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Research Article

Influence of waste textile on the unconfined compressive strength of cohesive soil

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ABSTRACT

The increasing need for sustainable and environmentally friendly solutions in geotechnical engineering has prompted significant interest in utilizing waste materials for soil improvement. This study explores the utilize of waste denim fabric as a reinforcement material for clayey silt soil, aiming to enhance soil properties while contributing to the recycling of textile waste. Waste denim was prepared in three aspect ratios (A1: 6×6 mm, A2: 6×12 mm, and A4: 6×24 mm) and incorporated to the soil in different ratios based on dry weight (0.4%, 0.8%, and 1.6%). Unconfined compressive strength (UCS) tests were conducted to analyze the effects of denim reinforcement on stress-strain behavior, UCS value, elastic modulus, UCS increase ratio, deformability index, and normalized energy absorption capacity. The results demonstrated a significant enhancement in the mechanical properties of the reinforced soil compared to the unreinforced soil. The UCS increased notably with denim reinforcement, with the highest strength achieved by A4-sized fabric at 1.6% and 0.4% reinforcement rates, yielding approximately 41.67% and 40.91% increases, respectively. Furthermore, the energy absorption index showed the most substantial improvement with A4-sized fabric, reaching a normalized value of 1.4, highlighting its superior ability to dissipate energy under loading. Additionally, the elastic modulus, representing soil stiffness, increased with denim reinforcement, particularly with 0.4% A4 fabric, which achieved the highest value among all configurations. The study concludes that waste denim fabric is a viable, sustainable material for soil improvement, offering an eco-friendly alternative to traditional soil stabilization methods.

Introduction

Environmental pollution has become a critical problem threatening natural ecosystems due to the rapid increase in industrialization and urbanization. Increasing global population, changing consumption patterns and intensifying industrial activities have significantly increased the volume of environmental waste. In particular, the accumulation of non-biodegradable materials such as plastics, heavy metals, and various synthetic wastes in nature has negatively affected the quality of water resources, soil and air [1], [2], [3], [4]. Waste management is recognized as one of the most effective strategies to address these challenges. Practices such as recycling, reuse and waste minimization play a vital role in reducing the negative impact of waste on the environment. However, certain types of waste are often overlooked or poorly managed in these processes, limiting their overall effectiveness. The textile industry in particular is a major contributor to environmental pollution and waste denim fabrics pose a significant challenge in this context [5]. Therefore, recycling or disposing of waste denim through environmentally sound methods is a crucial step to reduce pollution and promote sustainable practices.

Waste management requires the contribution of many engineering disciplines to reduce environmental pollution and use resources more efficiently, and geotechnical engineering plays an important role in this process. Soil improvement techniques enable the reuse of waste, reducing the amount of waste and providing economic benefits. The use of geotechnical engineering in waste management has become a critical component for a sustainable environment. With geotechnical engineering applications, many waste materials are both disposed of by removing them from nature and improve soil behavior [6], [7]. In geotechnical engineering, waste materials such as construction demolition waste [8], fly ash [9], biopolymers [10], plastic waste [11], geopolymers [12], PVC fibers [13], and various solid wastes [14] used for soil stabilization and improvement.

Unconfined Compressive Strength (UCS) tests are a primary method for assessing the mechanical behavior of cohesive soils [15], [16], [17]. These tests provide the opportunity to analyze soil stability, strength and deformation behavior by determining the UCS of the soil. It plays an important role in determining soil bearing capacity and evaluating the effectiveness of different stabilization methods, especially in construction projects. UCS tests are also widely used to compare the performance of soils improved with waste additives and to model soil behavior [18], [19], [20]. Therefore, UCS test results are a critical source of data for geotechnical design decisions.

In a recent study conducted by Öztürk (2024) [6], the use of waste modified expanded polystyrene (WMEPS) as a material for enhancing soil properties was investigated to address the dual challenges of environmental sustainability and geotechnical performance enhancement. The research aimed to demonstrate three main benefits: recycling waste EPS from the environment, developing lightweight backfill materials and improving the compressive properties of soils. To achieve this, waste EPS was subjected to thermal modification and then mixed into the clayey soil at different ratios (0.5% to 6% by dry weight). UCS tests were conducted on the prepared specimens cured for 1 and 28 days. The findings revealed that the incorporation of 5% WMEPS reduced the dry density of the soil by 15%, while increasing the UCS by 45.22% for specimens cured for 28 days. Notably, even small amounts of WMEPS1 significantly improved soil behavior, with a 28.9% UCS increase observed for 1 day cured samples containing 0.5% WMEPS1. However, excessive incorporation above 6% resulted in reduced strength gains. In a study by Yadav et al. (2022) [21], the strength and ductility behavior of rubber-granule and rubber-fiber reinforced cementitious clayey soils were investigated. The research included UCS tests to assess the effects of rubber content and cement proportions. The results demonstrated that the inclusion of rubber particles increased the ductility and toughness of cemented clay soil. In particular, the study reported an improvement in UCS of 5.08% and 3.46% with the addition of rubber granules and fibers at optimum content levels (2.5% and 5%, respectively). However, excessive rubber content led to strength reductions and rubber granules had a more pronounced effect than fibers. In particular, the toughness index and absolute toughness were maximized at 5% granules and 7.5% fibers. Choobbasti et al. (2019) [22] investigated the effects of carpet waste fibers and nano calcium carbonate on the geotechnical properties of clayey soils. The study used a comprehensive set of tests, including UCS tests, to evaluate the mechanical behavior of soil treated with these additives. The study revealed that specimens with 1.2% nano calcium carbonate content cured for 42 days had an optimum strength increase of approximately 100%. Bekhiti et al. (2019) [23] investigated the effects of waste tire rubber fibers on the UCS, ductility and swelling characteristics of cement-stabilized bentonite clay. The experimental program included varying the cement content (5%, 7.5% and 10%) and rubber fiber content (0%, 0.5%, 1% and 2%) by weight to evaluate their effects on soil behavior. The findings indicated that the inclusion of waste tire rubber fibers decreased the dry density, swelling potential and swelling pressure of the soil while increasing the optimum water content, which was attributed to the lightweight nature of the fibers and the water absorption capacity of the cement. Strength and ductility were significantly improved by UCS testing; the highest UCS and ductility index were noted at 2% rubber fiber content.

The compaction and recompaction indices increased proportionally with higher fiber and cement content, highlighting the beneficial role of fibers in improving soil deformability. Xu (2019) [24] highlights the relationship between UCS, curing age and other mechanical properties in his study on municipal solid waste incineration (MSWI) bottom ash. The findings reveal that initial elastic modulus and UCS of MSWI bottom ash increase logarithmically with curing age, indicating increasing material stability over time. The UCS values of saturated specimens increased from 326 to 926 kPa, while unsaturated specimens ranged from 305 to 810 kPa after 28 days of curing. Similarly, the elastic modulus increased significantly, underlining the increased stiffness of the material with curing. In addition, the study showed strong correlations between UCS, elastic modulus and ultrasonic wave velocity, demonstrating the applicability of non-destructive testing to predict mechanical behavior.

Despite the growing interest in the use of waste materials for soil stabilization, the use of waste denim textiles as a reinforcement for cohesive soils has not been extensively investigated in the existing literature. Although previous studies have investigated the effects of various waste materials on soil properties, the specific effect of waste denim textiles on the UCS of cohesive soils has not been explored. This gap provides an opportunity to evaluate the potential of waste denim as an innovative and sustainable reinforcement material addressing both geotechnical and environmental challenges.

In this study, waste denim fabrics were used as a sustainable material to enhance the geotechnical properties of cohesive soils. The waste denim fabrics were processed without any chemical treatment and Added to the soil in different proportions (0.4%, 0.8%, and 1.6% by dry weight of soil). The waste fabrics were approximately cut into three different sizes: 6× 6 mm, 6 × 12 mm and 6 × 24 mm, corresponding to aspect ratios of 1, 2 and 4, respectively. A series of UCS experiments were conducted on the prepared samples after a 7-day curing period. The effects of waste denim fabric inclusion on UCS value, deformability index, elastic modulus, normalized energy absorption index, and UCS increase ratio were evaluated. The findings highlight the feasibility of using waste denim fabrics as a reinforcement material for improvement of soil properties and offer an environmentally friendly alternative to conventional soil remediation methods.

Material and Method

In this study, clayey silt soil was used. According to ASTM D2487 and AASHTO M145 standards, the soil was classified as ML and A-7-5, respectively. The grain distribution curve and soil properties are given in Figure 1 and Table 1, respectively. The standards of index tests used to determine the properties of the soil are given in Table 1.

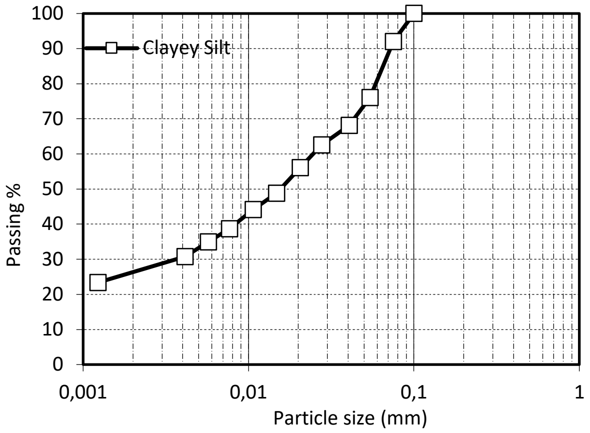

Figure 1. Particle size distribution of clayey silt

Table 1. Properties of clayey silt

Properties	Used Standards	Values
Specific gravity	ASTM D854 [25]	2.73
Optimum water content (%)	ASTM D698 [26]	23.54
Maximum dry density (g/cm3)	ASTM D698 [26]	1.71
Liquid limit (LL) %	ASTM D4318 [27]	41.60
Plastic limit (PL) %	ASTM D4318 [27]	26.80
Plasticity index (PI) %	ASTM D4318 [27]	14.80
Clay (%)	ASTM D7928 [28]	25
Silt (%)	ASTM D7928 [28]	67
Sand (%)	ASTM D2487 [29]	8
AASHTO Soil classification	AASHTO M145 [30]	A-7-5
Unified Soil classification	ASTM D2487 [29]	ML

In this study, waste denim fabric collected from a tailor shop was used as reinforcement material. The thickness of the waste denim fabric was determined to be 0.7 mm. The fabric was approximately cut into three different sizes: 6 mm × 6 mm, 6 mm × 12 mm and 6 mm × 24 mm, corresponding to aspect ratios of 1, 2 and 4, respectively. These cut pieces of waste denim were added to the soil at different dry weight ratios of 0.4%, 0.8% and 1.6%. A photo of 3 different aspect ratios of waste denim fabrics is illustrated in Figure 2.

(a) (b) (c)

Figure 2. Waste denim fabrics a) 6 mm × 6 mm b) 6 mm × 12 mm c) 6 mm × 24 mm

The experiments were conducted at a soil water content of 30%, which exceeds the optimum value. The selection of 30% water content is based on the understanding that the strength of cohesive soils is greatly influenced by their moisture content. Cohesive soil strength enhances with increasing moisture content up to a specific threshold, beyond which additional water content leads to a decrease in strength [31]. While embankments are typically compacted with soil at optimum moisture content, precipitation exposure can increase the moisture content of the soil, potentially reducing its strength and compromising structural integrity [32]. The study of soil behavior under high water content is critical for geotechnical engineering.

After mixing, both waste fabric reinforced and unreinforced soil specimens were compacted manually into molds in 3 layers and cured for seven days under airtight conditions to ensure uniform curing. As each layer was compacted, the surface of the previous compacted layer was roughened to ensure adherence with the next layer. Unconfined compressive strength (UCS) tests were performed on these specimens in accordance with ASTM D2166. The tests were performed up to 20% strain to fully capture stress-strain behavior. If the highest stress occurred before 20% strain, it was recorded as the maximum stress. Otherwise, the stress value at 20% strain was considered as the maximum stress. This methodology was performed to provide a comprehensive understanding of the mechanical behavior of the reinforced soil under tension.

The test conditions and procedures were used to evaluate the effect of both aspect ratio and content of denim reinforcement on the UCS and deformability properties of the cohesive soil and to highlight the potential of waste denim as a sustainable soil improvement material. The experimental results were assessed in terms of UCS increase ratio, UCS value, deformability index, , elastic modulus and energy absorption index.

Results and Discussion

The curves are not presented in the same graph for better comparison since presenting the curves in a single graph creates confusion. The aspect ratio and soil participation rate of the waste additive material are used as abbreviations in the graphs. A1 (6x6 mm), A2 (6x12 mm) and A4 (6x24 mm) represent the aspect ratio and 0.4%, 0.8% and 1.6% represent the incorporation rate: for example, A1-0.8% means that the material with an aspect ratio of 1 is incorporated into the soil at a rate of 0.8%. The UR abbreviation in the graphs represents unreinforced soil. The results for soils containing different proportions of admixtures at the same aspect ratio are given in Figure 3, Figure 4 and Figure 5, respectively.

The figures show in detail the stress-strain behavior of soils reinforced with different proportions of waste denim fabric. The unreinforced soil has the lowest stress capacity and exhibits poor performance due to the increase in deformation. This shows that without reinforcement, the load bearing capacity of the soil is limited and stability problems become more pronounced. The curves of the reinforced soils show a stronger slope, indicating that these soils can withstand higher stresses and have a higher load carrying capacity. A significant enhancement in the mechanical performance of the soils was observed with increasing reinforcement rates (0.4%, 0.8% and 1.6%). In particular, the soil reinforced with 1.6% and 0.4% denim fabric reached the highest stress value, providing maximum stability and significantly increasing the resistance of the soil to deformation. The soils with 0.4% addition of waste additive exhibited almost similar behavior to the soils with 1.6% addition of waste additive. In particular, the soil reinforced with 1.6% denim fabric achieved maximum stability by reaching the highest stress value and significantly increased the resistance of the soil to deformation. In addition, the 0.4% and 0.8% reinforced soils also exhibited a much higher load bearing capacity compared to the unreinforced soil. The soils with 0.4% waste additives exhibited almost similar behavior to the soils with 1.6% waste additives. However, when the stress-strain curves were analyzed, it was observed that for all aspect ratios, the increase in additive content did not linearly increase strength. The addition of 0.8% of additive showed less performance improvement compared to 0.4% of additive content. If a comparison is made in terms of stress-strain performances for all aspect ratios, the order from best to worst is 1.6%, 0.4%, 0.8% and UR. Accordingly, the reinforcement of the soil with 0.4% can be chosen as the optimum value since it performs better than the reinforcement with 0.8% and similar to 1.6%.

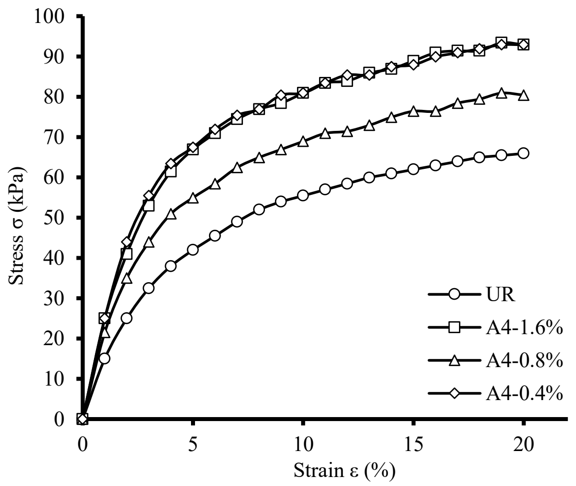

Figure 3. Stress-strain curves in aspect ratio 4

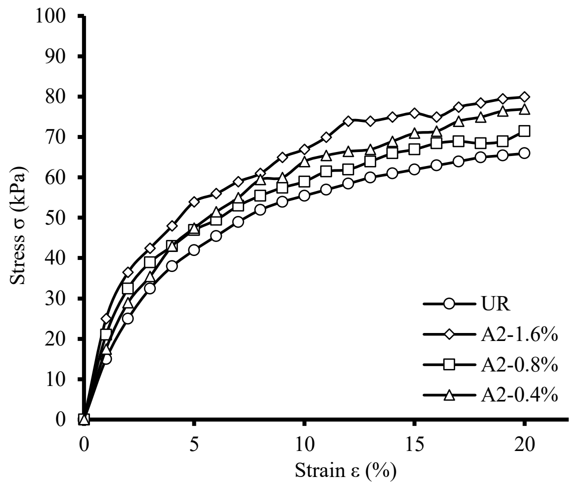

Figure 4. Stress-strain curves in aspect ratio 2

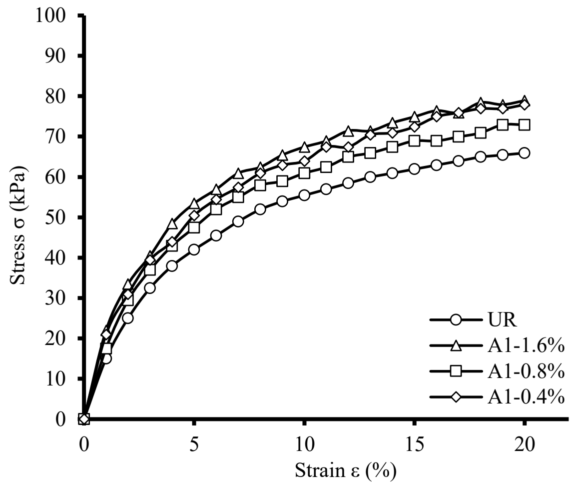

Figure 5. Stress-strain curves in aspect ratio 1

The results of the effects on the stress-strain behavior of soils with different aspect ratios (A1, A2 and A4) at the same admixture rate are given in Figure 6, Figure 7 and Figure 8, respectively. The unreinforced soil has the lowest bearing capacity and rapidly loses performance with increasing deformation. This indicates that the load carrying capacity of the soil is limited and the stability is inadequate without the addition of the waste leveling admixture. The mechanical properties of the soil have improved significantly with the addition of the waste soil admixture, but the extent of this improvement varies according to the size of the waste fabric used. In particular, the soil reinforced with A4 sized waste denim fabric achieved the maximum stability by reaching the highest stress values among all samples. A4 sized waste denim fabrics showed a steeper slope along the stress-strain curve and best improved the soil's resistance to deformation. A2 and A1 waste denim fabrics outperformed the unreinforced soil and provided a similar improvement; however, were lower than the contribution of A4 in terms of deformation resistance and load carrying capacity. This indicates that the larger size denim pieces created a stronger mechanical bond with the soil and increased its load bearing capacity. There was no direct relationship between the aspect ratio of the waste denim fabric and the stress-strain behavior.

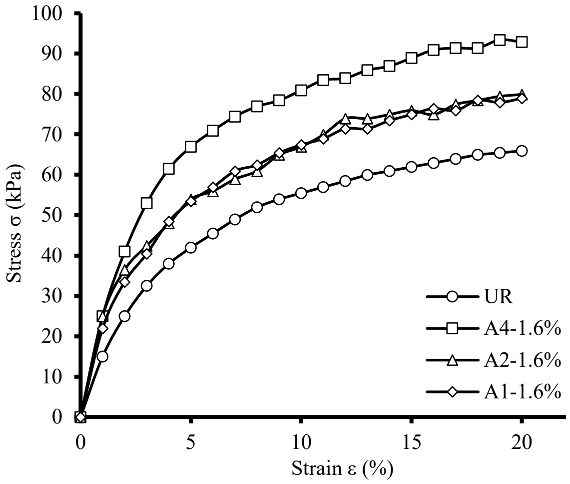

Figure 6. Stress-strain curves at 1.6% participation rate

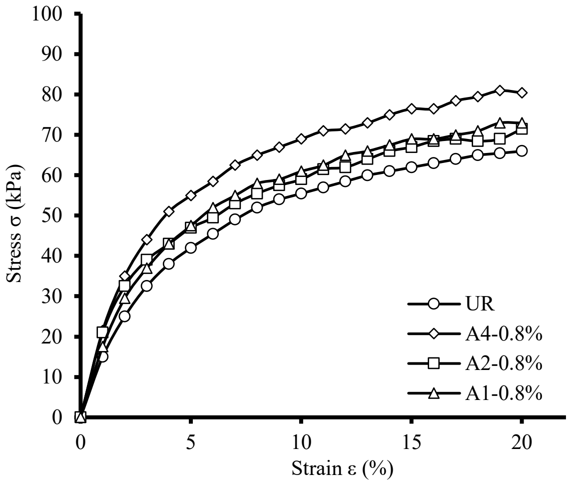

Figure 7. Stress-strain curves at 0.8% participation rate

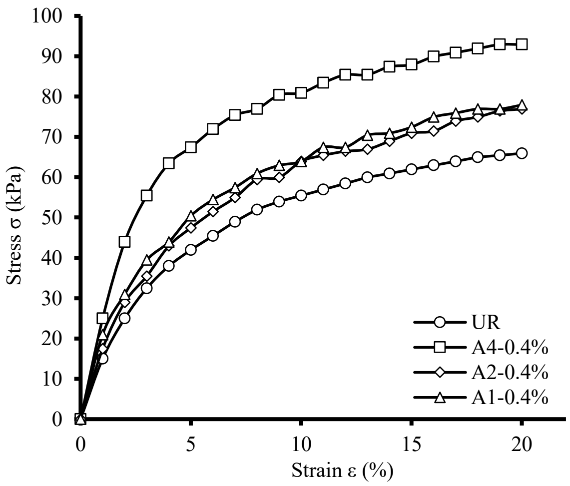

Figure 8. Stress-strain curves at 0.4% participation rate

Figure 9 and Figure 10 demonstrate the effect of different proportions and sizes of waste denim additives on the uniaxial compressive strength (UCS) and UCS increase ratio of the soil. The unreinforced soil had the lowest UCS value and showed a strength of approximately 70 kPa. A significant increase in UCS values was observed with the addition of waste denim fabric admixtures, but this increase varied depending on the size of denim used and the admixture rate. The highest UCS value was achieved by soil reinforced with 1.6% and 0.4% of A4 sized denim fabric, with strengths of 93.4 kPa and 92.9 kPa, respectively. However, the smaller size denim pieces (A2 and A1) reached a lower UCS value compared to the A4 size. For all aspect ratios, the UCS value of 0.4% and 1.6% waste admixture soil is similar and higher than the UCS value of the 0.8% waste admixture soil. Similar interpretations are valid for the UCS increase ratio graph given in Figure 10. Figure 10 indicated that the best strength increase is 41.67% and 40.91% for A4-1.6% and A4-0.4% respectively.

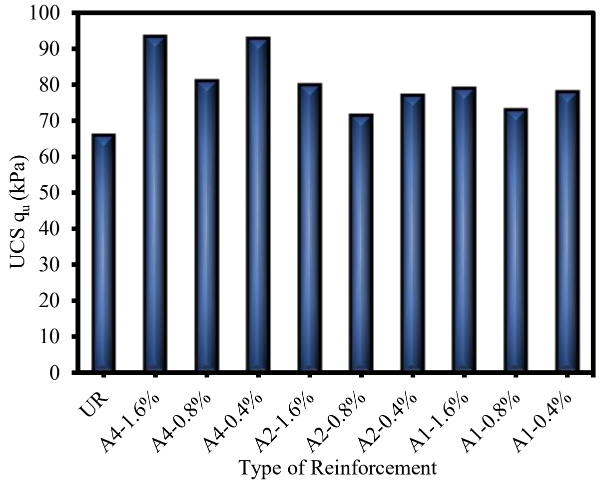

Figure 9. UCS value vs waste denim sizes and contents

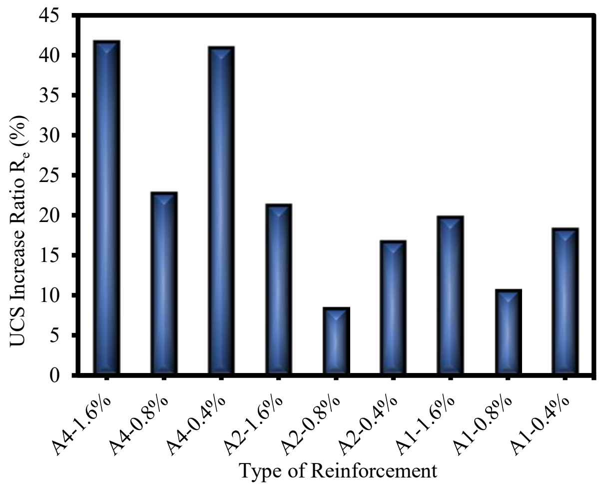

Figure 10. UCS increase ratio vs waste denim sizes and contents

Figure 11, Figure 12 and Figure 13 present the comparison of elastic modulus, deformability index and normalized energy absorption index values of unreinforced soil and soils with different sizes and proportions of waste denim fabrics, respectively. The elastic modulus of the soil is a measure of the material's stiffness. It was determined by calculating the slope of the initial portion of the stress-strain curve corresponding to the elastic deformation phase. A general increase in the elastic modulus values is observed with the addition of the waste denim. In particular, the soil reinforced with 0.4% of A4 size of waste cement reached the highest elastic modulus value. According to Veena and James (2022) [33], the deformability index was calculated by taking the ratio of the strain at peak stress in the reinforced test to the strain at peak shear stress in the unreinforced experiment. Since the soil has a water content exceeding the optimum water content, the stress-strain curves do not show abrupt decreases in stress. As a result, the strain values at the point of maximum stress are quite comparable, leading to deformability index values that lack sufficient distinctiveness for meaningful interpretation. The energy absorption capacity is associated with the area of the stress-strain curve prior to failure. This means that the larger the area under the curve, the greater the material's ability to absorb energy before breaking. In this study, following the approach of Yadav et al. (2019) [21], the area under the curve up to the peak stress was used to calculate the energy absorption capacity. This method ensures a consistent and reliable way to compare the energy absorption performance of different soil mixtures. Subsequently, the energy absorption values for the reinforced mixtures were standardized by dividing them of the unreinforced soil. The normalized energy absorption index values greater than 1 indicate that the waste denim admixture is effective in rising the energy absorption capacity during load bearing. A value above 1 suggests that the addition of waste denim fibers enhances the soil's ability to resist deformation under stress. In particular, the A4 size leveling admixture performed the best, reaching an energy absorption index of about 1.4 when used at 1.6% and 0.4%. This finding highlights the potential of optimized denim fiber reinforcement in improving the mechanical performance of soil, especially in applications requiring enhanced energy absorption.

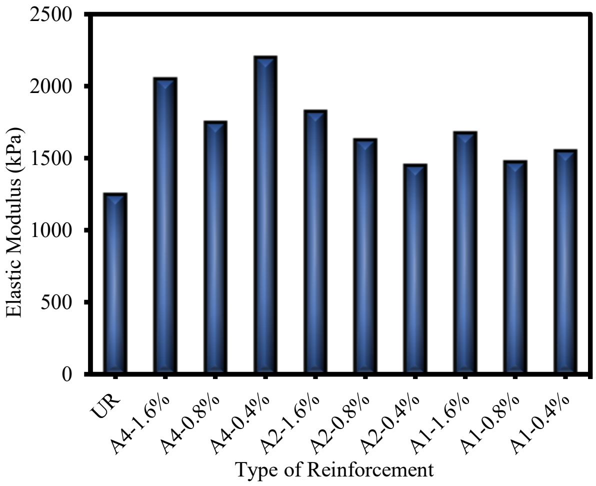

Figure 11. Elastic modulus vs waste denim sizes and contents

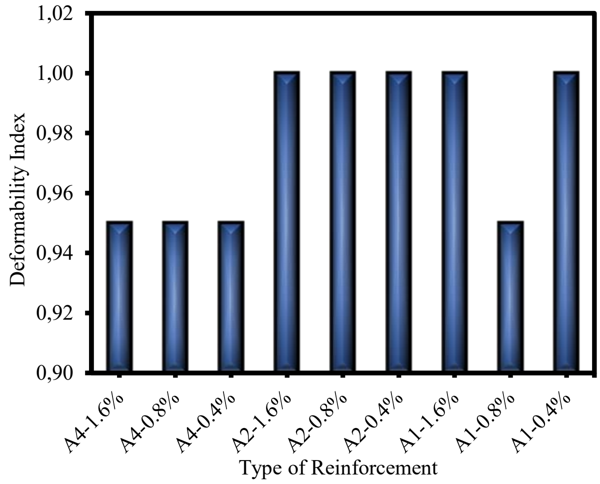

Figure 12. Deformability index vs waste denim sizes and contents

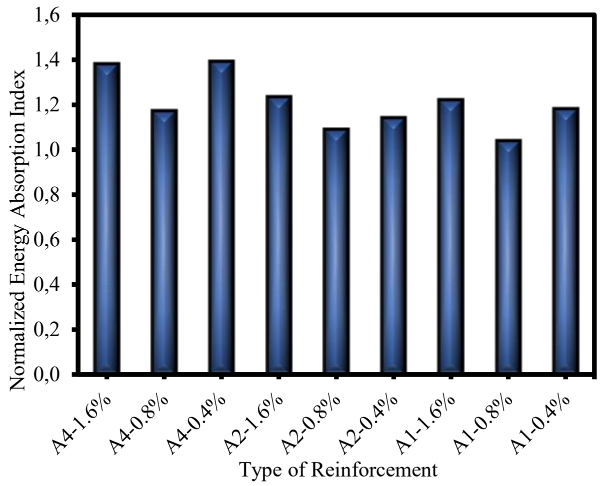

Figure 13. Normalized energy absorption index vs waste denim sizes and contents

Conclusions

This study aimed to evaluate the potential of waste denim fabric as a sustainable soil improvement material, focusing on its impact on mechanical properties such as unconfined compressive strength (UCS), UCS increase ratio, elastic modulus, deformability index, and energy absorption capacity. Waste denim fabric was prepared in three aspect ratios (A1, A2, and A4) and incorporated into clayey silt soil at varying proportions (0.4%, 0.8%, and 1.6%) by dry weight of the soil. The reinforced and unreinforced soil specimens were cured for seven days, and their stress-strain behaviors were experimentally investigated. The following conclusions were drawn:

- The addition of waste denim fabric significantly improved the mechanical performance of the soil, with reinforced specimens outperforming unreinforced ones in terms of UCS, elastic modulus, and energy absorption index.
- Soils reinforced with A4-sized denim fabric showed the highest UCS, elastic modulus and energy absorption capacity, indicating that larger denim pieces create stronger mechanical bonds with the soil, enhancing its load-bearing capacity and deformation resistance
- Among all proportions, 0.4% and 1.6% reinforcement provided the best results, with similar UCS and energy absorption values. This suggests that 0.4% can be considered an optimum reinforcement ratio as it yields comparable performance to 1.6% while requiring less material.
- The elastic modulus of the soil increased with denim reinforcement, with the highest value observed for 0.4% of A4-sized fabric.
- Reinforcement of clayey silt soil with waste denim fabric presents an eco-friendly approach to waste management while improving soil behavior. It also demonstrates the feasibility of utilizing waste fabrics in geotechnical engineering, contributing to sustainable construction practices.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared

There is no conflict of interest with any person / institution in the article prepared

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