Karadeniz Fen Bilimleri Dergisi, 15(3), 1094-1118, 2025. DOI: 10.31466/kfbd.1609555

KFBD

Karadeniz Fen Bilimleri Dergisi
The Black Sea Journal of Sciences
ISSN (Online): 2564-7377 https://dergipark.org.tr/tr/pub/kfbd

Araştırma Makalesi / Research Article

A Comparative Study on the Performance of Freeze-Thaw Cycled Alluvial Soils Stabilized with Lime and Fly Ash

Eylem ARSLAN[1], Inci DEVELIOGLU[2*], Hasan Fırat PULAT[3]

Abstract

This paper presents a comparison of the stabilization of alluvial soils using lime and fly ash. It aims to draw basic inferences for these soils based on the test results obtained. In this regard, lime and fly ash were added to silty alluvial soil at different rates, and the s1amples were subjected to different curing periods. The cured samples underwent 0 and 1 freeze-thaw cycles in a closed-system cabinet by maintaining the specimens at -24°C and +24°C for 24 hours each, to evaluate the influence of temperature changes. Based on the undrained shear strength values obtained from the unconsolidated-undrained triaxial tests, the most prominent finding is that stabilization with fly ash performed better than with lime, as the alluvial soil was rich in silts. The optimal stabilization period was determined as 28 days for both stabilizers. The increased curing time was influenced by mechanisms potentially arising from the use of calcium-based stabilizers in a sulfate-containing environment, which was most evident in lime stabilization. While the most effective lime stabilization was achieved between 3% and 6%, this range increased to as much as 20% for fly ash. Although fly ash stabilization yielded better results in terms of undrained shear strength, lime stabilization demonstrated better performance against freeze-thaw cycles.

Keywords: Alluvial soil, Fly ash, Freeze-thaw, Lime, Triaxial compression test.

Kireç ve Uçucu Kül ile Stabilize Edilmiş Donma-Çözülme Döngülü Alüvyonel Zeminlerin Performansına İlişkin Karşılaştırmalı Bir Çalışma

Öz

Bu çalışma, alüvyonlu zeminlerin kireç ve uçucu kül ile stabilizasyonunun bir karşılaştırmasını oluşturmakta ve elde edilen deney sonuçları doğrultusunda bu zeminler için temel çıkarımlarda bulunmayı amaçlamaktadır. Bu bağlamda, siltli alüvyonlu zemine farklı oranlarda kireç ve uçucu kül ilave edilmiş ve numuneler farklı sürelerde kürlenmiştir. Kürlenen numuneler, sıcaklık değişimlerinin etkisini de içerecek şekilde, -24 ve +24 C°'de 24 saat tutularak kapalı sistem bir dolapta 0 ve 1 donma-çözülme çevrimlerine maruz bırakılmıştır. Konsolidasyonsuz-drenajsız üç eksenli deneylerle elde edilen drenajsız kayma dayanımı değerinden yapılan çıkarımlarda, alüvyonlu zeminin silt bakımından zengin olması nedeniyle uçucu kül ile stabilizasyonun kireç ile stabilizasyondan daha iyi sonuç verdiği sonucuna ulaşılmıştır. Her iki stabilizatör için de en optimum stabilizasyon süresi 28 gün olarak belirlenmiştir. Kür süresinin artması, sülfat içeren bir ortamda kalsiyum bazlı stabilizatörlerin kullanılması sonucu oluşabilecek mekanizmalardan etkilenmiştir. Bu, kireçle stabilizasyonda en belirgin şekilde görülmüştür. En etkili stabilizasyon kireç için %3 ila 6 arasında elde edilirken, bu oran uçucu kül için %20'ye kadar çıkmıştır. Ancak, kireçle stabilize edilmiş alüvyonlu zeminler donma-çözülme döngüsüne karşı daha iyi direnç sağlamıştır.

Anahtar Kelimeler: Alüvyonel zemin, Donma-çözülme, Kireç, Uçucu kül, Üç eksenli basınç deneyi.

[1]Sakarya University, Civil Engineering Department, Sakarya, Türkiye, eylemarslan@sakarya.edu.tr
[2]Izmir Katip Celebi University, Civil Engineering Department, Izmir, Türkiye, inci.develioglu@ikcu.edu.tr
[3]Izmir Katip Celebi University, Civil Engineering Department, Izmir, Türkiye, hfirat.pulat@ikcu.edu.tr

[*]Sorumlu Yazar/Corresponding Author

Geliş/Received: 29.12.2024 **Kabul/Accepted:** 22.04.2025 **Yayın/Published:** 15.09.2025

Arslan, E., Develioglu, I., Pulat, H.F. (2025). A Comparative Study on the Performance of Freeze-Thaw Cycled Alluvial Soils Stabilized with Lime and Fly Ash. *Karadeniz Fen Bilimleri Dergisi*, 15(3), 1094-1118.

1. Introduction

The safety and cost of construction projects are primarily influenced by the characteristics of the subgrade soil. In weak soils, the underlying layer is not suitable for safely bearing the loads imposed by the proposed structure. As the extent of damage to structures built on weak soils became more evident, researchers began focusing on improving their undesirable engineering properties using various methodologies, especially through chemical stabilization. Rather than replacing the weak soil with stronger material, stabilization has been recognized as a more cost-effective and practical solution for the project budgets (Sharma et al. 2012; Firoozi et al. 2017; Teber and Akoguz, 2024). The most common outcomes of stabilization include improved strength and durability, reduced swelling potential, and decreased compressibility, permeability, and plastic of the soil (Hausmann 1990; Sherwood 1993; Prabakar et al. 2004; Naeini et al. 2012; Estabragh et al. 2013; Das 2015). To ensure the long-term strength and stability of the structures, understanding the stabilization mechanism of the subgrade soil becomes essential. One of the important aspects of soil stabilization in achieving soil with the desired quality is selecting an appropriate stabilizer and using its variable parameters at effective ratios (Nalbantoglu 2004; Barbhuiya et al. 2009; Maaitah 2012; Balkis 2017). Excessive use of stabilizers and extended curing can lead to high costs and may even negatively affect soil strength (Golhashem & Uygar 2020). Therefore, investigating the interaction mechanism between different stabilizers and soils has become essential for determining the optimal values of variable parameters during the stabilization process (Arslan et al., 2024; Sert et al., 2024).

A wide range of soil stabilizers has been introduced and applied to meet the desired physical and chemical properties of soils. Among them, the most widely applied stabilizers are cement, lime, and fly ash due to their pozzolanic nature (Sharma et al. 2012; Sherwood 1993; Little 1999; Nalbantoglu & Gucbilmez 2002). The immediate and long-term reactionsthat occur when these calcium-based stabilizers are used are largely responsible for enhancing the strength and durability of the soils, resulting in the production of a higher-quality material. In the short term, as a result of the flocculated structure formed after the cation exchange between the soil and the stabilizers, a decrease in soil plasticity and an increase in the pH value of the environment are observed. When the pH value reaches a threshold level (generally considered to be 10.5) in the long term, pozzolans in the soil, such as silica and alumina, are released and react with the available calcium in the environment, leading to strength gains. The main compounds responsible for this mechanism are cementitious gels, namely, Calcium-Silicate-Hydrates (CSH) and Calcium-Aluminate-Hydrates (CAH) gels, which are the products of pozzolanic reactions. The newly formed matrix significantly alters the properties of the soil, resulting in a stronger and more durable soil structure to be formed (Firoozi et al. 2017). Among these types of stabilizers, fly ash, which is a by-product material, (Parsons & Milburn 2003; Phanikumar & Sharma 2004; Arora & Aydilek 2005). By incorporating waste materials such as fly ash into the soil, a sustainable approach can be achieved from both economic and environmental perspectives. Fly ash is a waste material produced from the combustionof coal and serves as a type of stabilizer. whose properties may vary depending on the chemical composition of the burned coal. Its amorphous structure, rich in siliceous and aluminous compounds, and its fine-grained texture are among the main reasons for its pozzolanic feature. In general, fly ash is classified into two main categories, Class-C and Class-F, based on the cementitious properties they exhibit. Class C fly ash, which has self-cementing properties due to its high lime content (CaO > 8%), does not require the use of an additional activator for soil stabilization. In contrast, Class F fly ash contains less lime (CaO < 8%) and has a less reactive nature (Manz 1999). As with any stabilizers, the soil type and mineralogical composition are as important as the chemical properties of the fly ash. Past studies have shown that fly ash yields successful results, particularly in silty and sandy soils, the degree of improvement decreases with increasing plasticity (Firoozi 2017; Arora & Aydilek 2005; Acosta 2002; Bhuvaneshwari et al. 2005). In a study conducted by Parsons & Milburn (2003), three different soil types (CH, ML, SM) were stabilized using fly ash, cement, and lime. The study demonstrated that fly ash produced the highest strength gain in low-plasticity silt (ML) soils. In cases where plastic soils are encountered, lime is typically the recommended stabilizer. The possibility that fly ash may be insufficient in some conditions also increases the preference for commercial stabilizers such as lime. While the use of fly ash as a waste material offers significant environmental advantages, the fact that lime is inexpensive and widely available can, in certain cases, provide even greater benefits (Bhuvaneshwari et al. 2005; Little & Nair 2009). When the soil types used in stabilization are examined, it can be observed that most studies have focused on expansive soils in order to prevent significant volumetric changes under loading conditions. However, there are a limited number of studies that primarily address the stabilization of a crucial type of soil type: alluvial soils. Alluvial soils are one of the recently formed loamy soil types, characterized by large pores formed as a result of sedimentation processes (Yadav et al. 2017). This type of soil exhibits significant settlement behavior due to its low bearing capacity and high void ratio. Nevertheless, it is one of the most commonly encountered soil types in transportation systems as base material or beneath structures as a sub-base material. Special attention should be given to the stabilization of these soils with the aforementioned materials. Moreover, due to the large voids in the alluvial soils, seasonal changes that cause freeze-thaw cycles within these voids, and the related parameters that contribute to strength reduction, must be investigated in detail. From this point of view, it can be concluded that the stabilization of alluvial soils, particularly targeting their problematic properties, represents a relevant subject of study; however, there are still gaps in the existing literature on this topic (Malikzada et al. 2022). Additionally, the sensitivity of alluvial soil strength to temperature fluctuations indicates that the parameters considered in the stabilization of these soils with different materials should not be limited to material properties alone, but should also account for environmental effects. From this perspective, the number of studies that consider environmental effects in the stabilization of alluvial soils using materials such as lime and fly ash remains limited. It is important to note that, when evaluated in conjunction with temperature fluctuations, the general conclusions drawn in previous studies regarding lime and fly ash stabilization may vary depending on the characteristics and classification of the alluvial soil (Arslan et al., 2023). Previously, Arora & Aydilek (2005) investigated the influence of several parameters, such as fine and water content, curing time, activator type, and cohesion, on key engineering properties of fly ash stabilized sandy soils. Unconfined Compression (UCS) and California Bearing Ratio (CBR) tests were conducted using lime and cement as activators. While the soil samples stabilized with 40% of fly ash, cement, and lime were added as 1, 2, 4, 5, 7 %, and 4, 7, 10 % of this mixture, respectively. Additionally, to increase sample cohesion, 10% kaolinite was added to some of the mixtures. The effect of temperature was incorporated into the study by subjecting the samples to freeze-thaw cycles, freezing at −23°C and thawing at room temperature, over 2, 4, 8, and 12 cycles. The UCS and CBR values increased with cement addition (up to 5%) but decreased with increasing lime content. UCS values also increased with the number of freeze-thaw cycles in cement-treated samples but decreased in lime-treated samples. The study revealed that an increase in the cohesion of stabilized soil negatively affects its durability under temperature fluctuations. The phenomenon, particularly observed in compacted clay samples, was attributed to the formation of ice lenses within the soil, leading to an increase in cracking (Benson & Othman 1993). Cheng et al. (2021) also studied the freeze-thaw response of salinized soils stabilized with fly ash. The freeze-thaw process was followed by maintaining the samples at −13.9 ºC for 6 hours and at 20 ºC for another 6 hours. Following the application of 0, 1, 3, 5, 7, 9, and 11 cycles of freeze-thaw; triaxial shear, unconfined compression, and scanning electron microscopy tests were performed. The results demonstrated that the strength parameters decreased significantly after the freeze-thaw cycles. For stabilized soils, the strength initially increased with the addition of fly ash but began to decrease beyond a certain content. The maximum cohesion and internal friction angle were achieved at 15% of fly ash. Moreover, Yılmaz & Fidan (2018) performed a study on the freeze-thaw performance of clayey soils using lime and perlite as stabilizers. When comparing the activity of the two materials, perlite was found to be the most negatively affected by the application of freeze-thaw cycles. In addition, Nguyen et al. (2019), based on UCS test results, reported that lime stabilization under freeze-thaw conditions yielded better performance in low-plasticity silty soils. Based on the aforementioned studies, it is evident that there are almost no addressing the stabilization of alluvial soils under freeze-thaw conditions. Considering that these soils already possess large voids, and may experience critical settlements during freeze-thaw cycles, identifying the most effective stabilization method becomes crucial.

While previous studies frequently employed lime and fly ash as stabilizers, they remain insufficient in addressing the stabilization of alluvial soils and fail to provide insight into how these soils respond to temperature fluctuations in both stabilized and natural states. To address this gap in the literature, the present study investigates the stabilization of alluvial soils using two different stabilizers, followed by strength and microstructural analyses after the application of freeze-thaw cycles. Lime and fly ash were applied in varying proportions and curing times, and their effectiveness on alluvial soils under temperature changes was compared. This study seeks to answer key questions regarding the selection of appropriate stabilizers for naturally occurring alluvial soils: which commonly used material is more suitable for stabilization, how environmental conditions affect performance, and what the optimal ratio and curing time should be. The undrained shear strength was selected as the primary strength parameter as it reflects the short-term response and represents the lower bound of strength behavior. Unlike past studies, the undrained shear strength in this research was determined through UU tests under various confining pressures, rather than UCS tests where confinement is neglected. Although the UU test tends to yield the lowest strength values for fine-grained soils under short-term loading, it offers an advantage over the UCS test by enabling the evaluation of potential effects of confining pressure. At the same time, the preference for this rapid test is important in capturing short-term changes, such as those induced by freeze-thaw effects. For its ability to reflect both the targeted mechanical behavior and related secondary effects, the UU test was chosen. The study also explores the soil matrix formed by the different stabilizers and includes comparisons across several factors, such as stabilizer content, curing periods, durability under both freeze-thaw and normal conditions, stress-strain behavior, and failure mechanisms.

2. Materials and Methods

The materials and methodology employed in this study are described in detail in this section.

2.1. Alluvial Soil

In the current study, fine-grained alluvial soil obtained from the İzmir province of Turkey was used due to its high variable and weak geotechnical properties. Alluvial soils exhibit soft soil behavior with low shear strength, which may lead to significant settlements during construction. According to a geotechnical characterization study conducted in the field by Semerci et al. (2018) (Figure 1), the alluvial soil primarily consists of low-plasticity clay or silt, although its composition ranges from gravel to clay.

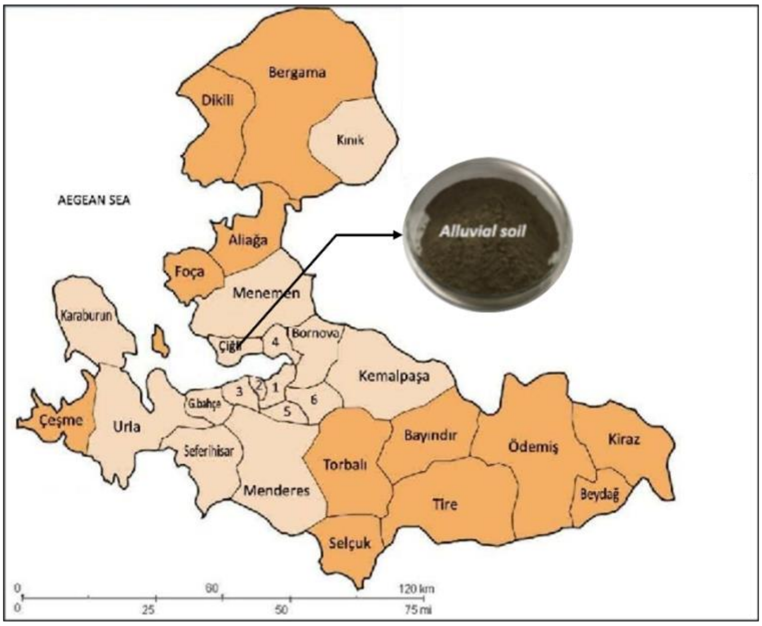

Figure 1. The construction site and alluvial soil sample.

In this study, silty soils were selected from among various alluvial soils collected from the field, as they exhibit a greater tendency to freeze compared to other soil types (Wang et al. 2014). The geotechnical index properties of the silty soil specimen used in the study are shown in Table 1.

Table 1. Characterization of the soil.

Parameter	Value	Unit	ASTM Standard
Liquid limit (LL)	36.5	%	D4318-10
Plastic limit (PL)	28.7	%	D4318-10
Plasticity index (PI)	7.8	%	D4318-10
Specific gravity (G_s)	2.7	-	D854-14
Optimum moisture content (OMC)	20	%	D698-12
Max. dry density (MDD)	16.3	kN/m^3	D698-12
Fine content (F_c)	67.0	%	D1140-17
pH	8.41	-	D4972-19
Soil class (USCS)	ML	-	D2487-11
Clay fraction (HT)	15	%	D7928-17
Clay fraction (LDM)	8.6	%	ISO 13320:2020

*HT: Hydrometer test, LDM: Laser Diffraction Method

The properties reflecting the particle size distribution of the soil, especially the fine content and clay fraction, were determined using both the Laser Diffraction Method (LDM) and the Hydrometer Test (HT). The LDM was employed as it is increasingly recommended for evaluating soil particle size distribution due to its simplicity and its ability to provide (Miller & Schaetzl 2012; Yang et al. 2019). To ensure the accuracy of the results and to allow for comparison, the hydrometer test was also performed alongside the LDM. One of the most influential parameters in soil stabilization is the mineralogical composition of the soil. Therefore, X-ray diffraction (XRD) analysis was conducted to identify the dominant minerals present in the soil (Figure 2). Based on the peak patterns observed in the XRD results, the major mineral components were determined. The most notable finding was the presence of sulfate-containing minerals such as melanterite, epsomite, and polyhalite.

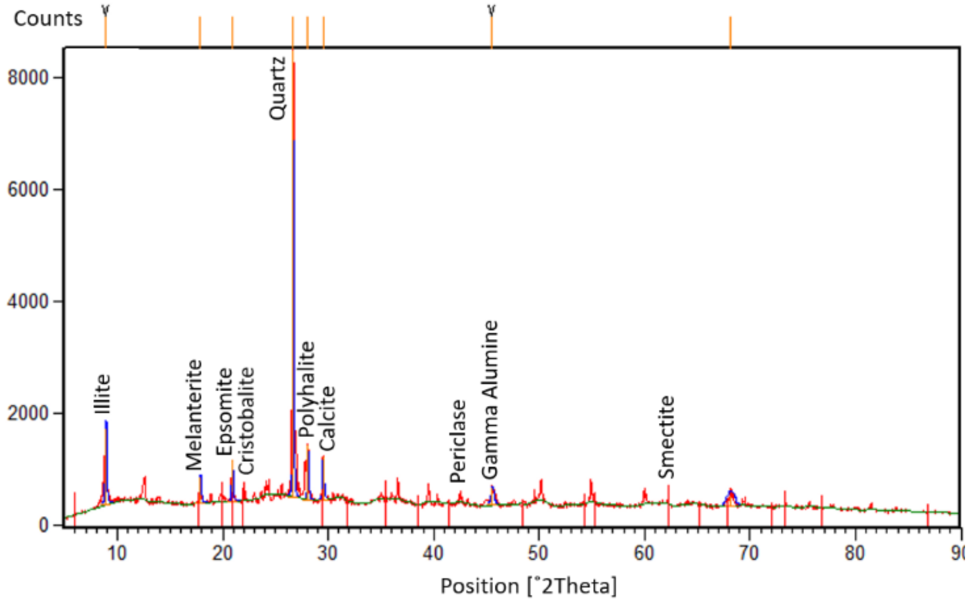

Figure 2. XRD pattern of the alluvial soil.

2.2. Hydrated Lime

In this study, slaked lime, —commonly used and readily available—was selected as the stabilizing agent. The maximum particle size of the lime was 0.075 mm. To meet the requirements of effective soil stabilization, a lime type rich in calcium oxide was preferred. According to the results of the X-ray diffraction (XRD) analysis, the lime consisted of 67.3% calcite and 32.7% vaterite.

2.3. Fly Ash

Studies have indicated that the utilization of fly ash remains significantly lower than the amount produced (Sharma et al. 2012). In this study, Class C fly ash obtained from the Soma Thermal Power Plant located in Manisa, Turkey, was used. The maximum particle size of the fly ash was 0.075 mm. The primary advantage of using Class C fly ash lies in its self-cementing nature, which eliminates the need for additional activators during the stabilization process due to its inherent lime content. This characteristic reduces the overall stabilization cost in engineering projects, as no extra chemical additives are required (Phanikumar & Sharma 2004; Bhuvaneshwari et al. 2005; Horpibulsuk et al. 2013).

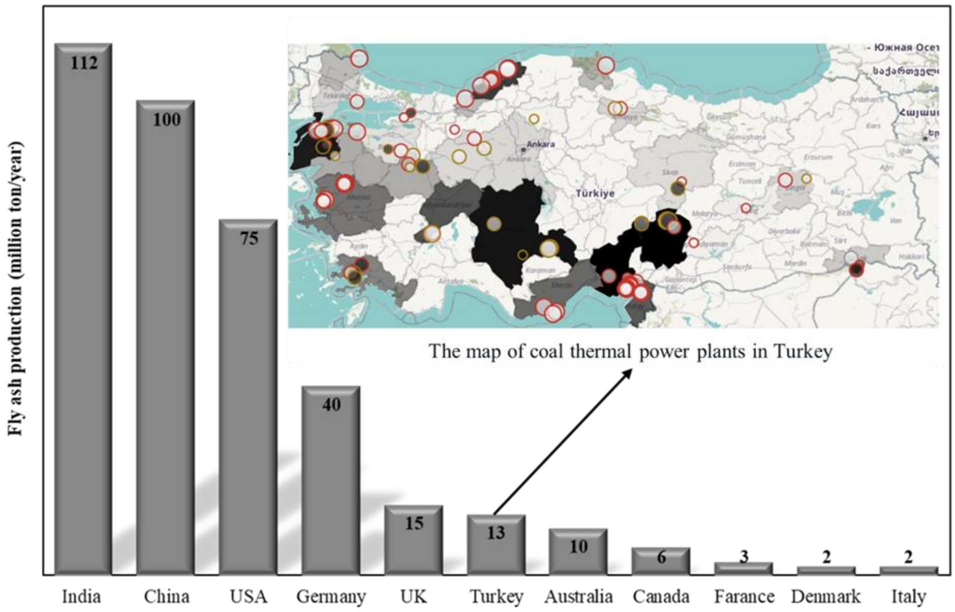

Figure 3. Fly ash production in different countries (Degirmenci et al. 2007; Horpibulsuk et al. 2013).

2.4. Sample Preparation

The laboratory testing program in this study involved the preparation of natural and stabilized alluvial soil samples using lime and fly ash, the application of predetermined curing periods, consistency limit tests on the cured samples, and repeated freeze-thaw cycles. In the final stage, the samples were subjected to unconsolidated-undrained (UU) triaxial compression tests to determine their undrained shear strength parameters. Due to the presence of multiple variables in the UU tests, the samples were coded according to their test conditions, as presented in Tables 2 and 3.

Table 2. Sample codes of lime stabilized samples for varying parameters.

Sample Code	Lime (%)	Curing (days)	FT cycles
0L1D0C	0	1	0
0L1D1C			1
3L7D0C	3	7	0
3L7D1C			1
6L7D0C	6		0
6L7D1C			1
12L7D0C	12		0
12L7D1C			1
3L28D0C	3	28	0
3L28D1C			1
6L28D0C	6		0
6L28D1C			1
12L28D0C	12		0

12L28D1C			1
3L56D0C	3	56	0
3L56D1C			1
6L56D0C	6		0
6L56D1C			1
12L56D0C	12		0
12L56D1C			1

*The letters L stand for lime content, D for days of curing, and C for cycle no.

Table 3. Sample codes of fly ash stabilized samples for varying parameters.

Sample Code	Fly ash (%)	Curing (days)	FT cycles
10F7D0C	10	7	0
10F7D1C			1
20F7D0C	20		0
20F7D1C			1
30F7D0C	30		0
30F7D1C			1
10F28D0C	10	28	0
10F28D1C			1
20F28D0C	20		0
20F28D1C			1
30F28D0C	30		0
30F28D1C			1
10F56D0C	10	56	0
10F56D1C			1
20F56D0C	20		0
20F56D1C			1
30F56D0C	30		0
30F56D1C			1

*The letters F stand for fly ash content, D for days of curing, and C for cycle no.

The experimental schedule was organized based on the lime and fly ash contents and the designated curing periods. The natural soil samples (first group in Table 2) were prepared by mixing oven-dried alluvial soil with distilled water in accordance with their maximum dry density and optimum water content. Each mixture was prepared separately to ensure homogeneity. Specifically, all materials were weighed and prepared following the sample preparation guidelines outlined in the ASTM D2850 standard for Unconsolidated-Undrained (UU) Triaxial Compression tests. Each sample was compacted in three layers into a cylindrical mold with a diameter of 5 cm and a height of 10 cm, using a tamper to achieve the target density. Initially, the soil-water mixture was manually stirred for 2 minutes using a steel rod to ensure uniform water distribution. This was followed by mechanical mixing at 60 rpm for 3 minutes until a uniform consistency was obtained. Considering the compaction energy required by Standard Proctor method, 20 blows using a tamper weighing approximately 11.8 N were sufficient to compact the samples. After compaction, the samples were extruded from the mold using a hydraulic extruder, immediately wrapped with cling film and placed in zip-lock bags to minimize moisture loss. The wrapped samples were then stored in a humidity-controlled curing chamber at 20°C ± 2°C for 7 days to ensure uniform curing. This moisture preservation process was chosen after testing various sealing materials such as aluminum foil, cling film, and various types of zip lock bags. Among these, the most effective preservation method was chosen to maintain constant water content during the curing time and FT process. Moisture loss measured prior to testing showed an average decrease of 0.5%, which was deemed negligible. To ensure the reliability of the results, two identical samples were prepared for each UU test condition, and the test was repeated in cases where results were inconsistent. The degree of water saturation of the tested samples ranged from 84.6 and 85.2%. Based on the literature, samples with saturation levels above 80% are generally considered partially saturated (Kamata et al. 2009). Thus, the samples used in this study were treated as partially saturated. The decision to maintain partial saturation during sample preparation was made to preserve the characteristic properties of the soil, such as water content and void ratio. Furthermore, the testing procedures were aligned with recommendations found in the literature to prevent any potential effects associated with full saturation (Vanapalli & Fredlund 1997; Nishimura 2006; Tsukamoto 2019).

2.5. Sample Curing

After the samples were prepared and properly stored, multiple curing periods were selected to allow for chemical reactions between the soil and the stabilizers. Previous studies have shown that a 7-day curing period is generally sufficient to initiate reactions for lime, whereas fly ash typically requires 28 days (Nalbantoglu 2004; Boardman et al. 2001). It is also well established that longer curing durations result in stabilized samples with higher shear strength. To develop a more comprehensive understanding of the influence of curing time on the undrained shear strength of stabilized soils, specimens treated with lime and fly ash were cured for 7, 28, and 56 days. The curing was conducted in desiccators to protect the specimens from adverse ambient conditions. For comparison, natural (unstabilized) soil samples were cured for one day to ensure uniform moisture distribution within the sample. Each specimen was weighed before and after curing to confirm that water loss remained within acceptable limits. The primary objective of defining multiple curing periods in this study was to identify the most effective curing duration for the tested soil type, particularly in response to freeze-thaw (FT) exposure.

2.6. Geotechnical Index Tests

Before conducting the strength tests, the geotechnical index parameters of both the natural and stabilized samples were found to evaluate how compressive behavior and consistency limits of the soil responded to stabilization. As given in Table 1, optimum moisture content, maximum dry density, plastic limit, liquid limit, and plasticity index were designated using the relevant standards. The primary objective of this phase was to assess the compression behavior and phase changes in the soil resulting from the addition of lime and fly ash, and to establish a relationship with the strength development mechanism in stabilized soils. For this reason, it was essential to determine the consistency limits following stabilization and curing.

2.7. Freeze-Thaw (FT) Cycles

Before performing triaxial tests on both natural and stabilized soils, the samples were exposed to simulated seasonal temperature variations using a freeze-thaw cabinet. The manually equipment was capable of applying temperatures ranging from -30ºC to +30ºC with an accuracy of 0.1ºC. A closed type system without a water supply unit was used, meaning the only moisture present was the water content initially contained in the soil (Qu et al. 2019). Since fine-grained soils exhibit low permeability, the freeze-thaw behavior can be considered as occurring under undrained consitions. The FT cycles applied in this study were conducted in accordance with ASTM D560. A critical consideration in designing the freeze-thaw exposure was the selection of temperature conditions that reflect both the regional climate and broader environmental contexts in which alluvial soils are typically found. In addition to mimicking the regional climate—where average seasonal temperatures range from +20 °C in summer to −8 °C in winter—more extreme temperature boundaries were adopted to capture a wider range of potential freeze-thaw effects. It has been noted in the literature that applying only a single, narrow-range freeze-thaw cycle may not adequately capture the degradation potential. Therefore, samples were frozen at −24 °C and thawed at +24 °C, with each phase lasting 24 hours, resulting in a complete freeze-thaw (FT) cycle of 48 hours. The internal temperature of the cabinet was monitored using a thermometer, and occasional fluctuations within ±2 °C were recorded and deemed acceptable. The primary objective of this phase of testing was to assess the freeze-thaw performance of stabilized soils. Specifically, the study sought to understand how FT exposure affects the ductility of stabilized silty soils. The response of the soil addressed this research question by capturing the combined effects of both strength degradation and potential self-healing mechanisms.

2.8. Unconsolidated-Undrained (UU) Triaxial Tests

Unconsolidated-undrained (UU) triaxial compression tests were conducted on specimens that had completed the first three stages of the testing program—sampling, curing, and freeze-thaw conditioning—in order to determine their undrained shear strength. A schematic illustration of the test procedure is presented in Figure 4.

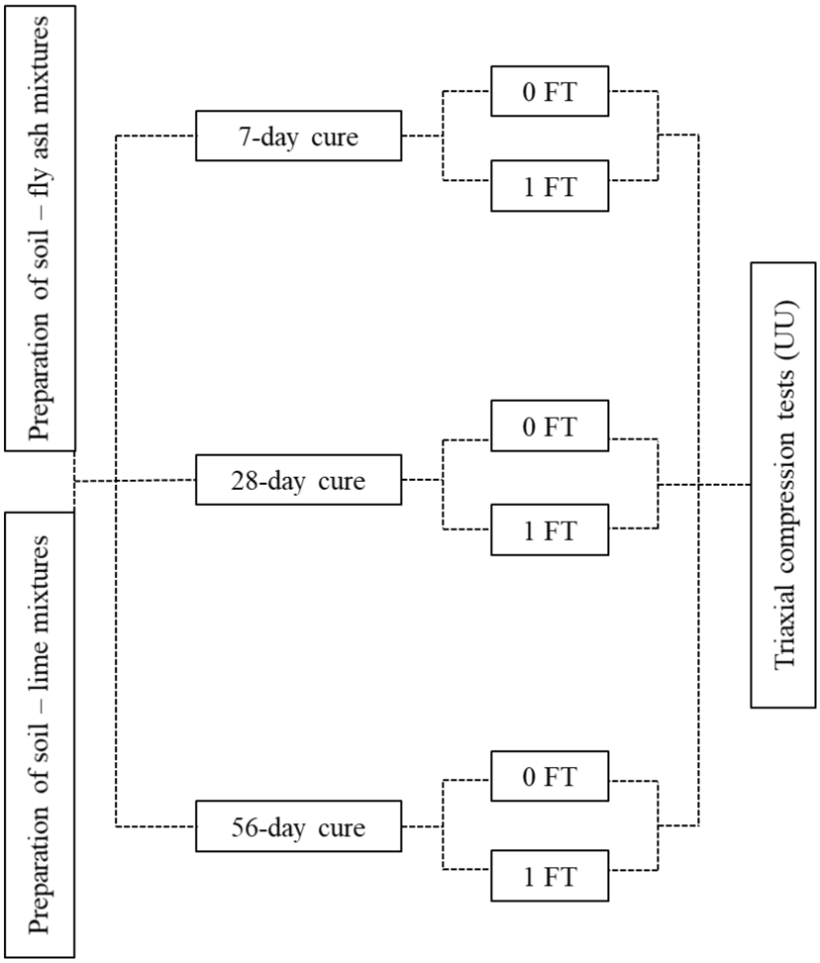

Figure 4. The schematic representation of the test procedure.

In the UU test procedure, the samples were subjected to, axial shear under undrained conditions, while being confined by water-imposed lateral pressure. The loading rate was selected according to sample properties; however, previous research has shown that rates between 0.05% and 1% per minute are sufficient to minimize the influence of strain rate on test results (Nishimura 2006). In the present study, a shear rate of 0.1 mm/min was adopted, as it offered a balance between testing efficiency and eliminating shear rate effects. Loading was continued until a strain of 15% was reached, at which point the test was terminated, in accordance with ASTM D2850. This level of strain corresponded to approximately 15 mm of axial deformation. Each sample was weighed before and after the test to monitor any changes in moisture content. As previously mentioned, the samples were partially saturated before testing, and no saturation process was applied before the triaxial compression tests in order to preserve their initial moisture content and structural characteristics. Although no drainage was allowed during testing, changes in volume and degree of saturation were expected due to compression of air within the soil matrix (ASTM D2850). As a result, it was anticipated that samples with identical physical properties would not behave in the same manner as fully saturated soils under UU conditions, particularly when subjected to different levels of confining stress. Taking the partially saturated condition into account, each sample—identified by the codes listed in Tables 2 and 3—was tested under confining pressures (σ_3) of 100, 200, and 300 kPa, respectively. A total of 108 samples were tested, as illustrated in Figure 5.

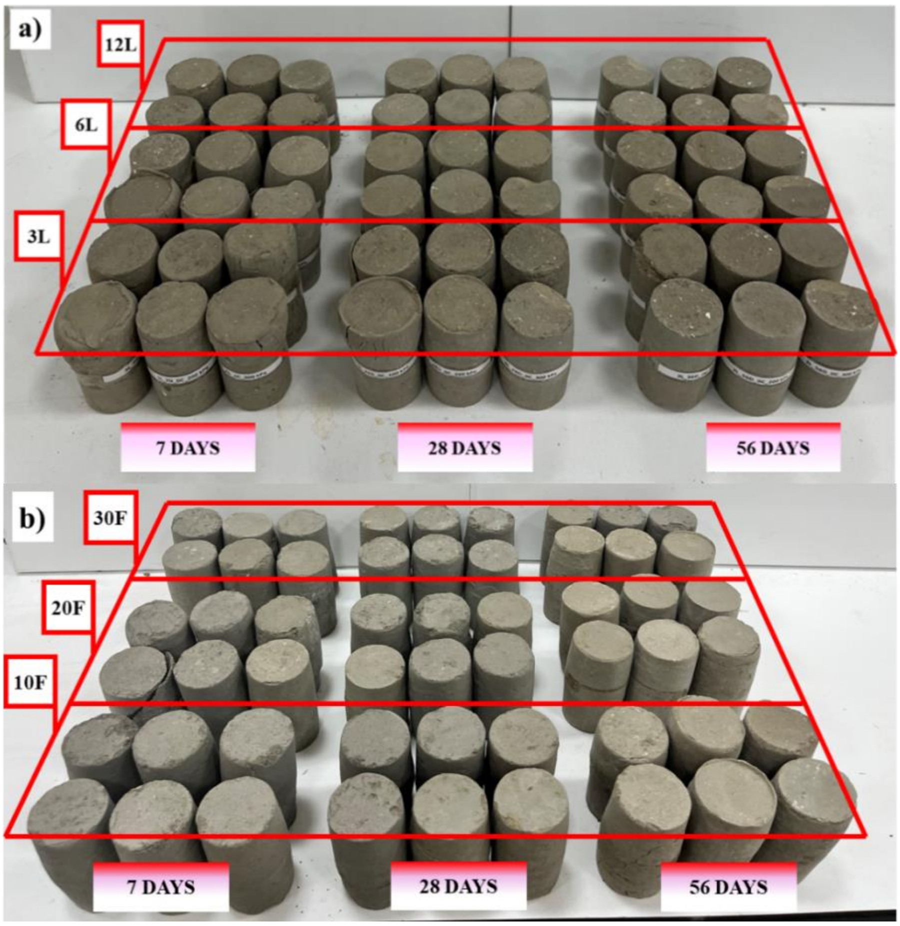

Figure 5. Tested samples after UU a) Lime stabilized, b) Fly ash stabilized.

3. Findings and Discussion

In the paper, where the effects of both lime and fly ash and stabilization on alluvial soils were examined, unconsolidated – undrained (UU) triaxial compression tests were carried out with consideration of the potential influences of freeze-thaw (FT) cycle and curing time. Variations in undrained shear strength values were analyzed based on the test results. The obtained data for the undrained shear strength with lime or fly ash content and FT cycle is illustrated in Figure 6. In the bar graphs, the average undrained shear strength values derived from tests conducted under three different confining pressures are illustrated. These graphs also reflect the influence of FT cycles and the variation in strength associated with different curing durations. The relationships shown provide a general summary of the key findings of the study. Additionally, the overall results are categorized and discussed under the following main topics.

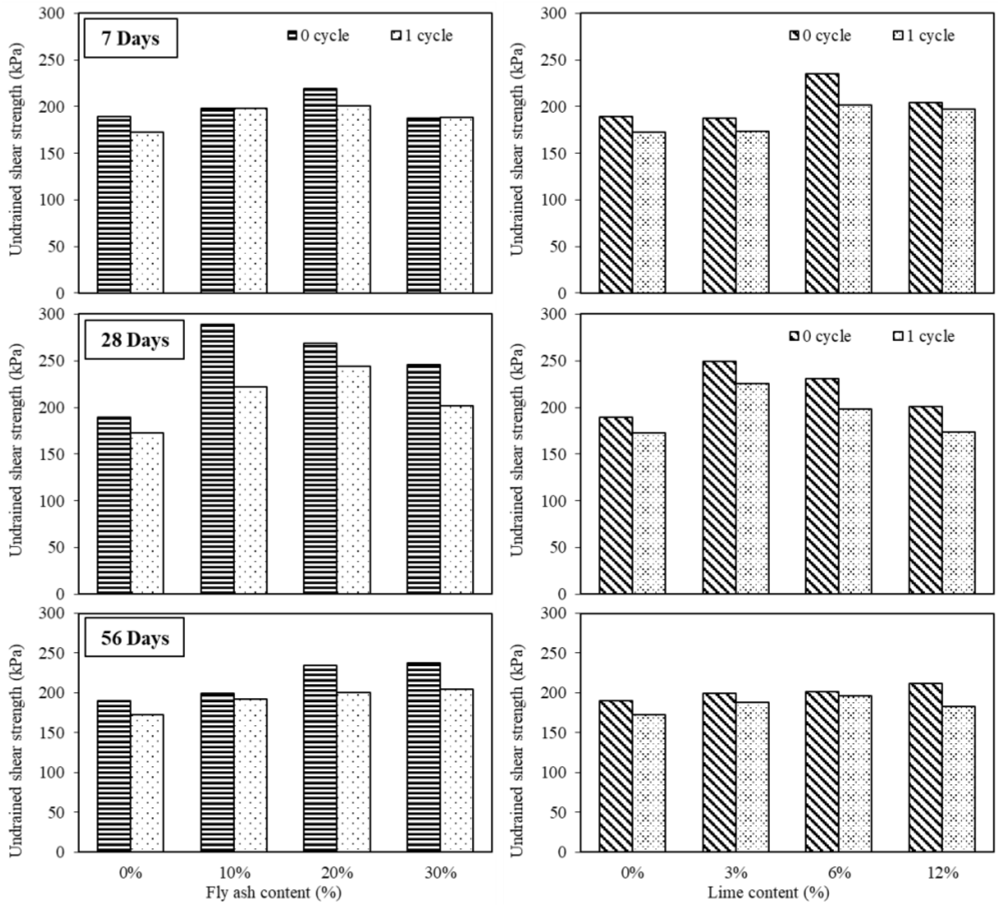

Figure 6. The summary results obtained from the tests.

3.1. Failure of Undrained Shear Strength for Lime and Fly Ash Stabilization

According to Figure 6, increasing the content of fly ash and lime generally led to an improvement in strength; however, the rate of increase tended to decrease beyond a certain level. The FT cycle typically resulted in a reduction in undrained shear strength. The highest strength values were generally observed at moderate stabilization levels, specifically at 10%–20% fly ash and 3%–6% lime content. As the curing period increased, strength development was more pronounced, indicating that the stabilization reactions progressed over time. In samples exposed to the FT cycle, longer the curing periods were associated with reduced strength loss. The most evident correlation observed in Figure 6 is that stabilization with fly ash in alluvial soils yields more effective results than lime, particularly at 28 and 56 days of curing. It can be seen that the undrained shear strength of alluvial soil increases significantly with the addition of fly ash. While lime stabilization resulted in relatively modest strength gains, fly ash led to considerably higher improvements. This is likely due to the fact that the soil being stabilized is silty, and fly ash has been shown to perform well in silty soils, as reported in previous studies (Firoozi et al. 2017; Arora & Aydilek 2005; Acosta 2002).

Both the physical and chemical characteristics of fly ash contribute to its effectiveness in stabilization. The high pozzolanic activity of class C fly ash, driven by its high silica and lime content, explains its more active role in stabilization process compared to lime. Premkumar et al. (2017) described the underlying mechanism, noting that Ca^{2+} and OH^- ions dissolved in pore water react with alumina and silica in the soil to form cementing materials such as calcium silicate and calcium aluminate. Extended curing periods enhance the strength contribution of fly ash by allowing additional hydration reactions and the formation of more cementing materials. The development of cementitious bonds between silt particles and fly ash is a key factor in strength improvement. Moreover, higher the CaO content and greater CaO/SiO_2 (or $CaO/(SiO_2 + Al_2O_3)$) ratios in class C fly ash correlate with increased strength (Raja & Thyagaraj 2019). Additionally, fly ash particles within the 2–25 μm size range, especially those with spherical morphology, are known to exhibit higher reactivity, as confirmed by current findings (Moghal 2017). In contrast, lime tends to be more effective in soils with a high clay content and high activity, which further explains the relatively lower strength gains observed in the present study (Parsons & Milburn 2003).

When the relationship was examined in greater detail, it was determined that strength development increased with curing time due to pozzolanic reactions. However, after an initial increase, the strength either stabilized or began to decrease. In particular after 56 days of curing, the effect of stabilization diminished to a level that can be could be considered negligible. This decline, especially in lime-stabilized samples, may be attributed to the formation of detrimental minerals in the sulfated environment of the alluvial soil, combined with the effects of temperature fluctuations. These conditions may hinder or even suppress the continuation of pozzolanic reactions (Arnett et al. 2001; Jallad et al. 2003; Raja & Thyagaraj 2019).

On the other hand, in addition to the stabilization content, the optimum curing period for both stabilizing agents was determined to be 28 days, although the optimal content levels differed. For lime stabilization, the optimal content ranged between 3 and 6%, whereas for fly ash, it reached levels exceeding 10%. Although the higher dosage of fly ash might typically be considered a disadvantage, the substantial strength gain achieved at these levels offsets this concern—rendering it negligible, and in fact, turning it into a potential advantage. Ultimately, this results in a sustainable and cost-effective approach for stabilizing alluvial soils.

The absence of sharp strength reductions in lime-stabilized samples became particularly evident when the FT cycle was applied. At first glance, the resistance of lime stabilized soils to freeze-thaw effects appeared to be higher than that of fly ash-stabilized soils. In contrast, significant strength reductions were observed in fly ash-stabilized samples after 28 and 56 days of curing. This behavior can be attributed to the frost-susceptible nature of silty soils, which are sensitive to temperature fluctuations (Wang et al. 2014). In fly ash stabilization, where the fly ash amplifies the silt-like behavior of the soil, this inherent sensitivity becomes more pronounced, and the freeze-thaw process plays a more active and detrimental role (Horpibulsuk et al. 2013).

In general, it was observed that the application of the FT cycle leads to a reduction in strength. This is primarly due to the volumetric expansion caused by ice formation during freezing, which gives way to the development of micro-cracks upon thawing. As a result, a wide range of strength outcomes may be experienced. In certain cases, however, changes in the internal structure of the samples following freeze-thaw exposure, such as the redistribution of pore water, alterations in dry unit weight, or minor differences in testing conditions, may result in an unexpected increase in strength after FT cycle (Liu et al. 2016). In the present study, this phenomenon was particularly evident in experiments conducted under high confining pressures and was observed in certain cases involving fly ash stabilization. The effect became more pronounced with longer curing durations, especially at specific fly ash content levels, where increased interaction between the soil and stabilizer contributed to the observed strength behavior.

From another perspective, the undrained shear strength results obtained under different confining pressures, both with and without the application of a freeze-thaw (FT) cycle, were examined using a single graph (Figure 7), focusing on soils stabilized with lime and fly ash. Basic inferences continued to be drawn by analyzing the strength variations across different stabilizer contents. In the graph, the upper and lower limits of strength values for each stabilizer were identified, and average strength curves were generated based on the variations in stabilizer ratio. Although a highly distinct trend is not observed from the individual data points in Figure 7, the curves provide valuable insight by illustrating the lower and upper boundary strength envelopes for stabilized alluvial silts, both with and without FT exposure. Overall, the lime stabilization curve is significantly lower than that of fly ash, and a generally concave trend can be observed. While the fly ash curve has not yet fully developed a concave shape, the peak strength values appear to occur between 15% and 25% content. In cases where alluvial soils with similar physical and chemical properties require stabilization, these reference curves offer preliminary guidance for estimating the potential degree of strength improvement under different conditions. Moreover, the graph suggests that both lime and fly ash contribute to strength enhancement up to an optimum range (~10%–20%). Beyond this range, further increases in stabilizer content may adversely affect the soil structure, leading to reductions in shear strength.

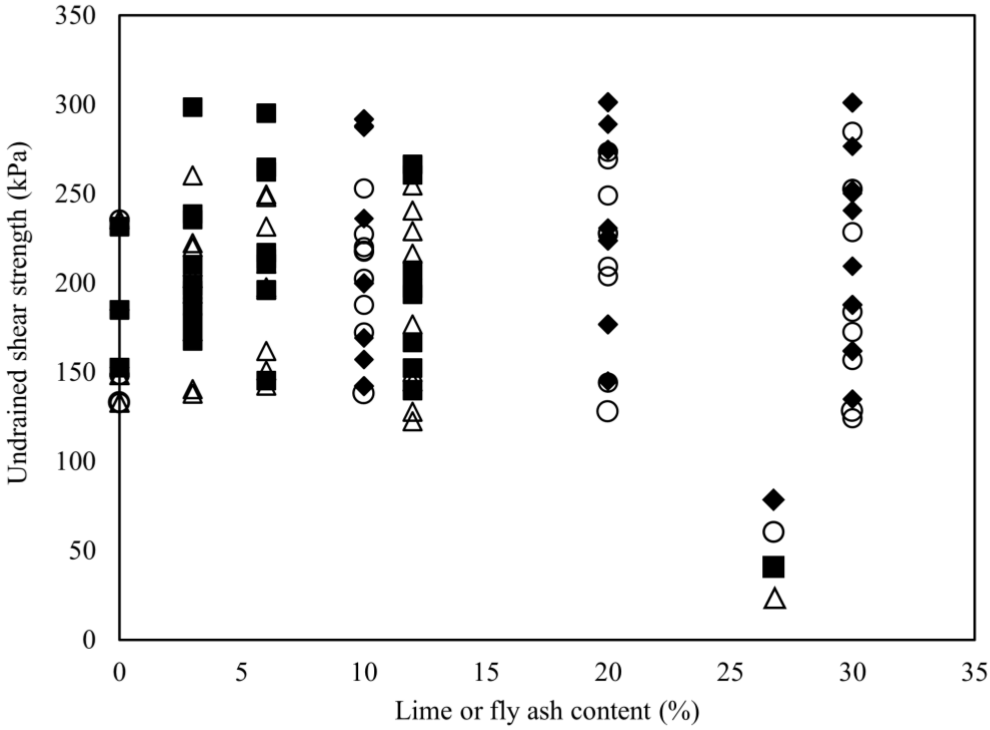

Figure 7. The reference curves for lime and fly ash stabilization.

In Figure 8, the effect of the freeze-thaw (FT) cycle on lime and fly ash stabilization is examined separately, and average strength curves corresponding to each curing period are presented. As observed in the figure, the application of the FT cycle does not significantly alter the results for lime; the curves for different curing periods tend to converge, indicating that the influence of curing time becomes negligible under freeze-thaw conditions. In contrast, an opposite trend is observed for fly ash stabilization. When the FT cycle is applied, curing time becomes a dominant factor. This behavior may be attributed to the fact that, in the case of 7-day curing, the pozzolanic reactions associated with fly ash stabilization are still incomplete, whereas strength values for longer curing durations (28 and 56 days) are closer to one another, reflecting more advanced reaction stages. This observation is consistent with previous findings suggesting that fly ash-stabilized soils typically develop their full strength between 28 and 90 days (Premkumar et al. 2017).As shown in Figure 8, both lime and fly ash stabilization initially enhance the undrained shear strength of the soil; however, their effectiveness reduces at higher content levels due to over-stabilization or structural weakening. The 28-day curing period yields the highest strength values, indicating that stabilization reactions are most active and effective at this stage. Although freeze-thaw cycles reduce the strength of the soil overall, the loss is more pronounced at higher stabilizer contents. This suggests that excessive amounts of stabilizer may increase the soil's vulnerability to FT-related damage. The optimum stabilization levels appear to be approximately 6% for lime and between 10% and 20% for fly ash. Moreover, long-term curing (56 days) does not result in significant strength improvement compared to 28 days, suggesting that the effects of stabilization tend to plateau beyond the 28 day curing period.

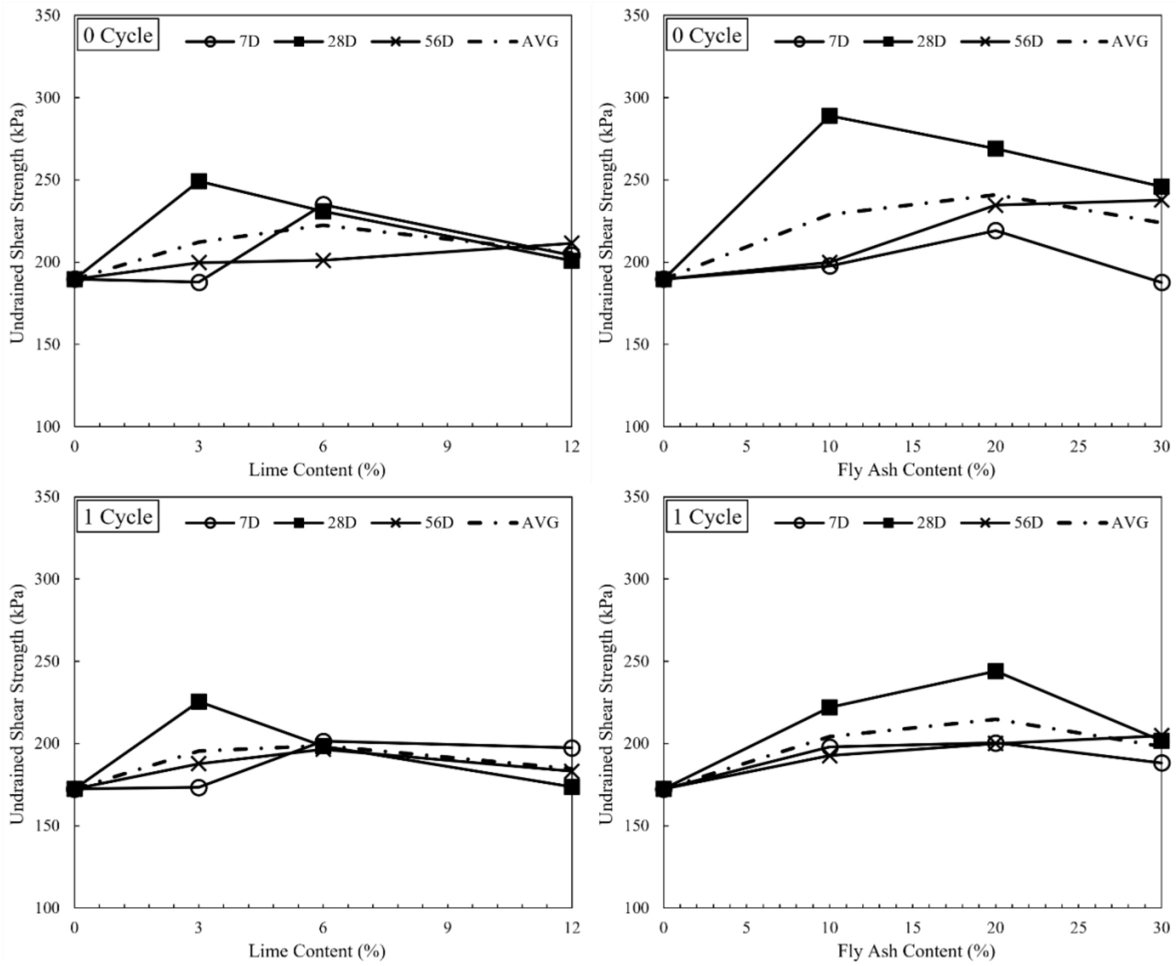

Figure 8. Undrained shear strength vs. stabilizer content for 0 and 1 cycle.

3.2. Stress-Strain Relations and Failure Modes

The stress–strain relationship differs significantly between lime and fly ash-stabilized soils. These differences are primarily arise from the contrasting brittle and ductile behaviors exhibited by the stabilized materials. Ductile soils maintain theirstrength after reaching a certain level of deformation to resist stress—a behavior known as strain hardening. On the contrary, brittle soils fail abruptly after reaching peak strength, followed by a decline in stress, which is indicative of strain-softening behavior. These behavioral differences also result in distinct failure modes for stabilized samples. Figure 9 presents typical stress–strain curves for lime and fly ash stabilization, while Figure 10 illustrates representative failure modes. The curves in Figure 9 reflect the general patterns observed for each stabilizer type and are included for comparative purposes. As shown, lime-stabilized soils tend to exhibit ductile behavior, whereas fly ash-stabilized samples show a more brittle response. The observed failure modes corroborate these findings. Strain-softening behavior in fly ash-stabilized soils was only evident at high stabilizer contents. Conversely, strain-hardening behavior in lime-stabilized soils remained consistent across all stabilization levels, indicating a stable mechanical response regardless of content. Although the axial deformation at failure varied between the two stabilizers, the range of elastic behavior, defined by the linear portion of the stress–strain curve, was found to be similar for both lime and fly ash up to a certain strain level.

In conclusion, the sharp post-peak drop in stress observed in the tests indicates a brittle failure behavior, which is characteristic of fly ash-stabilized samples. In contrast, lime-stabilized samples exhibit a distinct strain-hardening phase prior to failure, followed by a stabilization of stress at residual strength levels.

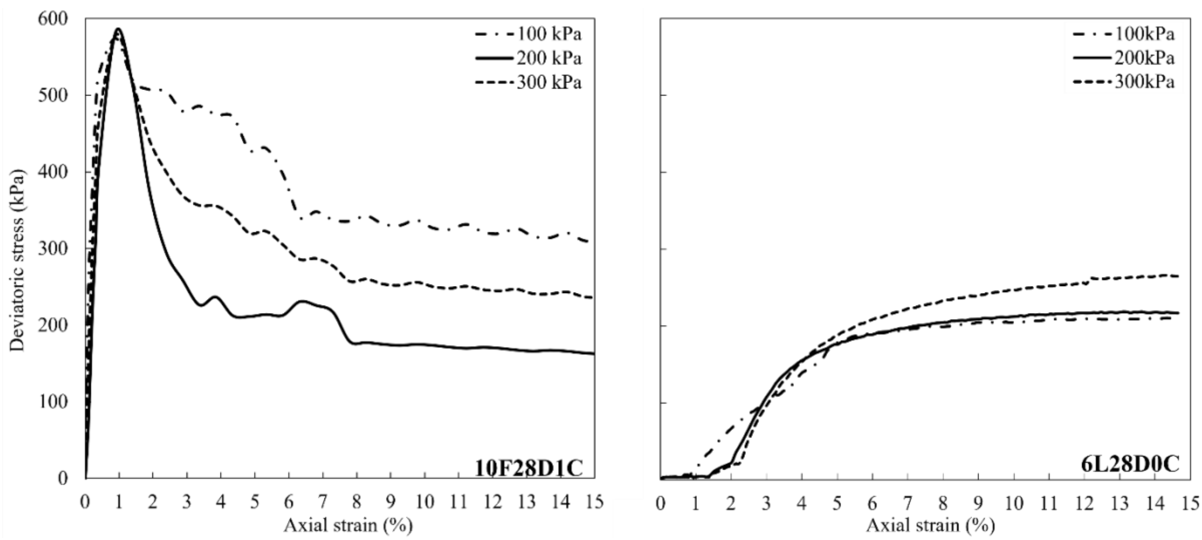

Figure 9. Stress-strain curves of fly ash and lime stabilized soil samples.

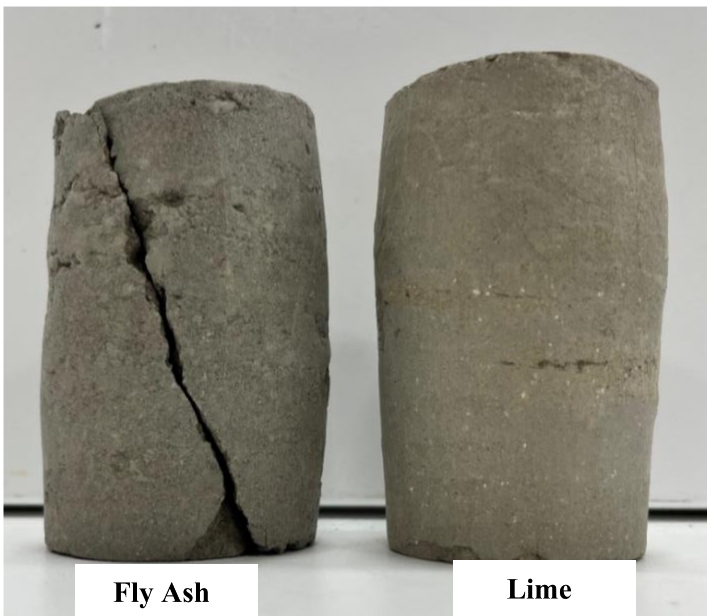

Figure 10. Different failure modes for stabilized soil samples.

Figure 11 presents the stress-strain relationships of two different fly ash-stabilized samples. Upon examining the curves, it was observed that the elastic phase lasted longer in the absence of the FT cycle, whereas exposure to FT resulted in a shorter elastic interval. Both the elastic modulus value and the compressive strength decreased alongside the reduction in elastic behavior under FT conditions. This outcome is attributed to the effects of the freeze–thaw process, which increases the formation of voids and microcracks within the soil, thereby compromising its internal structure (Zhao et al. 2020).

In both cases, deviatoric stress increased with rising confining pressure, indicating that higher confinement enhances soil strength. However, the sample subjected to the freeze–thaw (FT) cycle exhibited lower overall deviatoric stress values, suggesting that the FT cycle led to strength degradation. Strain-hardening behavior was more evident in the sample that was not exposed to FT, as reflected by its higher residual stress levels. These results demonstrate that while fly ash stabilization effectively improves the strength of silty soils, this enhancement diminishes following FT cycles—particularly under higher confining pressures.

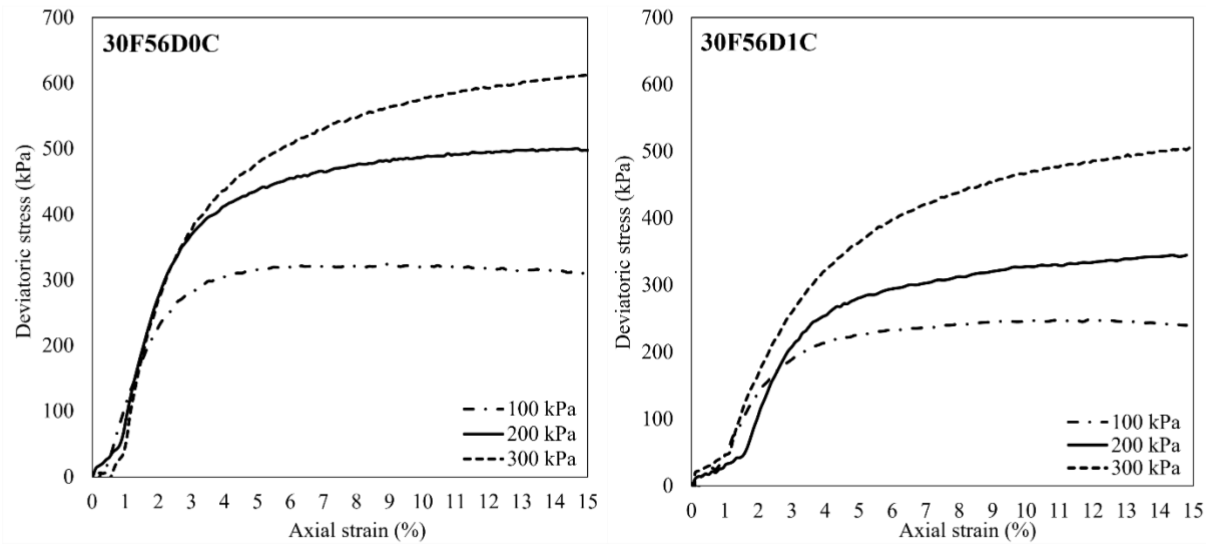

Figure 11. Stress-strain curves of fly ash stabilized soil samples for 0 and 1 cycle.

Yan et al. (2013) reported that freeze–thaw (FT) cycles can alter the shape of stress–strain curves, shifting the behavior from strain-softening to strain-hardening. This observation was partially confirmed in the present study, but only for certain confining pressure levels. In contrast, Wang et al. (2007) suggested that such a transition occurs only after exceeding a critical confining pressure.

As shown in Figure 11, this shift was generally observed in fly ash-stabilized samples at confining pressures above 200 kPa. However, in the case of lime-stabilized samples, strain-hardening behavior remained consistent regardless of FT exposure, and no noticeable change was observed in the shape of the stress–strain curves.

4. Conclusions and Recommendations

In this paper, the stabilization principles of alluvial soils under freeze-thaw conditions were discussed. Two common stabilizers, lime and fly ash, were utilized in different proportions, and their mechanisms were examined over varying curing periods. To capture the freeze-thaw behavior of silty soils, the samples were subjected to 0 and 1 FT cycles. The key findings and comparisons between the two stabilization mechanisms are as follows:

(1) The undrained shear strength of fly ash-stabilized alluvial soils was significantly higher than that of lime stabilized soils in almost all cases, as the interaction between silty soils and fly ash tends to yield more effective results. Lime stabilization, on the other hand, is more suitable for soils with high activity and plasticity. Therefore, the stabilization effectiveness of lime remained lower compared to that of fly ash.

(2) When the effects of different curing times were examined, it was observed that the increase in curing duration had remained almost ineffective in stabilization with lime. The presence of detrimental minerals,which may form due to the use of calcium-based stabilizers in sulfated soils, appeared to dominate the behavior of lime-stabilized samples, likely due to lime’s higher calcium content. In contrast, fly ash, stabilization improved with longer curing periods. However, in both cases, the most effective stabilization was achieved at 28 days.

(3) The optimum stabilization rate was found to be between 3-6% for lime, and 15-25% for fly ash. This finding highlights the potential of fly ash as a sustainable solution by enabling the recycling of this waste material in the stabilization of alluvial soils.

(4) Lime stabilized soils preserved their structural integrity more effectively, while fly ash-stabilized soils experienced greater strength loss under freeze–thaw conditions, particularly after 28 and 56 days of curing. Although the influence of silt becomes negligible under higher confining pressures, further research is needed involving additional freeze–thaw cycles and increased confining pressure levels to better understand this behavior.

(5) A wide range of data on the stabilization of alluvial soils using fly ash and lime was compiled and presented graphically, resulting in the development of reference curves that can provide preliminary guidance. These curves offer a foundation for understanding stabilization behavior in alluvial soils and also serve as a useful reference when freeze–thaw cycles are considered. Overall, the graphs contribute to addressing a significant gap in the literature on the stabilization of alluvial soils.

(6) The strain-hardening behavior of lime-stabilized soils and the strain-softening behavior of fly ash-stabilized soils with higher content and longer curing times became dominant. Correspondingly, lime stabilized samples exhibited a ductile failure mode, whereas fly ash-stabilized samples failed in a brittle manner. The stress-strain curves of fly ash-stabilized samples were also affected by the freeze-thaw cycle, showing reduced elastic behavior. At higher confining pressures, the behavior of fly ash-stabilized soils began to shift from strain-softening to strain hardening. As this transition may occur beyond a critical confining pressure threshold, future studies should investigate fly ash stabilization under higher confining pressures.

Authors' Contributions

All authors contributed equally to the study.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

Acknowledgement

We would like to express our gratitude to İrem DÜZEN for her valuable contributions to this study.

References

Acosta, H. A. (2002). *Stabilization of soft subgrade soils using fly ash*. Master Science Thesis, University of Wisconsin, Madison.

Arnett, S. J., Macphee, D. E., and Crammond, N. J. (2001). Solid Solutions Between Thaumasite and Ettringite and Their Role in Sulfate Attack. *Journal of Concrete Science Engineering*, 3, 209-215.

Arslan, E., Develioglu, I., Pulat, H. F. (2023). The effect of curing time and freeze-thaw cycles on the undrained shear strength of lime-stabilized alluvial soils. *Revista de la Construcción*, 22(2). http://dx.doi.org/10.7764/rdlc.22.2.348

Arslan, E., Ekinci, E., Garip, Z. Küçük, F., Sert, S. (2024). A sustainable solution for soil improvement: a decision tree model combined with metaheuristic optimizations for fiber reinforced clays. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-05554-w

Arora, S., and Aydilek, A. H. (2005). Class F Fly-Ash-Amended Soils as Highway Base Materials. *Journal of Materials in Civil Engineering*, 17(6), 640-649.

ASTM D1140-17 (2017). *Standard Test Methods for Determining the Amount of Material Finer than 75-µm (No. 200) Sieve in Soils by Washing*. West Conshohocken, PA: ASTM International.

ASTM D2487-17 (2020). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*. West Conshohocken, PA: ASTM International.

ASTM D2850 (2015). *Standard test method for unconsolidated-undrained triaxial compression test on cohesive soils.* West Conshohocken, PA: ASTM International.

ASTM D4318-17e1 (2018). *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. West Conshohocken, PA: ASTM International.

ASTM D4972-19 (2019). *Standard Test Methods for pH of Soils*., West Conshohocken, PA: ASTM International.

ASTM D560 (2016). *Standard test methods for freezing and thawing compacted soil–cement mixtures*. West Conshohocken, PA: ASTM International.

ASTM D698-12 (2021). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)).* West Conshohocken, PA: ASTM International.

ASTM D7928-21e1 (2021). *Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis*. West Conshohocken, PA: ASTM International.

ASTM D854-14 (2016). *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*. West Conshohocken, PA: ASTM International.

Balkis, A. P. (2017). The effects of waste marble dust and polypropylene fiber contents on mechanical properties of gypsum stabilized earthen. *Construction and Building Materials*, 134, 556-562.

Barbhuiya, S. A., Gbagbo, J. K., Russell, M. I., and Basheer, P. A. M. (2009). Properties of fly ash concrete modified with hydrated lime and silica fume. *Construction and Building Materials*, 23(10), 3233-3239.

Benson, C. H., and Othman, M. A. (1993). Hydraulic conductivity of compacted clay frozen and thawed in situ. *Journal of Geotechnical Engineering,* 119, 276-294.

Bhuvaneshwari, S., Robinson, R. G., and Gandhi, S. R. (2005). *Stabilization of expansive soils using fly ash.* Fly Ash Utilization Programme, (FAUP), Technology Information Forecasting & Assessment Council (TIFAC), Department of Science and Technology (DST), New Delhi, India.

Boardman, D. I., Glendinning, S., and Rogers, C. D. F. (2001). Development of stabilization and solidification in lime–clay mixes. *Geotechnics*, 51(6), 533-543

Cheng, Y., Tang, C., Xie, Y., Liu, B., & Pan, X. (2021). Experimental Study on Structure Strength of Loess Improved by Microbial Induced Calcite Precipitation. *Journal of Engineering Geology*, 9(1), 44-51.

Das, B.M. (2015). *Principles of foundation engineering*. Boston: Cengage Learning.

Degirmenci, N., Okucu, A., and Turabi, A. (2007). Application of phosphogypsum in soil stabilization. *Building and Environment*, 42(9), 3393-3398.

Estabragh, A. R., Bordbar, A. T., and Javadi, A. A. (2013). A study on the mechanical behavior of a fber-clay composite with natural fiber. *Geotechnical and Geological Engineering*, 31(2), 501-510.

Firoozi, A. A., Guney, O. C., Firoozi, A. A., and Baghini, M. Z. (2017). Fundamentals of soil stabilization. *International Journal of Geo-Engineering*, 8(26).

Golhashem, M. R., and Uygar, E. (2020). Volume change and compressive strength of an alluvial soil stabilized with butyl acrylate and styrene. *Construction and Building Materials*, 255.

Hausmann, M. R. (1990). *Engineering principles of ground modification.* Maidenheach: McGraw-Hill.

Horpibulsuk, S., Phetchuay, C., Chinkulkijniwat, A., and Cholaphatsorn, A. (2013). Strength development in silty clay stabilized with calcium carbide residue and fly ash. *Soils and Foundation*, 53(4), 477–486.

Jallad, K. N., Santhanam, M., and Cohen, M. D. (2003). Stability and Reactivity of Thaumasite at Different pH Levels. *Cement and Concrete Research*, 33(3), 433-437.

Kamata, T., Tsukamato, Y., and Ishihara, K. (2009). Undrained shear strength of partially saturated sand in triaxial tests. *Bulletin of the New Zealand Society for Earthquake Engineering*, 42(1), 57-62.

Kavak, A., & Akyarli, A. (2007). A field application for lime stabilization. *Environmental Geology*, 51, 987-997.

Li, J., Zhou, K., Liu, W., and Zhang, Y. (2018). Analysis of the effect of freeze–thaw cycles on the degradation of mechanical parameters and slope stability. *Bulletin of Engineering Geology and Environment*, 77(2), 573-580.

Little, D. N., and Nair, S. (2009). *Recommended practice for stabilization of subgrade soils and base material.* NCHRP, Texas A&M University, Texas, Transportation Research Board of the National Academies.

Little, D. N. (1999). Evaluation of structural properties of lime stabilized soils and aggregates. *Prepared for the national lime association*, 1, 1–89.

Liu, J. K., Chang, D., and Yu, Q. M. (2016). Influence of freeze-thaw cycles on mechanical properties of a silty sand. *Engineering Geology*, 210, 23-32.

Maaitah, O. N. (2012). Soil stabilization by chemical agent. *Geotechnical and Geological Engineering*, 30(6), 1345-1356.

Malikzada, A., Arslan. E., and Develioglu, I. (2022). Determination of strength characteristics of natural and stabilized alluvial subgrades. *Arabian Journal of Geoscience*, 15(535).

Manz, O. E. (1999). Coal fly ash: a retrospective and future look. *Fuel,* 78(2), 133-136.

Miller, B. A., and Schaetzl, R. J. (2012). Precision of soil particle size analysis using laser diffractometry. *Soil Science Society of America Journal*, 76(5), 1719-1727.

Moghal, A. A. B. (2017). State-of-the-art Review on the Role of Fly Ashes in Geotechnical and Geoenvironmental Applications. *Journal of Materials in Civil Engineering*, 29(8).

Naeini, S. A., Naderinia, B., and Izadi, E. (2012). Unconfined compressive strength of clayey soils stabilized with waterborne polymer. *KSCE Journal of Civil Engineering*, 16(6), 943-949.

Nalbantoglu, Z., and Gucbilmez, E. (2002). Utilization of an industrial waste in calcareous expansive clay stabilization. *Geotechnical Testing Journal*, 25(1), 78-84.

Nalbantoglu, Z. (2004). Effectiveness of class C fly ash as an expansive soil stabilizer. *Construction and Building Materials*, 18(6), 377-381.

Nguyen, T. T. H., Cui, Y. J., Ferber, V., Herrier, G., Ozturk, T., Plier, F., Puiatti, D., Salager, S., and Tang, A. M. (2019). Effect of freeze-thaw cycles on mechanical strength of lime-treated fine-grained soils. *Transportation Geotechnics*, 21.

Nishimura, T. (2006). Drained shear test for unsaturated soil with different axial strain rate. *Proceedings of Geo-Kanto*, Kanto Branch of Japanese Geotechnical Society.

Parsons, R., and Milburn, J. (2003). Engineering behavior of stabilized soils. *Transportation Research Record*, 1837, 20-29.

Phanikumar, S. R., and Sharma, R. S. (2004). Effect of fly ash on engineering properties of expansive soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(7), 764-767.

Prabakar, J., Dendorkar, N., and Morchhale, R. (2004). Influence of fly ash on strength behavior of typical soils. *Construction and Building Materials*, 18, 263-267.

Premkumar, S., Piratheepan, J., and Rajeev, P. (2017). Effect of brown coal fly ash on dispersive clayey soils. *Proceeding of the Institution of Civil Engineering and Ground Improvement*, 170, 231–244.

Qu, Y. L., Chen, G. L., Niu, F. J., Ni, W. K., Mu, Y. H., and Luo, J. (2019). Effect of freeze-thaw cycles on uniaxial mechanical properties of cohesive coarse-grained soils. *Journal of Mountain Science*, 16(9), 2159-2170.

Raja, P. S. K., and Thyagaraj, T. (2019). Effect of short-term sulphate contamination on lime-stabilized expansive soil. *International Journal of Geotechnical Engineering*, 15(8), 964-976.

Semerci, B., Develioglu, I., and Pulat, H. F. (2018). Geotechnical Characterization of Alluvial Soil in Çiğli - Balatçık Region. *Eurasian Journal of Civil Engineering and Architecture*, 2(2), 44-50.

Sert, S., Arslan, E., Ocakbaşı, P. Ekinci, E., Garip, Z., Özocak, A., Bol, E., Ndepete, C. P. (2024). Stabilization of Expansive Clays with Basalt Fibers and Prediction of Strength by Machine Learning. *Arabian Journal of Science and Engineering*, 49, 13651–13670. https://doi.org/10.1007/s13369-024-08752-w

Sharma, N. K., Swain, S. K., and Sahoo, U. C. (2012). Stabilization of a Clayey Soil with Fly Ash and Lime: A Micro Level Investigation. *Geotechnical and Geological Engineering*, 30, 1197-1205.

Sherwood, P. (1993). *Soil stabilization with cement and lime*. College Park: Transport Research Laboratory.

Tastan, E. O., Edil, T. B., Benson, C. H., and Aydilek, A. H. (2011). Stabilization of Organic Soils with Fly Ash. *Journal of Geotechnical and Geoenvironmental Engineering*, 137, 819-833.

Teber, D., and Akoğuz, H. (2024). Kireç ve Sodyum Aljinat Biyopolimeri ile İyileştirilen Yüksek Plastisiteli Kil Zeminin Donma-Çözülme Özelliklerinin Araştırılması. *Karadeniz Fen Bilimleri Dergisi*, 14(3), 1371-1383.

TS ISO 13320 (2021). *Particle Size Analysis – Laser Diffraction Methods.* Türkiye: Türk Standardı.

Tsukamoto, Y. (2019). Degree of saturation affecting liquefaction resistance and undrained shear strength of silty sands. *Soil Dynamics and Earthquake Engineering*, 124, 365-373.

Vanapalli, S. K., and Fredlund, D. G. (1997). Interpretation of undrained shear strength of unsaturated soils in terms of stress state variables. *Proceedings of the 3rd Brazilian Symposium on Unsaturated Soils* (pp. 22-25). Rio de Janeiro, Brasil.

Wang, D., Ma, W., Niu, Y., Chang, X., and Wen, Z. (2007). Effects of cyclic freezing and thawing on mechanical properties of Qinghai – Tibet clay. *Cold Regions Science and Technology*, 48, 34-43.

Wang, T. L., Bu, J. Q., and Wang, Y. (2014). Thaw subsidence properties of soils under repeated freeze–thaw cycles. *Chinese Journal of Geotechnical Engineering*, 36(4), 625-632.

Yadav, A. K., Gaurav, K., Kishor, R., and Suman, S. K. (2017). Stabilization of alluvial soil for subgrade using rice husk ash, sugarcane bagasse ash and cow dung ash for rural roads. *International Journal of Pavement Research and Technology*, 10(3), 254-261.

Yan, H., Liu, J., and Wang, T. (2013). Experimental research of influence of freeze-thaw on the mechanical properties of silty soil. *Journal of Beijing Jiaotong University*, 37(4), 73-77.

Yang, Y., Wang, L. J., Wendroth, O., Liu, B. Y., Cheng, C. C., Huang, T. T., and Shi, Y. Z. (2019). Is the laser diffraction method reliable for soil particle size distribution analysis. *Soil Science Society of America Journal,* 83(2), 276-287.

Yilmaz, F., and Fidan, D. (2018). Influence of freeze-thaw on strength of clayey soil stabilized with lime and perlite. *Geomechanics and Engineering*, 14(3), 301-306.

Zhao, T., Yang, G., Xi, J., Shen, Y., and Song, K. (2020). Factorial Experiment Study on the Mechanical Properties of Sandstone–Concrete Specimens Under Different Freeze–Thaw Conditions. *Frontiers in Physics,* 8(322).