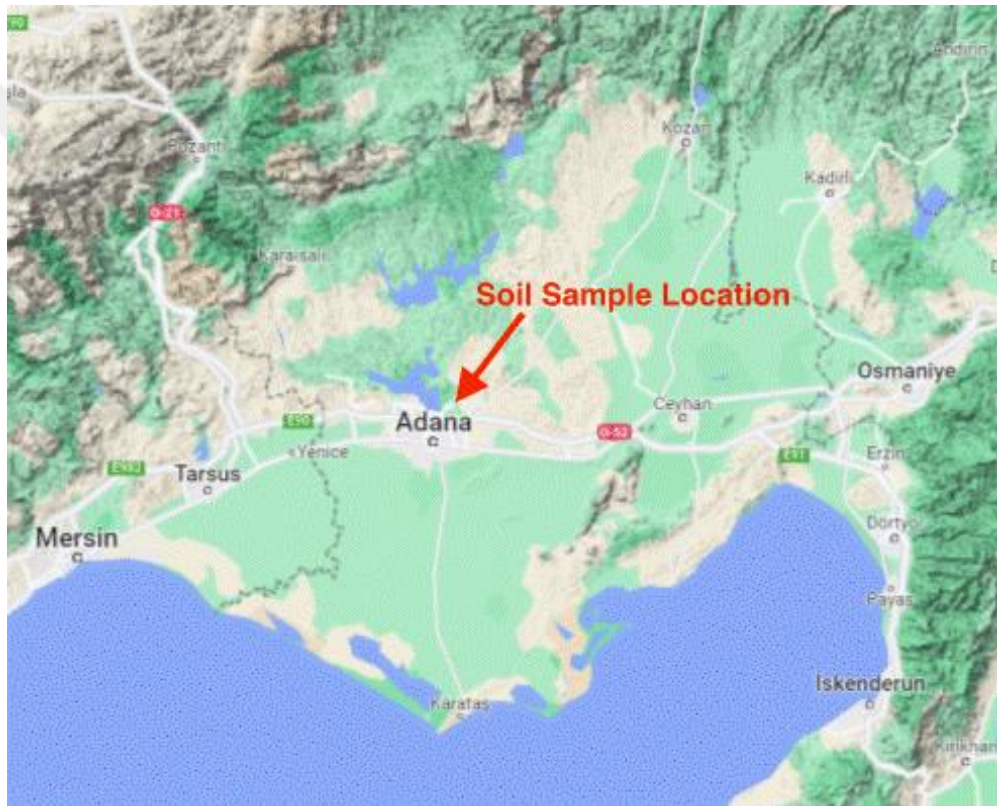


Figure 3.1. Location of the sampling area. The image is taken from Google Earth.

##### 3.1.2. Ferrochromium Slag

Ferrochromium slag, a by-product of ferrochromium production, plays a significant role in the stainless-steel manufacturing process. This alloy, composed of iron and chromium, contributes to the strength and corrosion resistance of stainless steel. However, the story of ferrochromium slag is multifaceted, as it combines both promise and peril.

When chromite ore undergoes smelting with coke as a reducing agent in an electric arc furnace at temperatures around 1500°C, ferrochromium slag emerges. This slag contains a diverse array of elements, including chromium, iron, calcium, magnesium, aluminum, and silicon. Its

mechanical properties make it a candidate for various construction applications, serving as aggregate, filler, or stabilizer.

Yet, beneath its potential lies a cautionary tale. Ferrochromium slag poses environmental and health risks, primarily due to chromium leaching. Of particular concern is the presence of carcinogenic chromium (VI) compounds. To unlock its benefits while safeguarding against harm, proper treatment or stabilization protocols are essential before incorporating ferrochromium slag into construction practices.

### **3.1.3. Agar Gum**

Agar (AG), a remarkable biopolymer, consists of complex sugar molecules known as polysaccharides. Specifically composed of galactose units linked in numerous ways, AG plays a pivotal role in diverse applications.

AG comprises two primary components: agarose and agarpectin. Agarose, a linear polymer, forms robust gels, while agarpectin, a branched polymer, exhibits weaker gelling properties and contains charged groups. With a neutral and inert backbone, AG resists reactions with other substances. Its appearance is semi-translucent, ranging from shiny white to pale yellow, and it remains odorless and tasteless.

AG is extracted from red algae within the Rhodophyceae group, with *Gelidium* and *Gracilaria* as notable examples. The quality and quantity of AG depend on the specific algae species and environmental conditions. Historically, AG has served as a food additive, functioning as an emulsifier, thickener, stabilizer, flavor enhancer, and absorbent. It features prominently in dairy products, bakery goods, candies, and certain meat items, where it forms gels that enhance texture and structure. Beyond the food industry, AG finds applications in microbiology, medicine, and dentistry. The AG used in this research was sourced from KIMBIOTEK Chemical Company.

## **3.2. Methods**

The AG and FS were blended with the soil using three distinct weight ratios. A series of laboratory tests were conducted on the soil-biopolymer mixtures to assess their physical and mechanical characteristics. These tests included Atterberg limits, compaction (standard proctor), and unconfined compressive strength (UCS) measurements. To understand the influence of time on strength development, the UCS samples were cured for varying periods. The obtained results were then compared with those from the natural soil to evaluate the enhancement achieved through the combination of biopolymers and Ferrochromium. All laboratory procedures adhered to the standards set by the American Society for Testing and Materials (ASTM).

### **3.2.1. Soil Classification**

Upon arrival at the laboratory, the soil samples underwent an assessment of their index properties for classification. These properties encompassed grain sizes (both sieve and hydrometer), specific gravities, and Atterberg limits. For each sample, three tests were meticulously conducted, and the resulting averages were calculated. If the discrepancy between the values obtained from the initial three tests exceeded 0.03, the test was repeated. To minimize any potential error, the same pycnometer was consistently employed across all three tests for each sample. Additionally, the density of water at the test temperature was sourced from the table specified in TS 1900-1.

### **3.2.2. Atterberg Limits**

The Atterberg limits test is a laboratory procedure used to measure the water content of fine-grained soils at different states of consistency. It consists of two parts: the liquid limit test and the plastic limit test. The liquid limit (LL) is the water content at which the soil transitions from a liquid to a plastic state. The plastic limit (PL) is the water content at which the soil changes from a plastic to a semi-solid state. The plasticity index (PI) is the difference between the LL and the PL, indicating the range of water content over which the soil behaves plastically.

In the liquid limit test, a portion of soil is placed in a standard cup, and a groove of standard dimensions is made in the soil with a special spatula. The cup is then dropped from a height of 10 mm at a rate of two drops per second until the groove closes by 13 mm (1/2 in.). The number of drops required to close the groove is recorded, and the soil's water content is determined. The test is repeated with different water contents until a curve relating the number of drops to the water content is obtained. The LL is the water content corresponding to 25 drops.

The plastic limit test involves rolling a portion of soil on a smooth surface with the palm of the hand until it forms a thread 3.2 mm (1/8 in.) in diameter. The thread is then broken into several pieces and re-rolled until it crumbles. The water content of the crumbled soil is determined and reported as the PL. These tests were conducted in compliance with ASTM D4318-17e1 standard (ASTM, 2017).

In this research, the effect of adding biopolymers and their combinations with Ferrochromium to the clayey soil on the Atterberg limits was investigated by performing the test for each mixture at different ratios of all materials.

### **3.2.3. Compaction Test (Standard Proctor)**

The standard proctor test is a laboratory technique used to measure the relationship between moisture content and the dry unit weight of soils. This test identifies the optimal moisture content (OWC) and the maximum dry unit weight (DD) for a given compaction effort. The procedure involves compacting soil samples in a cylindrical mold with a diameter of 4 inches (101.6 mm) using a hammer weighing 10 lbf (44.5 N). The hammer is dropped from a height of 18 inches (457 mm)

onto each layer of soil, delivering a compaction effort of 56,000 ft-lbf/ft<sup>3</sup> (2,700 kN-m/m<sup>3</sup>). The test is repeated with different moisture contents until a curve is produced showing the variation of dry unit weight with moisture content. The OWC is the moisture content at the peak of this curve, while the DD is the dry unit weight at that point. The standard proctor test was conducted according to ASTM D698-04 (ASTM, 2023).

#### **3.2.4. Unconfined Compressive Strength Test**

The unconfined compressive stress test is a laboratory technique used to measure the maximum compressive strength of fine-grained soils without any lateral confinement. This test estimates the soil's shear strength and bearing capacity for engineering applications. It involves placing a cylindrical soil sample in a loading device and applying an axial load until the sample fails. The load and deformation of the sample are recorded to calculate the stress-strain curve and determine the soil's unconfined compressive strength.

In this research, the effect of adding biopolymers to clay soil on the unconfined compressive strength was investigated by performing the test on each mixture at different ratios of all four biopolymers. The samples were prepared and cured for 1, 7, 14, 21, and 28 days before testing. To prevent moisture loss, the samples were stored in sealed bags inside desiccators. The tests were conducted according to ASTM D2166-04 standards (ASTM, 2016).

#### **3.2.5. Direct Shear Test**

It is known that stresses occur in soils due to the loads applied on the soil surface, as well as their own weights. For shear failure to occur in soils, the shear resistance along a possible shear plane must be exceeded. General shear occurs as a result of the combined effect of normal and shear stresses acting on a certain shear plane. The shear strength of soil is defined as the maximum shear stress that the soil can resist without shearing. The shear strength of soil is determined by the shear box test device.

The shear box test is a laboratory method that measures the shear resistance of soil by applying a normal load and a horizontal displacement to a soil sample that is confined laterally and drained from the top and bottom surfaces. The test uses an oedometer cell, a consolidation ring, and porous disks. The consolidation ring prevents any lateral deformation of the soil sample, and the porous disks allow water drainage from the top and bottom surfaces of the soil sample. The oedometer cell is filled with water that can overflow from the top surface of the disk.

The natural clay soil sample and the natural clay soil sample mixed with biopolymer, ferrochrome, and their combination at optimum water content by wet mixing method according to the optimum improvement ratio were used for the shear box test. The soil sample placed in the ring was placed in the cell. The cell consists of a porous stone, a soil sample (in the ring), a porous stone, and a loading plate from bottom to top. The prepared cell was fixed with a fixing ring and tightened

with screws. The cell was placed in the test system and the loading arm was brought to a horizontal position. It was fixed and balanced so that it would touch the part that would transfer load to the sample. The comparator clock was placed to measure the movement between the base of the cell and the loading plate. The test system was saturated with water and prepared.(ASTM, 2023)

### **3.2.6. Mixing Method**

This research used the wet mixing method to mix the biopolymers with the soil. The wet mixing method involves dissolving the biopolymer powder in water and then adding the solution to the dry soil. This method is preferred over the dry mixing method, which involves mixing the biopolymer powder and the soil before adding water, because it can achieve higher productivity and uniformity. The amount of biopolymer used was determined based on the weight of the soil and the desired concentration for the tests performed. The biopolymer solution and the soil were mixed thoroughly using a mixer until a homogeneous mixture was obtained.

### **3.2.7. Freeze-Thaw Cycles**

The test samples used in this study were prepared at optimum moisture contents and predetermined mixture ratios, and they were exposed to freeze-thaw effects. To prevent changes in moisture content, the samples were kept in desiccators. The number of freeze-thaw cycles applied in this study was 2, 4, 8, and 16. The temperature values were  $-20^{\circ}\text{C}$  for freezing and  $+25^{\circ}\text{C}$  for thawing, with a waiting time of 6 hours at each temperature. The samples were wrapped in foil and placed in the freeze-thaw cabinet, remaining there throughout the test.

The freeze-thaw process involved initially bringing the samples to  $-20^{\circ}\text{C}$  and holding them for 6 hours, followed by raising the temperature to  $+25^{\circ}\text{C}$  and holding for another 6 hours. This 12-hour period constituted one complete freeze-thaw cycle. After completing the designated number of cycles, the samples were subjected to unconfined compression and direct shear tests.



## 4. RESULTS AND DISCUSSIONS

### 4.1. Atterberg Limits

The consistency and behavior of soil are crucial properties that impact its engineering performance. The natural soil used in this study had a liquid limit (LL) of 42%, a plastic limit (PL) of 26%, and a plasticity index (PI) of 16%. These values indicate that the soil is moderately plastic according to ASTM D2487-06, meaning it can be easily molded into different shapes.

Biopolymer was added to the soil at different ratios (0.75%, 0.85%, 1%, and 1.15%) to investigate its effect on the soil's consistency and behavior. The results showed that the biopolymer had a negligible effect on the PL of the soil, which remained almost constant at 26%. The biopolymer also had a minor effect on the LL of the soil, which decreased slightly to 40% at 1% and 1.15% ratios. In relation of this, the PI values also decreased. These results suggest that the biopolymer did not significantly alter the consistency and behavior of the clay soil.

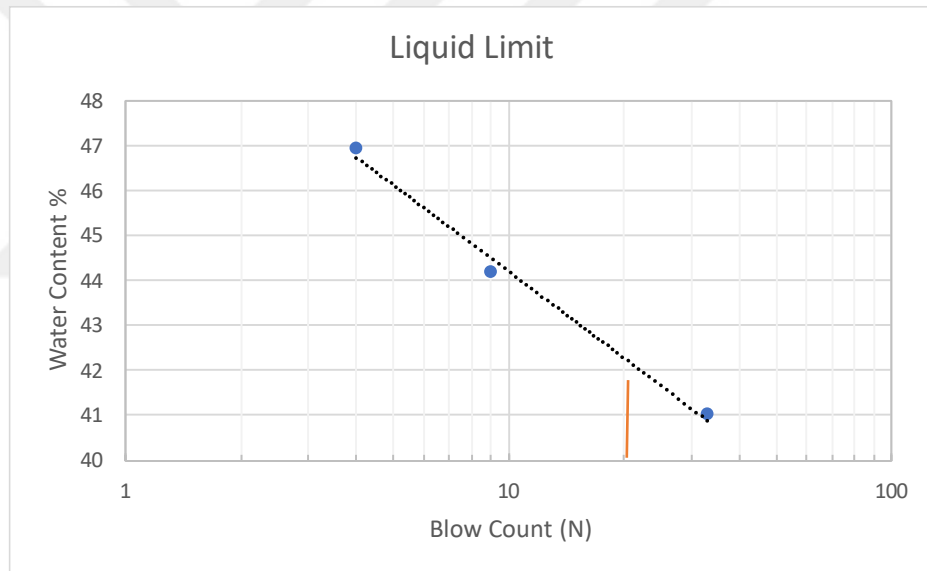


Figure 4.1. Liquid Limit chart for the natural clayey soil.

Table 4.1 LL, PL and PI values for different AG mixture ratios.

AG Concentration (%)	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)
0% (Natural)	42.19%	25.63%	16.56%
0.75%	40.63%	25.88%	14.75%
0.85%	40.38%	25.97%	14.41%
1.00%	40.13%	26.06%	14.07%
1.15%	39.88%	26.15%	13.73%

Table 4.2 LL, PL and PI values for different FC mixture ratios.

FC Concentration (%)	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)
0% (Natural)	42.19%	25.63%	16.56%
0.25%	41.94%	25.69%	16.25%
0.50%	41.69%	25.75%	15.94%
0.75%	41.44%	25.81%	15.63%
1.00%	41.19%	25.88%	15.31%

#### 4.2. Soil Classification

The results of the sieve analysis and hydrometer test are given in grain size distribution curve as shown in Figure 4.2. The soil sample consists of approximately 7% sand, 45.47% clay, and 47.30% silt in total. The results of the specific gravity test are conducted in accordance with ASTM D 854 standard (ASTM, 2004) and summarized in Table 4.3.

Table 4.3 Specific gravity test results

Test Number	1	2	3
Pycnometer Weight (gr)	71.13	71.15	71.15
Pycnometer + Sample Weight (gr)	106.41	106.29	106.32
Sample Weight (gr)	35.28	35.14	35.17
Pycnometer + Sample. + Pure Water Weight (gr)	333.76	334.93	334.83
Pycnometer + Pure Water Weight (gr) A	311.16	312.5	312.5
Temperature (°C)	84	76.5	76.2
Water Unit Weight at given temperature (Gw)	0.9693	0.9737	0.9737
Soil Unit Weight (Gs)	2.6969	2.692	2.6954
Average	2.69		

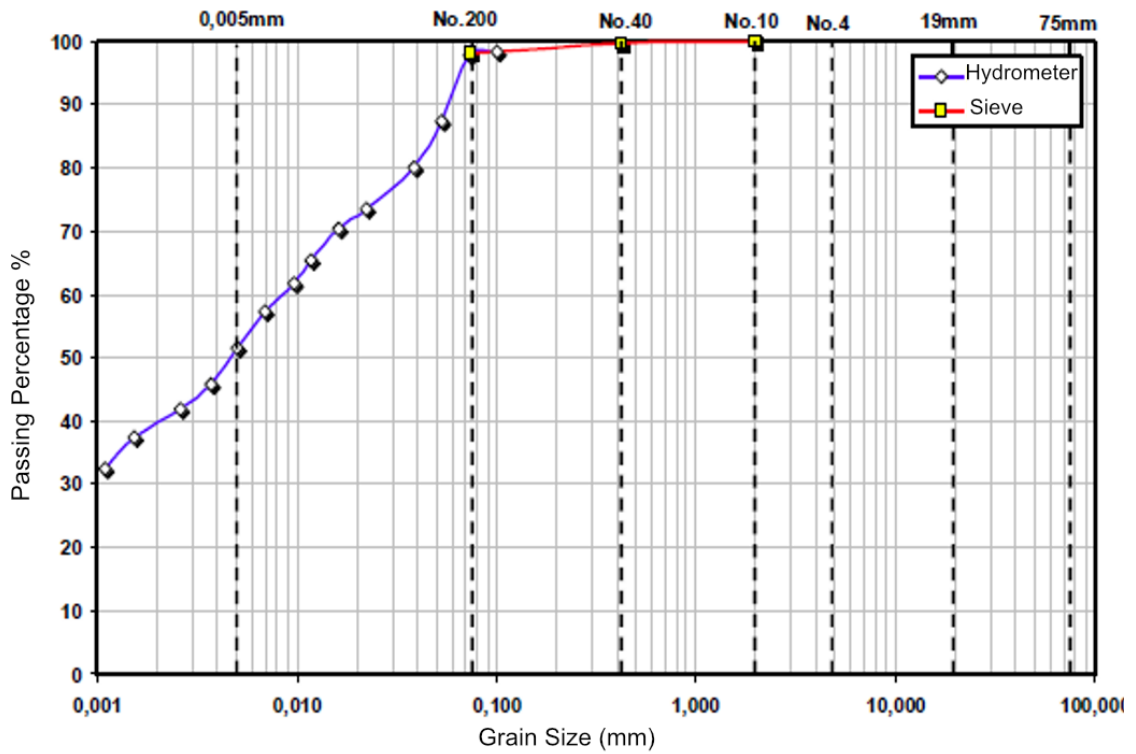


Figure 4.2. Gradation curves for the clay soil.

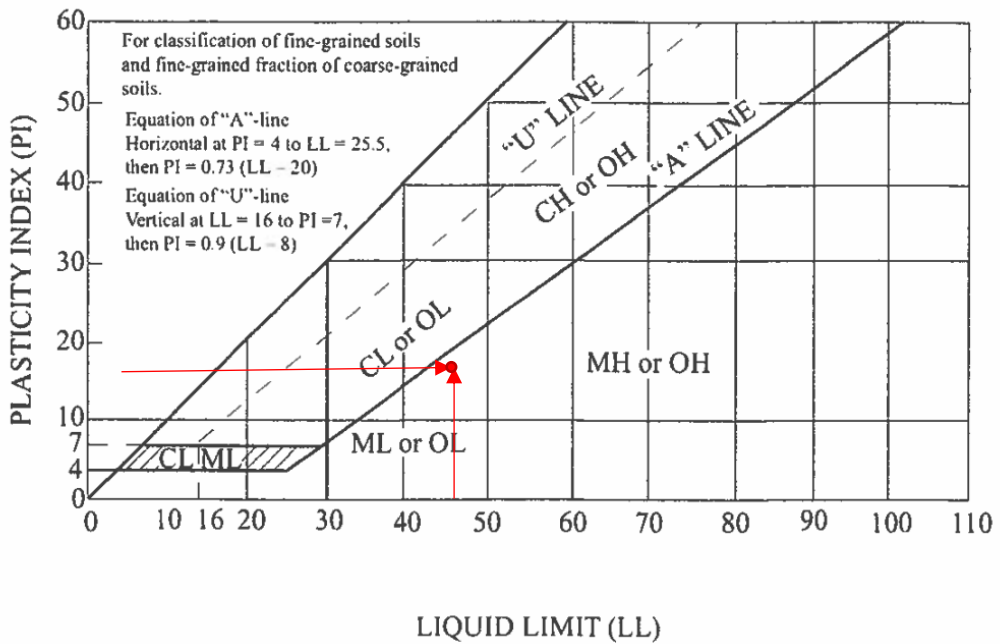


Figure 4.3. Plasticity Chart marked with Atterberg test results for the natural clayey soil.

The soil class of the sample was determined as "CL" low plasticity clay by plotting the values on the plasticity chart and looking at the intersection point.

Table 4.4 Soil classification results summary for the natural clayey soil.

Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	Dry Unit Weight (Gs)	USCS Classification
42.19%	25.63%	16.56%	2.69	CL

### 4.3. Compaction Test (Standard Proctor)

The Compaction test, following ASTM D1557-00 standards, employs a heavier rammer and higher drop height than the standard Proctor test, making it suitable for soils requiring higher compaction energy, such as coarse-grained soils or soils with high plasticity.

The objective of this test was to compare the OWC and MDD of natural soil with that of soil mixed with biopolymer. Biopolymers are natural substances extracted from plants or animals, which can improve soil properties by forming gels and coating soil particles. The biopolymer used in this study was Agar Gum (AG), derived from seaweed.

The test results showed that the natural soil had an OWC of 17.50% and an MDD of 1.83 g/cm<sup>3</sup>. Soil mixed with 1% AG biopolymer had an OWC of 16.85% and an MDD of 1.865 g/cm<sup>3</sup>. Another sample mixed with 1.15% AG biopolymer had an OWC of 16.75% and an MDD of 1.877 g/cm<sup>3</sup>. The results indicated that adding AG biopolymer slightly reduced the OWC and slightly increased the MDD of the soil, suggesting that the soil became denser and less susceptible to water-induced volume changes. The results also suggested that the optimum mixture ratio of AG biopolymer was 1%, as it achieved the highest MDD among the tested samples.

Table 4.5 Proctor Test results for the natural clayey soil

OWC	17.50%
Dry Unit Weight (gr/ cm <sup>3</sup> )	1.83

Table 4.6 OWC and Dry Unit Weight values for different AG mixture ratios.

AG Concentration (%)	Optimum water content (%)	Dry unit weight (gr/ cm <sup>3</sup> )
0.75	17.123	1.841
0.85	17.042	1.858
1	16.847	1.865
1.15	16.738	1.877

Table 4.7 OWC and Dry Unit Weight values for different FC mixture ratios.

FC Concentration (%)	Optimum water content (%)	Dry unit weight (g/cm <sup>3</sup> )
0.25	17.28	1.833
0.5	17.06	1.836
0.75	16.84	1.839
1	16.62	1.842

## 4.4. Unconfined Compressive Strength Test

### 4.4.1. Natural Clay Soil

The behavior of soils under load depends on their strength and deformation characteristics, which in turn are influenced by their moisture content and microfabric properties. Unconfined compression tests were performed to determine the strength and strain characteristics of the clay soil and the mixtures at various curing periods (1, 7, 14, 21, and 28 days) and mixing ratios. As seen in Figure 4.6, some samples exhibited stress-hardening behavior, meaning there were no clear drops or pronounced peaks (failure points) on the slopes of the curves. In such cases, it is suggested that 10–20% shear deformation should be considered the failure point (Liu and Evett, 1984; ASTM D3080-98, 2003).

In this study, unconfined compression tests were conducted to determine the strength and strain characteristics of natural soil and soil enhanced with biopolymers and Ferrochromium slag, considering different curing periods and mixing ratios. This was done to examine the changes in soil properties before and after treatment. The tests were performed in accordance with ASTM D2166 standards. The compression stress of the natural soil was found to be 1.7932 kg/cm<sup>2</sup>, as shown in Figure 4.5.

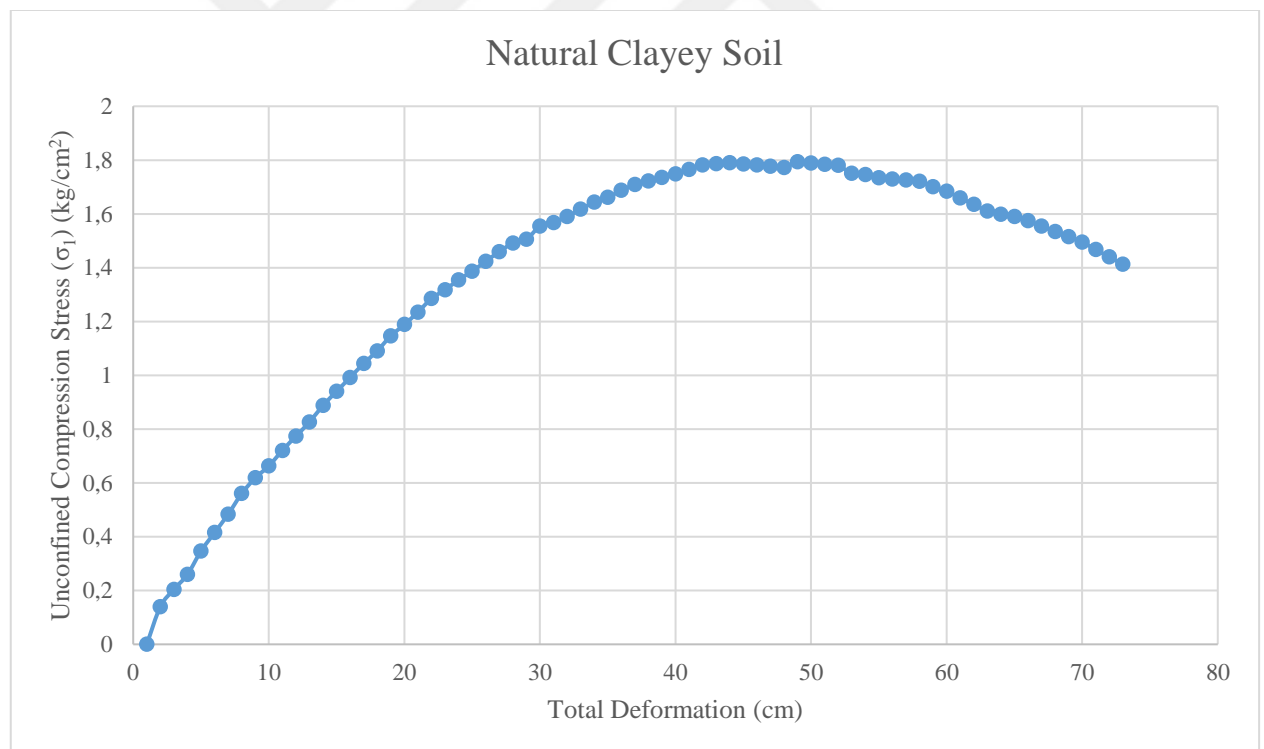


Figure 4.4. UCS stress-strain curve of the natural clay soil.

The biopolymers used as soil improvers were agar gum and Ferrochromium slag, which were tested in three different mixing ratios. The results of the unconfined compression tests showed an increase in the compression stress after adding the biopolymers and Ferrochromium slag. This

improvement was attributed to the strong bonding effect of these materials, which reduced the porosity of the clay soil.

#### **4.4.2. Biopolymer Additive**

The results of unconfined compression tests on clay soil samples mixed with various proportions of Agar Gum (AG) biopolymer revealed interesting findings. After determining the optimum water content through the Proctor test, the samples underwent curing for different durations (1, 7, 14, 21, and 28 days) prior to testing.

Specifically, at 21 days of curing time, the maximum compressive strength values for AG biopolymer were observed at 0.85% and 1% AG content, measuring 2.186 and 2.104 kg/cm<sup>2</sup>, respectively. These values represented increases of 22% and 17% over the compressive strength of the natural soil, which stood at 1.7932 kg/cm<sup>2</sup>. However, compressive strength values decreased with higher AG content (1% and 1.15%), indicating an optimal range of AG content for soil enhancement. Figure 4.6 illustrates the variation of compressive strength with AG content at 21 days of curing time. The optimal AG content for soil enhancement was determined to be 1%, resulting in significant improvements in compressive strength values over varying curing periods. For instance, at 1 day of curing time, the compressive strength increased from 1.8380 kg/cm<sup>2</sup> to 2.4925 kg/cm<sup>2</sup> at 28 days of curing time, marking improvement percentages of 2.5% and 39%, respectively. This trend indicates that longer curing times lead to higher compressive strength values, attributed to the formation of stronger bonds between AG biopolymer and soil particles. Figure 4.7 illustrates the variation of compressive strength with curing time at 1% AG content. These results underscore the effectiveness of AG biopolymer in enhancing the compressive strength of clay soil by reducing its porosity and enhancing its stiffness.

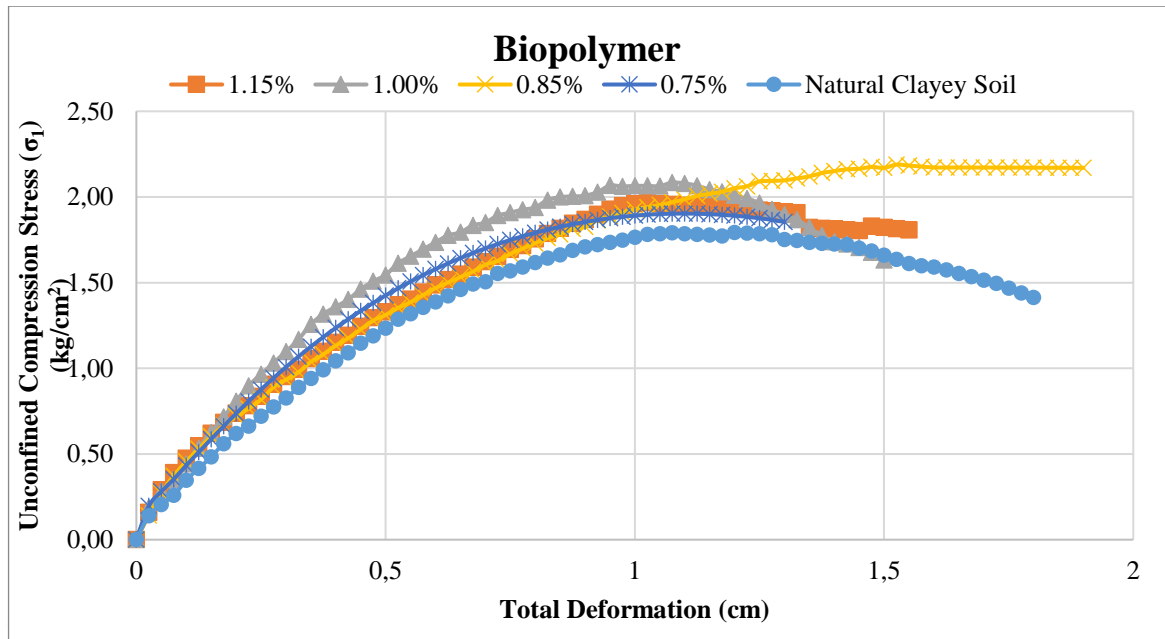


Figure 4.5. UCS stress-strain curves of the natural clay soil mixed with various percentages of AG at 21 days of curing.

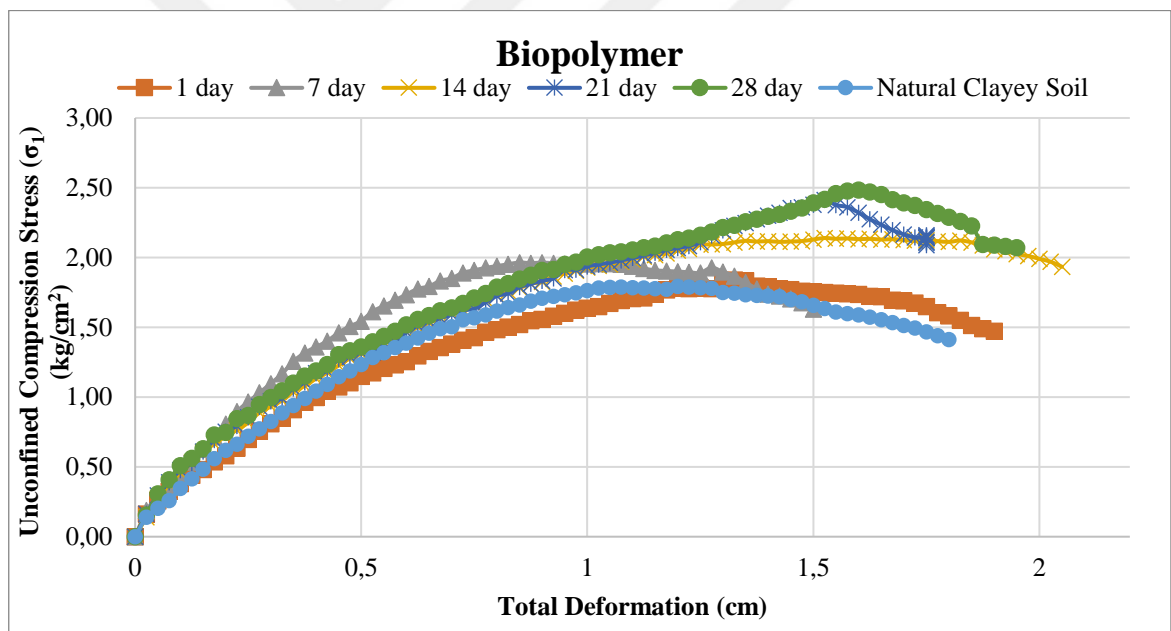


Figure 4.6. UCS stress-strain curves of natural clay soil mixed with optimum 1% of Agar Gum biopolymer at various curing times.

#### 4.4.3. Ferrochromium Slag Additive

The addition of FC slag to the soil at the optimal water content, determined by the Proctor test, yielded insightful results:

- As FC slag content increased up to 1%, the soil's compressive strength rose, reaching a peak of 2.188 kg/cm<sup>2</sup>, marking a remarkable 21.99% improvement over the natural soil. This enhancement can be attributed to the filling effect and pozzolanic reaction of FC slag, which reduced void ratio and increased soil density.

- However, further increases in FC slag content beyond 1% led to a decline in compressive strength, indicating an optimal range for FC slag content in soil stabilization. Figure 4.8 illustrates the variation of compressive strength with FC slag content at various mixture ratios.

These findings suggest that FC slag can serve as an effective additive to improve the compressive strength of clay soil by altering its physical and chemical properties.

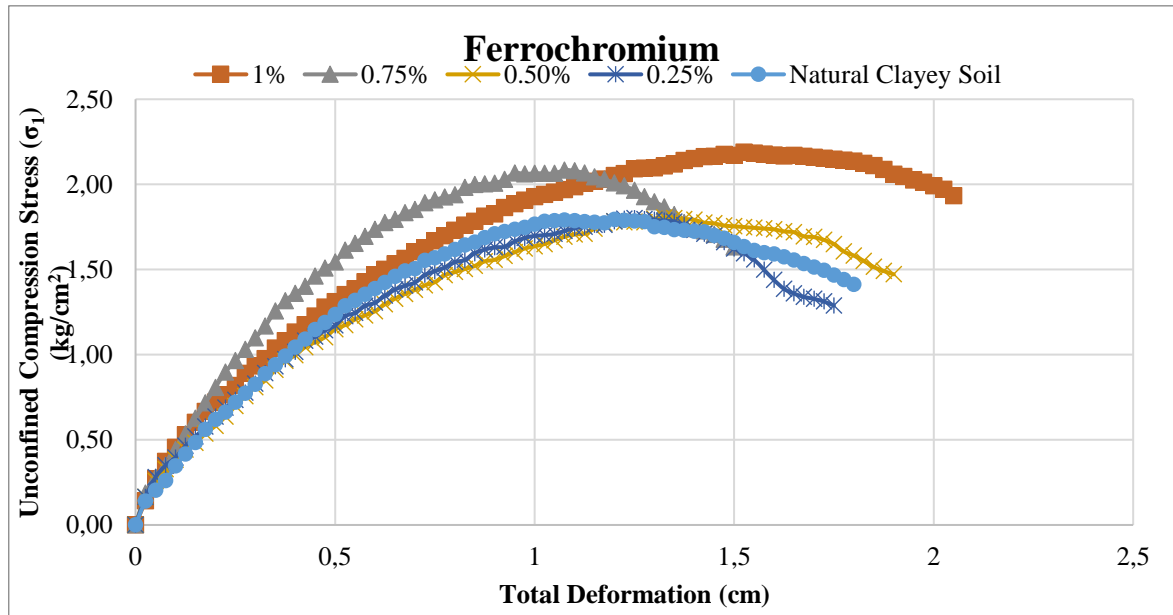


Figure 4.7. UCS stress-strain curves of the natural clay soil mixed with various percentages of Ferrochromium slag additive.

#### 4.4.4. Biopolymer and Ferrochromium Mixture Additive

The experimental investigation explored the feasibility of employing FC slag and AG biopolymer as soil stabilizers for clay soil. The determination of optimum water content, FC slag content, and AG content was based on Proctor test, unconfined compression test, and Atterberg limits test results. Soil samples were prepared with optimum water content and different combinations of FC slag and AG biopolymer. Unconfined compression tests were conducted after curing the samples for 1, 7, 14, 21, and 28 days. The findings revealed:

- The combination of FC slag and AG biopolymer significantly enhanced the compressive strength of clay soil. The highest compressive strength value, achieved at 1% FC slag and 1% AG biopolymer, measured 2.6357 kg/cm<sup>2</sup> after 21 days of curing. This value marked a substantial 46.9% increase over the natural soil compressive strength of 1.7932 kg/cm<sup>2</sup>. Figure 4.9 illustrates the variation of compressive strength with curing time for different combinations of FC slag and AG biopolymer.

- The improvement in compressive strength stemmed from the synergistic effect of FC slag and AG biopolymer on soil structure. FC slag served as a filler material and pozzolanic agent,

reducing void ratio and increasing soil density. AG biopolymer functioned as a binder material and water retention agent, enhancing soil cohesion and stiffness.

- The optimal combination of FC slag and AG biopolymer also reduced the plasticity index and swelling potential of clay soil, enhancing its workability and durability.

These results suggest that FC slag and AG biopolymer can serve as effective and environmentally friendly additives for stabilizing clay soil in various engineering applications.

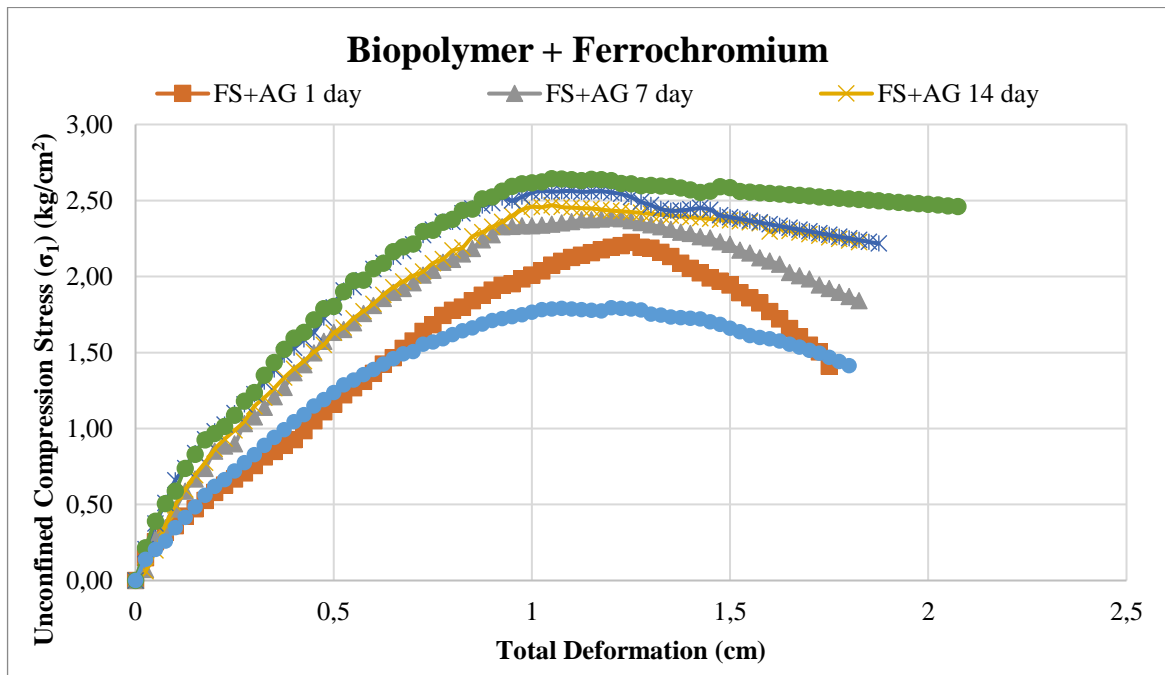


Figure 4.8. UCS stress-strain curves of the natural clay soil mixed with optimum 1% of Agar Gum biopolymer and 1% Ferrochromium slag additive at various curing times.

#### 4.4.5. Freeze-Thaw Performance

In regions with subzero temperatures, soils utilized in engineering structures are susceptible to freeze-thaw damage, a significant cause of soil constituent deterioration. This study aimed to assess the freeze-thaw resistance of clay soil samples stabilized with Agar Gum (AG) biopolymer, Ferrochromium (FC) slag, and their optimal mixture (1% FC slag and 1% AG biopolymer). The samples underwent 2, 4, 8, and 16 cycles of freezing and thawing, following ASTM D560 standards, with unconfined compression tests conducted after each cycle. The findings revealed:

- All stabilized samples exhibited higher compressive strength than the natural soil (1.7932 kg/cm<sup>2</sup>) after each cycle, indicating an enhancement in freeze-thaw resistance.

- FC slag-stabilized samples displayed the highest compressive strength values among the three types of stabilized samples, ranging from 1.6397 kg/cm<sup>2</sup> to 1.3862 kg/cm<sup>2</sup> as the number of cycles increased from 2 to 16. This suggests that FC slag was more effective than AG biopolymer in improving the freeze-thaw resistance of clay soil.

- AG biopolymer-stabilized samples exhibited the lowest compressive strength values among the three types of stabilized samples, ranging from 1.52 kg/cm<sup>2</sup> to 0.986 kg/cm<sup>2</sup> as the number of cycles increased from 2 to 16. This indicates that AG biopolymer was less effective than FC slag in enhancing the freeze-thaw resistance of clay soil.

- Optimum mixture-stabilized samples displayed intermediate compressive strength values between FC slag-stabilized and AG biopolymer-stabilized samples, ranging from 1.5756 kg/cm<sup>2</sup> to 1.079 kg/cm<sup>2</sup> as the number of cycles increased from 2 to 16. This suggests that the optimal mixture moderately enhanced the freeze-thaw resistance of clay soil.

- Compressive strength values of all stabilized samples decreased with an increasing number of cycles, indicating gradual deterioration of soil structure due to repeated freezing and thawing. Figures 4.10 to 4.12 depict the variation of compressive strength with the number of cycles for various types of stabilized samples.

These results imply that FC slag and AG biopolymer can effectively serve as soil stabilizers to improve the freeze-thaw resistance of clay soil, albeit with varying degrees of effectiveness depending on their proportions and the number of cycles.

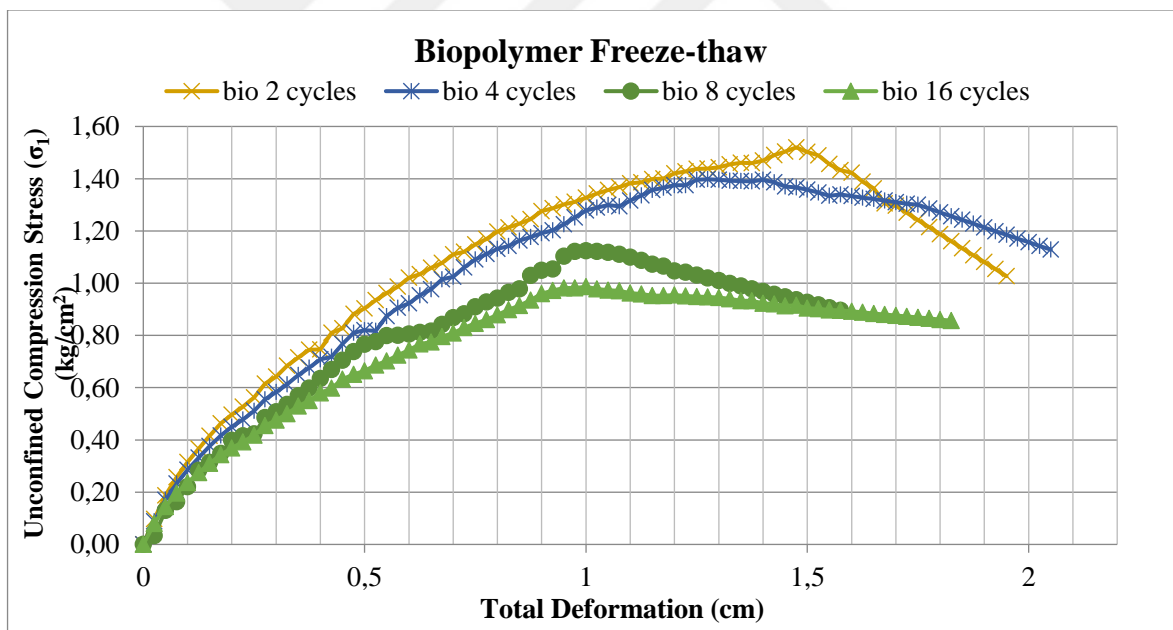


Figure 4.9. UCS stress-strain curves of the natural clay soil mixed with optimum 1% of Agar Gum biopolymer at various freeze-thaw cycles.

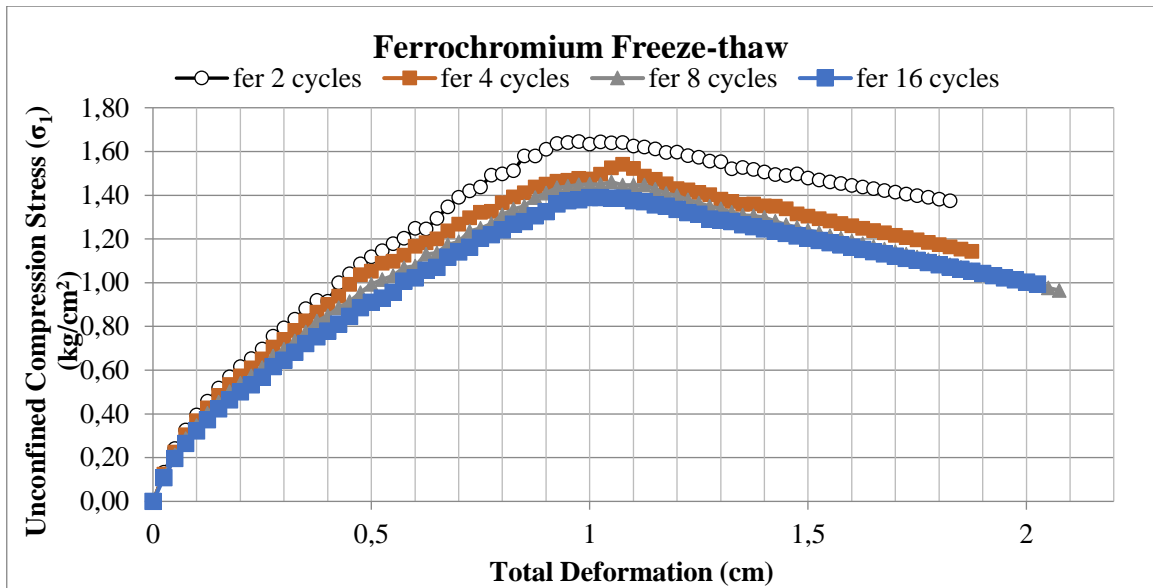


Figure 4.10. UCS stress-strain curves of the natural clay soil mixed with optimum 1% Ferrochromium slag additive at various freeze-thaw cycles.

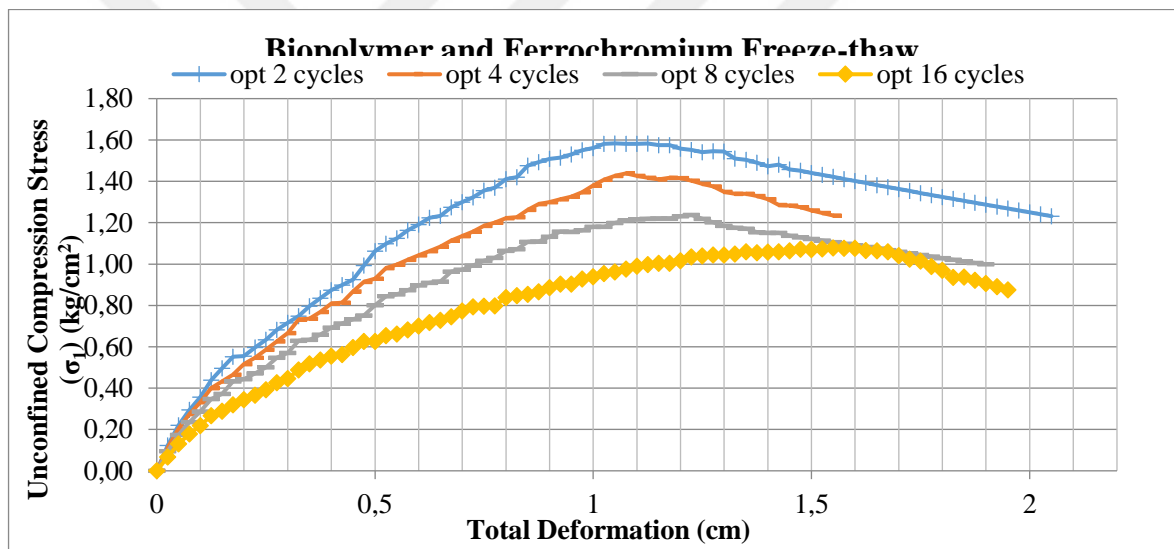


Figure 4.11. UCS stress-strain curves of the natural clay soil mixed with both optimum 1% Ferrochromium slag additive and 1% Agar Gum biopolymer at various freeze-thaw cycles

#### 4.5. Direct Shear Test

The employed Direct Shear Test was to assess how ferrochrome slag and agar gum biopolymer impact the shear strength properties of clay soil, particularly cohesion and internal friction angle. Clay soil samples blended with different proportions of these additives underwent shear box tests, a standard technique for evaluating soil's shear behavior under varying levels of normal stress. To simulate realistic stress conditions encountered in practical applications, vertical loads of 3, 6, and 12 kg were applied, alongside a uniform shear displacement rate of 1 mm/min during the tests.

#### 4.5.1. Natural Clay Soil

The native clay soil demonstrated specific shear properties as follows: a cohesion coefficient of 0.4 kg/cm<sup>2</sup> and an internal friction angle of 11.5 degrees. Moreover, shear stress values were obtained under varying normal loads of 3 kg, 6 kg, and 12 kg, corresponding to normal pressures of 1.67 kg/cm<sup>2</sup>, 3.33 kg/cm<sup>2</sup>, and 6.69 kg/cm<sup>2</sup>, respectively. These parameters play pivotal roles in delineating the shear strength of the clay soil. A cohesion coefficient of 0.4 kg/cm<sup>2</sup> signifies the inherent cohesion of the soil, while the internal friction angle of 11.5 degrees indicates its resistance to shear deformation.

The obtained shear stress values under different normal loads unveil critical insights into the soil's behavior under distinct stress conditions. As expected in soil mechanics, the shear stress escalates with increasing normal load, illustrating the soil's sensitivity to applied stress. The augmentation in shear stress, from 0.74 kg/cm<sup>2</sup> at 3 kg normal load to 1.13 kg/cm<sup>2</sup> at 12 kg normal load, underscores the soil's bolstered strength and heightened resistance to shear as the normal load intensifies—an observation consistent with Coulomb's law of shear strength. The demonstrated increase in shear stress with escalating normal loads suggests a strain-hardening behavior, wherein the soil's shear strength enhances with higher levels of deformation, a characteristic typical of cohesive soils such as clays. The consistent trend in shear stress values with increasing normal loads implies the reliability of the test outcomes and signifies that the soil's shear properties can be reasonably predicted using cohesion and internal friction angle parameters.

Table 4.8 Direct shear test results of the natural clay soil

Natural				
kg	$\sigma_N$	$\tau$	c (kg/cm <sup>2</sup> )	$\phi$
3	1.667	0.7379	0.4	11.5
6	3.334	0.7541		
12	6.668	1.1255		

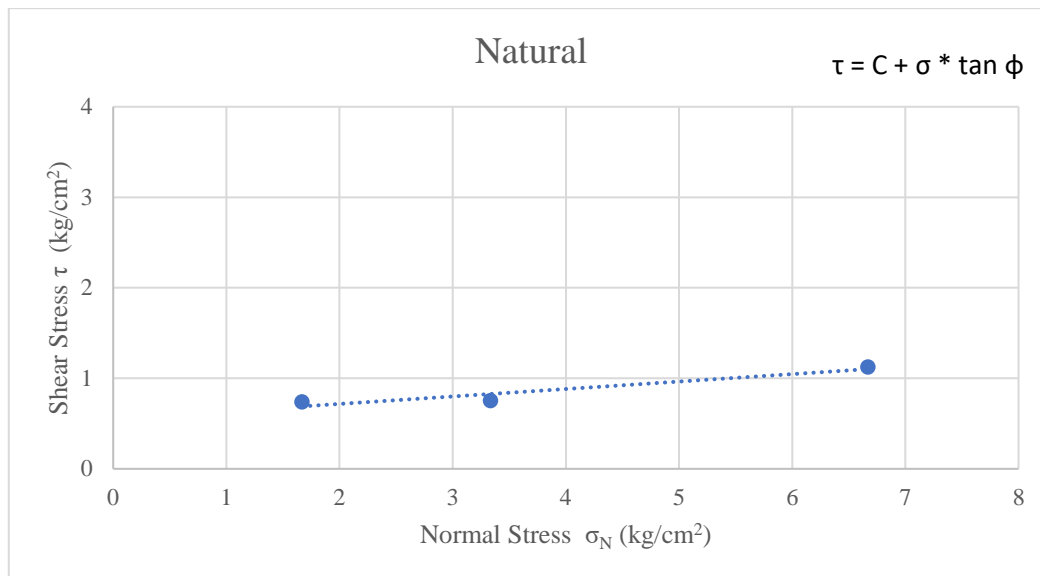


Figure 4.12. Failure envelope of the natural clay soil.

#### 4.5.2. Biopolymer Additive

In this study, the impact of agar gum biopolymer on the shear behavior of clay soil was explored. Agar gum biopolymer, sourced from red algae, is a natural polysaccharide with a history of use in soil stabilization. The experiment involved blending clay soil with 1% agar gum biopolymer by dry weight and subjecting it to various curing periods (1, 7, 14, 21, and 28 days). The shear strength of the soil-biopolymer mixture was assessed via direct shear tests under different normal loads (3, 6, and 12 kg).

The findings indicated that the inclusion of agar gum biopolymer bolstered the shear strength of clay soil by augmenting its cohesion coefficient and internal friction angle—parameters indicative of the soil's resistance to sliding along potential failure planes. Moreover, the optimal curing time for achieving maximal shear strength was identified as 21 days, allowing adequate duration for the formation and hardening of hydrogels that bind the soil particles together.

These results suggest that agar gum biopolymer presents itself as a sustainable and cost-effective alternative to conventional chemical additives for enhancing clay soil's shear strength. Derived from renewable sources, agar gum biopolymer exerts negligible adverse environmental impacts and necessitates low dosages to bring about substantial improvements in soil properties.

Table 4.9 Shear test results of sample mixed with optimum 1% Agar Gum biopolymer additive at various curing days.

Biopolymer					
Time	kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c (kg/cm <sup>2</sup> )	$\phi$
1 day	3	1.667	0.65	0.35	10.02
	6	3.334	0.66		
	12	6.668	0.97		
7 days	3	1.667	1.08	0.59	16.86
	6	3.334	1.11		
	12	6.668	1.66		
14 days	3	1.667	1.78	0.97	27.76
	6	3.334	1.82		
	12	6.668	2.72		
21 days	3	1.667	1.92	1.04	29.95
	6	3.334	1.96		
	12	6.668	2.94		
28 days	3	1.667	1.56	0.85	24.33
	6	3.334	1.59		
	12	6.668	2.38		

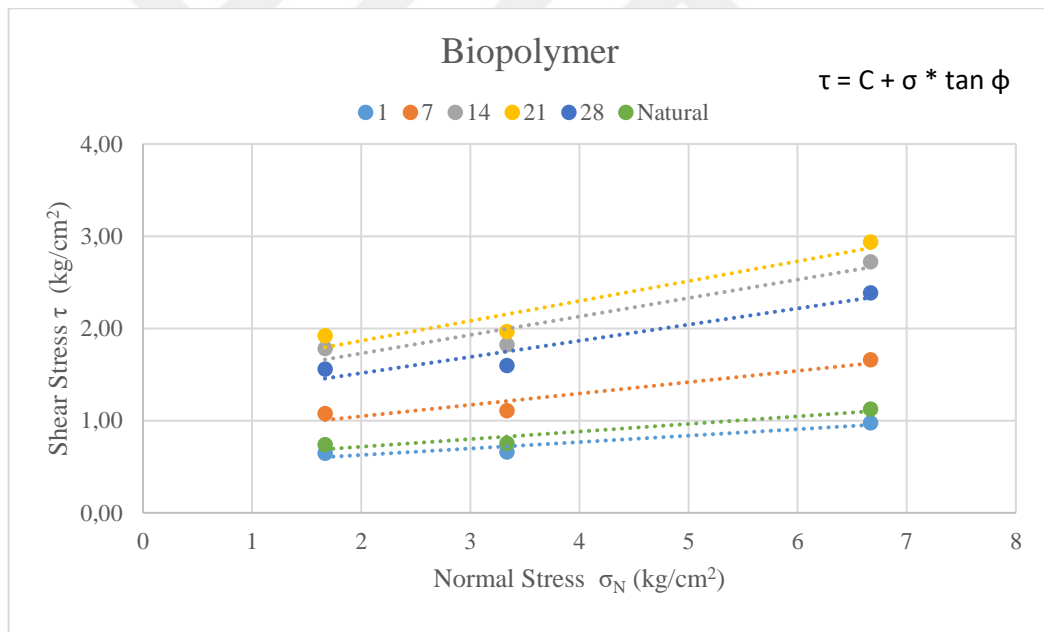


Figure 4.13. Failure envelope of the soil mixed with optimum 1% Agar Gum biopolymer additive.

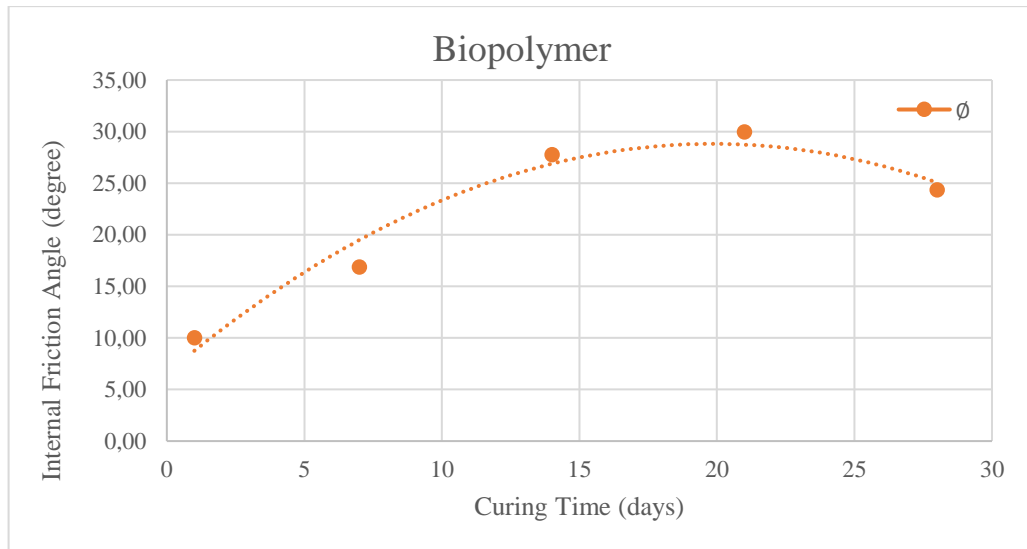


Figure 4.14 The relationship between Internal Friction Angles ( $\phi$ ) and curing time.

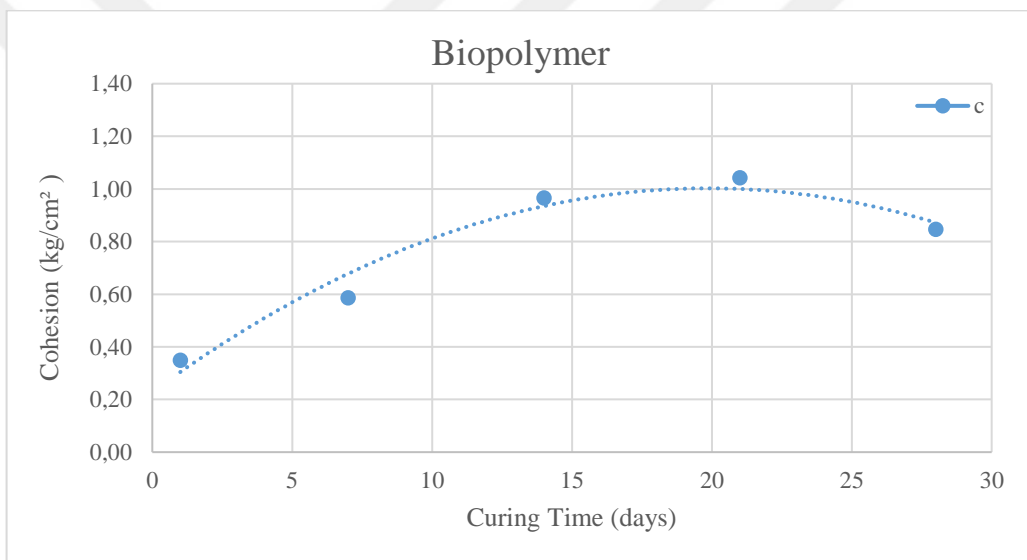


Figure 4.15. The relationship between Cohesion (c) and curing time.

Table 4.10 Shear test results of samples mixed with optimum various Agar Gum biopolymer additive.

Biopolymer (21 days)					
%	kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c (kg/cm <sup>2</sup> )	$\phi$
0.75%	3	1.667	0.78	0.50	13.14
	6	3.334	0.84		
	12	6.668	0.91		
0.85%	3	1.667	0.85	0.56	13.89
	6	3.334	0.90		
	12	6.668	1.13		
1%	3	1.667	0.89	0.61	15.21
	6	3.334	0.96		
	12	6.668	1.27		
1.15%	3	1.667	0.95	0.65	15.90
	6	3.334	1.03		
	12	6.668	1.39		

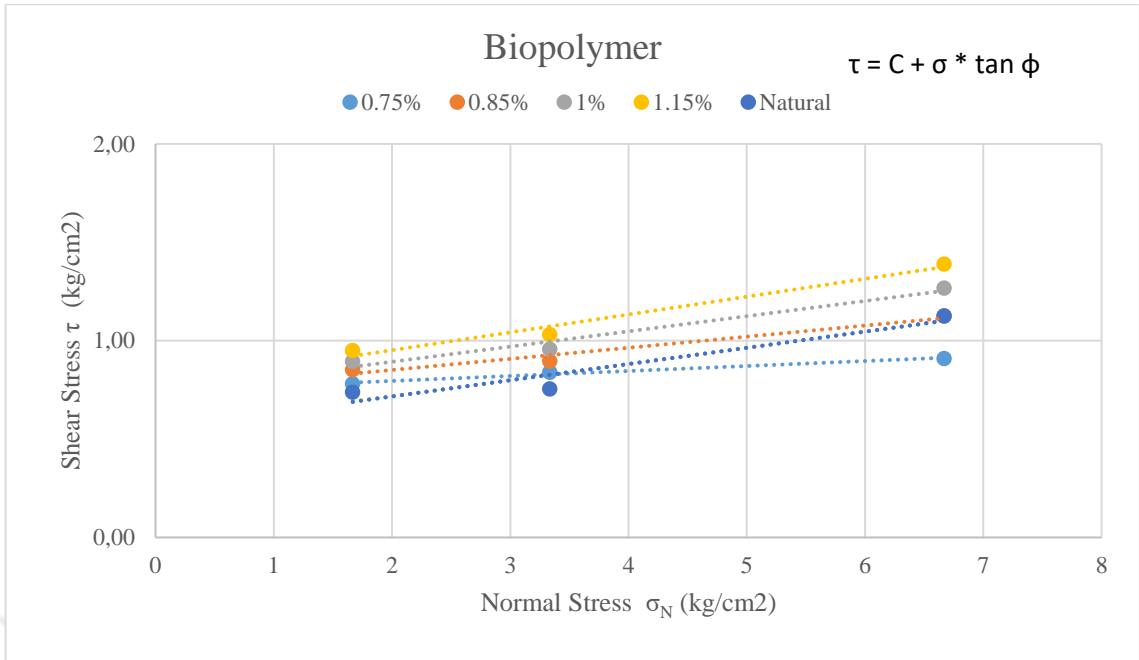


Figure 4.16. Failure envelope of the samples mixed with Agar Gum biopolymer at various ratios.

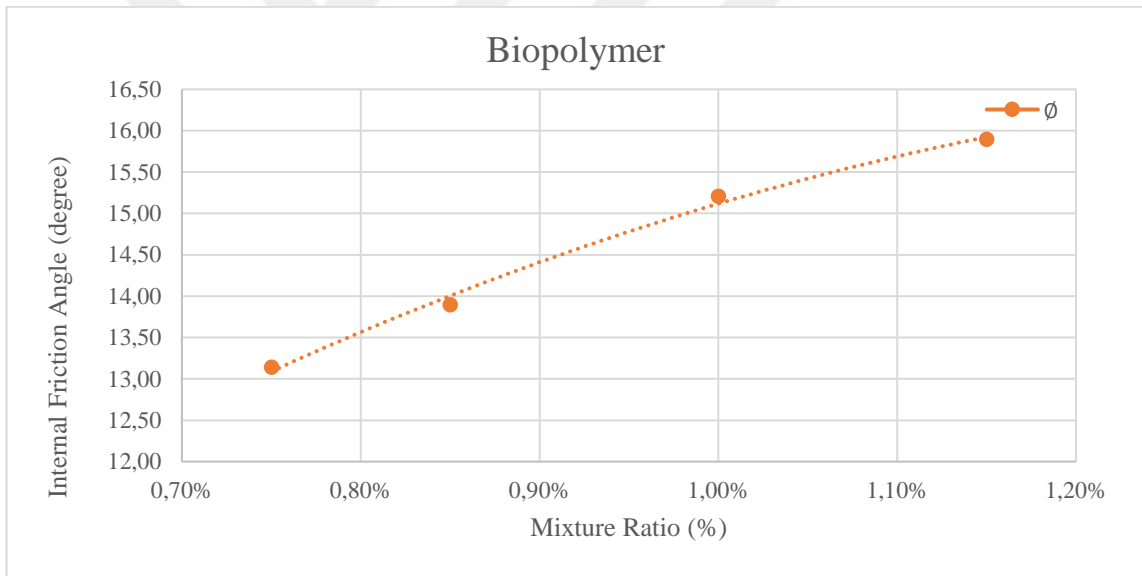


Figure 4.17. Comparison between Internal Friction Angle ( $\phi$ ) values by various AG mixing ratios.

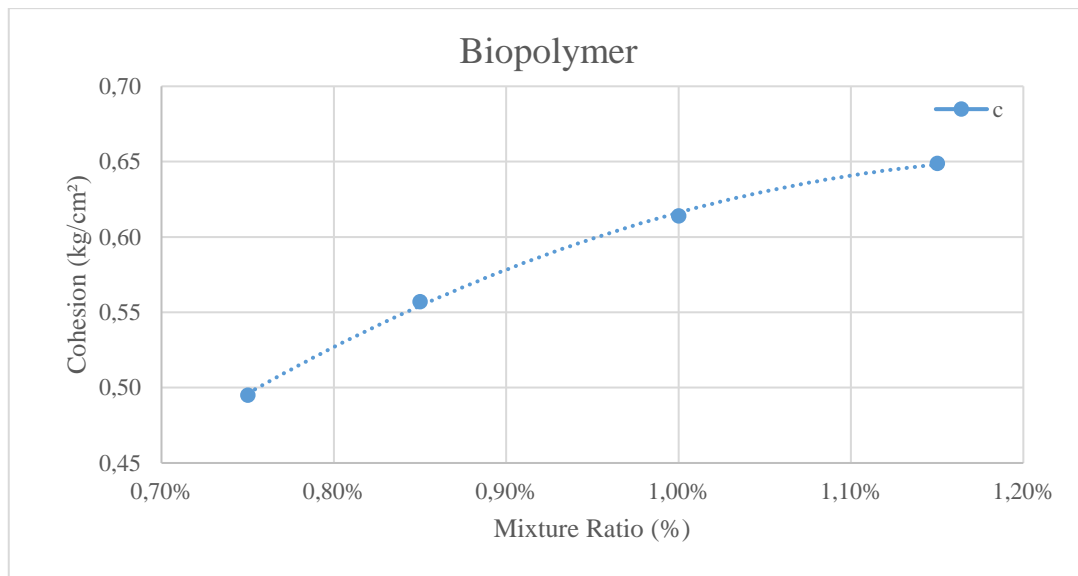


Figure 4.18. Comparison between Cohesion (c) values by various AG mixing ratios.

#### 4.5.3. Ferrochromium Slag Additive

The direct shear test conducted on clay soil mixed with 1% ferrochromium slag, to ascertain its performance. The soil-slag mixture demonstrated a cohesion coefficient of 0.5 kg/cm<sup>2</sup> and an internal friction angle of 14.48 degrees, indicative of the soil's resistance to sliding along potential failure planes. As expected, the shear stress of the soil-slag mixture increased with the normal load, albeit at a diminishing rate. Specifically, under normal loads of 3 kg, 6 kg, and 12 kg, the shear stresses were recorded as 0.93 kg/cm<sup>2</sup>, 0.95 kg/cm<sup>2</sup>, and 1.42 kg/cm<sup>2</sup>, respectively.

The results underscore the beneficial influence of ferrochromium slag on the shear properties of clay soil. The slag notably augmented the cohesion coefficient and internal friction angle, essential parameters signaling the soil's resistance to shear failure. Additionally, the observed increase in shear stress with normal load aligns with anticipated soil behavior under shear loading conditions, further affirming the efficacy of ferrochromium slag as a soil enhancer. Some of the several noteworthy findings are:

- The impact of ferrochromium slag on the shear strength of clay soil is moderate, with the soil-slag mixture exhibiting a cohesion coefficient 0.1 kg/cm<sup>2</sup> higher and an internal friction angle 1.4 degrees higher compared to natural clay soil. These enhancements signify heightened resistance to shear failure in the soil-slag mixture, although not as much as the AG.

- The effect of ferrochromium slag on the shear strength of clay soil remains consistent across different normal loads. The linear increase in shear stress with normal load implies a constant slope of the shear stress-normal load curve, indicative of uniform and stable shear behavior in the soil-slag mixture under varying normal loads.

- Ferrochromium slag emerges as a promising alternative to conventional chemical additives for enhancing the shear strength of clay soil. Its status as a recyclable waste product contributes to reduced environmental impact and disposal costs. Moreover, requiring low dosages for significant

soil property improvement underscores its cost-effectiveness in geotechnical engineering applications.

Table 4.11 Shear test results of sample mixed with optimum 1% Ferrochromium slag additive.

1% Ferrochromium				
kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c (kg/cm <sup>2</sup> )	$\phi$
3	1.667	0.93	0.50	14.48
6	3.334	0.95		
12	6.668	1.42		

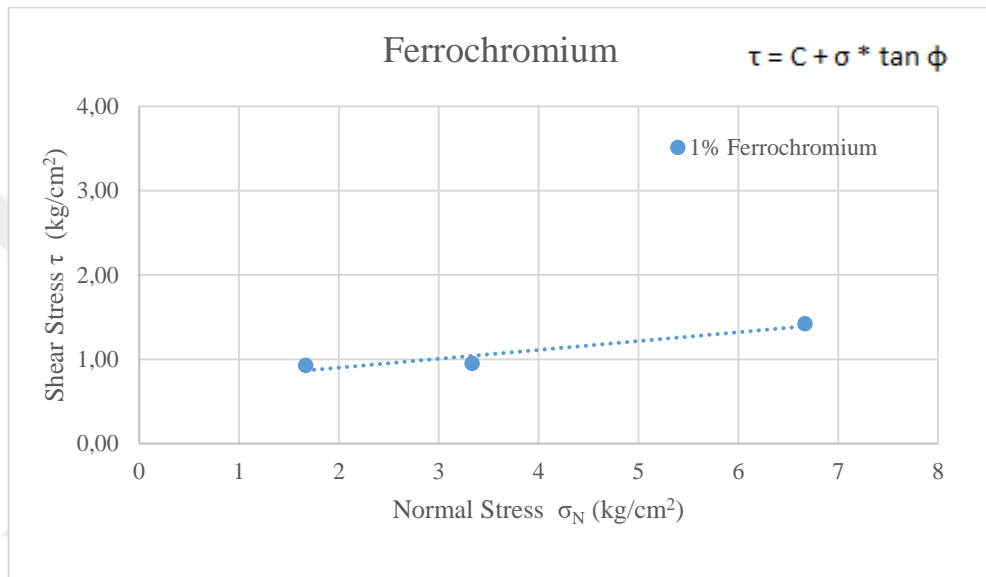


Figure 4.19. Failure envelope of the soil mixed with optimum 1% Ferrochromium slag additive.

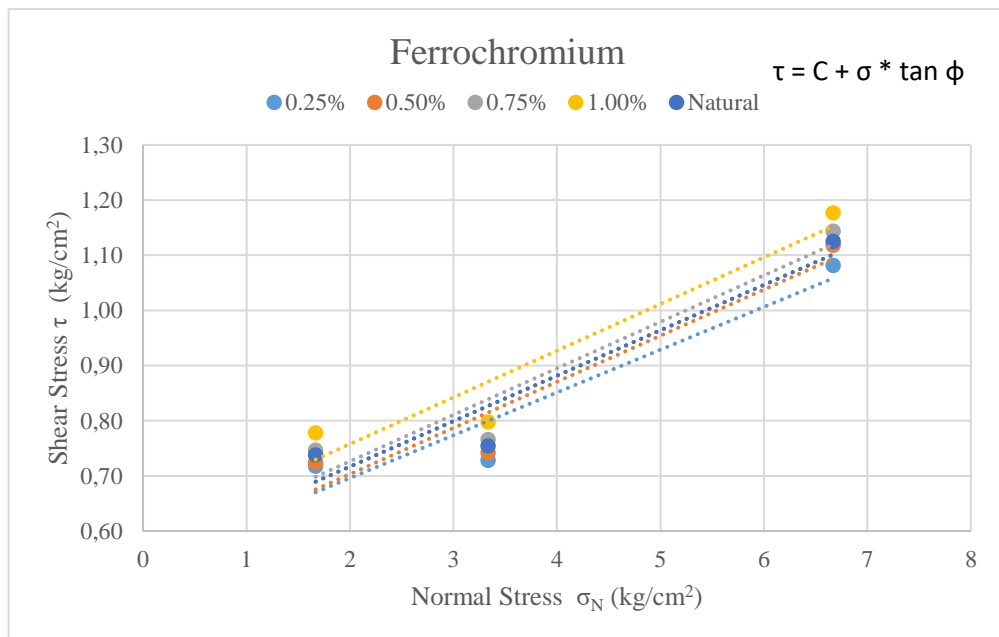


Figure 4.20. Failure envelope of the samples mixed with Ferrochromium Slag additive at various ratios.

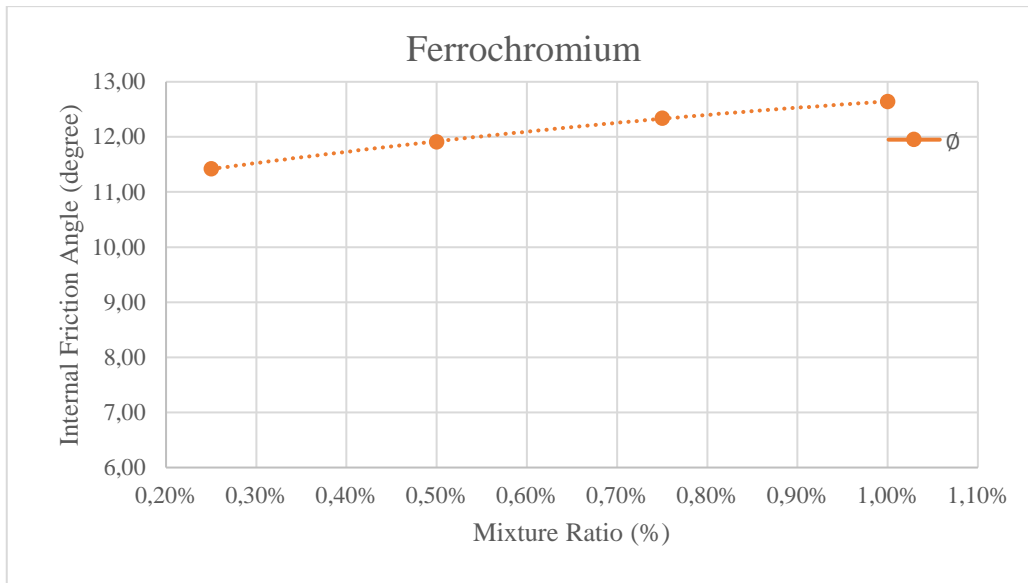


Figure 4.21. Comparison between Internal Friction Angle ( $\emptyset$ ) values by various FC mixing ratios.

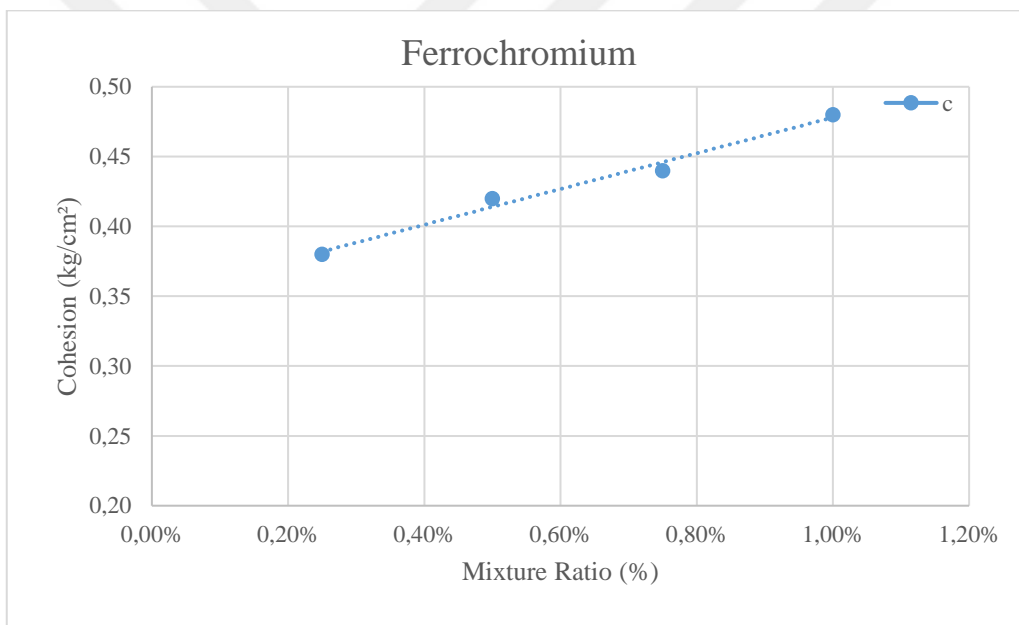


Figure 4.22. Comparison between Cohesion (c) values by various FC mixing ratios.

#### 4.5.4. Biopolymer and Ferrochromium Mixture Additive

The cohesion coefficient and internal friction angle of the soil-slag-biopolymer mixture were scrutinized across various curing periods, illustrating the soil's resistance to sliding along failure planes. Additionally, the shear stress under different normal loads (3, 6, and 12 kg) was evaluated for each curing period, reflecting the force per unit area causing soil layers to slide over one another.

Following the homogenization of soil with 1% agar gum biopolymer and 1% ferrochromium slag for 1 day, the cohesion coefficient measured 0.39 kg/cm<sup>2</sup>, with an internal friction angle of 11.17 degrees. Correspondingly, shear stress under normal loads of 3 kg, 6 kg, and 12 kg recorded 0.72 kg/cm<sup>2</sup>, 0.73 kg/cm<sup>2</sup>, and 1.09 kg/cm<sup>2</sup>, respectively.

After 7 days of homogenization, the cohesion coefficient rose to 0.67 kg/cm<sup>2</sup>, and the internal friction angle reached 16.16 degrees. Simultaneously, shear stress values under normal loads of 3 kg, 6 kg, and 12 kg surged to 1.22 kg/cm<sup>2</sup>, 1.26 kg/cm<sup>2</sup>, and 1.88 kg/cm<sup>2</sup>.

With 14 days of homogenization, the cohesion coefficient further elevated to 1.02 kg/cm<sup>2</sup>, while the internal friction angle reached 29.37 degrees. Under normal loads of 3 kg, 6 kg, and 12 kg, shear stress measurements ascended to 1.88 kg/cm<sup>2</sup>, 1.93 kg/cm<sup>2</sup>, and 2.88 kg/cm<sup>2</sup>, respectively.

At 21 days of homogenization, the cohesion coefficient stabilized at 1.09 kg/cm<sup>2</sup>, and the internal friction angle settled at 31.45 degrees. Correspondingly, shear stress values under normal loads of 3 kg, 6 kg, and 12 kg reached 2.02 kg/cm<sup>2</sup>, 2.06 kg/cm<sup>2</sup>, and 3.08 kg/cm<sup>2</sup>.

Finally, after 28 days of homogenization, the cohesion coefficient slightly decreased to 0.89 kg/cm<sup>2</sup>, with the internal friction angle reducing to 25.48 degrees. Shear stress under normal loads of 3 kg, 6 kg, and 12 kg measured 1.63 kg/cm<sup>2</sup>, 1.67 kg/cm<sup>2</sup>, and 2.50 kg/cm<sup>2</sup>, respectively.

The results affirm that the addition of agar gum biopolymer and ferrochromium slag augmented both the cohesion coefficient and internal friction angle, signaling enhanced resistance to shear failure in the soil-slag-biopolymer mixture compared to natural clay soil.

Furthermore, optimal curing time for maximum shear strength was identified as 21 days, facilitating the formation and hardening of hydrogels binding soil particles. Beyond this period, a decrease in shear strength indicated increased brittleness and decreased ductility in the soil-slag-biopolymer mixture.

Additionally, the soil-slag-biopolymer mixture demonstrated increased ductility and reduced brittleness under higher normal loads, indicating its favorable response to elevated stress conditions.

Table 4.12 Shear test results of sample mixed with both optimum 1% Agar Gum biopolymer and Ferrochromium slag additive at various curing days.

Ferrochromium +Biopolymer					
Time	kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c (kg/cm <sup>2</sup> )	$\phi$
1 day	3	1.667	0.72	0.39	11.17
	6	3.334	0.73		
	12	6.668	1.09		
7 days	3	1.667	1.22	0.67	19.16
	6	3.334	1.26		
	12	6.668	1.88		
14 days	3	1.667	1.88	1.02	29.37
	6	3.334	1.93		
	12	6.668	2.88		
21 days	3	1.667	2.02	1.09	31.45
	6	3.334	2.06		
	12	6.668	3.08		
28 days	3	1.667	1.63	0.89	25.48
	6	3.334	1.67		
	12	6.668	2.50		

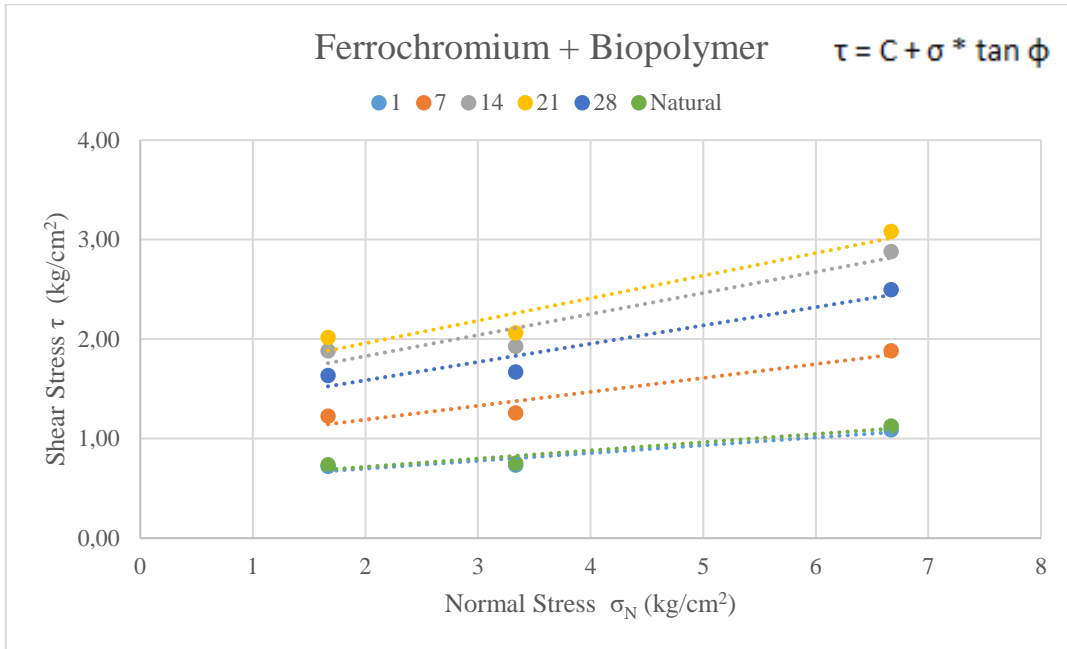


Figure 4.23. Failure envelope of the soil mixed with both optimum 1% Agar Gum biopolymer and 1% Ferrochromium slag additive.

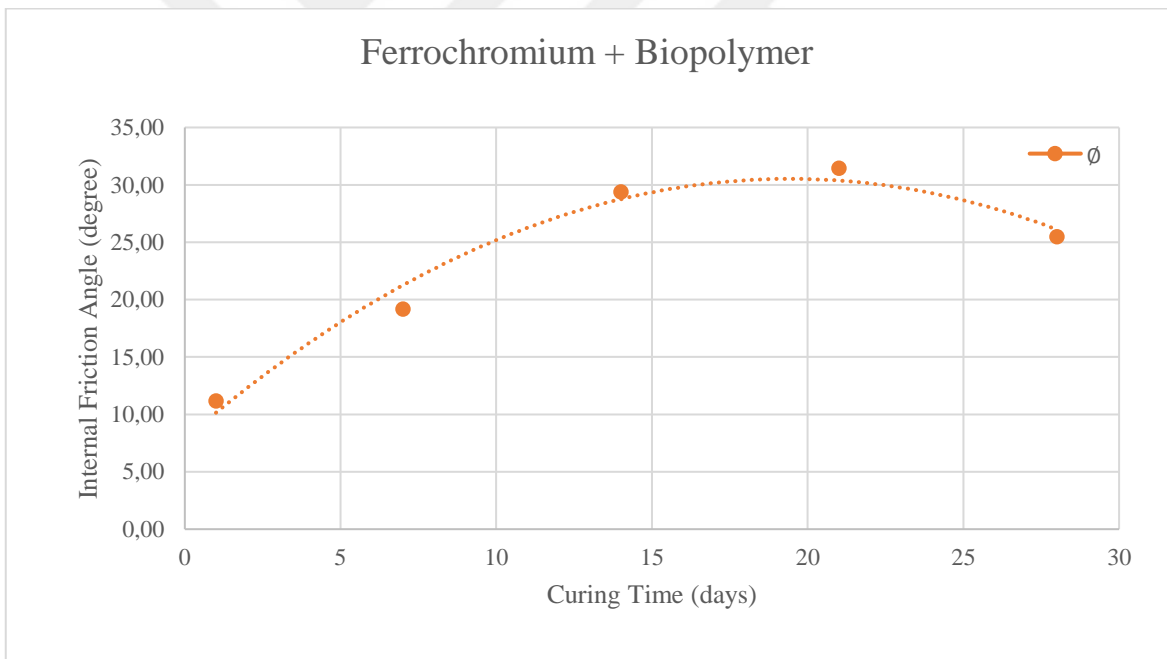


Figure 4.24. Comparison between Internal Friction Angle ( $\phi$ ) values by curing days.

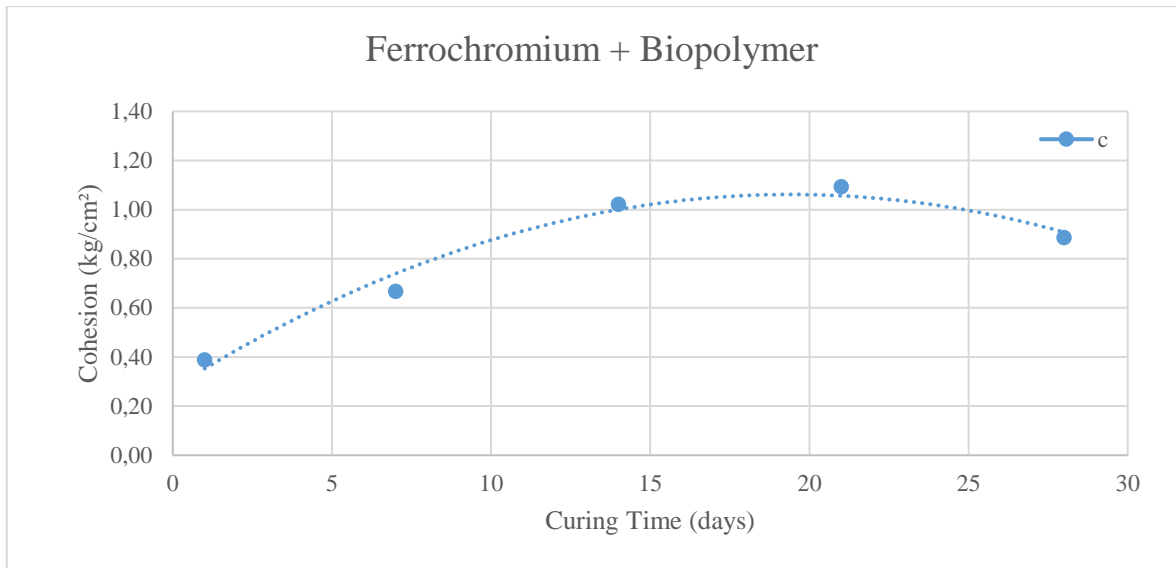


Figure 4.25. Comparison between Cohesion (c) values by curing days.

Table 4.13 Shear test results of samples mixed with Agar Gum biopolymer additive at various mixing ratios.

Ferrochromium (21 days)					
%	kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c (kg/cm <sup>2</sup> )	$\phi$
0.25%	3	1.667	0.72	0.38	11.42
	6	3.334	0.73		
	12	6.668	1.08		
0.50%	3	1.667	0.72	0.42	11.91
	6	3.334	0.74		
	12	6.668	1.12		
0.75%	3	1.667	0.75	0.44	12.34
	6	3.334	0.77		
	12	6.668	1.14		
1.00%	3	1.667	0.78	0.48	12.64
	6	3.334	0.80		
	12	6.668	1.18		

#### 4.5.5. Freeze-Thaw Performance

The examination of soil mixed with 1% Agar Gum biopolymer and 1% Ferrochromium slag after multiple freeze-thaw cycles revealed significant alterations in shear properties. Here's a breakdown of the findings and their implications:

- After subjecting the soil-slag-biopolymer mixture to 2, 4, 8, and 16 freeze-thaw cycles, both cohesion coefficient and internal friction angle decreased. This indicates reduced resistance to shear failure, suggesting that freeze-thaw cycles compromised the soil's stability and integrity.

- The shear stress of the soil-slag-biopolymer mixture declined under all normal loads (3, 6, and 12 kg) as the number of freeze-thaw cycles increased. This decline in shear strength suggests

diminished stability and structural integrity, rendering the mixture less capable of withstanding shear forces.

- The study concludes that the soil-slag-biopolymer mixture may not be suitable for regions experiencing frequent freeze-thaw cycles. The decrease in shear parameters and shear stress highlights the mixture's susceptibility to frost action, which can lead to compromised shear strength and stability over time.

- To mitigate the adverse effects of freeze-thaw cycles, protective measures such as insulation or drainage systems (e.g., geotextiles, geomembranes, or geocomposites) are recommended. These measures can help shield the soil-slag-biopolymer mixture from frost action and preserve its shear strength and stability.

- While agar gum biopolymer and ferrochromium slag offer potential benefits for soil stabilization under normal conditions, their inability to withstand freeze-thaw cycles raises concerns about their long-term efficacy in cold climates. However, their utilization may still have a lower environmental impact compared to certain chemical additives, as they utilize natural and recycled materials that are less harmful to the soil ecosystem and groundwater quality.

- The study underscores that the soil-slag-biopolymer mixture becomes increasingly susceptible to frost action with prolonged exposure to freeze-thaw cycles. This highlights the importance of considering environmental factors, such as climate conditions, when selecting soil stabilization methods for engineering projects.

In summary, while agar gum biopolymer and ferrochromium slag can enhance the shear performance of clay soil under normal conditions, their effectiveness may be compromised in environments prone to freeze-thaw cycles. Implementing protective measures and considering alternative stabilization methods may be necessary to address the challenges posed by freeze-thaw conditions and ensure the long-term stability of engineered soil structures.

Table 4.14 Shear test results of sample mixed with optimum 1% Agar Gum biopolymer additive at various freeze-thaw cycles.

Biopolymer					
Cycles	kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c (kg/cm <sup>2</sup> )	$\phi$
2 cycles	3	1.667	0.63	0.34	9.78
	6	3.334	0.64		
	12	6.668	0.95		
4 cycles	3	1.667	0.57	0.31	8.87
	6	3.334	0.58		
	12	6.668	0.86		
8 cycles	3	1.667	0.47	0.25	7.29
	6	3.334	0.48		
	12	6.668	0.71		
16 cycles	3	1.667	0.41	0.22	6.39
	6	3.334	0.42		
	12	6.668	0.62		

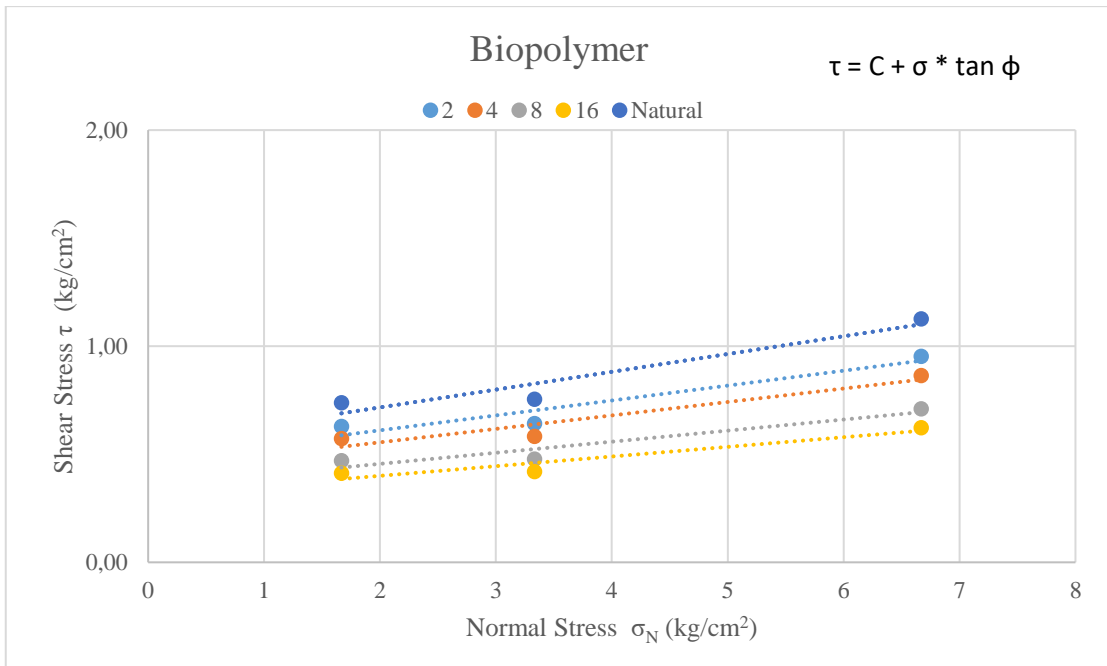


Figure 4.26. Failure envelopes of sample mixed with optimum 1% Agar Gum biopolymer additive at various freeze-thaw cycles.

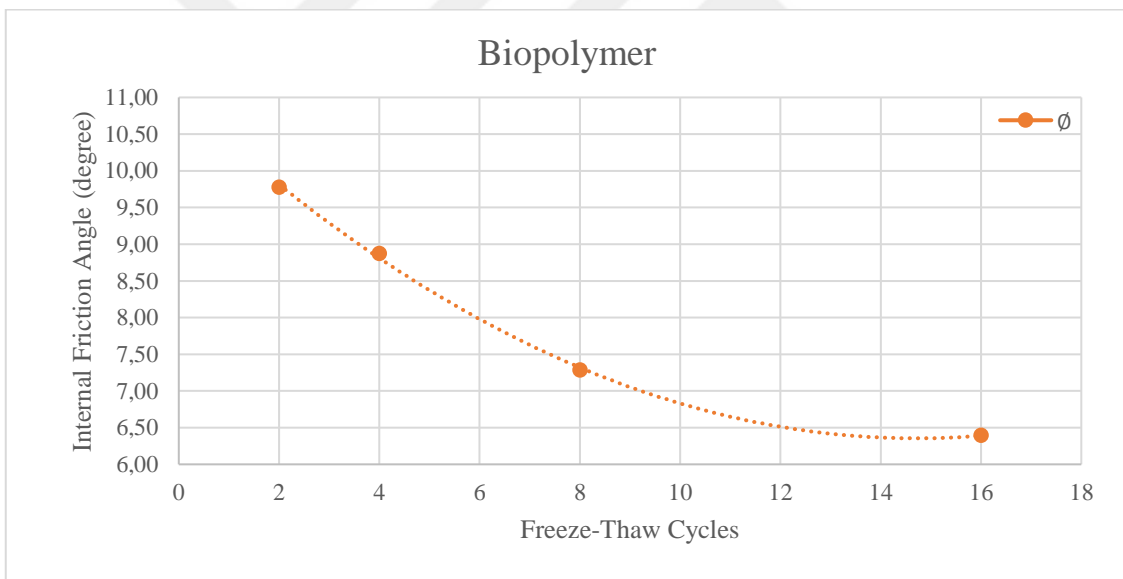


Figure 4.27. Comparison between Internal Friction Angles ( $\phi$ ) by freeze-thaw cycles.

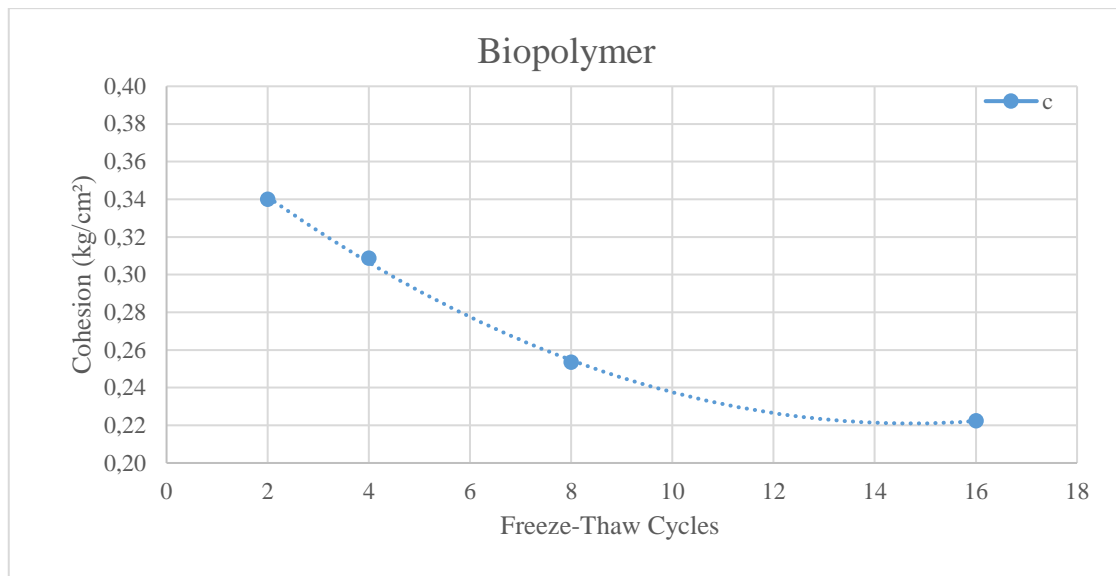


Figure 4.28. Comparison between Cohesion (c) values by freeze-thaw cycles.

Table 4.15 Shear test results of sample mixed with optimum 1% Ferrochromium slag additive at various freeze-thaw cycles.

Ferrochromium					
Cycles	kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c	$\phi$
2 cycles	3	1.667	0.68	0.37	10.59
	6	3.334	0.69		
	12	6.668	1.03		
4 cycles	3	1.667	0.64	0.35	9.93
	6	3.334	0.65		
	12	6.668	0.97		
8 cycles	3	1.667	0.60	0.33	9.35
	6	3.334	0.61		
	12	6.668	0.91		
16 cycles	3	1.667	0.56	0.30	8.64
	6	3.334	0.57		
	12	6.668	0.84		

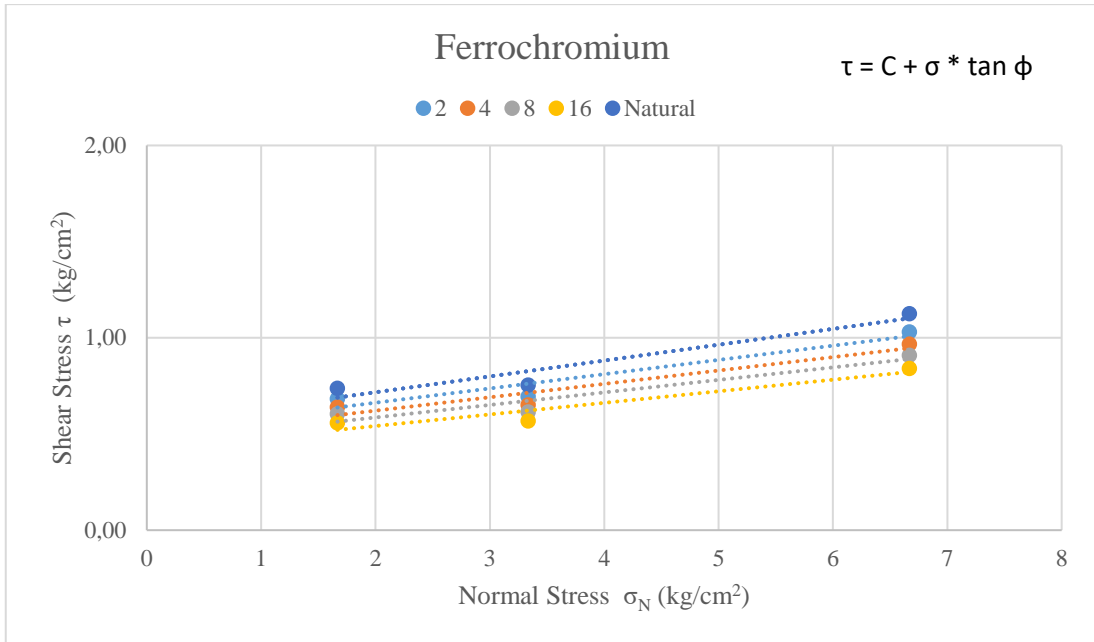


Figure 4.29. Failure envelopes of sample mixed with optimum 1% Ferrochromium slag additive at various freeze-thaw cycles.

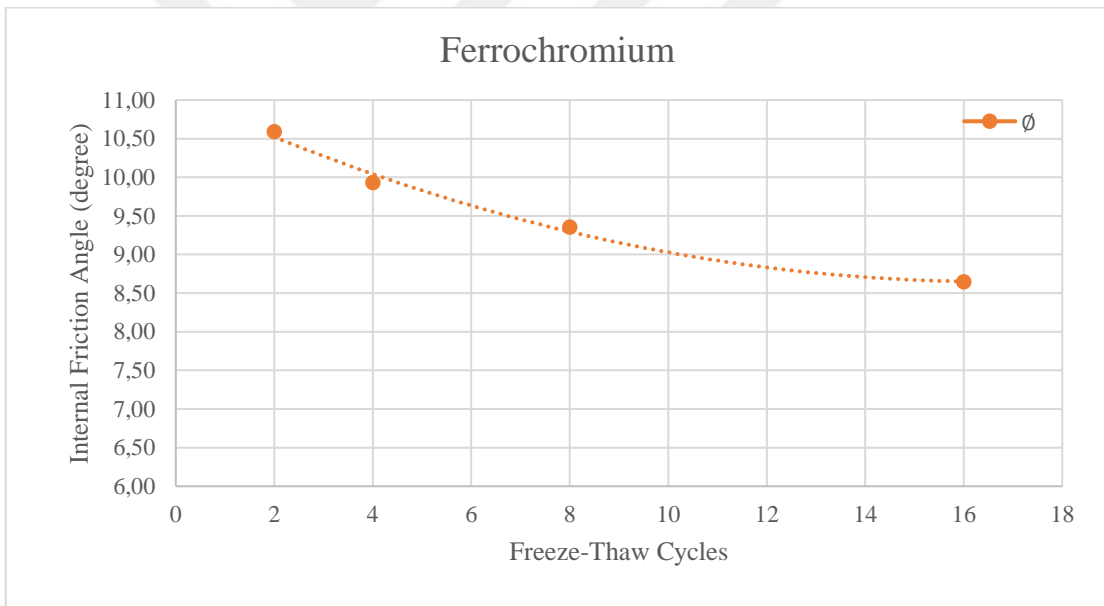


Figure 4.30. Comparison between Internal Friction Angles ( $\phi$ ) by freeze-thaw cycles.

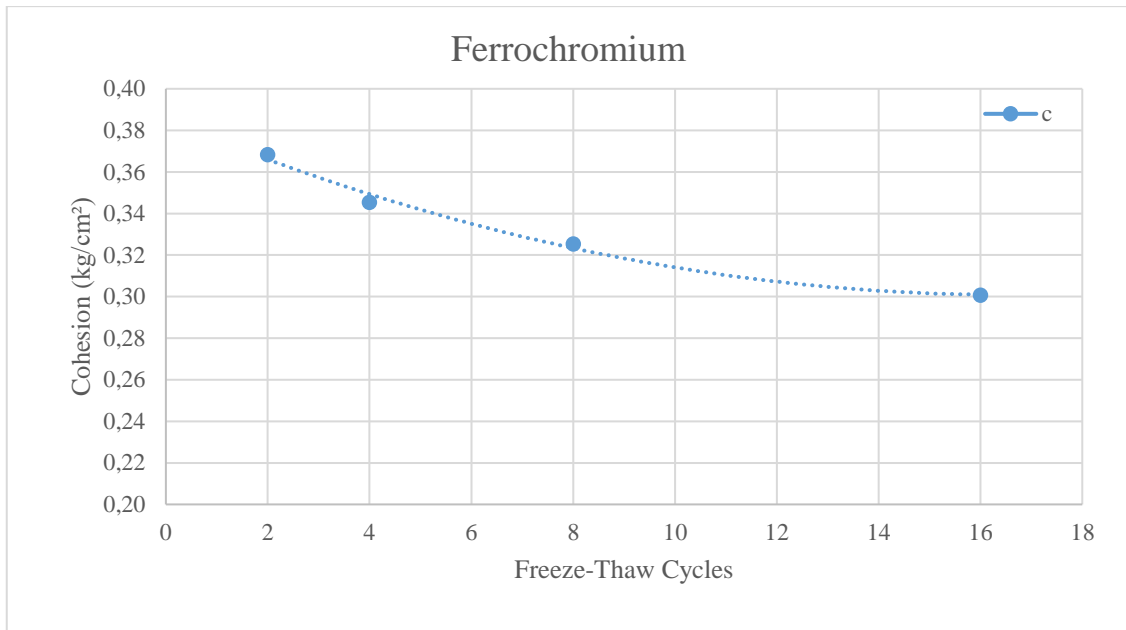


Figure 4.31. Comparison between Cohesion (c) values by freeze-thaw cycles.

Table 4.16 Shear test results of sample mixed with both optimum 1% Agar Gum biopolymer and Ferrochromium slag additive at various freeze-thaw cycles.

Ferrochromium + Biopolymer					
Cycles	kg	$\sigma_N$ (kg/cm <sup>2</sup> )	$\tau$ (kg/cm <sup>2</sup> )	c	$\phi$
2 cycles	3	1.667	0.66	0.35	10.17
	6	3.334	0.67		
	12	6.668	0.99		
4 cycles	3	1.667	0.60	0.32	9.24
	6	3.334	0.61		
	12	6.668	0.90		
8 cycles	3	1.667	0.52	0.28	7.97
	6	3.334	0.52		
	12	6.668	0.77		
16 cycles	3	1.667	0.46	0.25	7.08
	6	3.334	0.46		
	12	6.668	0.69		

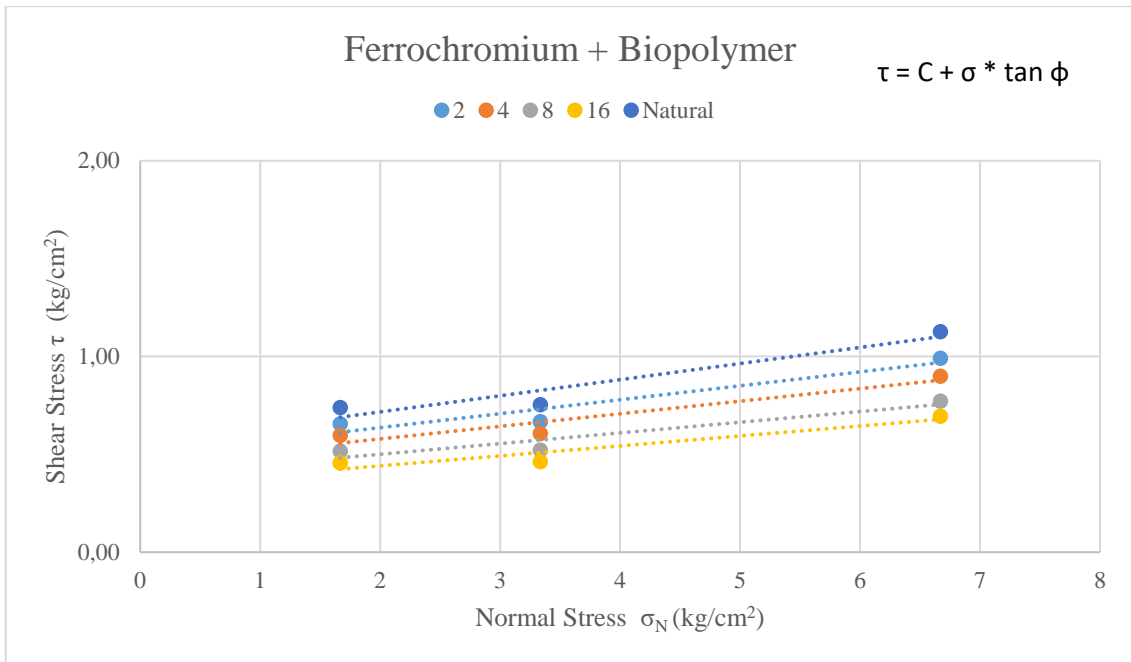


Figure 4.32. Failure envelopes of sample mixed with both optimum 1% Agar Gum biopolymer and Ferrochromium slag additive at various freeze-thaw cycles.

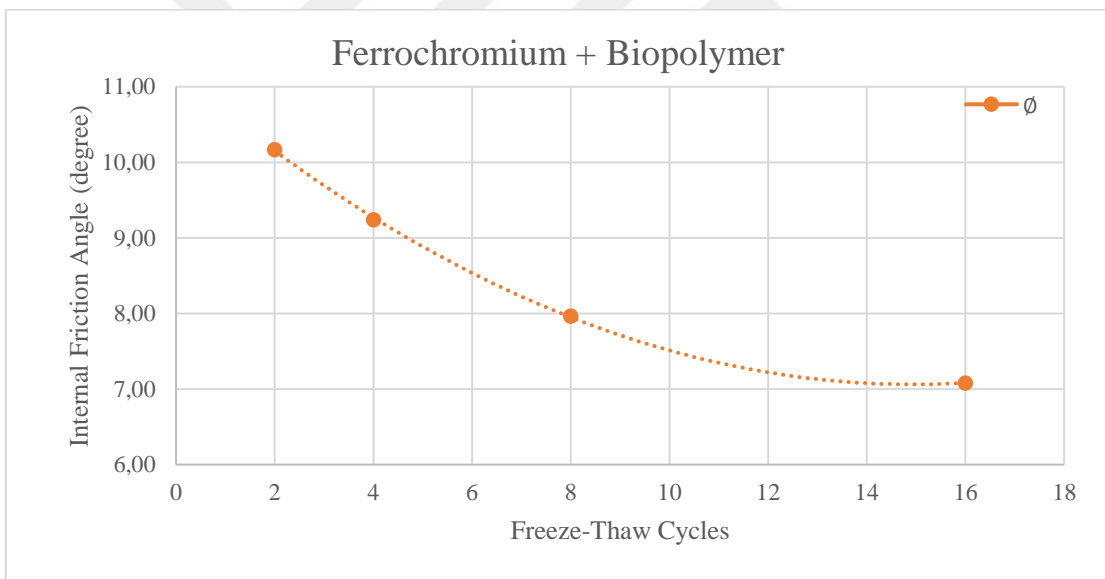


Figure 4.33. Comparison between Internal Friction Angles ( $\phi$ ) by freeze-thaw cycles.

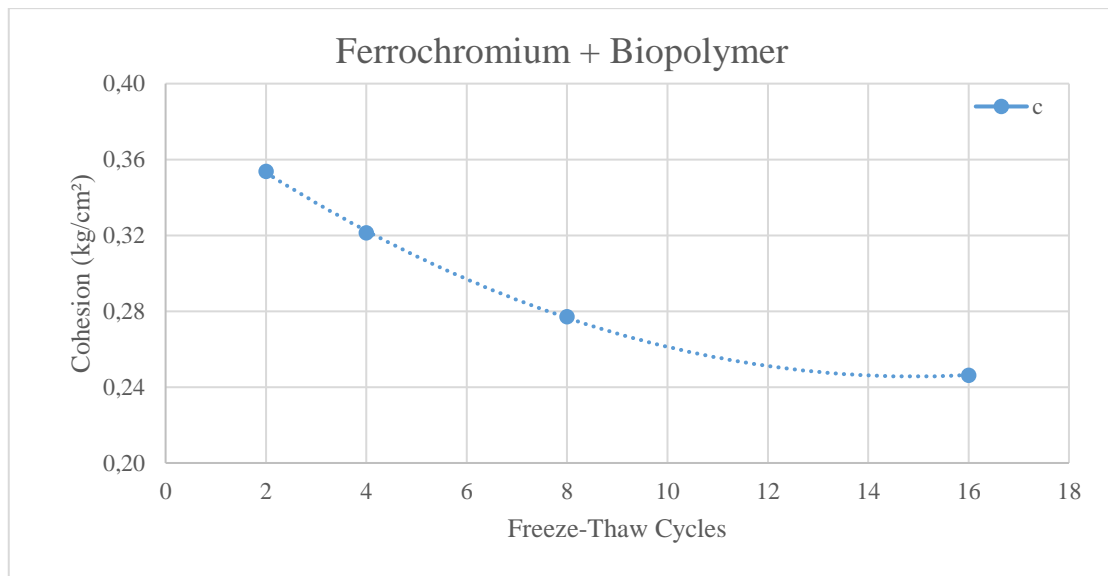


Figure 4.34. Comparison between Cohesion (c) values by freeze-thaw cycles.

#### 4.6. Microscopic Analysis

As previously discussed, Ferrochromium Slag (FS) presents certain environmental and health risks, necessitating treatment before safe use. This study explored the feasibility of using AG biopolymer in combination with FS. The hypothesis was that this combination would enhance the soil's mechanical properties while mitigating the potential environmental impact of FS, without compromising its soil improvement capabilities. Given that FS is granular and the treated biopolymer forms a gelatinous matrix, proper mixing was expected to encase the FS grains within the biopolymer. This encapsulation would reduce direct contact with the soil and minimize groundwater interaction, thereby lowering the risk of chromium leaching and other environmental hazards. Similar methodologies have been applied in earlier studies on soil stabilization using biopolymers with various admixtures. Figure 4.35 illustrates microscopic views of soil treated with FS alone compared to soil treated with a combination of FS and AG biopolymer. In the FS-treated soil, FS grains are visible in their uncoated, crystalline form with a metallic luster (Figure 4.35 a,b). In contrast, in the FS + AG-treated soil, the FS grains and other soil constituents are enveloped by the AG biopolymer, effectively eliminating direct contact with the soil and reducing the potential for chromium leaching (Figure 4.35 c–f) (Çetin et al., 2024).

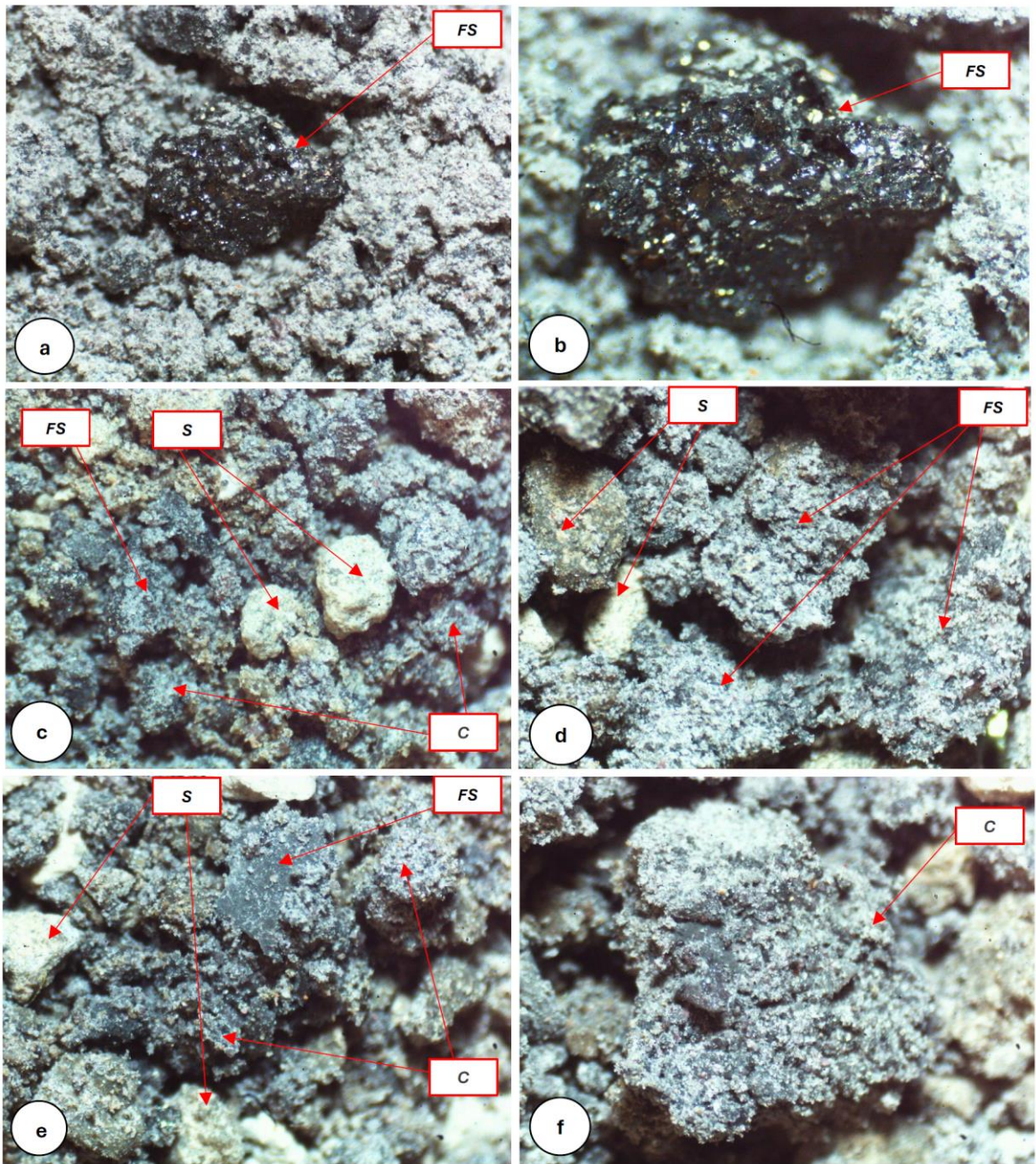


Figure 4.35. The microscopic views of (a) FS grain surrounded by silt grains and clay domains not treated with AG, (b) a close-up view of the exact FS grain, (c) a general view of the sample with both FS and AG admixtures together, (d) a close-up view of FS and AG admixtures together, (e) FS grain partially coated with AG, and (f) a clay domain coated with AG. Notice the uncoated (a,b), coated (d), and partially coated (e) nature of the FS grains surrounded by other constituents. FS: Ferrochromium Slag, S: silt, C: clay domain. Photo lengths: (a) 1.5 mm, (b,f) 1 mm, (c,e) 5 mm, and (d) 3 mm.

## 5. CONCLUSIONS

The main aim of this study was to investigate the feasibility and efficiency of using FeCr alongside with biopolymer as a soil stabilizer for clayey soils. The soil samples with different combinations of the FeCr and biopolymer additives were subjected to various tests such as Atterberg limits, compaction, unconfined compression, and direct shear as well as various curing periods and freeze-thaw cycles.

The following main conclusions were obtained:

The results indicate that the addition of biopolymer decreased the LL of the soil slightly, from 42% to 40%, and PI, from 16% to 14%, at higher ratios of 1% and 1.15%, while not affecting the PL of the soil which remained around 25%.

The compaction test results showed that AG biopolymer addition slightly reduced the OMC and increased the MDD of the soil. The OMC decreased from 17.50% for the natural soil to 16.85% for the soil mixed with 1% AG biopolymer, while the MDD increased from 1.83 g/cm<sup>3</sup> for the natural soil to 1.87 g/cm<sup>3</sup> for the soil mixed with 1% AG biopolymer.

The unconfined compressive strength increased from 1.79 kg/cm<sup>2</sup> to 2.19 kg/cm<sup>2</sup> (22 % increase) up to the mixing ratio of 0.85%; then it decreased to 1.98 kg/cm<sup>2</sup> at the mixing ratio of 1.15%, indicating an optimum mixing ratio of 0.9% AG. Additionally, the strength increased to 2.49 kg/cm<sup>2</sup> (39 % increase) after 28 days of curing time. The higher the curing time the higher the unconfined compressive strengths of the AG-treated soil.

The unconfined compressive strength soil increased with increasing FC slag content up to 1%, reaching a maximum value of 2.19 kg/cm<sup>2</sup>, which is 21.99% higher than the original strength. This improvement may be attributed to the filling effect and pozzolanic reaction of FC slag, which reduced the void ratio and increased the density of the soil. The compressive strength decreased with further increasing FC slag content beyond 1%, indicating an optimum FC slag content range for soil stabilization.

The combination of FC slag and AG biopolymer improved the compressive strength of clay soil significantly. The maximum unconfined compressive strength of 2.64 kg/cm<sup>2</sup> was obtained for the curing period of 28 days, which is 47% higher than the original value of 1.79 kg/cm<sup>2</sup>.

As for the freeze-thaw resistance, the FC slag-stabilized samples had the highest compressive strength values among the three types of stabilized samples, ranging from 1.64 kg/cm<sup>2</sup> to 1.39 kg/cm<sup>2</sup> as the number of cycles increased from 2 to 16. This implies that FC slag is more effective than AG biopolymer in enhancing the freeze-thaw resistance of clay soil.

The AG biopolymer-stabilized samples had the lowest compressive strength values, ranging from 1.52 kg/cm<sup>2</sup> to 0.99 kg/cm<sup>2</sup> as the number of cycles increased from 2 to 16, suggesting that AG biopolymer was less effective than FC slag in improving the freeze-thaw resistance of clay soil.

The optimum mixture-stabilized (1% FC slag and 1% AG biopolymer) samples had intermediate compressive strength values between the FC slag-stabilized and AG biopolymer-stabilized samples, ranging from 1.58 kg/cm<sup>2</sup> to 1.08 kg/cm<sup>2</sup> as the number of cycles increased from 2 to 16, indicating that the optimum mixture had a moderate effect on enhancing the freeze-thaw resistance of clay soil.

For the soil mixed with 1% optimal ferrochromium slag, the shear strength increased from 1.13 kg/cm<sup>2</sup> to 1.42 kg/cm<sup>2</sup> (26 % increase). Under the same conditions, the cohesion increased from 0.4 kg/cm<sup>2</sup> to 0.5 kg/cm<sup>2</sup> (25 % increase) and the internal friction angle increased from 11.5 to 14.48 degrees (26 % increase). The higher the normal pressure the higher the shear strength.

For the soil mixed with 1% optimal Agar Gum biopolymer, the shear strength increased from 1.13 kg/cm<sup>2</sup> to 2.94 kg/cm<sup>2</sup> (160 % increase) under 6.67 kg/cm<sup>2</sup> normal pressure after 21 days of curing time. Also, under the same conditions, the cohesion increased from 0.4 kg/cm<sup>2</sup> to 1.04 kg/cm<sup>2</sup> (160 % increase) and the internal friction angle increased from 11.5 to 29.95 degrees (160 % increase). The higher the normal pressure the higher the shear strength. The higher the curing time the higher the shear strength, cohesion and internal friction angle up to 21 days. Also, the higher the normal pressure the higher the shear strength.

For the soil mixed with 1% optimal Agar Gum biopolymer and 1% optimal ferrochromium slag, the shear strength increased from 1.13 kg/cm<sup>2</sup> to 3.08 kg/cm<sup>2</sup> (173 % increase) under 6.67 kg/cm<sup>2</sup> normal load and after 21 days of curing time. Under the same conditions, the cohesion increased from 0.4 kg/cm<sup>2</sup> to 1.09 kg/cm<sup>2</sup> (173 % increase), the internal friction angle increased from 11.5 to 31.45 degrees (173 % increase). The higher the curing time the higher the shear strength, cohesion and internal friction angle up to 21 days. Also, the higher the normal pressure the higher the shear strength.

As for the freeze-thaw resistance, for the soil mixed with 1% optimal Agar Gum biopolymer, the shear strength decreased from 1.13 kg/cm<sup>2</sup> to 0.62 kg/cm<sup>2</sup> (45 % decrease) under 6.67 kg/cm<sup>2</sup> normal load and after 16 cycles of freeze-thaw. Also, the cohesion decreased from 0.4 kg/cm<sup>2</sup> to 0.22 kg/cm<sup>2</sup> (45 % decrease), and the internal friction angle decreased from 11.5 to 6.39 degrees (44 % decrease) under 6.67 kg/cm<sup>2</sup> normal load. The higher the freeze-thaw cycle the lower the shear strength, cohesion and internal friction angle.

For the soil mixed with 1% optimal ferrochromium slag, the shear strength decreased from 1.13 kg/cm<sup>2</sup> to 0.84 kg/cm<sup>2</sup> (22 % decrease) under 6.67 kg/cm<sup>2</sup> normal load and after 16 cycles of freeze-thaw. Also, the cohesion decreased from 0.4 kg/cm<sup>2</sup> to 0.30 kg/cm<sup>2</sup> (25 % decrease), and the internal friction angle decreased from 11.5 to 8.64 degrees (25 % decrease) under 6.67 kg/cm<sup>2</sup> normal

load. Again, the higher the freeze-thaw cycle the lower the shear strength, cohesion and internal friction angle.

Moreover, for the soil mixed with 1% optimal Agar Gum biopolymer and 1% optimal ferrochromium slag, the shear strength decreased from  $1.13 \text{ kg/cm}^2$  to  $0.69 \text{ kg/cm}^2$  (39 % decrease) under  $6.67 \text{ kg/cm}^2$  normal load and after 16 cycles of freeze-thaw. Also, the cohesion decreased from  $0.4 \text{ kg/cm}^2$  to  $0.25 \text{ kg/cm}^2$  (38 % decrease), and the internal friction angle decreased from 11.5 to 7.08 degrees (39 % decrease) under  $6.67 \text{ kg/cm}^2$  normal load. Again, the higher the freeze-thaw cycle the lower the shear strength, cohesion and internal friction angle.

The geotechnical parameters of biopolymer and ferrochrome-treated soils increased considerably compared to the pure clay soil especially after 21 days of curing time, at the optimal percentage of 1% for both additives.

Finally, the results indicate that the optimal mixtures of 1% Agar Gum biopolymer and 1% ferrochromium slag alone as well as together with can be used above ground water tables where low permeability and high strength are needed in fills such as highway embankments, bridge abutments and backfills behind retaining structures especially when low bearing capacity and high settlement problems exist. The results may be particularly useful in cases where soil improvement is needed, considering criteria such as bearing capacity, settlement, swelling potential, permeability, liquefaction potential, and behavior under seismic loads. These potential application settings and the totality of the results are indicative of the improvement of the soil under the seismic effects generated by an Earthquake.

Furthermore, the result of this study demonstrates that biopolymer and ferrochrome additives are environmentally friendly and economical methods. Freeze-thaw cycles in cold seasons seem, however, to have an adverse effect on the shear strength. The soil constituents and in turn, the structure or fabric seem to deteriorate as a result of tensile cracking of the grains caused by pore water pressures within the pores of individual grains as well as between the grains themselves after each cycle.

In summary, the geotechnical parameters of biopolymer and ferrochrome-treated soils increased considerably compared to the pure clay soil. The results may be particularly useful in cases where soil improvement is needed, considering criteria such as bearing capacity, settlement, swelling potential, permeability, frost resistance, liquefaction potential, and behavior under seismic loads. Furthermore, the result of this study demonstrates that biopolymer and ferrochrome additives are environmentally friendly and economical methods. Therefore, the results of this study may be beneficial in the fields of soil engineering, civil engineering, road engineering, and infrastructure engineering.



## REFERENCES

- Abdeldjouad, L., Asadi, A., Nahazanan, H., Huat, B.B.K., Dheyab, W., Elkhebu, A.G. (2019). International Journal of Geosynthetics and Ground Engineering, 5:4 <https://doi.org/10.1007/s40891-019-0157-y>
- Abdelkader, H.A.M., Hussein, M.M.A and Ye, H. (2021). Influence of Waste Marble Dust on the Improvement of Expansive Clay Soils. Advances in Civil Engineering, 2021:3192122. <https://doi.org/10.1155/2021/3192122>
- Agarwal, N. (2010). Effect of stone dust on some geotechnical properties of soil. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE, 12(1): 61–64. <https://doi.org/10.9790/1684-12116164>
- Agarwal, N. (2015). Effect of stone dust on some geotechnical properties of soil. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 12(1): 61–64.
- Al-Jabri, K. (2018). Research on the use of Ferro-Chrome slag in civil engineering applications. MATEC Web of Conferences. <https://doi.org/10.1051/mateconf/201814901017>
- Annagür, H.M. and Çetin, M.Y. (2023). Performance and Geotechnical Properties of the Aggregates Used for the Turkish Trans-European Motorway Truck Escape Ramps. Transportation Infrastructure Geotechnology, 1–25. <https://doi.org/10.1007/S40515-023-00333-Y>
- Arabani, M., & Shalchian, M. M. (2023). A review of the use of bio-based substances in soil stabilization. Environment, Development and Sustainability 2023, 1–53. <https://doi.org/10.1007/S10668-023-03241-W>
- Ashraf, M. S., Azahar, S. B., & Yusof, N. Z. (2017). Soil Improvement Using MICP and Biopolymers: A Review. IOP Conference Series: Materials Science and Engineering, 226(1). <https://doi.org/10.1088/1757-899X/226/1/012058>
- ASTM, D 698-12 (2021). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lb/ft<sup>3</sup> (600 kN-m/m<sup>3</sup>)). In: Annual Book of ASTM Standards, West Conshohocken, PA, USA. <http://www.astm.org/cgi-bin/resolver.cgi?D698-12R21>
- ASTM D 854-23 (2023). Standard Test Method for Specific Gravity of Soils by the Water Displacement Method. In: Annual Book of ASTM Standards. ASTM, Philadelphia, PA, USA.
- ASTM D 2166-06. (2006) Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. In: Annual Book of ASTM Standards, West Conshohocken, PA, USA.

- ASTM D 2487-06 (2010). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). In: Annual Book of ASTM Standards, West Conshohocken, PA, USA. <http://www.astm.org/cgi-bin/resolver.cgi?D2487-06>
- ASTM D 3080-04 (2012). Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. In: Annual Book of ASTM Standards, West Conshohocken, PA, USA. <http://www.astm.org/cgi-bin/resolver.cgi?D3080-04>
- ASTM D 4318-17e1 (2018). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. In: Annual Book of ASTM Standards, West Conshohocken, PA, USA.
- Ayeldeen, M. K., Negm, A. M., & El Sawwaf, M. A. (2016). Evaluating the physical characteristics of biopolymer/soil mixtures. *Arabian Journal of Geosciences*, 9(5). <https://doi.org/10.1007/s12517-016-2366-1>
- Bağrıaçık, B. (2021). Utilization of alkali-activated construction demolition waste for sandy soil improvement with large-scale laboratory experiments. *Construction and Building Materials* 302:124173.
- Bağrıaçık, B., Uslu, F.M., Yiğittekin, E.S., Delik, A., Dinçer, S. (2021). The behavior of *Bacillus* sp. improved soils under the freeze-thaw effect. *NOHU J. Eng. Sci.*, 10(2):704-711.
- Basu, D., Misra, A., & Puppala, A. J. (2015). Sustainability and geotechnical engineering: Perspectives and review. *Canadian Geotechnical Journal*, 52(1): 96–113. <https://doi.org/10.1139/cgj-2013-0120>
- Biju, M. S., & Arnepalli, D. N. (2019). Biopolymer-modified soil: Prospects of a promising green technology. *Lecture Notes in Civil Engineering*, 16: 163–169. [https://doi.org/10.1007/978-981-13-0899-4\\_20/COVER](https://doi.org/10.1007/978-981-13-0899-4_20/COVER)
- Blakemore, W. R., & Harpell, A. R. (2009). *Food stabilizers, thickeners and gelling agents*. Oxford: Blackwell Publishing.
- Brune, P., Perucchio, R., Ingraffea, A. R., & Jackson, M. D. (2010). The toughness of imperial Roman concrete. *Proceedings of the 7th International Conference on Fracture Mechanics of Concrete and Concrete Structures*, Jeju Island, Korea, 23–28.
- Caliskan, S., Turk, K. & Yazicioglu, S. (2005). Mechanical Properties of Self-Compacting Concrete at Different Curing Conditions. In: *Cement Combinations for Durable Concrete*, Proceedings of the International Congress, Global Construction: Ultimate Concrete Opportunities, Ravindra R. K., Thomas, A. H. & Moray, D. N. (Eds.), 5-7 July 2005, Dundee, UK, pp. 441 – 448.

- Casagrande, A. (1948). Classification and identification of soils. *Transactions ASCE*, 113:901-930.
- Casagrande, A., & Wilson, S. D. (1951). Effect of rate of loading on the strength of clays and shales at constant water content. *Geotechnique*, 2(3): 251–263.
- Cetin, H., Soylemez, M. (2004). Soil-particle and pore orientations during drained and undrained shear of cohesive sandy silt–clay soil. *Canadian Geotechnical Journal*, 41: 1127–1138.
- Cetin, H., Fener, M., & Gunaydin, O. (2006). Geotechnical properties of tire-cohesive clayey soil mixtures as a fill material. *Engineering Geology*, 88(1–2): 110–120.
- Çetin, M. Y., Bağrıaçık, B., Annagür, H. M., & Topoliński, S. (2024). Improvement of Geotechnical Properties of Clayey Soil Using Biopolymer and Ferrochromium Slag Additives. *Polymers*, 16(10), 1306. <https://doi.org/10.3390/polym16101306>
- Chang, I., & Cho, G. (2012). Strengthening of Korean residual soil with  $\beta$ -1, 3/1, 6-glucan biopolymer. *Construction and Building Materials*, Elsevier, 30: 30–35. <https://doi.org/10.1016/j.conbuildmat.2011.11.030>
- Chang, I., Lee, M., Tran, A. T. P., Lee, S., Kwon, Y. M., Im, J., & Cho, G. C. (2020). Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices. *Transportation Geotechnics*, 24: 100385. <https://doi.org/10.1016/j.trgeo.2020.100385>
- Chen, C., Peng, Z., Gu, J., Peng, Y., Huang, X., & Wu, L. (2020). Exploring environmentally friendly biopolymer material effect on soil tensile and compressive behavior. *International Journal of Environmental Research and Public Health*, 17(23): 9032. <https://doi.org/10.3390/ijerph17239032>
- Chen, H., & Wang, Q. (2006). The behavior of organic matter in the process of soft soil stabilization using cement. *Bulletin of Engineering Geology and the Environment*, 65(4): 445–448. <https://doi.org/10.1007/S10064-005-0030-1>
- Chu, J., & Ivanov, V. (2014). Iron-and calcium-based bio grouts for soil improvement. *Geo-Congress 2014: Geo-Characterization and Modeling for Sustainability*, 1596–1601.
- Consoli, N. C., Daassi-Gli, C. A. P., Ruver, C. A., Lotero, A., Scheuermann Filho, H. C., Moncaleano, C. J., & Lourenço, D. E. (2021). Lime–Ground Glass–Sodium Hydroxide as an Enhanced Sustainable Binder Stabilizing Silica Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 147(10): [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0002624](https://doi.org/10.1061/(ASCE)GT.1943-5606.0002624)
- Cristelo, N., Glendinning, S. & Pinto, A. T. (2011). Deep soft soil improvement by alkaline activation. *Ground Improvement*, 164(G12): 73–82. <https://doi.org/10.1680/grim.900032>

- Cristelo, N., Glendinning, S., Fernandes, L., Pinto, A. T. (2013). Effects of alkaline-activated fly ash and Portland cement on soft soil Stabilisation. *Acta Geotechnica*, 8:395-405. DOI: 10.1007/s11440-012-0200-9
- Das, B. B. (2014). Characterization of ferrochrome slag as an embankment and pavement material. MS Thesis, National Institute of Technology, Rourkela. <http://ethesis.nitrkl.ac.in/6593/>
- Delatte, N. J. (2001). Lessons from Roman cement and concrete. *Journal of Professional Issues in Engineering Education and Practice*, 127(3): 109–115.
- Dixit, M. S., & Patil, K. A. (2016). Utilization of stone dust to improve the properties of expansive soil. *International Journal of Civil Engineering and Technology (IJCIET)*, 7(4): 440–447.
- Etim, R.K., Ekpo, D.U., Ebong, U.B., Usanga, I.N. (2021a). Influence of periwinkle shell ash on the strength properties of cement-stabilized lateritic soil. *International Journal of Pavement Research and Technology*, 1(17): 1062-1078. <https://doi.org/10.1007/s42947-021-00072-8>
- Etim, R.K., Attah, I.C., Ekpo, D.U., Usanga, I.N. (2021b). Evaluation on stabilization role of lime and cement in expansive black clay - oyster shell ash composite. *Transportation Infrastructure Geotechnology*, 9(6): 729-763. <https://doi.org/10.1007/s40515-021-00196-1>
- Etim, R.K., Ekpo, D.U., Etim, G.U., Attah, I.C. (2021c). Evaluation of lateritic soil stabilized with lime and periwinkle shell ash (PSA) admixture bound for sustainable road materials. *Innovative Infrastructure Solutions*, 7: 1-17. <https://doi.org/10.1007/s41062-021-00665-z>
- Etim, R.K., Ekpo, D.U., Attah, I.C., Onyelowe, K.C. (2021d). Effect of micro sized quarry dust particle on the compaction and strength properties of cement stabilized lateritic soil. *Cleaner Materials*, 2: 100023. <https://doi.org/10.1016/j.clema.2021.100023>
- Fasihnikoutalab, M. H., Pourakbar, S., Ball, R. J., Unluer, C., & Cristelo, N. (2020). Sustainable soil stabilisation with ground granulated blast-furnace slag activated by olivine and sodium hydroxide. *Acta Geotechnica*, 15(7): 1981–1991. <https://doi.org/10.1007/S11440-019-00884-W>
- Fattah, M. Y., Rahil, F.H., Al-Soudany, K.Y.H. (2013). Improvement of Clayey Soil Characteristics Using Rice Husk Ash. *Journal of Civil Engineering and Urbanism*, 3(1):12-18.
- Fisher, L. V, & Barron, A. R. (2019). The recycling and reuse of steelmaking slags—A review. *Resources, Conservation and Recycling*, 146: 244–255.

- Flórez, M., Cazón, P., & Vázquez, M. (2023). Selected Biopolymers' Processing and Their Applications: A Review. *Polymers* 2023, Vol. 15, Page 641, 15(3): 641. <https://doi.org/10.3390/POLYM15030641>
- Ghazavi, M. and Roustaei, M. (2010). The influence of freeze- thaw cycles on the unconfined compressive strength of fiber-reinforced clay, *Cold Regions Science and Technology*, 61:125-131. <https://doi.org/10.1016/j.coldregions.2009.12.005>
- Gencel, O., Sutcu, M., Erdogmus, E., Koc, V., Cay, V. V., & Gok, M. S. (2013). Properties of bricks with waste ferrochromium slag and zeolite. *Journal of Cleaner Production*, 59: 111–119.
- Gencel, O., Munir, M. J., Kazmi, S. M. S., Sutcu, M., Erdogmus, E., Velasco, P. M., & Quesada, D. E. (2021). Recycling industrial slags in production of fired clay bricks for sustainable manufacturing. *Ceramics International*, 47(21): 30425–30438.
- Gökalp, İ., Uz, V. E., Saltan, M., & Tutumluer, E. (2018). Technical and environmental evaluation of metallurgical slags as aggregate for sustainable pavement layer applications. *Transportation Geotechnics*, 14: 61–69.
- Gu, J., Li, R., Chen, S., Zhang, Y., Chen, S., & Gu, H. (2020). Microstructure and wear behavior of laser cladded Ni45+ high-carbon ferrochrome composite coatings. *Materials*, 13(7): 1611.
- Gu, F., Zhang, Y., Tu, Y., Wu, X., Zhu, Y., Yuyang Long, Y., Shen, D. (2022). Assessing magnesia effect on preparing refractory materials from ferrochromium slag. *Ceramics International*, 48:13100–13107.
- Hazirbaba, K., Zhang, Y., and Hulse, J.L. (2011). Evaluation of temperature and freeze-thaw effects on excess pore pressure generation of fine-grained soils. *Soil Dynamics and Earthquake Engineering*, 31:372-384. <https://doi.org/10.1016/j.soildyn.2010.09.006>
- Hussein, A. H., Muhawiss, F. M., Hassan, N. A., & Theyab, A. F. (2023). Evaluating the shear strength of agar gum-treated gypseous soil. *Smart Geotechnics for Smart Societies*, 498–504. <https://doi.org/10.1201/9781003299127-60/>
- Jain, A.K., Jha, A.K., Shivanshi, (2020). Geotechnical behaviour and micro-analyses of expansive soil amended with marble dust. *Soils and Foundations*, 60:737–751. <https://doi.org/10.1016/j.sandf.2020.02.013>
- Jalal, F. E., Xu, Y., Jamhiri, B., & Memon, S. A. (2020). On the recent trends in expansive soil stabilization using calcium-based stabilizer materials (CSMs): A comprehensive review. *Advances in Materials Science and Engineering*, 2020: 1510969. <https://doi.org/10.1155/2020/1510969>

- Jang, C., Yang, B., Hong, W., Ahn, J., & Jung, J. (2024). Soil improvement using agar gum polymer for seismic liquefaction mitigation. *Soil Dynamics and Earthquake Engineering*, 177: 108405. <https://www.sciencedirect.com/science/article/pii/S0267726123006504>
- Jang, J. (2020). A review of the application of biopolymers on geotechnical engineering and the strengthening mechanisms between typical biopolymers and soils. *Advances in Materials Science*, 2020. <https://www.hindawi.com/journals/amse/2020/1465709/abs/>
- Jayapal, J., Boobathiraja, S., Thanaraj, M. S., & Priyadarshini, K. (2020). Weak soil stabilization using different admixtures - A comparative study. *Advances in Materials Science and Engineering*, 3(10): 57-63. [www.ijert.org](http://www.ijert.org)
- Kartal, G., Güven, A., Kahvecioğlu, Ö., Timur, S. (2003). Environmental effects of metals-II. *Metalurji Journal*, 137: 46-51. [https://www.metalurji.org.tr/dergi/dergi137/d137\\_4651.pdf](https://www.metalurji.org.tr/dergi/dergi137/d137_4651.pdf)
- Kulanthaivel, P., Selvakumar, S., Soundara, B., Krishnaraja, A.R. (2023). Strength Enhancement of Clay Soil Stabilized with Ordinary Portland Cement, Sodium Silicate and Sodium Hydroxide. *International Journal of Pavement Research and Technology*, 16:1297–1310. <https://doi.org/10.1007/s42947-022-00197-4>
- Kumar, S., Thomas, B. S., Gupta, V., Basu, P., & Shrivastava, S. (2018). Sandstone wastes as aggregate and its usefulness in cement concrete – A comprehensive review. *Renewable and Sustainable Energy, Reviews*, 81: 1147–1153.
- Kumar, B.S. and Preethi, TV (2014). Behavior of Clayey Soil Stabilized with Rice Husk Ash & Lime. *International Journal of Engineering Trends and Technology (IJETT)*, 11(1):44-48.
- Latifi, N., Horpibulsuk, S., Meehan, C. L., Abd Majid, M. Z., Tahir, M. M., & Mohamad, E. T. (2017). Improvement of problematic soils with biopolymer—An environmentally friendly soil stabilizer. *Journal of Materials in Civil Engineering*, 29(2):04016204. [https://doi.org/10.1061/\(ASCE\)mt.1943-5533.0001706](https://doi.org/10.1061/(ASCE)mt.1943-5533.0001706)
- Lind, B.B., A.-M. Fallman, A.M, Larsson, L.B. (2001). Environmental impact of ferrochrome slag in road construction. *Waste Management*, 21:255-264
- Li, Y., & Dai, W. (2018). Modifying hot slag and converting it into value-added materials: A review. *Journal of Cleaner Production*, 175: 176–189.
- Liu, C. and Evett, J.B., 2000, *Soil Properties; Testing, Measurement, and Evaluation*: Prentice-Hall, Inc., Upper Saddle River, NJ.
- Liu, J., Wang, T., and Tian, Y. (2010). Experimental study of the dynamic properties of cement- and lime-modified clay soils subjected to freeze-thaw cycles. *Cold Regions Science and Technology*, 61:29-33. <https://doi.org/10.1016/j.coldregions.2010.01.002>

- Mahent, R., & Joshi, R. (2015). Improvement soil index properties by adding stone dust mix. *International Journal of Science Technology and Engineering (IJSTE)*, 2(2): 61–68.
- Mahmutluoğlu, B. and Bağrıaçık, B. (2020). Effect of glass waste sludge on the freezing-thawing behavior of clayey soils. *Çukurova University Journal of the Faculty of Engineering and Architecture*, 35(3):783-796. <https://doi.org/10.21605/cukurovaummfd.846739>
- Marks, B. D. (1970). Sodium-Chloride and Sodium-Chloride-Lime Treatment Of Cohesive Oklahoma Soils. PhD Thesis, Oklahoma State University, Stillwater.
- McHugh, D.J. (2003). A Guide to the Seaweed Industry. FAO Fisheries Technical Paper 441, Food and Agriculture Organization of the United Nations, Rome, Italy.
- Mendonça, A., Morais, P. V., Pires, A. C., Chung, A. P., & Oliveira, P. V. (2021). A review on the importance of microbial bi-polymers such as xanthan gum to improve soil properties. *Applied Sciences (Switzerland)*, 11(1): 1-14. MDPI AG. <https://doi.org/10.3390/app11010170>
- Mitchell, J.K. (1993). *Fundamentals of Soil Behavior*. John Wiley and Sons, New York.
- Muntohar, A.S. (2002). Utilization of uncontrolled burnt rice husk ash in soil improvement. *Dimensi Teknik Sipil*, 4(2):100-105.
- Muntohar, A.S., Widiarti, A., Hartono, E., and Diana, W. (2013). Engineering Properties of Silty Soil Stabilized with Lime and Rice Husk Ash and Reinforced with Waste Plastic Fiber. *Journal of Materials in Civil Engineering*, 25:1260-1270. DOI: 10.1061/(ASCE)MT.1943-5533.0000659
- Okagbue, C.O. and Onyeobi, S.U.T. (1999) Potential of Marble Dust to Stabilise Red Tropical Soils for Road Construction. *Engineering Geology*, 53:371-380. [https://doi.org/10.1016/S0013-7952\(99\)00036-8](https://doi.org/10.1016/S0013-7952(99)00036-8)
- Oliveira, P. J. V., Freitas, L. D., & Carmona, J. P. S. F. (2017). Effect of soil type on the enzymatic calcium carbonate precipitation process used for soil improvement. *Journal of Materials in Civil Engineering*, 29(4): 04016263.
- Onyelowe Ken, C., Okafor, F. O., & Nwachukwu, D. (2010). Geophysical use of quarry dust (as admixture) as applied to soil stabilization and modification-a review. *ARNP Journal of Earth Sciences*, 1(1): 6–8.
- Panda, C., Mishra, K., Panda, K., & Nayak, B. (2013). Environmental and technical assessment of ferrochrome slag as concrete aggregate material. *Pavement and Building Materials*, 49: 262-271. <https://www.sciencedirect.com/science/article/pii/S0950061813007320>

- Patla, S., Mondal, S., & Choudhary, A. (2021). On Improving the Performance of Silty Soil by Treating with Ferrochrome Slag: An Experimental Study. Conference 2019: IGC-2019, Springer, 2. [https://link.springer.com/chapter/10.1007/978-981-33-6370-0\\_29](https://link.springer.com/chapter/10.1007/978-981-33-6370-0_29)
- Paul, A., Anumol, V. S., Moideen, F., Jose, J. K., & Abraham, A. (2014). Studies on the improvement of clayey soil using eggshell powder and quarry dust. *International Journal of Engineering Research and Applications*, 4(4): 55–63.
- Piatak, N. M., Parsons, M. B., & Seal II, R. R. (2015). Characteristics and environmental aspects of slag: A review. *Applied Geo-chemistry*, 57: 236–266.
- Qi, J.L., Zhang, J.M., Zhu, Y.L. (2004). Influence of freezing–thawing on soil structure and its soils mechanics significance. *Chinese Journal of Rock Mechanics and Engineering* (Supp. 2), 2690–2694.
- Ren, Y., Ren, Q., Wu, X., Zheng, J., & Hai, O. (2020). Recycling of solid wastes ferrochromium slag for preparation of eco-friendly high-strength spinel–corundum ceramics. *Materials Chemistry and Physics*, 239: 122060.
- Saadeldin, R., & Siddiqua, S. (2013). Geotechnical characterization of a clay–cement mix. *Bulletin of Engineering Geology and the Environment*, 72: 601–608.
- Sahu, N., Biswas, A., & Kapure, G. (2016). A short review on utilization of ferrochromium slag. *Mineral Processing and Extractive Metallurgy Review*, 37(4): 211–219. <https://www.tandfonline.com/doi/abs/10.1080/08827508.2016.1168415>
- Schmidt, G.C., 1961. Stratigraphic nomenclature for the Adana region petroleum district VII. *Petroleum Administration Bulletin* 6:47–63.
- Soosan, T. G., Sridharan, A., Jose, B. T., & Abraham, B. M. (2005). Utilization of quarry dust to improve the geotechnical properties of soils in highway construction. *Geotechnical Testing Journal*, 28(4): 391–400.
- Terzaghi, K. (1943). *Theoretical soil mechanics*. John Wiley And Sons, Inc. New York.
- Topaloğlu, S. (2019). Investigation of the Effects of Ferrochrom Slag Aggregate on Performance of Permeable Bituminous Mixtures. MS Thesis, Department of Civil Engineering, Bartın University, Bartın, Türkiye. <http://acikerisim.bartın.edu.tr/handle/11772/6422>
- Topaloglu, S., Cetin, A., Dayioglu, A. Y., & Aydilek, A. H. (2024). Laboratory Testing of Ferrochrome Slag as an Aggregate in Porous Pavements. *Geotechnical Testing Journal*, 47(1).
- Uysal, F. F., & Bahar, S. (2018). Slag types and utilization areas. *Trakya University Journal of Engineering Sciences*, 19(1): 37–52.

- Waheed, A., Arshid, M.U., Khalid, R.A., Gardezi, S.S.S. (2021). Soil Improvement Using Waste Marble Dust for Sustainable De-velopment. *Civil Engineering Journal*, 7(09):1594-1607. <https://www.researchgate.net/publication/354445838>
- Wang, G. C. (2016). *The utilization of slag in civil infrastructure construction*. Woodhead Publishing, Amsterdam.
- Yazıcıoğlu, S., Gönen, T., & Çobanoğlu, Ö. C. (2005). The influence of Elazig Ferrochromium Slag on compressive strength and impact energy of concrete. *Science and Engineering Journal of Fırat University*, 17(4): 681-686.
- Yildirim, S. (2019). *Investigation of the Effects of Ferrochrome Slags on Usability Performance in Highway Lower Filler*. MS Thesis, De-partment of Civil Engineering, Sakarya Applied Sciences University, Sakarya, Türkiye. <https://acikbilim.yok.gov.tr/handle/20.500.12812/222353>
- Yılmaz A (2002) Investigation of electric-arc furnace slag and silica fume of Antalya ferrochrome establishment, as filler material in asphalt concrete. MS Thesis, Akdeniz University, Antalya, Türkiye. <http://dspace.akdeniz.edu.tr/handle/123456789/922>
- Yılmaz, A. (2017). Investigation of the environmental impacts of slag wastes used in the pavement base layers. *The Journal of Graduate School of Natural and Applied Sciences of Mehmet Akif Ersoy University*, 8(2): 123–134.
- Yılmaz, A., & Karaşahin, M. (2010). Mechanical properties of ferrochromium slag in granular layers of flexible pavements. *Materials and Structures*, 43: 309–317.
- Yussif, K., Dompheh, E. B., & Gasparatos, A. (2023). Sustainability of urban expansion in Africa: a systematic literature review using the Drivers–Pressures–State–Impact–Responses (DPSIR) framework. *Sustainability Science* 2023 18:3, 18(3), 1459–1479. <https://doi.org/10.1007/S11625-022-01260-6>
- Zaimoğlu, A.Ş., Hattatoğlu, F. and R. K. Akbulut, R.K. (2013). Freezing-thawing behavior of fine-grained soils subjected to sur-charge loads. *Pamukkale University Journal of Engineering Sciences*, 19(3):117-121. <https://doi.org/10.5505/pajes.2013.35744>
- Zhang, Y.X., Liu, S.L., OuYang, S.L., Zhang, X.F., Zhao, Z.W., Jia, X., Du, Y.S., Deng, L., Li, BW (2020). Transformation of unstable heavy metals in solid waste into stable state by the preparation of glass-ceramics. *Materials Chemistry and Physics*, 252:123061.



## **CURRICULUM VITAE**

Mustafa Yasin ÇETİN, Completed primary school in 2010, while completed the high school at Adana Science High School 2017, began undergraduate studies at Çukurova University Department of Civil Engineering, and graduated in 2021. In 2022, he began his graduate studies for a master's degree in Çukurova University.

