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Research Article

Investigation of Durability Performance of High Plasticity Silty Soil Improved with Alkali Activated Fly Ash and Polypropylene Fiber

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Abstract

This study investigates the durability performance of high-plasticity silty soil stabilized with alkali-activated fly ash and reinforced with polypropylene fibers. Unlike conventional practice, the effect of different lengths of fiber reinforcement combinations on durability was investigated in this study. The study combines alkali activation technology with hybrid fiber reinforcement, utilizing a mixture of 3 mm and 12 mm length polypropylene fibers. While traditional methods usually focus on wetting-drying or freeze-thaw cycles for durability assessment, the durability effect was achieved in this study through wetting tests involving long saturation periods. Within the scope of the study, specimen residues obtained from three-point bending tests were used as test specimens. The study investigated the effects of reinforcement content and hybrid reinforcement effect parameters on durability performance. Key findings of the study include: (1) The increase in sodium silicate content increased the durability performance of the material. (2) Both 3 mm and 12 mm length fiber addition increased the durability performance. (3) Length hybrid fiber combinations showed better durability performance compared to single length fiber reinforcements.

Keywords: Alkali-activated fly ash, Durability, Soaking, Soil stabilization, Hybrid fiber reinforcement

Alkali Aktifleştirilmiş Uçucu Kül ve Polipropilen Elyaf Ile Iyileştirilmiş Yüksek Plastisiteli Siltli Zeminin Durabilite Performansının Incelenmesi

Öz

Bu çalışmada, alkali aktive edilmiş uçucu kül ve polipropilen liflerle takviye edilmiş yüksek plastisiteli siltli bir zeminin durabilite performansı araştırılmıştır. Geleneksel uygulamadan farklı olarak, farklı uzunluklardaki lif kombinasyonlarının durabilite üzerindeki etkisi irdelenmiştir. Geleneksel yöntemler, durabilite değerlendirmesi için genellikle ıslatma-kurutma veya donma-çözülme döngülerine odaklanırken, bu çalışmada durabilite performansı uzun doygunluk dönemlerini içeren ıslatma testleri yoluyla değerlendirilmiştir. Çalışma kapsamında, üç nokta eğme testlerinden elde edilen numune artıkları deney numunesi olarak kullanılmıştır. Su içerisinde doygunluğa 7 gün, 30 gün ve 60 gün süre ile maruz bırakılan numunelerin serbest basınç deneyine tabi tutulmaları neticesinde durabilite performansları incelenmiştir. Çalışmada, fiber katkı içeriğinin ve uzunlukça hibrit fiber katkı etkisi gibi parametrelerin durabilite performansı üzerindeki etkileri araştırılmıştır. Çalışmanın temel bulguları şunlardır: (1) Sodyum silikat içeriğindeki artış, malzemenin durabilite performansını arttırmıştır. (2) 3 mm ve 12 mm uzunluğundaki lif katkısı durabilite performansını arttırmıştır. (3) Uzunlukça hibrit fiber kombinasyonları, tek uzunluktaki fiber donatılara kıyasla daha iyi durabilite performansı göstermiştir.

Anahtar Kelimeler: Alkali aktif uçucu kül, Durabilite, Islatma, Zemin stabilizasyonu, Hibrit elyaf takviyesi

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1. Introduction

Due to the demand for growth and industrialization, there is a growing shortage of foundation soil with suitable geotechnical properties for civil engineering structures. Therefore, mechanical or chemical soil stabilizing techniques have become required, especially in the last few years. Using affordable, ecologically friendly, and sustainable stabilizing agents is crucial in geotechnical engineering. Binding materials like cement and lime are frequently utilized in chemical stabilization applications. However, the massive amount of CO_2 released during manufacturing is the primary environmental issue with these binding materials [1, 2]. Since alkali-activated binders reduce carbon footprint by 40 – 80%, they are a suitable substitute for traditional binders [3, 4]. The utilization of geopolymers and alkali-activated materials for soil stabilization applications has been the subject of much research over the last ten years. Some studies have focused on the availability of low-cost and low-CO_2 emission waste materials as an alternative to conventional binders. Industrial by-products [5, 6], waste materials [7, 8], or industrial materials [9] can be utilized as alkali-alumina sources for soil stabilization applications. Various alkaline solutions such as sodium hydroxide [10], sodium silicate [11], magnesium oxide [12], or potassium oxide [13, 14] can be used to activate the alkali-alumina sources.

One of the significant aims of soil stabilization application is to enhance the durability performance of the stabilized soil. A wide range of studies investigated the effects of several parameters on the durability characteristics of geopolymer-stabilized soil. Some of these studies have focused on determining the optimum amount of binder and activator. In addition, there are studies investigating the effect of binder type and activator type on durability performance [15–18]. In general, the durability performance of the stabilized soil samples is evaluated by subjecting the samples to wetting-drying or freezing-thawing cycles [19–22]. On the other hand, some studies have suggested that wetting tests are more important than freeze-thaw or wetting-drying cycles for durability assessments because wetting tests have the ability to simulate field conditions more accurately. Although there are many studies about the assessment of durability performances of stabilized soil considering conventional methods, the number of studies considering the soaking performance of stabilized soil is very few [23, 24].

In soil improvement applications using both conventional binders and alkaline active binders, although the material gains considerable strength, its brittleness also increases. The use of fiber is a common practice to reduce this brittleness and increase the ductility of the material [25–27]. In the literature, there are generally studies examining the effects of fiber reinforcement on unconfined compressive strength [28], stress-strain properties [29,30], shear strength parameters [31], durability properties [32], swelling-shrinkage behavior [33], flexural-tensile strength [34]. Depending on the types of fibers, the properties that they contribute to the improvement of the material vary. For example, while steel fibers play a role in improving flexural and toughness performance, synthetic fibers play an important role in bridging micro-cracks and preventing durability problems [35,36]. By using different types of fibers, hybrid systems can be created by making use of different properties of fibers at the same time [37]. The use of hybrid fibers is preferred because it provides visible improvement against micro and macro-sized cracks in the material. From the literature, it is seen that the positive properties of each fiber can be used in a single mixture as a result of combining different types of fibers in a matrix [38,39].

The use of hybrid fibers can be evaluated under three different headings according to the principles of benefiting from their structural properties, benefiting from their functions, and benefiting from their length [40]. As a result of the use of different length (hybrid) fibers, the way the fibers work in the material can be explained under two aspects. Accordingly, while short fibers reduce the formation of micro-cracks under stress, long fibers act as a preventive

function in macro-sized cracks [41]. Based on these data, it can be hypothesised that the use of hybrid length reinforcement can improve the durability properties of improved soil layers.
In this study, behavior of a high plasticity silty soil stabilized with fiber reinforcement and alkali-activated fly ash against the soaking effect was investigated. The study addresses several gaps in the current literature. As a result of the short literature review, it was observed that the use of fiber in soil improvement applications is widespread. On the other hand, the effect of the use of hybrid length fibers on soil freeze-thaw behavior is a gap in the literature. The study, explores the synergistic effects of combining alkali-activated fly ash with fiber reinforcement, an approach that has received limited attention in soil stabilization studies. Secondly, the use of hybrid fibers, specifically the combination of 3 mm and 12 mm length polypropylene fibers, represents a novel approach in geotechnical engineering, aiming to provide multi-scale reinforcement within the soil matrix. Thirdly, this study emphasizes the use of soaking tests to evaluate durability, offering a more realistic simulation of field conditions compared to conventional wetting-drying or freezing-thawing cycles. By examining these factors in combination, this research provides valuable insights into enhancing the durability of stabilized soils, particularly in environments prone to water ingress or flooding. In context of the study, the effects of $Na_2SiO_3/NaOH$ ratio, 3 mm length fiber content, 12 mm length fiber content, and combinations of 3 mm – 12 mm length fiber contents on UCS values of soaked samples were examined. The durability performance of the 90-day cured samples was evaluated by subjecting the samples to 7 days, 30 days, and 60 days soaking periods.
Specimens prepared for three-point or four-point bending tests can also be used to determine the unconfined compressive strength of the samples after the bending test [42–44]. The study is a continuation of Kamiloğlu et al. (2023) [45]. The study investigated the effects of $Na_2SiO_3/NaOH$ ratio, 3 mm length fiber content, 12 mm length fiber content, and combinations of 3 mm – 12 mm length fiber contents on mechanical properties of high plasticity silty soil stabilized with fiber reinforcement and alkali-activated fly ash [45]. In this context a set of three point bending tests and UCS tests were performed. In this study, new soil samples for UCS tests were not prepared. Instead of that, sample residues obtained from the three-point bending tests performed by Kamiloğlu et al. (2023) were used. The 90 days cured sample residues with 40mmx40mmx160mm dimensions were reevaluated for UCS tests. Thus, soil identification tests, activator and binder optimization were not performed for the new study.

2. Material

2.1. Soil

High plasticity silty soil was stabilized with alkali activated fly ash and polypropylene fiber inclusions with various lengths (3 mm and 12 mm). Plots obtained from the sieve analysis and laser diffraction particle size analysis were presented in Fig.1a and 1b respectively. Liquid and plastic limits of the soil were determined as 60.70% and 33.20% respectively. As a result of standard compaction test, optimum moisture content, and maximum dry density were determined as 24.60%, and 13.67 kN/m^3. Dominant minerals of the soil was obtained as; calcite, quartz, and nontronite [45].

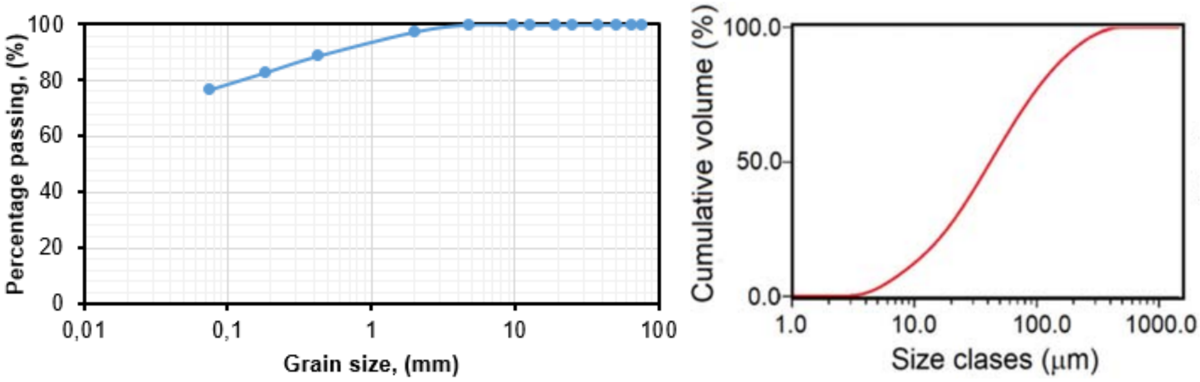


Fig.1. Plots obtained from the (a) Sieve analysis, (b) Laser diffraction particle size analysis

2.2. Fly ash

Fly ash evaluated as alkali activated binder was supplied from the İSKEN Sugözü Powerplant Ltd., İskenderun/Turkiye. Detailed information about physical features and oxide components of the fly ash was presented in Table 1. Major minerals of the fly ash were determined as Calcite, Quartz, and Anhydrite. The fly ash was classified as class-C type due to comprising SiO_2, Al_2O_3, and Fe_2O_3 oxides more than 80% of the total mass [45].

Table.1. Some physical features and oxide components of the fly ash.

Physical features	**Value**
Above 45 μ (%)	4.0
Specific gravity	2.44
Blaine (cm^2/g)	2496
Pozzolanic activity	15.8
Oxide components (%)	**Value**
SiO_2 (%)	23.08
Al_2O_3 (%)	6.25
Fe_2O_3 (%)	2.58
CaO (%)	47.03
MgO (%)	1.60
SO_3 (%)	14.61
K_2O (%)	0.47
Na_2O (%)	0.32
Loss of ignition (%)	3.95

2.3. Activator

The solution comprising a mixture of 10 M NaOH and Na_2SiO_3 was used to activate the fly ash by means of creating high alkali media. The major components of the Na_2SiO_3 solution are 28.65% SiO_2, and 64.72% H_2O, and 8.85% Na_2O. The specific gravity of the solution is 1.46 g/cc. NaOH pellets with 98% purity were used in preparation of 10M NaOH solution. The activator used in the study was obtained by mixing the prepared solutions at variable ratios by mass.

2.4. Fiber

Two types of polypropylene fiber with 3 mm and 12 mm lengths was used in soil stabilization applications (Fig.2a and 2b). Alkali and corrosion resistance of the fibers are high and tensile strength of the material is 900 MPa [45].

(a) (b)

Fig.2. Fibers with various length used in the stabilization (a) 3mm, (b) 12 mm

3. Method

Within the scope of the study, no specimens were prepared to investigate the durability effect. Instead, the residual specimens used in the study where the effects of the same parameters on flexural performance were investigated were evaluated [45]. The procedure given in Fig.3 was followed for the study. In the study, the optimum amount of binder and alkali activator gaining maximum unconfined compression strength were determined with Response Surface Methodology (RSM). Three-point bending test samples with dimensions of 40 x 40 x 160 mm were prepared considering the optimum amounts.

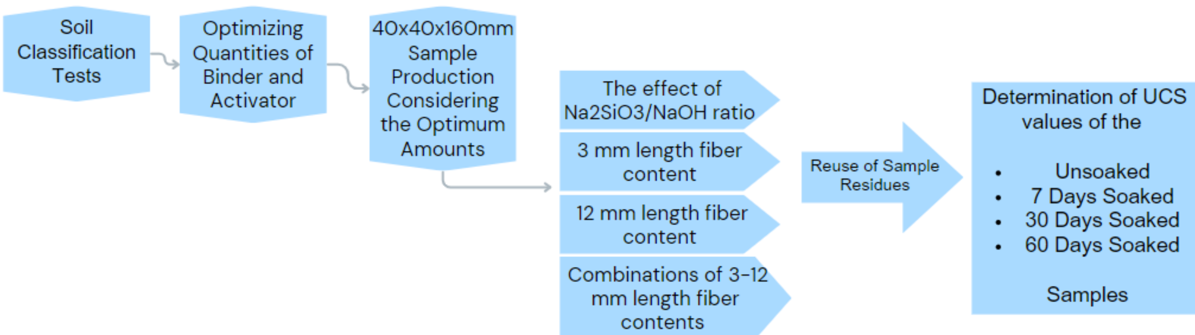
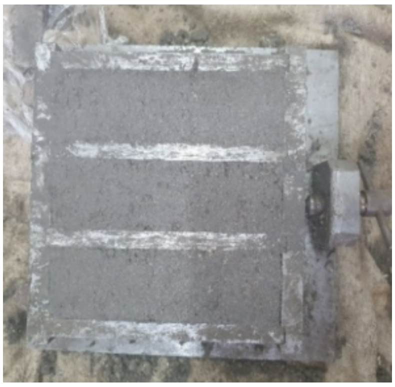


Fig.3. Flow chart summarizing the study

Five different activator solutions were used to evaluate the effect of NaOH- Na_2SiO_3 composition on the flexural strength. The optimum amount of activator content was taken into account for sample preparation. The proportions of sodium hydroxide (SH) and sodium silicate (SS) by mass in the activator are 50%SH-50%SS, 40%SH-60%SS, 30%SH-70%SS, 20%SH-80%SS, 10%SH-90%SS. Soil samples were prepared by mixing different proportions of fiber additives with optimum amounts of binder and activator. The proportions used in sample preparation were 0.5%, 0.75%, 1.0%, 1.5%, 1.75%, and 2.0% according to the soil mass for 3mm and 12 mm length fibers. As a result of the tests performed with various fiber additive ratios, the performance of the hybrid fiber additive was examined by considering the fiber content that showed the best performance. The optimum hybrid fiber content was assumed to

be 1.75% since both 3 mm length fiber and 12 mm length fiber reinforcement gave the best UCS value at a 1.75% reinforcement ratio. This optimum value for hybrid fiber content has not been verified by experimental data. However, since the optimization of the hybrid fiber content may be the subject of another study, the optimum value was accepted as 1.75%. In the hybrid fiber application, variable fiber blends were prepared for a constant amount of fiber. These proportions are 0% 3mm-100%12mm, 30% 3mm-70%12mm, 50% mm-50%12mm, 70%3mm-30%12mm, and 0%3mm-100%12mm by mass of the total fiber amount [45].
The specimens were prepared by compacting the specimens in the mold (40x40x160 mm^3) with a standard proctor hammer in 3 levels with a total of 21 blows (standard compaction energy), taking into account the above-mentioned procedure (Fig.4a). The specimens were left to cure at 27 °C for 28 days until the flexural tests. After the flexural tests, the curing process of the sample residues was continued under the same conditions for 90 days (Fig.4b).



(a)

(b)

Fig.4. Soil samples used in the study (a) Three-point flexural test samples before the test, (b) The residual flexural test samples reused in the study

4. Results

4.1. Visual observations

Figure 5 shows the post-soaking conditions of the specimens stabilized with a mixture of alkali-activated fly ash and activator without fiber addition of fiber. The effect of activator content was investigated in the study. The mixture used as an activator in the study was modified by mixing NaOH and Na_2SiO_3 components in different ratios. The proportions of sodium hydroxide (SH) and sodium silicate (SS) by mass in the activator are 50%SH-50%SS, 40%SH-60%SS, 30%SH-70%SS, 20%SH-80%SS, 10%SH-90%SS. The conditions of the samples after exposure to soaking for 7 days, 30 days, and 60 days are presented in Figures 5a, 5b, and 5c, respectively. As can be seen from the figures, soaking caused visible deterioration in a certain part of the samples. Increasing Na_2SiO_3 ratio in the activator increases durability of the samples. Depending on the increasing soaking time, there is also an increase in the sample groups that are subject to deterioration (Fig.5a-5c). For example, in the group exposed to soaking for 7 days, deterioration was observed only in 50%SH-50%SS (Fig.5a), while in the group exposed to soaking for 60 days, deterioration was observed in groups 50%SH-50%SS, 40%SH-60%SS, and 30%SH-70%SS (Fig. 5c).

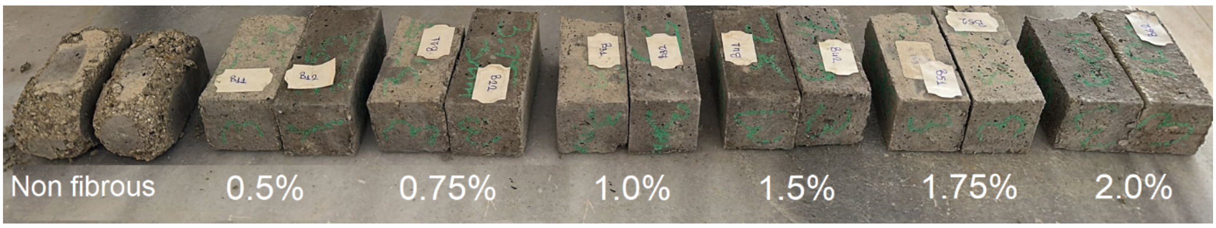
(a)

(b)

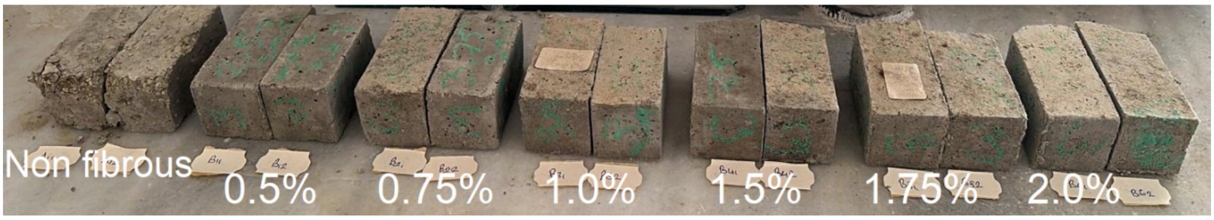
(c)

Fig.5. The effect of $NaOH/Na_2SiO_3$ ratio on samples subjected to soaking effect for various times (a) 7 days, (b) 30 days, (c) 60 days.

The effect of 3 mm length fiber content on the soaking performance of the stabilized soil was examined. In this context, soil samples were prepared by mixing various amounts of 3 mm length fiber with optimum amounts of fly ash and activator. In the activator combination 50%SH-50%SS ratio was considered. Figure 6 presents the samples after being subjected to soaking conditions for various days. Figures 6a, 6b, and 6c show samples that were soaked for 7 days, 30 days, and 60 days, respectively. In the figures, samples stabilized with fiber inclusion were compared with stabilized samples without fiber addition. In all samples, the activator and binder amounts (optimum amounts), and $NaOH/Na_2SiO_3$ content of activator (50%SH-50%SS) were kept constant. From the figures, it is seen that fiber-reinforced samples were not subjected to remarkable deterioration with respect to non fibrous stabilized samples. Although the soaking time has a serious effect on the non-fibrous samples, it is seen that the soaking period of 7 to 60 days does not cause any significant deterioration in the samples with fiber addition.



(a)

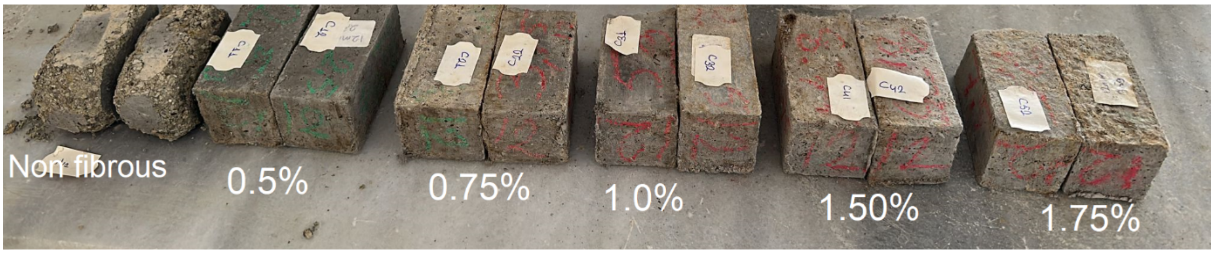


(b)

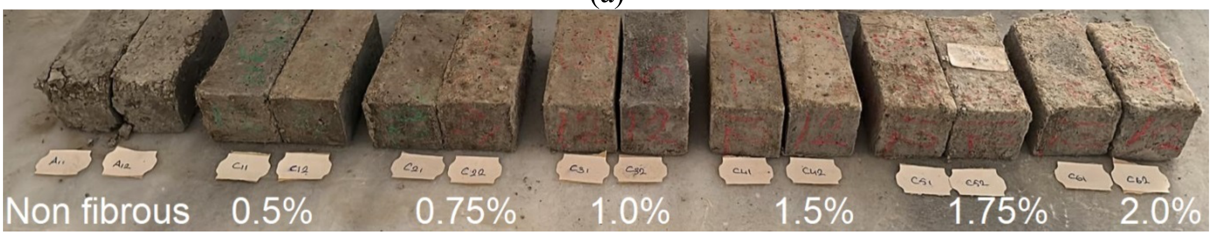
(c)

Fig.6. The effect of 3mm length fiber content on samples subjected to soaking effect for various times (a) 7 days, (b) 30 days, (c) 60 days.

Figure 7 presents the effect of 12 mm length fiber content on samples subjected to soaking effect for 7 days (Fig.7a), 30 days (Fig.7b), and 60 days (Fig.7c). In order to have a logical comparison, similar procedures were followed in the preparation of samples with and without fiber addition. From the figures it is seen that fiber inclusion shows effective durability performance with respect to non-non fibrous samples independent from the fiber content. No significant deterioration was observed in the fibrous samples after 7 days, 30 days and 60 days of soaking periods.



(a)



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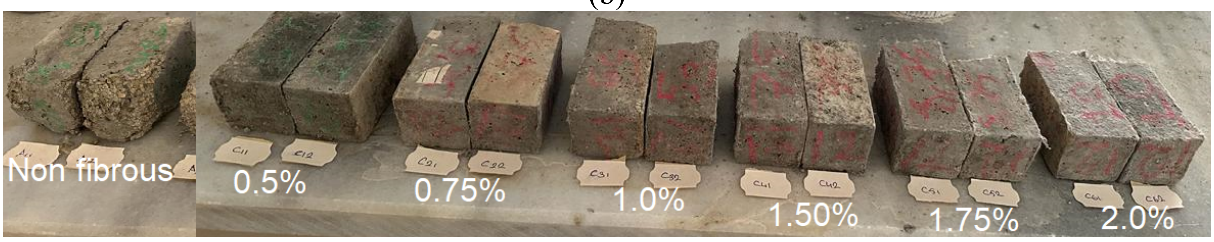
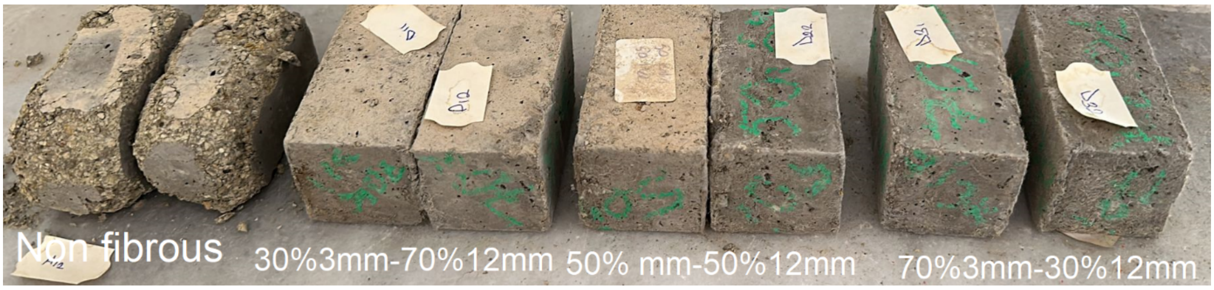


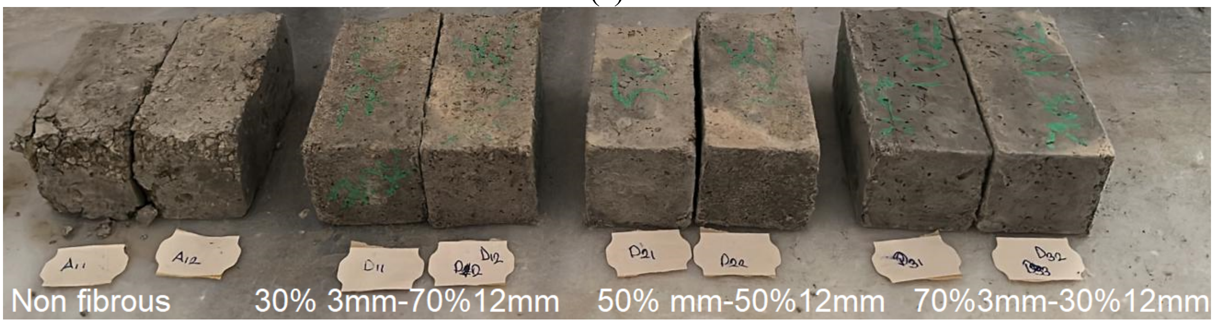
(c)

Fig.7. The effect of 12mm length fiber content on samples subjected to soaking effect for various times (a) 7 days, (b) 30 days, (c) 60 days.

The effect of 3mm-12mm length fiber combinations on the durability performance of the samples subjected to soaking effect for various times was presented in Fig.8. In this part of the study similar soil stabilization process with above mentioned samples was followed. Unlike other sample preparation process, a constant fiber content giving best UCS value (1.75%) was taken into account for sample preparation. For a constant fiber content (1.75%), the percentages of 3 mm and 12 mm length fibers that make up the reinforcement were kept variable. Similar observations with 3 mm and 12 mm length fibers were obtained for hybrid fiber applications. There is almost no deterioration observed on the samples stabilized with hybrid fiber inclusion.



(a)



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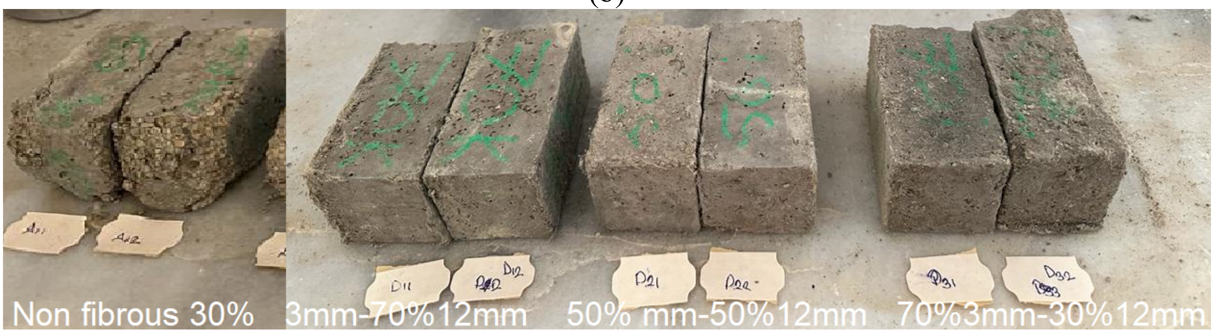

(c)

Fig.8. The effect of 3mm-12mm length fiber combinations on samples subjected to soaking effect for various times (a) 7 days, (b) 30 days, (c) 60 days.

4.2. Soaking-unconfined compression strength (UCS) relation

Fig.9a represents the variation of UCS values versus different soaking conditions and $NaOH/Na_2SiO_3$ ratio for a constant activator content. It can be seen from the figure that there is a significant decrease in UCS values in the samples under the soaking effect. Consistent with visual inspection, the decreasing trend in strength values after soaking decreases with increasing sodium silicate content. Fig.9b shows the durability performance of stabilized soil reinforced with various fiber contents with 3mm length. The strength loss of the fiber-reinforced soil is notably lower than non-fibrous samples. Increasing fiber content leads to an increase in UCS values of unsoaked samples. In addition, UCS values of the 7-day, 30-day, and 60-day soaked samples increase with increasing fiber content. The best UCS values were obtained for the samples stabilized with 1.75% fiber content.

The effect of 12 mm length fiber content on UCS values of stabilized samples for various soaking conditions was presented in Fig.9c. The durability performance of soils stabilized with 12 mm length fiber additive is similar to that of soils stabilized with 3 mm length fiber. Due to the fiber inclusion, the strength loss of the stabilized soil is remarkably low with respect to non-fibrous samples. UCS values of both unsoaked and soaked samples increase with increasing fiber content. The fiber contents of 1.0%, 1.50%, and 1.75% give the best UCS value for unsoaked and soaked conditions.

The effectiveness of this optimum value can be explained by considering different situations. (1) At 1.75% fiber content, the distribution of fibers within the soil matrix appears to reach an optimal level. This distribution allows for efficient stress transfer between the soil particles and the fibers, leading to improved mechanical interlocking and enhanced composite strength. (2) The 1.75% fiber content may represent a threshold where the fiber-matrix interface reaches its maximum effectiveness. Beyond this point, the addition of more fibers may lead to fiber agglomeration, reducing the efficiency of the fiber-matrix interaction. (3) The addition of fibers up to 1.75% may help fill voids within the soil matrix, increasing the overall density and strength of the composite. However, excessive fiber content beyond this point could potentially create new voids or disrupt the soil structure, leading to a decrease in strength. (4) The 1.75% fiber content likely provides an optimal balance of tensile reinforcement throughout the soil matrix. This reinforcement helps resist crack propagation and enhances the overall ductility of the material.

Fig. 9d shows the UCS performance of the hybrid fiber reinforcement versus various soaking conditions. In Fig.9d, 100-0, 70-30, 50-50, 30-70, and 0-100 represent 0% 3mm-100%12mm, 30% 3mm-70%12mm, 50% 3mm-50%12mm, 70%3mm-30%12mm, and 0%3mm-100%12mm by mass of the total fiber amount respectively. From the figure, it is seen that UCS values of the hybrid fibers are better than solely 3mm length, and 12 mm length. 50% 3mm-50%12mm, 70%3mm-30%12mm are the best fiber combinations for both the soaked and unsoaked conditions. This positive effect can be explained by the synergistic effects of using fiber combinations of different lengths. (1) Multi-scale reinforcement: The combination of 12 mm and 3 mm fibers provides reinforcement at different scales within the soil matrix. Shorter fibers (3 mm) are more effective at bridging micro-cracks, while longer fibers (12 mm) provide better resistance to macro-crack propagation. (2) The hybrid fiber system allows for a more uniform stress distribution throughout the soil matrix. Shorter fibers can transfer stresses at a finer scale, while longer fibers can bridge larger potential crack openings. (3) The combination of different fiber lengths may result in improved fiber packing within the soil matrix. This optimized packing can lead to better overall composite performance, as it minimizes weak zones and ensures more uniform reinforcement throughout the material. (4) The presence of fibers at different length scales provides a more effective crack arrest mechanism. Micro-cracks encountered by shorter fibers are less likely to propagate into macro-cracks, which can then be bridged by the longer fibers. (5) The hybrid fiber system at 1.75% content likely offers an optimal balance between improved ductility (typically associated with longer fibers) and enhanced strength (often attributed to shorter fibers).

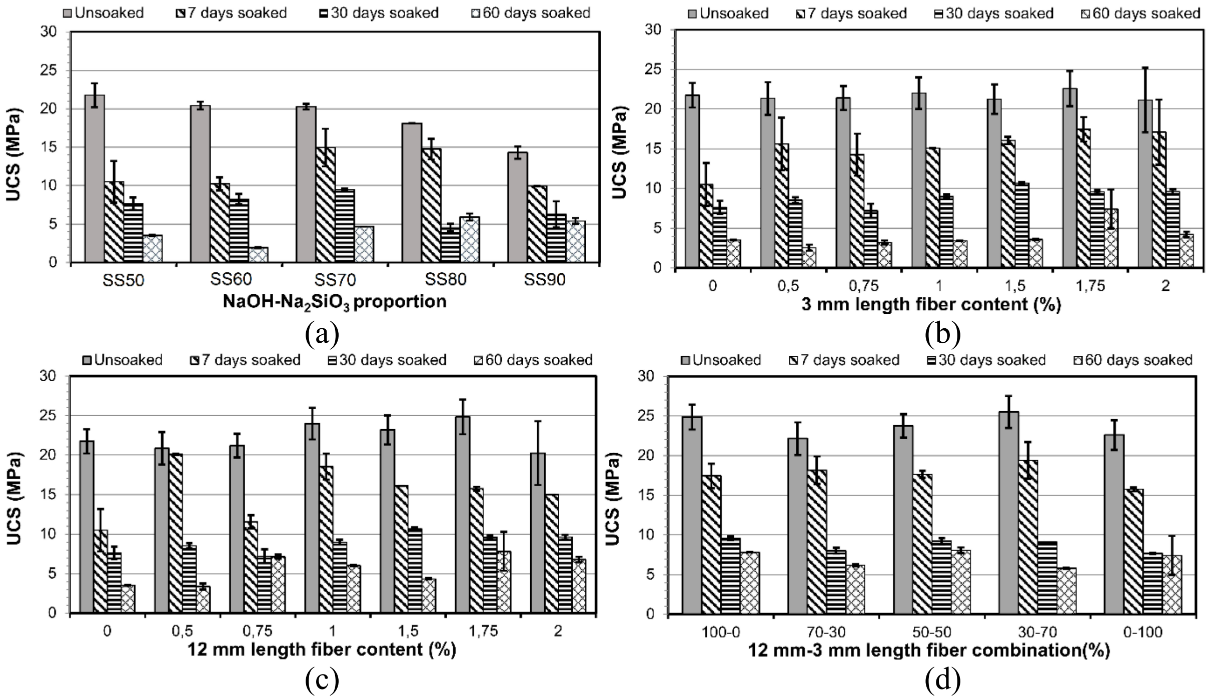

Fig.9. The effect of some parameters on the UCS value of the samples subjected to several soaking conditions (a) UCS-NaOH/Na_2SiO_3 ratio relation, (b) UCS-3mm length fiber content relation, (c) UCS-12mm length fiber content relation, (d) UCS-hybrid fiber composition relation.

4.3. Soaking-strength reduction ratio (SRR) relation

The unconfined strength reduction due to the soaking effect was investigated with the strength reduction ratio (SRR). The SRR is the ratio of the difference in UCS values before and after soaking to the UCS value before soaking. In this way, the UCS change originating from soaking can be expressed numerically. In Fig.10a, variations of SRR value versus various NaOH/Na_2SiO_3 ratios were presented for three different soaking conditions. Strength reduction increases with increasing soaking time, as it is expected. Increasing Na_2SiO_3 content leads to a decrease in the strength loss. Fig.10b shows the change of SRR for various 3mm length fiber content and compares nonfibrous and fibrous samples based on the SRR parameter. The strength loss of the fiber reinforced samples is relatively lower than the nonfibrous materials for 7-day and 30-day soaked samples. On the other hand, despite the UCS values of the 60-day soaked samples being relatively high (Fig.9b), there are not remarkable changes in SRR values for 60-day soaked samples (Fig.10b). In Fig.10c, a change of SRR value versus increasing 12 mm length fiber content subjected to soaking conditions is presented. From Fig.10b and 10c, remarkable differences between 3mm length and 12 mm length fibers on strength reduction are seen. The strength reduction performance of the 1.75% 12 mm length fiber content is better than the other 12mm length fiber contents and 3 mm length fiber contents. %70 3mm length-%30 12 mm length hybrid fiber combination reduces the strength loss with respect to solely 3mm and 12 mm fibers for 7-day soaked samples. On the other hand, despite small differences strength reduction of the hybrid fiber combinations is negligible for 30-day and 60-day soaked samples (Fig.10d).

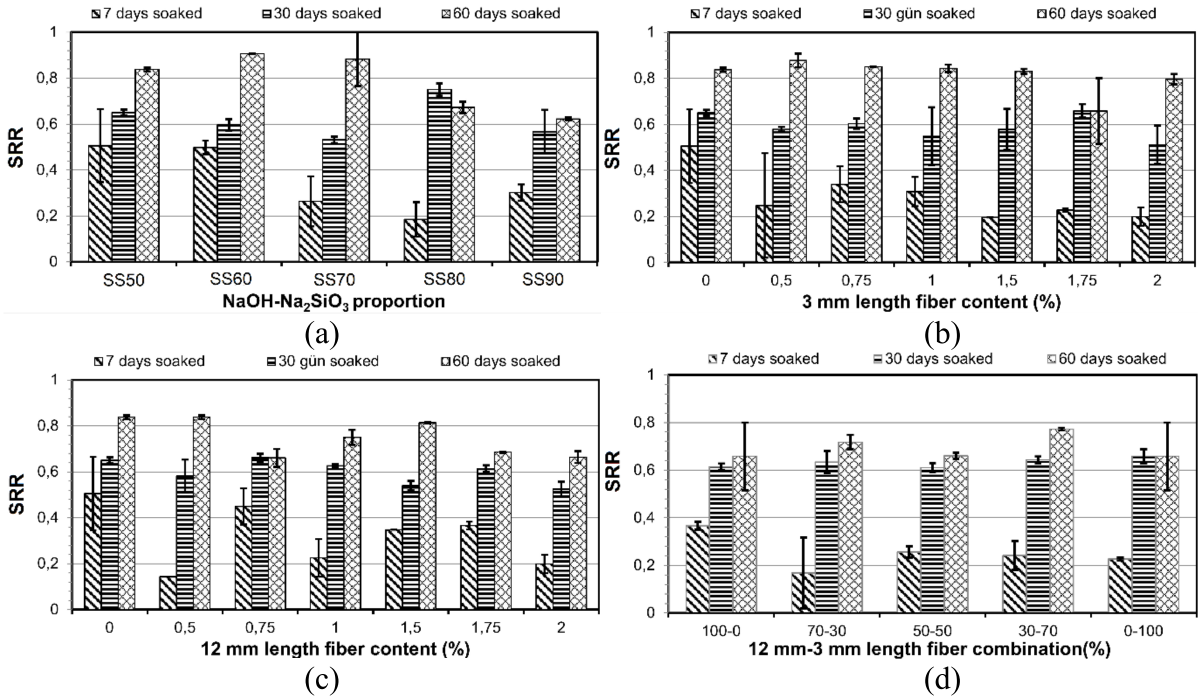

Fig.10. The effect of some parameters on the SCR value of the samples subjected to several soaking conditions (a) SCR -$NaOH/Na_2SiO_3$ ratio relation, (b) SCR -3mm length fiber content relation, (c) SCR -12mm length fiber content relation, (d) SCR -hybrid fiber composition relation.

5. Conclusion

In this study, the behavior of a high plasticity silty soil stabilized with polypropylene fiber and alkali-activated fly ash against soaking effects was investigated. The study aimed to examine the effects of $Na_2SiO_3/NaOH$ ratio, 3 mm and 12 mm length fiber content, and combinations of 3 mm – 12 mm length fiber contents on the deterioration, UCS, and strength reduction for various soaking conditions. The durability performance of the samples was investigated with 7-day, 30-day, and 60-day soaking periods. Following conclusions were drawn as a result of the study:

- The study established that a Na2SiO3/NaOH ratio of 1.5 provides optimal activation for fly ash in soil stabilization, resulting in maximum unconfined compressive strength (UCS)
- The research determined that a fiber content of 1.75% (by weight of dry soil) yields the highest UCS for both single-length and hybrid fiber combinations. This optimal fiber content strikes a balance between improved strength and workability of the stabilized soil.
- Visual observations revealed that the soaking effect caused visible deterioration in non-fibrous stabilized samples, with the extent of damage increasing with longer soaking periods. However, the addition of polypropylene fibers, both 3 mm and 12 mm in length, demonstrated effective durability performance, as the fiber-reinforced samples showed significantly lower deterioration compared to non-fibrous samples.

- UCS test results present the positive effects of fiber reinforcement on the stabilized soil. The UCS values of fiber-reinforced samples, both 3 mm and 12 mm in length, were notably higher than non-fibrous samples for both unsoaked and soaked conditions. The novel approach of using hybrid fibers (combination of 12 mm and 3 mm lengths) demonstrated superior performance compared to single-length fibers. Hybrid fiber reinforcement improved UCS by up to 15% compared to non-reinforced samples and showed enhanced durability under prolonged soaking conditions.

- The relation between soaking and strength reduction ratio (SRR) was employed to examine the impact of soaking on strength reduction, showing that fiber-reinforced samples, especially those with hybrid fibers, experienced lower strength loss compared to non-fibrous samples. Samples reinforced with hybrid fibers exhibited significantly better resistance to strength reduction under extended soaking periods, with 20% less strength reduction after 28 days of soaking compared to non-reinforced samples. This finding has important implications for soil stabilization in water-prone environments.

In conclusion, this study presents a promising approach to enhancing the durability and strength of high plasticity silty soils through the combination of alkali-activated fly ash and hybrid fiber reinforcement. The findings contribute to the development of more resilient and sustainable soil stabilization techniques, potentially revolutionizing geotechnical practices in challenging environments.

Ethics in Publishing

There are no ethical issues regarding the publication of this study

Author Contributions

Hakan Alper Kamiloğlu: Designing the study, evaluating the results, writing the article, Muhammet Oğuz Durrak, Kutluhan Kurucu: Collecting the data, writing the article.

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