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Hybrid stabilization of high-plasticity clay soil with silica fume and glass fiber: Investigation of swelling and bearing capacity

Yüksek plastisiteli kil zeminin silis dumanı ve cam elyaf ile hibrit stabilizasyonu: Şişme ve taşıma kapasitesinin incelenmesi

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Abstract

In road infrastructure, improving the low bearing capacity and swelling potential of high-plasticity (CH) clay soils is of significant importance. This study adopts a hybrid improvement method using silica fume waste, an industrial byproduct, and glass fiber. In this context, CH clay stabilization studies were carried out using silica fume at 5%, 10%, and 15% by weight, and glass fiber at 0.5%, 1.0%, and 1.5% by weight. CBR samples, compacted with compaction energy at optimum water content, were cured under high relative humidity for 0, 14, and 28 days. Subsequently, swelling behavior and subsequent changes in CBR were determined under soaked conditions for 96 hours. The swelling potential of unimproved clay is 4.8%, and its CBR value is 1.80%. With the addition of silica fume and glass fiber, the lowest swelling behavior was 0.22%, and the highest CBR value was 7.49%, obtained after 28 days of curing with clay containing 15% silica fume and 1.5% glass fiber. While CH clay exhibits very poor properties for use in transportation infrastructure, the addition of silica fume and glass fiber transformed it into an acceptable/medium-grade subgrade material even after 96 hours of soaking.

Keywords: CH clay, Glass fiber, Silica fume, Soil improvement, CBR

Öz

Karayolu altyapılarında yüksek plastisiteli (CH) kil zeminlerde düşük taşıma kapasitesi ve şişme potansiyeli iyileştirilmesi önem arz eden durumlardır. Bu çalışmada sanayi yan ürünü olan silis dumanı atığı ve cam elyaf kullanılarak hibrit bir iyileştirme yöntemi benimsenmiştir. Bu kapsamda ağırlıkça %5, %10, %15 oranlarında silis dumanı ve %0.5, %1.0, %1.5 oranlarında cam elyaf kullanılarak CH kili stabilizasyon çalışması gerçekleştirilmiştir. Optimum su içeriğinde kompaksiyon enerjisi ile sıkıştırılan CBR numuneleri 0, 14 ve 28 günlük yüksek bağıl nem ortamında kürlenmiştir. Ardından, numuneler 96 saat boyunca suda bekletilerek şişme davranışı incelenmiş ve sonrasında CBR değişimi belirlenmiştir. İyileştirilmemiş kilin şişme potansiyeli %4.8 ve CBR değeri ise %1.80'dir. Silis dumanı ve cam elyaf ilavesiyle en düşük şişme davranışı %0.22 ve en yüksek CBR değeri %7.49 ile %15 silis dumanı ve %1.5 cam elyaf katkılı kilde 28 günlük kür sonrasında elde edilmiştir. CH kili ulaştırma altyapısında kullanımı için oldukça zayıf özellik gösterirken silis dumanı ve cam elyaf ile birlikte 96 saat suda bekletme koşulları sonrasında bile kabul edilebilir/orta dereceli bir alt taban malzemesi sınıfına dönüştürülmüştür.

Anahtar kelimeler: CH kili, Cam elyaf, Silis dumanı, Zemin iyileştirme, CBR

1 Introduction

In geotechnical applications, particularly in high-plasticity clay soils, low bearing capacity and high swelling potential are among the biggest problems [1, 2]. Flexible pavements constructed on such poor soils may undergo deformations and settlements over time [3]. Therefore, various traditional techniques such as cement and lime have been used for years to stabilize such soils. However, the production processes of these materials, due to costs and high CO2 emissions, are leading researchers to seek new solutions in waste management and the development of hybrid methods [4-6].

Silica fume, an industrial byproduct with high pozzolanic activity and a fine-grained, has gained widespread use in recent years, particularly in the improvement of problematic soils. Silica fume provides both physical filling properties and forms calcium-silicate-hydrate (C-S-H) gels in clayey soils. As demonstrated in numerous studies, this results in significant benefits such as increased soil strength and improved consistency limits [7, 8].

The use of pozzolanic admixtures improves clayey soils by imparting brittle properties. In addition, an increase in tensile strength is a desired property of the soil. In recent years, studies have highlighted the necessity of using fibers to reinforce soils in order to achieve this behavior [9-14]. Fibers increase peak strength by traversing the potential shear planes of the soil, while also contributing to increased ductility. Significant findings have been obtained indicating that fiber reinforcement improves the strength properties of soils and can reduce swelling potential and compressibility in cohesive soils [3, 15, 16]. Among these fibers, glass fiber,

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with its high tensile strength, forms a strong matrix with the soil in clay soils, creating a reinforcement network [17-20].

Although numerous studies exist in the literature on the separate use of silica fume and glass fiber in high-plasticity (CH) clays, studies investigating the performance of their hybrid application as a function of curing time are limited. Investigating the effect of silica fume additive in combination with glass fiber as a hybrid in CH clays on CBR load-penetration and swelling behavior is of significant importance. In particular, understanding the time-dependent behavior under curing conditions and the swelling behavior under soaked conditions represents a crucial area in the geotechnical field for comprehending the performance of clay materials.

In this study, the geotechnical properties of high-plasticity clay (CH) were investigated by adding 5%, 10%, and 15% by weight of silica fume and 0.5%, 1.0%, and 1.5% of glass fiber. First, silica fume was added to the CH clay, and its effects on consistency limits were examined. Then, standard compaction tests were applied to the CH clay with added silica fume, and the optimum water content and maximum dry density values of the clay under different mixing conditions were obtained. Samples were prepared with different silica fume (5%, 10%, and 15%) and glass fiber (0.5%, 1.0%, and 1.5%) mixtures under optimum water content (W_{opt}) and maximum dry density conditions, and California Bearing Ratio (CBR) tests were conducted. In this context, the samples placed in CBR molds were kept under 95% humidity for 0, 14, and 28 days, and then soaked for 96 hours to determine their swelling behavior. After a 96-hour soaking period, the load-penetration behavior of the samples was investigated using the CBR test.

2 Material and method

2.1 Material

In this study, a clay sample taken from the Bilecik region was identified as CH clay according to the Unified Soil Classification System (USCS). Silica fume and glass fiber were used for the stabilization of the CH clay; the materials used are shown in Figure 1. Silica fume has an amorphous structure containing more than 90% SiO_2. The grain distribution of CH clay and silica fume is shown in Figure 2. 12 mm long glass fibers were used in the study, and their technical properties are given in Table 1.

Figure 1. Experimental materials, respectively: Silica fume, Clay, Glass fiber

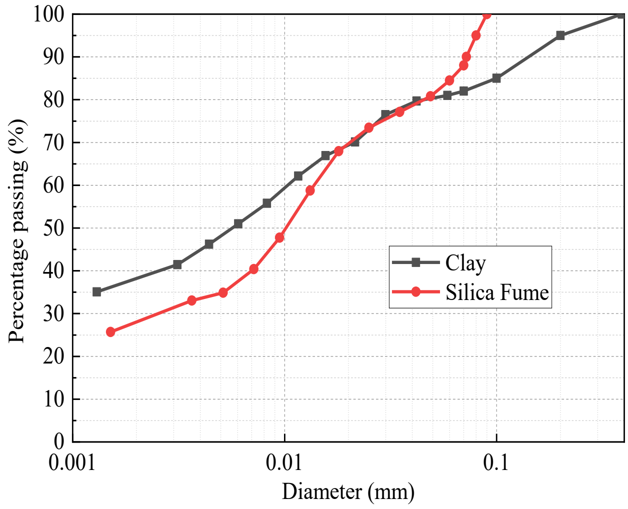

Figure 2. Grain distribution curves of clay and silica fume materials.

Tablo 1. Physical and mechanical properties of the glass fibers

Properties	Values
Tensile strength	3400 MPa
Modulus of Elasticity	77 GPa
Service Temperature Range	-60°C - +650°C
Melting Temperature	1120°C
Specific Gravity	2.60gr/cc
Fiber diameter	13-15 micron
Fiber length	12 mm
Length/Diameter	800-923

2.2 Method

Silica fume was used in CH clay at different concentrations of 5%, 10%, and 15%, and glass fiber at 0.5%, 1.0%, and 1.5%, and their effects on the geotechnical properties of the clay were investigated. In this context, experimental studies were prepared according to ASTM (American Society for Testing and Materials) standards. Several physical and mechanical tests were applied within the scope of the study. These included ASTM D6913-04 sieve analysis, ASTM D7928 hydrometer tests, ASTM D4318 Atterberg limit tests, ASTM D698 standard Proctor test, and ASTM D1883 California Bearing Ratio (CBR) tests, all conducted in accordance with ASTM standards as part of CH clay stabilization studies [21-25]. To ensure the reliability of the experimental data, CBR tests and swelling tests were performed twice for each mixture combination, and the arithmetic means were taken and graphs were created, provided that they were within the acceptable range specified in the relevant ASTM standards.

To prevent entanglement, clumping, and aggregation of the clay, silica fume, and glass fiber mixture during the sample preparation process, the following steps were followed: The clay material was separated into two parts. Each part was mixed with the clay and silica fume mixture, and the clay and glass fiber mixture, for 15 minutes. Then, these mixtures were combined in a cylindrical container, mixed again, and homogenization was ensured [26, 27]. By adhering to standardized mixing times, homogeneity and repeatability of the mixture is guaranteed.

Standard compaction tests were performed without the addition of glass fiber. This is because glass fiber has a low mass ratio, making its effect on soil density negligible. Furthermore, the water absorption capacity of glass fiber is practically considered zero [28, 29]. Atterberg limit tests were performed without glass fibers. This is because the Also, Atterberg limit test is conducted with material sieved through a 0.425 mm sieve. Including 12 mm glass fibers would physically disrupt the test mechanism (e.g., bridging the groove in the Casagrande cup). Furthermore, it is not a material that would alter the chemical properties of the mixture [30]. Hybrid CBR samples were compacted using the Wopt and γdmax values of their corresponding silica fume-only mixtures, since the low mass fraction and zero water absorption of the fibers do not alter the matrix compaction parameters.

3 Results and discussion

3.1 Atterberg limits tests

Within the scope of consistency limit tests conducted according to the ASTM D4318 standard, liquid limit and plastic limit tests were performed using the Casagrande test. The findings of the study conducted on CH clay with 0%, 5%, 10% and 15% silica fume additive are shown in Figure 3.

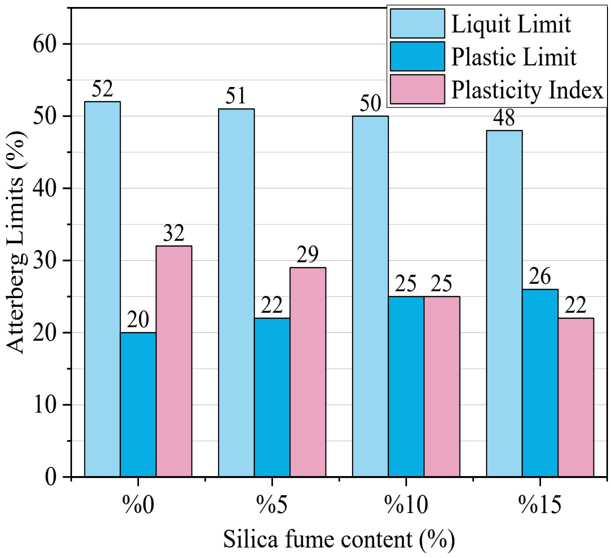

Figure 3. Variation of Atterberg limits with silica fume content

3.2 Standard proctor compaction tests

Standard Proctor Compaction Tests were performed in accordance with the ASTM D698 standard. In this context, the dry density-water content behavior of CH clay stabilized with 0%, 5%, 10%, and 15% silica fume was investigated. Standard compaction tests were performed without the addition of glass fiber. Figure 4 shows the relationship between dry density and water content depending on the change in silica fume ratio.

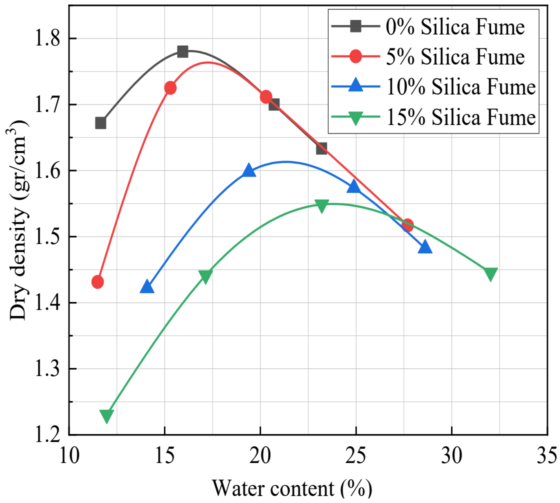

Figure 4. Dry density-water content relationship depending on silica fume ratio change

As seen in Figure 4, the increase in silica fume caused a decrease in the dry density curve values and an increase in the water content (%) values. Figure 5 shows the changes in optimum water content and max. dry density values of the compaction curves given in Figure 4. The bar graph given in Figure 5(a) shows that with the increase in silica fume from 0% to 15%, the maximum dry density value decreased from 1.78 to 1.55. This is due to the fact that silica fume has a lower specific gravity compared to CH clay. In addition, as seen in Figure 5(b), the increase in silica fume ratio also increases the optimum water content in the mixture. The optimum water content increased from 15.1% to 24% with the increase in silica fume. It physically makes the compaction of the grains more difficult due to its high specific surface area [31].

3.3 California bearing ratio (CBR) tests

In this part of the study, California Bearing Ratio (CBR) tests were performed according to the ASTM D1883 standard to evaluate the mechanical performance of the matrix formed by CH clay with added silica fume and glass fiber, and to assess its load-bearing capacity as a sub-base layer. Compression was performed at optimum water contents obtained from the standard Proctor test, and CBR samples with maximum density were obtained. Samples reinforced with 5%, 10%, and 15% silica fume and 0.5%, 1.0%, and 1.5% glass fiber were prepared for CBR tests on days 0, 14, and 28.

First, the prepared CBR samples were subjected to three different curing conditions (0, 14, and 28 days) to evaluate the pozzolanic reaction process. The samples, wrapped in stretch film to prevent water evaporation, were kept in an environment with at least 95% relative humidity. After the curing process was completed, the samples were subjected to soaked conditions for 96 hours. Swelling behavior was observed during this process. Clay soil material tends to swell when it absorbs water. This swelling directly affects the bearing capacity of that soil. The swelling behavior observed after 96 hours of soaked conditions applied to the CBR samples is given in Figure 6.

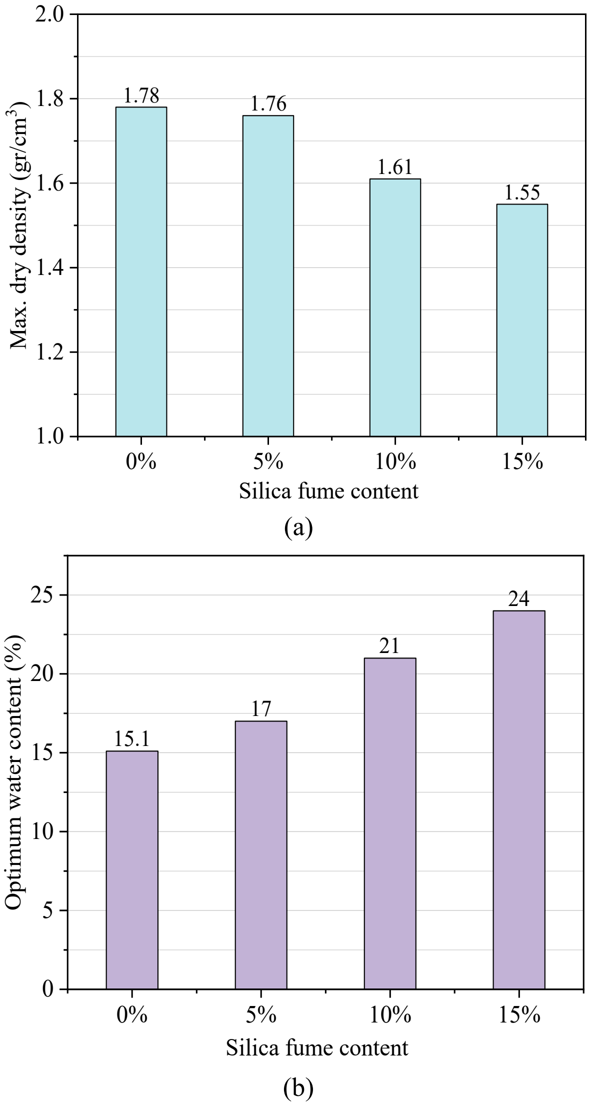

Figure 5. Silica fume content varies depending on the maximum dry density and optimum water content. (a) Max. dry density-silica fume content. (b) Opt. water content-silica fume content

As shown in Figure 6, it is clearly seen that silica fume and glass fiber have a reducing effect on the CBR swelling potential (4.80%) of the CH clay soil at the end of the curing times. Swelling percentages were lower compared to untreated clay under all conditions. The increased glass fiber ratio provided mechanical bridging by having a random distribution within the soil. In this way, it helped to control the swelling behavior. This effect is evident even on day 0. Similarly, studies have shown that fiber reinforcements prevent volumetric expansion by forming a network in the soil matrix [32, 33]. In addition, it is clearly seen that silica fume and curing time play an effective role in reducing the swelling rate. This is due to the pozzolanic activity of silica fume. A significant decrease in swelling was observed with increasing silica fume ratio from 5% to 15% and increasing curing times. After a 28-day curing period, the swelling rate was reduced to a negligible level of 0.22% with the addition of 15% silica fume and 1.5% glass fiber.

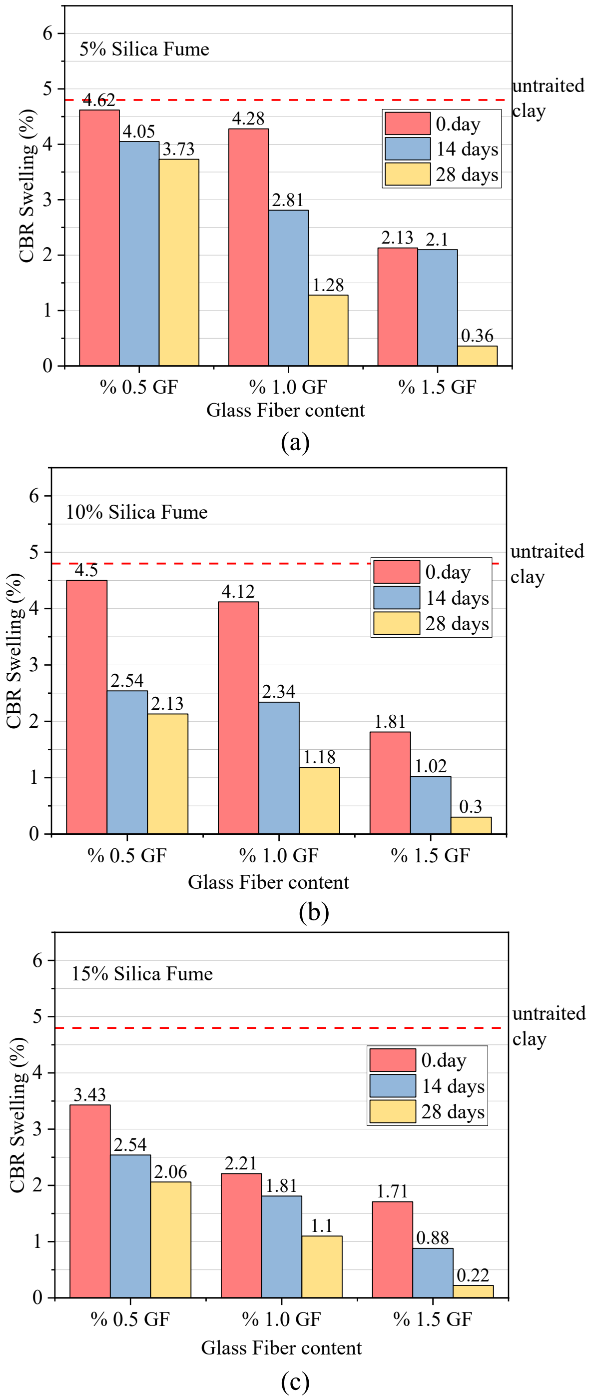

Figure 6. Swelling behavior of CBR at different silica fume and glass fiber ratios. (a) 5% Silica fume (b) 10% Silica fume (c) 15% Silica fume

For highways, a foundation soil with CH clay can cause problems in terms of bearing capacity. Therefore, its behavior under CBR testing is of great importance from an engineering perspective. After a 96-hour soaking period, the samples were removed from the water and the load-penetration measurement phase was initiated. Figure 7 shows the effect of different silica fume mixture ratios of 5%, 10%, 15% and glass fiber ratios of 0.5%, 1.0%, 1.5% on the load (kN)-penetration (mm) behavior of CH clay.

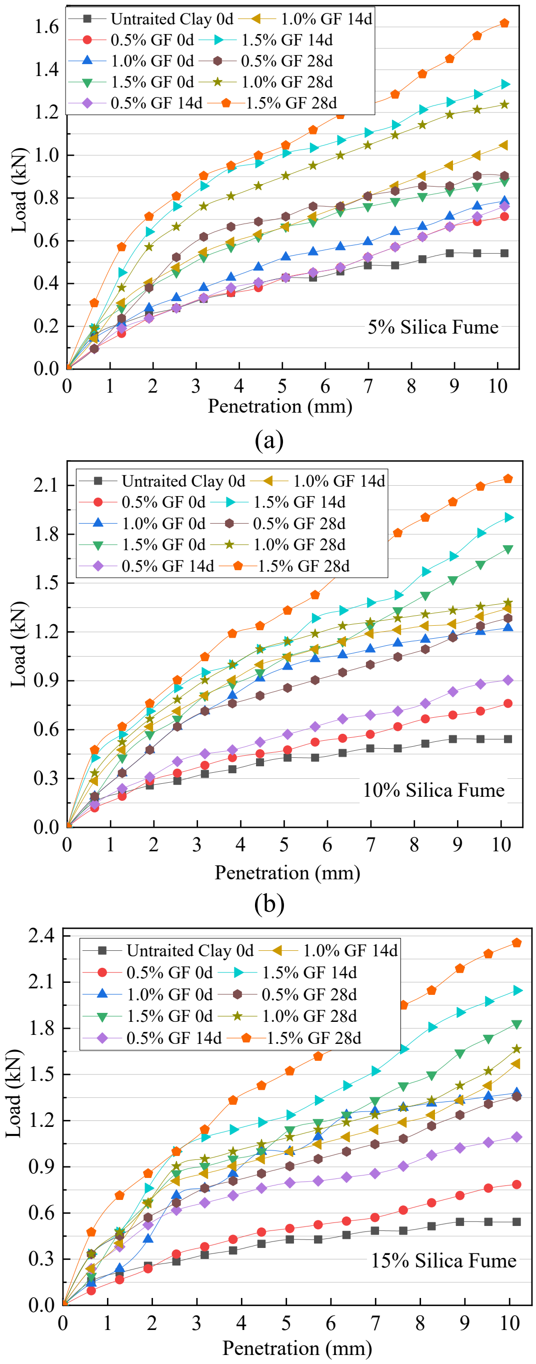

Figure 7. The effect of different silica fume and glass fiber ratios on load-penetration behavior (a) 5% Silica fume (b) %10 Silica fume (c) 15% Silica fume

When Figure 7 is examined, it is seen that the load-penetration curves increased with the addition of glass fiber and silica fume to the mixture. After soaking, the CH clay without the addition shows a very low stiffness and load-carrying capacity with a value of 0.54 kN. Under 5% silica fume conditions (Figure 7(a)), the highest load value reached 1.61 kN after 1.5% glass fiber and 28 days of curing. The highest load value was achieved with 1.5% glass fiber addition under day 0 curing conditions. Compared to the unadded and uncured clay conditions, the load value at 10 mm penetration increased by approximately 250% with the addition of 15% silica fume and 1.5% glass fiber. The performance increases occurring on day 0 are thought to be mainly due to the effect of the fibers. The fibers exhibit a bridging effect, showing random distribution and applying shear resistance against the piston [13, 34]. When the load-penetration curves are examined, the change under the influence of curing times is noteworthy. The observations made after 14 and 28 days of curing suggest that, under 95% relative humidity conditions, silica fume chemically reacts with CH clay due to its pozzolanic properties. In Figure 7(b), the increase in silica fume from 5% to 10% after 28 days of curing, together with 1.5% glass fiber, resulted in an increase to 2.14 kN. Furthermore, the increase in curing times caused the curves to become steeper. As a result, the soil matrix has gained rigidity over time. The highest silica fume content is given in Figure 7(c) with 15%. The highest load value among these curves is 2.35 kN, observed with 1.5% glass fiber and 28 days of curing. Chemical stabilization, through the silica fume and the fiber support providing adhesion to the soil, created a synergistic effect between the clay soil and the soil. Thanks to this, it exhibits high shear resistance and rigid behavior even under load. Consistent with these findings, the formation of chemical bonds and the densification of the clay matrix are consistent with stabilization microstructural studies using similar silica fume [4, 7, 31].

Figure 8 shows the % CBR values for penetration depths of 2.54 mm under different curing conditions after 96 hours of soaking, using 5%, 10%, 15% silica fume and 0.5%, 1.0%, and 1.5% glass fiber ratios. The CBR value for the pure clay was determined to be 1.80%. This indicates that the clay has a very poor subsoil classification.
Figure 8(a) shows the % CBR values under 5% silica fume conditions. Under day 0 conditions, glass fiber positively contributes to the CH clay, increasing the CBR value to 3.39. This represents an approximately 88% increase in CBR (%). With increasing curing time, the pozzolanic activity of silica fume increased the % CBR value to over 230% on the CH clay. Even on day 0 under 10% silica fume conditions, the addition of glass fiber increased the % CBR value by over 20% (Figure 8(b)). With increasing curing time, the CBR value increased to 6.42% by day 14 and to 6.78% by day 28. The mixture, under 1.5% glass fiber and 28-day curing conditions, showed a 276% increase in load-bearing capacity compared to unreinforced CH clay conditions. The highest percentage of silica fume in the study was 15%, and the change in % CBR under these conditions is shown in Figure 8c. The increase in % CBR with increasing silica fume is evident in all curing conditions and glass fiber contents. The integrity of the soil matrix was achieved by the pozzolanic reaction property of silica fume filling the matrix, and the bridging effect created by the glass fiber reinforcement in the soil matrix, and this was reflected in the % CBR value [13, 34]. The CBR value, which reached 6.78% on the 14th day of curing with the highest percentage of glass fiber (1.5%), increased to 7.49% as the curing time reached 28 days. Initially, considering the unimproved CH soil as exhibiting

very poor subsoil characteristics after 96 hours of soaking, the addition of 15% silica fume and 1.5% glass fiber resulted in a 316% increase in CBR, reaching 7.49%, making it acceptable as a subsoil despite the very poor subsoil characteristics after 96 hours of soaking.

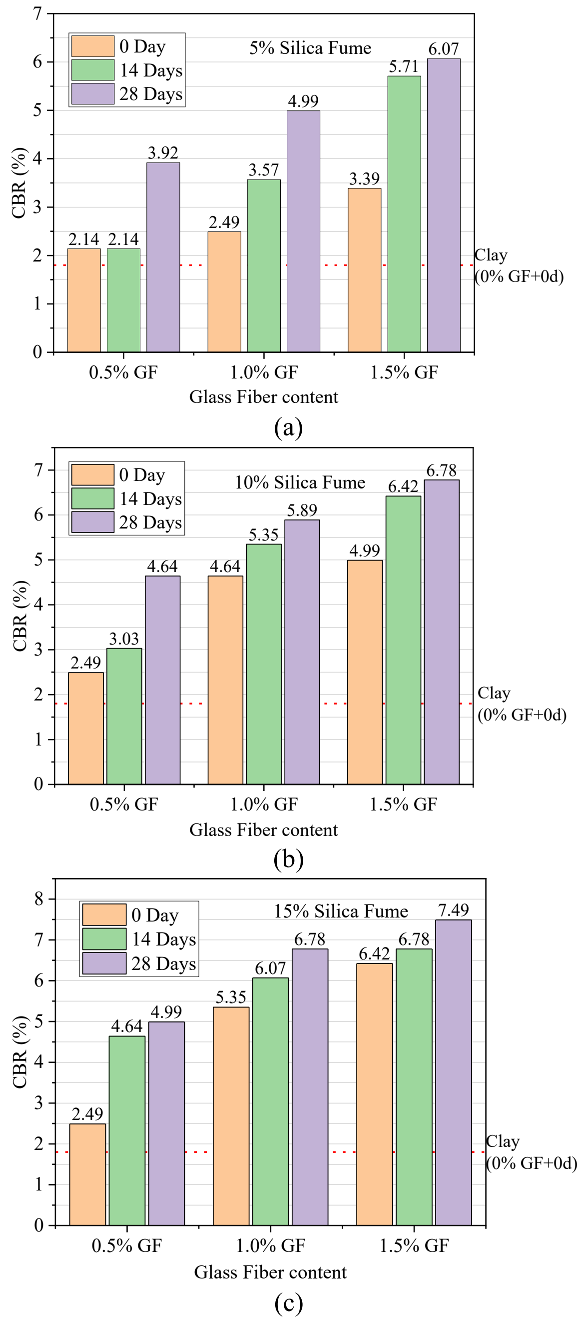

Figure 8. The effect of different silica fume and glass fiber ratios on % CBR (a) 5% Silica fume (b) %10 Silica fume (c) 15% Silica fume

4 Conclusion

The clay material used in this study is CH clay, which has a low load-bearing capacity and exhibits high swelling behavior. A hybrid stabilization study was conducted by adding 5%, 10%, and 15% by weight of silica fume and 0.5%, 1.0%, and 1.5% of glass fiber to the CH clay. The results obtained in this context are as follows: Adding silica fume to the CH clay material at a rate of 15% reduced the liquid limit and plasticity index. This shows that it significantly reduced the swelling property. According to the compaction test findings, the maximum dry density decreased with increasing silica fume ratio, while the optimum water content increased significantly. Samples were subjected to 95% curing conditions for 0, 14, and 28 days, followed by soaked conditions for 96 hours. Untreated clay exhibited a swelling behavior of 4.80%, while this value decreased to 0.22% after the addition of 15% silica fume and 1.5% glass fiber and a 28-day curing process. While CH clay received a relatively low maximum load of 0.54 kN, it was observed that this value increased to 2.35 kN after 28 days of curing (96-hour soaked) with the addition of 15% silica fume and 1.5% glass fiber. When comparing the % CBR values for a penetration depth of 2.54 mm, the highest value was again obtained with the addition of 15% silica fume and 1.5% glass fiber, at a rate of 7.49%. The pozzolanic reaction property of silica fume and the bridging effect of glass fiber in the soil matrix reveal the complementary role of the two materials. CH clay is in the problematic soil group in terms of load-bearing capacity and swelling behavior. The aim was to approximate real-field processes by applying 96 hours of soaked conditions to this soil. The study revealed that the best CH clay improvement mixture ratios were achieved with 15% silica fume and 1.5% glass fiber. Although CH clay inherently exhibits poor engineering properties for transportation infrastructure, it has been successfully upgraded to an acceptable sub-base material class with the inclusion of silica fume and glass fibers. While CH clay exhibits quite poor properties for use in transportation infrastructure, the addition of silica fume and glass fiber transformed it into an acceptable/medium-grade subgrade material. To ensure consistent results in the field with the developed mixing ratios, trial studies and pilot tests should be conducted to achieve homogeneity before proceeding to large-scale production

Furthermore, the use of silica fume, an industrial byproduct, offers a sustainable and highly cost-effective solution for field applications. In addition, the resulting clay matrix and fiber bridging network demonstrate that the material has a strong resistance potential to environmental degradation; therefore, it is recommended that the freeze-thaw resistance of this hybrid material be investigated in future studies.

CRediT authorship contribution statement

Semiha Poyraz: Conceptualization, Data curation, Formal analysis, Research, Methodology, Validation, Visualization, Writing - initial draft, Writing - review and editing.

Conflict of interest

The author declares no conflict of interest.

Similarity rate (iThenticate): 15%

Declaration of generative artificial intelligence (AI) and AI-assisted technologies in the writing process

The author did not use any artificial intelligence tools in the preparation of this work.

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