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Research Article

Study on the Mechanical Behavior of Fiber-Reinforced Recycled Sands Derived from Construction and Demolition Waste

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Abstract

In this study, the strength and permeability properties of recycled concrete aggregate and waste brick powder obtained from construction and demolition wastes were investigated under the effect of different mixing ratios and alkali solution molarities. For this purpose, alkali solution mixture-recycled soil was mixed at 15%, 20%, 25%, and 30% ratios. In order to determine the effect of an alkaline environment, alkali solution molarities were applied as 0.5M, 1M, 1.5M, 2M, and 2.5M. Fiber additive was applied at a constant rate, in lengths of 10 mm, 15 mm, and 20 mm. The results were evaluated with unconfined compressive strength and permeability tests. In addition, the behavior of soil samples under load was also investigated by considering the values of maximum unconfined compressive strength and axial strain corresponding to maximum strength test results. The results of this study showed that the mixture ratios were effective on the unconfined compressive strength and that the strength values increased as the mixture ratio increased. It was determined that the increase in the molarity of the alkali solution was more effective in increasing the strength compared to the mixture ratios and that this effect increased even more as the mixture ratio increased. It was observed that the fiber additive provided an increase in both the maximum strength and the strain values corresponding to these values and that it had positive effects on the load-carrying capacity and behavior of the soil.

Keywords: Construction and demolition waste, recycled concrete aggregate, recycled sand soil.

İnşaat ve Yıkıntı Atıklarından Elde Edilen Lif Takviyeli Geri Dönüştürülmüş Kumların Mekanik Davranışı Üzerine Bir Çalışma

Öz

Bu çalışmada, inşaat ve yıkıntı atıklarından elde edilen geri dönüştürülmüş beton agregası ve atık tuğla tozunun, farklı karışım oranları ve alkali çözeltisi molariteleri etkisi altındaki mukavemet ve geçirimlilik özellikleri incelenmiştir. Bu amaçla, alkali çözeltisi karışımı-geri dönüştürülmüş zemin %15, %20, %25 ve %30 oranlarında karıştırılmıştır. Alkali ortamın etkisinin belirlenebilmesi amacıyla da alkali çözeltisi molaritesi 0,5M, 1M, 1,5M, 2M ve 2,5M olarak uygulanmıştır. Lif katkısı ise sabit bir oranda, 10 mm, 15 mm ve 20 mm uzunluğunda uygulanmıştır. Sonuçlar, serbest basınç mukavemeti ve geçirimlilik deneyleri ile değerlendirilmiştir. Ayrıca, serbest basınç mukavemeti test sonuçlarından elde edilen, maksimum serbest basınç mukavemeti ve maksimum mukavemete karşılık gelen birim şekil değiştirme değerleri dikkate alınarak zemin örneklerinin yük altındaki davranışları da incelenmiştir. Bu çalışmanın sonuçları, karışım oranlarının serbest basınç mukavemeti üzerinde etkili olduğunu ve karışım oranı arttıkça mukavemet değerlerinin arttığını göstermiştir. Alkali çözeltisi molaritesinin artmasının, karışım oranlarına nispeten mukavemet artışında daha etkili olduğu ve karışım oranı arttıkça bu etkinin daha da arttığı belirlenmiştir. Lif katkısının hem maksimum mukavemet değerlerinde hem de bu değerlere karşılık gelen birim şekil değiştirme değerlerinde artış sağladığı ve zeminin yük taşıma kapasitesi ve davranışında olumlu etkiler meydana getirdiği gözlemlenmiştir.

Anahtar Kelimeler: İnşaat ve yıkıntı atığı, geri dönüştürülmüş beton agregası, geri dönüştürülmüş kum zemin.

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1. Introduction

Soil improvement has become even more important due to the decrease in suitable construction sites. Therefore, it is crucial to find economical and safe solutions for weak soils, as soil improvement is required in many construction projects. Portland cement is one of the most common materials used in traditional soil improvement methods. However, the use of Portland cement can cause significant harm to the environment and nature [1]. In this context, there has been growing interest in alternative materials in recent years, both to reduce environmental impacts and to utilize local resources such as waste. For example, various environmentally friendly solutions, such as industrial waste (fly ash, furnace slag, etc.) and recycled waste materials (waste brick, waste marble, etc.) that can acquire binding properties through alkali activation, are being researched by investigators as alternative binders [2–5]. The use of these materials provides both a means of recycling waste and a more environmentally friendly alternative to traditional materials.

Construction and demolition waste can cause numerous problems both environmentally and economically. For example, the asbestos pollution caused by the collapsed structures can create significant problems for the environment and human health [6]. Therefore, effective management of demolition waste can contribute to the national economy as a secondary raw material, prevent structural waste from harming the environment, and reduce carbon emissions, thereby providing numerous environmental benefits [7]. Construction and demolition waste consists of various types of building materials such as concrete, brick, wood, tile, and glass, and is generated as a result of the demolition of buildings or natural disasters such as earthquakes [8]. Waste materials such as concrete and bricks obtained from construction and demolition waste can be recycled with various additives and used in various fields such as road infrastructure and concrete aggregate [9].

Studies in the literature indicate that products derived from construction and demolition waste can be used as alternatives to traditional binding materials. For instance, Dobrescu and Calarasu [10] conducted a study to investigate the potential of recycled construction waste in soil improvement. They performed unconfined compressive strength and swell tests on soils mixed with different proportions of concrete and brick to evaluate the improvement results. They noted that optimal improvement effects were achieved at a waste concentration of 10% and that construction waste materials demonstrated significant improvements in swell pressure. They also emphasized that the reuse of waste as a by-product could be an effective method for protecting natural resources. In their studies, Zaharieva et al. [11] investigated the usability of recycled waste concrete powder and gypsum obtained from construction demolition waste as alternatives to traditional binders in the stabilization of clay soil. They found that the use of only 5% concrete powder resulted in significant improvements in cohesion and unconfined compressive strength. They suggested that utilizing gypsum at a level of 10% might achieve optimal engineering properties, while the addition of 5% gypsum to the clay-concrete powder mixture could further enhance engineering properties such as cohesion due to the formation of ettringite and the physical effects of gypsum powder. They emphasized that incorporating recycled concrete and gypsum board waste in soil improvement could reduce carbon emissions. Abregú et al. [12] carried out a study to determine the effects of recycled waste brick powder and gypsum powder on the geotechnical properties of high plasticity clay soil. In this context, they examined the impact of these additives on the unconfined compressive strength and dry density of soil samples using different proportions of brick powder (5%, 10%, and 15%) and gypsum powder (2.5%, 5%, and 7.5%). According to the results of the unconfined compressive tests, they noted that the strength of the soil sample increased by 322.2%, reaching a value of 28.8 kg/cm² from 6.3 kg/cm² after improvement. They emphasized that both recycled materials could serve as an effective solution to geotechnical problems in problematic soils.

Numerous studies in the literature have demonstrated that construction waste can also be utilized as embankment material. For instance, in their work, Akbas et al. [13] investigated the usability of concrete aggregates as subgrade embankment for roads. They applied California Bearing Ratio (CBR) and permeability tests on the recycled concrete aggregates obtained from an urban transformation facility. The results of the CBR tests conducted on both dry and wet facility sample specimens indicated CBR values of 79% and 76% for wet and dry samples, respectively. In the prepared samples, the CBR values for wet and dry conditions were reported as 45% and 106%, respectively. Furthermore, they determined that both samples exhibited a similar swelling rate of 1%. According to the results of permeability tests, the permeability coefficients of the prepared sample and the facility sample were reported to be 5.64×10^{-5} cm/s and 8.86×10^{-5} cm/s, respectively. In a study conducted by Ahmed et al. [14], a series of tests were carried out to investigate the usability of recycled concrete aggregate and fly ash in flexible pavement subgrades. For this purpose, different ratios of aggregate and fly ash were used, and the results of the samples regarding CBR, maximum dry density, and swell potential were evaluated. With the increase in the ratio of fly ash, both the optimum moisture content and CBR values also increased. In applications where a 5% ratio was used for both aggregate and fly ash, an increase in the CBR value was observed. They indicated that the swelling of soil samples decreased with the increase in both aggregate and fly ash content, and that minimum swelling was obtained from the samples with 15% fly ash. In their study, Saberian et al. [15] investigated the use of recycled concrete aggregate obtained from construction and demolition waste, crushed rock, waste glass, and scrap tire with the aim of significantly reducing quarry-based materials and lowering greenhouse gas emissions. For this purpose, they conducted CBR, modulus of elasticity, unconfined compressive strength, and modified compaction tests on soil samples. They noted that all samples met the recommended minimum CBR value of 80% for foundations. Furthermore, they indicated that the addition of crumb rubber at a rate of 1% decreased the strength and stiffness of the concrete aggregate and crushed rock mixtures, while the inclusion of crushed glass increased compressive strength and significantly reduced ductility. As a result, they emphasized that the designed mixtures could be considered an alternative low-carbon option for future foundation or sub-base applications. In their study, Khan et al. [16] investigated the suitability of recycled concrete aggregates for use in road bases or subbases. They determined that the abrasion and aggregate impact values of the aggregates yielded very good results in terms of mechanical and physical properties. They noted that the strength of the samples improved as the curing period increased, and that curing for 7 days met the minimum strength values of the Indian standards (3 and 4.5 MPa).

Aggregates obtained from demolition waste are among the most important resources for recycling [17]. However, it is understood from the literature that recycled aggregates are generally used in road subgrade. In addition, it appears that studies on the use of waste brick powder in soil improvement are quite limited and particularly focused on clay soils. Although the use of recycled concrete aggregates has been investigated in numerous studies, no research has been found regarding the synergistic effect of waste brick powder and recycled aggregate on the potential of soil improvement applications.

This study investigates the potential synergistic effects of recycled concrete aggregates and waste brick powder in soil improvement. In this context, a mixture of alkali solution and brick powder prepared by mixing with alkali solutions of different molarities was applied to recycled aggregates in various proportions. Additionally, the effects of natural fiber additives of different lengths on the strength development of the soil were also examined. The results were evaluated through unconfined compressive strength and permeability tests. Furthermore, considering the data obtained from unconfined compressive test results, the behavior of soil samples under load after improvement was also investigated. The findings of this study are believed to be beneficial in the re-evaluation of concrete and brick waste.

2. Material and Methods

2.1. Recycled aggregate

The use of concrete aggregates obtained through the mechanical crushing of construction debris waste will provide a sustainable alternative to natural sand for geotechnical applications, and it will also contribute to material sustainability, facilitating a transition towards more environmentally friendly construction practices [18]. This study investigates the applicability of recycled concrete aggregate, a product of construction debris waste, as sand soil. This soil, referred to as recycled sand (RS), has been obtained by mechanically crushing and grinding the concrete from a demolished building within the scope of urban transformation. Since it has been stated that washing recycled aggregates has a positive effect on strength development [19], RS has been washed and dried in order to eliminate impurities and achieve better strength development. The particle size distribution and basic physical properties of the soil are presented in Figure 1 and Table 1, respectively, according to the ASTM D2487 [20] criteria.

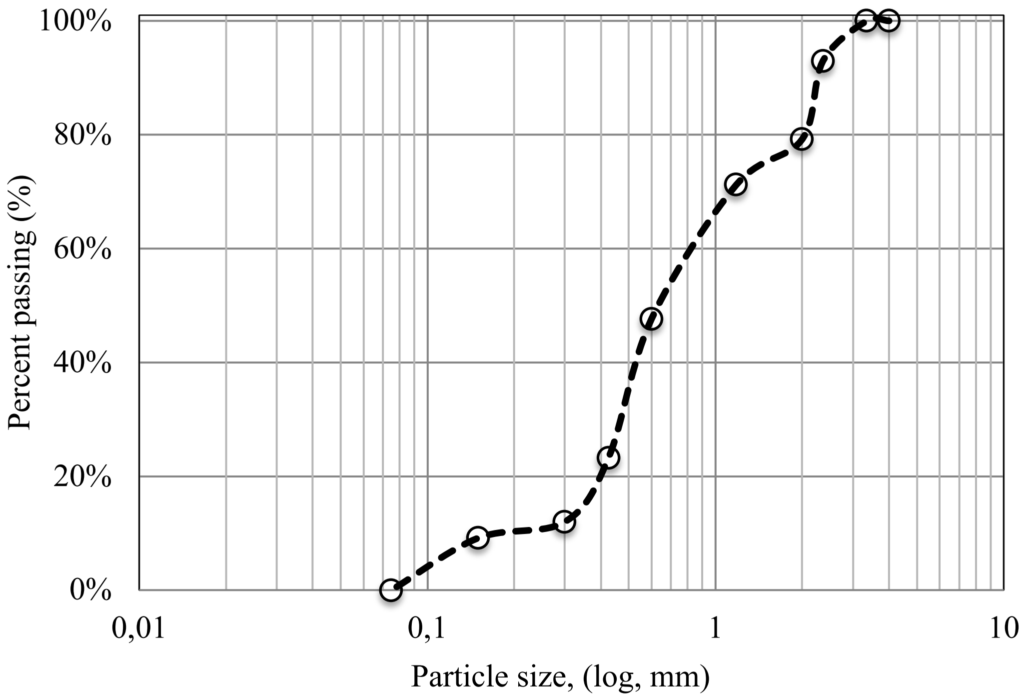

Figure 1. Particle size distribution of RS soil

Table 1. Basic physical properties of the RS soil

Soil	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	C_u	C_c
RS	0.18	0.47	0.81	4.5	1.52

2.2. Alkali activator (NaOH) and waste brick powder

The alkaline activator is one of the most important parameters in the geopolymerization process. In our study, NaOH pellets (Tekkim, ≥98%) were used as the alkaline activator. The properties of the NaOH pellets are presented in Table 2. To evaluate the effect of different alkaline activator concentrations on the geopolymerization process, NaOH concentrations of 0.5M, 1.0M, 1.5M, 2.0M, and 2.5M were utilized. While preparing the alkaline activator solution, the required amounts of NaOH pellets for the specified concentrations were weighed using a precision balance. Subsequently, the NaOH pellets were mixed with distilled water until a homogeneous mixture was achieved. The alkaline activator solutions were prepared 24 hours prior to application and stored at room temperature.

Waste bricks have been obtained from a building demolished within the scope of urban transformation. The impurities found in the waste bricks brought to the laboratory were cleaned and crushed into powder. Subsequently, brick powders with a particle size smaller than 75 µm were obtained by sieving (Figure 2).

Table 2. Technical specifications of NaOH

Chemical formula	Molar mass (g/mol)	Purity (%)	Sodium carbonate (Na_2CO_3) (%)	Sodium chloride (NaCl) (%)	Iron (Fe) (%)
NaOH	40,0	98,0	<= 0,5	<= 0,02	<= 0,001

Figure 2. RS soil and waste brick powder

2.3. Fiber

In our study, sisal fiber, a type of natural fiber that is frequently used in the literature, has been utilized, and an image of the fiber is presented in Figure 3. It has been reported in various studies that the best compressive strength results for sand substrates are achieved with a 0.6% incorporation of sisal fiber [21,22]. In this context, a sisal fiber ratio of 0.6% has been maintained as constant in our study. Furthermore, to determine the effect of sisal fiber length on the strength development of soil samples, various lengths of sisal fiber (10 mm, 15 mm, and 20 mm) were applied to soil samples, taking into account the literature [23,24]. To assess the impact of different sisal fiber lengths on samples prepared with varying molarities, applications were carried out for the optimum solution/RS soil ratio determined for each molarity. Thus, the influences of sisal fiber lengths on the strength development of soil samples were investigated.

Figure 3. Sisal fiber

2.4. Sample preparation method

In our study, the effects of alkali activator (NaOH) concentrations, brick powder-alkali activator mixture/soil ratios, and fiber additives on the improvement of RS soils were examined. For this purpose, designs based on different mixture ratios were developed. The NaOH solution/brick powder ratio was selected as 1.5, considering the long-term (365-day) strength results in the literature [25]. The mixture, prepared by adding approximately 66.67 g of brick powder to 100 ml of NaOH solution, was mixed for about 5 minutes until it became homogeneous. The mixture was homogeneously combined with RS soil at ratios of 15%, 20%, 25%, and 30% relative to the dry density of the RS soil, which has a dry density of 1.39 g/cm^3 for each molarity. The prepared mixtures were then placed into molds with a diameter of 38 mm and compacted in three pieces to a height of 76 mm. In the preparation of fiber-reinforced samples, sisal fibers of 10 mm, 15 mm, and 20 mm in length were incorporated into RS soils at a weight percentage of 0.6%, taking into account the optimum mixing ratios for each molarity, and were subsequently compacted.

One of the most important parameters in the geopolymerization process is the curing temperature. A low curing temperature can delay the early stages of geopolymerization [26]. It has been noted that a curing temperature of 50°C is sufficient to achieve complete geopolymerization [27]. For this purpose, to obtain optimum strength development, the specimens were kept in curing at 50 °C for 7 days [28] after improvement, and analyses were conducted thereafter.

2.5. Unconfined compressive strength test

To determine the strengths of the improved soil samples, unconfined compression tests were conducted in accordance with ASTM D2166 [29] standard. The unconfined compression tests were conducted using an unconfined compression testing device, a 1-ton capacity S-type load cell, a linear variable differential transformer (LVDT), and an 8-channel testing device. From the graphs generated after the tests, the maximum unconfined compressive strength and the axial strain corresponding to the maximum unconfined compressive strength were determined.

2.6. Permeability test

In order to determine the permeability of the improved soils, constant head permeability tests were conducted in accordance with ASTM D2434. Samples were prepared for permeability tests, taking into account the optimal mix designs established for each molarity of the alkaline solution. Additionally, the permeability coefficient of the untreated RS soil has been determined using the same method.

3. Results and Discussion

3.1. Unconfined compressive strength test results

The results of the unconfined compressive strength tests of the RS soils treated with alkaline solutions of different molarities and applied in various proportions are presented in Figure 4. From the results shown in Figure 4, it can be understood that both the molarity of the alkaline solution and the mixing ratios significantly affect the strength results. It is observed that the lowest strength results were obtained from a 15% mixing ratio, while the highest strength results were achieved with a 30% mixing ratio. However, some samples with a 15% mixing ratio were unable to retain their structural integrity upon removal from the molds, resulting in a loss of strength in these samples. Soil samples with a 15% mixing ratio can be seen in Figure 4. As understood from Figure 4, when the soil samples with molarities of 0.5M, 1M, and 1.5M were removed from the mold, they could not maintain their structural integrity and disintegrated. With the increase of the molarity of the alkaline solution to 2M or above, the soil samples were able to maintain their structural integrity; however, only strenght of 12.04 kPa and 18.88 kPa were obtained from the soil samples treated with 2M and 2.5M, respectively. These results indicate that the minimum mixing ratio that must be applied to the soil samples is 15%, and for this ratio, the molarity of the alkaline solution should be at least 2 M. As the value of the mixing ratio increased, the obtained resistance values also significantly increased. For instance, the average resistance values for samples with mixing ratios of 15%, 20%, 25%, and 30% were determined to be 15.46 kPa, 39.67 kPa, 48.92 kPa, and 70.97 kPa, respectively. However, in samples containing 0.5M, 1M, 1.5M, 2M, and 2.5M alkaline solutions, it has been found that the average strength increases by 20%, 22%, 42%, 103%, and 169%, respectively, as the mix ratio increases from 20% to 30%. This indicates that the increase in the mix ratio is even more effective on strength development as the molarity also increases. As a result, it is understood that the mix ratio has a significant impact on the strength development of soil samples and that optimum strength values are obtained at a mix ratio of 30%.

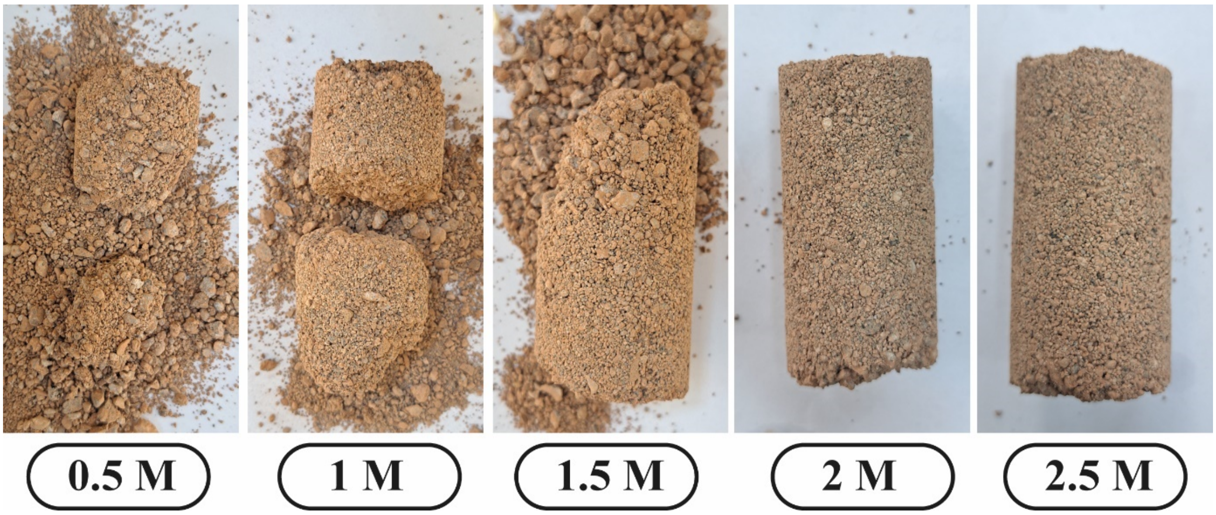

Figure 4. The effect of different alkaline solution molarities on samples with a 15% mixture ratio

The increase in the molarity of the alkaline solution has also had a positive effect on the strength development of soil samples. This situation can be clearly understood from Figure 4, which presents samples with a mixture ratio of 15%. Despite the mixture ratio remaining constant, the increase in molarity has allowed the soil samples to maintain their structural integrity. Furthermore, in other mixture ratios, the strength results have also increased as the molarity rises. For example, by raising the molarity of the alkaline solution from 0.5M to 2.5M, the strength increases in samples with mixture ratios of 20%, 25%, and 30% were recorded as 60%, 96%, and 259%, respectively. With the increase in the ratio of the mixture, the effect of the molarity of the alkaline solution has also intensified. Furthermore, the impact of molarity increase at each mixture ratio has occurred at different levels. For example, at a mixture ratio of 20%, the highest increase was observed between 0.5M and 1M, reaching 27%. When the mixture ratio is 25%, the highest increase was recorded at 34% between the 2M and 2.5M samples. At a mixture ratio of 30%, it was noted that the highest increase rate occurred at 57% between the 1.5M and 2.5M samples. Consequently, the increase in molarity at all mixture ratios has had a significant effect on strength development, and optimal strength results were obtained from soil samples containing 2.5M alkaline solutions. The previous studies also show that NaOH molarity is highly effective in strength development during the geopolymerization process. For instance, Hanjitsuwan et al. [30] used five different NaOH molarities in their study and stated that increasing the NaOH concentration resulted in a denser matrix in the microstructure of the geopolymer paste, resulting in higher compressive strength. Similarly, in our study, the strength increased with increasing NaOH molarity. However, while higher activator concentrations are commonly associated with improved strength, they can also increase brittleness, cause performance losses beyond certain limits, and raise overall costs [31]. It is understood that determining the optimum molarity and concentration is important both in terms of the strength properties of the samples and in terms of costs.

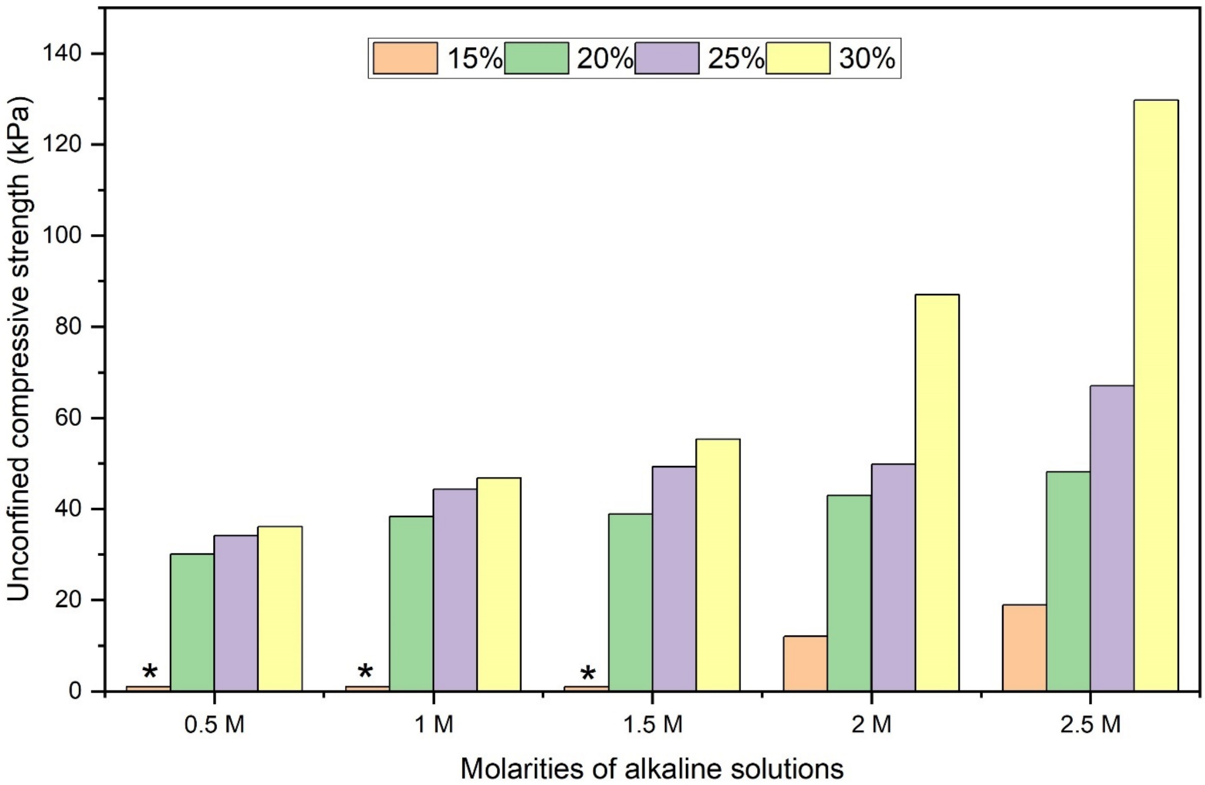

Figure 5. Results of the unconfined compressive strength tests of the improved soil samples

3.2. The effect of fiber additive

In order to determine the effect of fiber addition on the strength development of soil samples, fiber was applied at a fixed rate (0.6%) and different lengths (10 mm, 15 mm, and 20 mm) to samples with a 30% mixture ratio, where optimum strength development was achieved, and the results are presented in Figure 6. Additionally, the unconfined compressive strength versus axial strain curves obtained from the unconfined compressive strength tests of the soil samples, along with the strength data derived from these curves, are presented in Figure 7. From the results presented in Figure 6, it can be understood that fiber addition has a significant effect on the strength development of soils. For example, it was determined that the fiber addition of 10 mm length increased the strength values in samples containing 0.5M, 1M, 1.5M, 2M, and 2.5M alkaline solutions by 286.36%, 241.52%, 190.10%, 127.36%, and 90.25%, respectively, compared to the samples without fiber additives. The fiber addition has significantly increased the strength values and has also reduced the strength difference between samples with low molarity and those with high molarity. For instance, when the molarity was increased from 0.5 M to 2.5 M in samples with a mixture ratio of 30%, a 259% increase in strength was observed, whereas with a 10 mm fiber addition, this increase remained at 102%. This indicates that high strength values can also be achieved at lower molarities owing to the fiber addition. When the length of the fiber addition was increased to 15 mm, it was possible to obtain average strength values that were 11% higher compared to samples containing 10 mm fibers. However, when the fiber addition was 20 mm, it was revealed that the strength values decreased by an average of 21% compared to samples containing 15 mm fibers. In their study, Memon et al. [32] indicated that by incorporating short fibers (12.7 mm), higher strength values were achieved compared to samples without fiber additives, while the use of longer fibers (25.4 mm) resulted in a decrease in strength values compared to short fiber incorporation. Furthermore, they emphasized that although long fiber samples exhibited lower strength compared to short fiber samples, they nonetheless demonstrated higher strength values compared to samples without fiber additives. Similarly, in our study, although an increase in fiber length to 20 mm resulted in a decrease in strength values compared to samples with 15 mm fiber inclusion, an average strength improvement of 123% was obtained from samples with 20 mm fiber inclusion compared to samples without fiber additives. In their study, Hao et al. [33] investigated the improvement of soils with fiber reinforcement. According to the results of the unconfined compression tests conducted, they reported that the unconfined compressive strength of the fiber-reinforced soil sample was up to 2.1 times greater than that of the sample without fiber additives. In our study, it was observed that the maximum strength increase occurred at a similar range, with a factor of 2.23 in soil samples containing 15 mm of fiber reinforcement.

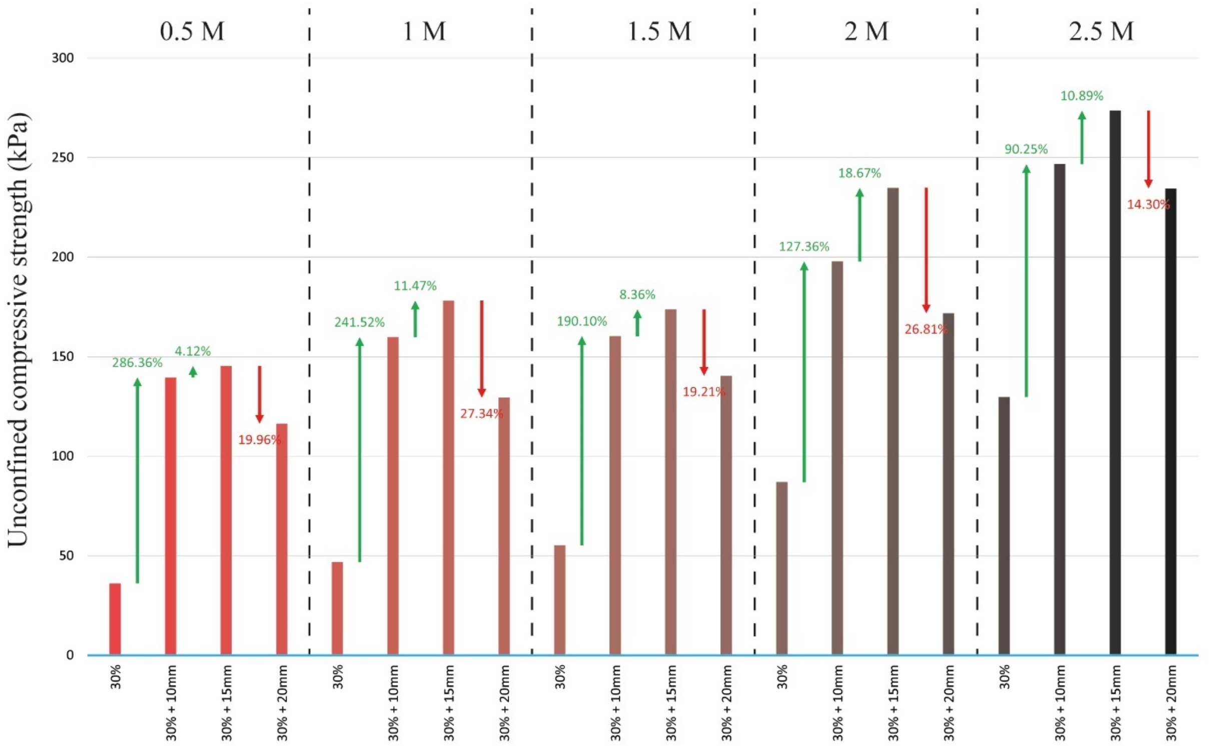

Figure 6. The effect of fiber additives on the unconfined compressive strength results of soil samples

As can be understood from Figure 7, the fiber addition plays a significant role in the maximum unconfined compressive strength of soil samples and the axial strain corresponding to maximum strength. While the axial strain value corresponding to maximum strength is on average 0.71% for the samples without fiber addition, it reaches average values of 1.53%, 1.65%, and 1.52% for fiber-added samples with lengths of 10 mm, 15 mm, and 20 mm, respectively. When these values obtained with fiber addition are examined, it can be seen that, similar to the maximum unconfined compressive strength, the highest average axial strain value was achieved with 15 mm long fibers, while the lowest value occurred in the samples with 20 mm fiber addition. Although the axial strain value at the moment of maximum unconfined compressive strength in samples containing 20 mm fibers is higher than that of samples without fiber, the 20 mm fiber length has shown lower performance in terms of both maximum strength and the axial strain corresponding to maximum strength compared to other fiber lengths. Based on the data obtained, it can be observed that using 15 mm long fibers demonstrates the most suitable performance compared to other options in terms of the examined strength properties. As a result, through the incorporation of fiber, not only are the maximum unconfined compressive strength values of the soils increased, but also the corresponding axial strain values, leading to a significant improvement in the failure behavior of the soil samples.

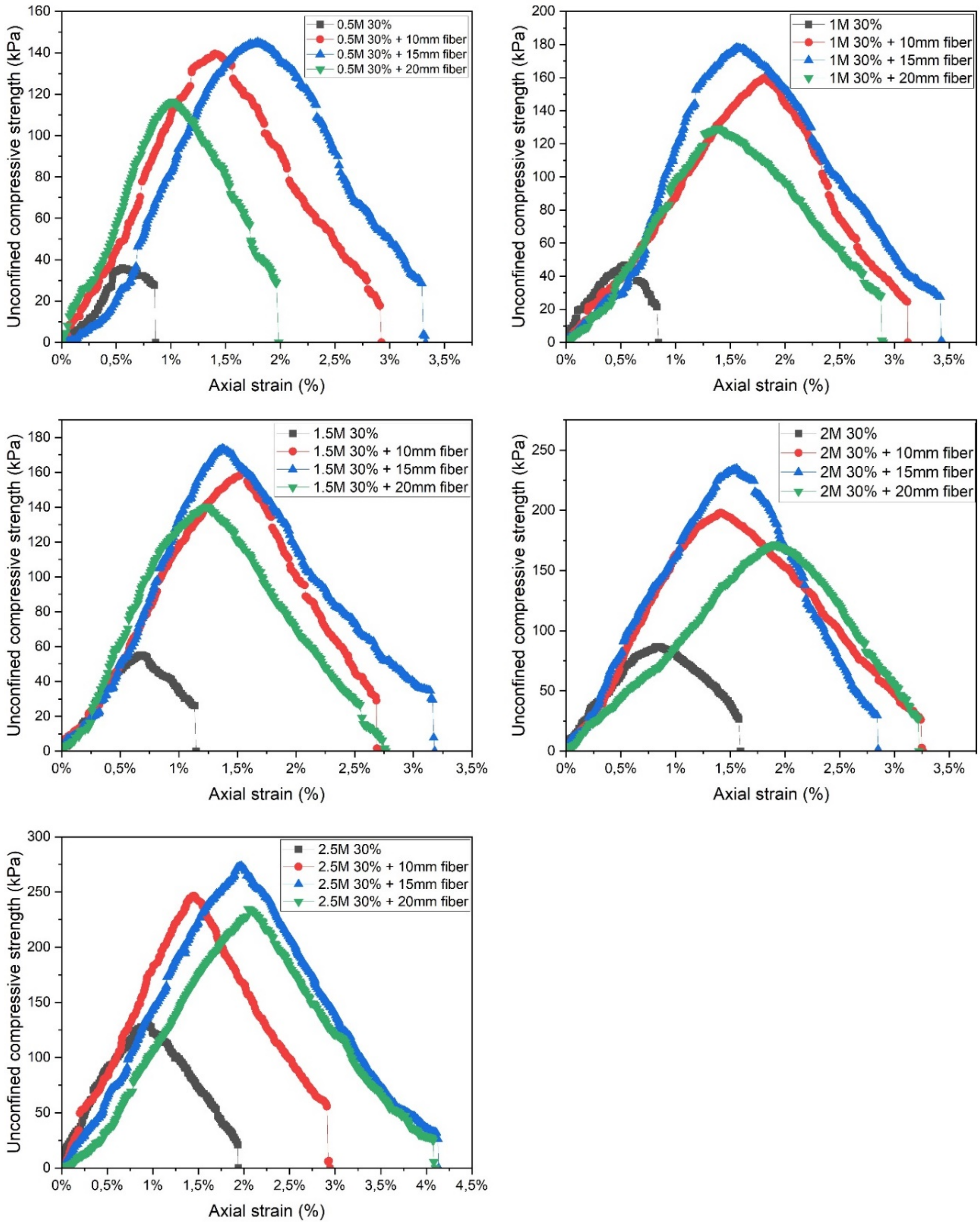

Figure 7. Results of the unconfined compressive strength tests of fiber-reinforced soil samples

3.3. Permeability test results

After soil improvement, the optimal strength results were achieved at a mixture ratio of 30%, and the permeability coefficients of soil samples with different molarities were determined, with the results presented in Figure 8. A permeability test was also conducted on RS soil, revealing a permeability coefficient of $1.49x10^{-4}$ m/s. According to the experimental results shown in Figure 8, it was found that the permeability coefficient of the improved soil samples decreased by an average of 8.4% compared to RS soil. The lowest permeability coefficient was obtained from the soil sample containing a 2.5M alkaline solution, which was $1.35x10^{-4}$ m/s, while the highest permeability coefficient was obtained from the soil sample containing a 1.5M alkaline solution as $1.38x10^{-4}$ m/s. However, although a decrease in permeability has been observed, the improved samples have exhibited permeability coefficients similar to that of RS soil (10^{-4}). This situation indicates that improved RS soils can be evaluated in different applications. For instance, permeable hard surfaces have many known advantages. Asphalt pavements with permeable surfaces provide a safe driving experience during rainy weather as they allow rainfall to permeate into the underlying layers [34]. Furthermore, the use of permeable hard surfaces provides numerous advantages in water management, such as reducing surface runoff that may occur due to rainfall and preventing floods [35]. Consequently, the findings obtained from our study demonstrate that improved RS soils can also be assessed in this direction in future studies.

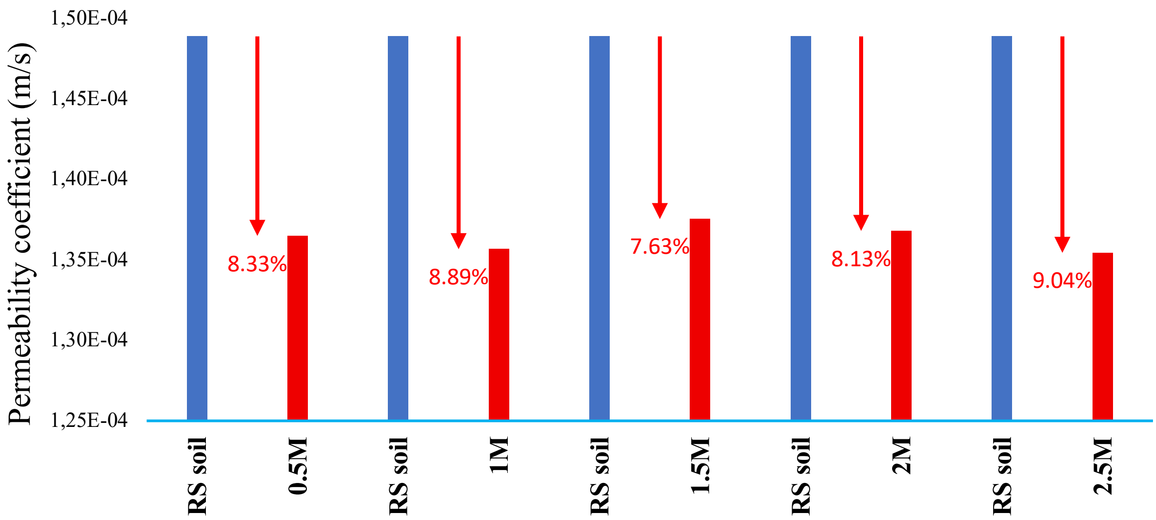

Figure 8. Permeability test results

4. Conclusion

In this study, the potential use of recycled concrete aggregates obtained from construction and demolition waste, specifically from concrete and bricks, and waste brick dust in soil improvement has been investigated. Recycled concrete aggregates have been evaluated as recycled sand soil, while waste brick dust has been considered as a binder. The effects of different molarities of alkali solutions and mixing ratios on soil improvement have been examined. Additionally, the impact of adding sisal fiber, a natural type of fiber, to the mixtures on the strength development of the soil samples has also been determined. The following conclusions can be drawn from this study:

(1) The mix ratio has played a critical role in the strength development of soil samples. An increase in the mix ratio has positively influenced the strength of the soil samples. By increasing the mix ratio from 15% to 30%, the average strength value of the soil samples has reached from 6.78 kPa to 70.97 kPa.
(2) It has been evaluated that the molarity of the alkaline solution is more effective in increasing the strength relative to the mixture ratio. As the molarity of the alkaline solution increases from 0.5M to 2.5M, it has been observed that the strength values increase on average by approximately 60%, 96%, and 259% in samples with 20%, 25%, and 30% mixtures, respectively. A higher mixture ratio has further amplified the effect of the alkaline solution molarity on strength.
(3) The fiber additive has had a significant impact on the maximum unconfined compressive strength. The average strength value of the soil samples without fiber additive with a 30% mix ratio was 70.97 kPa, whereas this value reached an average of 201.10 kPa in the soil samples with a fiber additive of 15 mm in length, where optimum strength development was achieved.
(4) According to the permeability test results, the permeability of the soil samples decreased following the improvement. However, since this reduction occurred at a limited level, it has been assessed that this technique could also be applied in situations involving permeable soil layers.

In this study, different NaOH molarities and mixture ratios were used; however, future studies investigating the effects of higher NaOH molarities and different mixture ratios on the strength and permeability properties of soil samples may contribute to the development of this technique and its more effective application. Additionally, the analysis of environmental effects such as freeze-thaw and wet-dry cycles may provide a more comprehensive perspective on the method's performance under field conditions.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

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