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Impact of a Coarse Material Sandwich Approach on the Performance of Geotextile-Reinforced Clay

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Abstract

In many cases, the natural soil of the site does not have enough strength. Therefore, it is necessary to modify soil properties. In this regard, by adding one or more elements to the soil, its overall performance can be improved. The use of geotextile as an element in soil has attracted the attention of engineers, but investigating its performance in soil requires more study. Using a set of unconsolidated undrained (UU) triaxial tests, the behavior of geotextile-reinforced clay has been investigated in this research. Moreover, the impact of sandwiching nonwoven geotextile in a thin layer of sand (sandwich technique) on enhancing the shear strength of reinforced clay has been examined. Confining pressures (100, 200, 300, and 400 kPa), the number of geotextile layers (one, two, and three layers), and the thicknesses of the sand layers (zero, two, four, and six mm) are the variables considered for tests. The results revealed that the shear strength of clay rose as the number of geotextile layers increased. The efficiency of reinforcing clay with nonwoven geotextile can be related to a growth in the apparent cohesion of the reinforced sample. Considering the sandwich approach, it was found that with increasing the thickness of sand layers around the geotextile, the maximum deviatoric stress increased. For example, for the sample reinforced with two layers of geotextile under CP of 100 kPa, the increase rate of maximum deviatoric stress reached from 37 to 77% with increasing the thickness of the sand layer from 0 to 6 mm. Finally, the optimum thickness of the sand layer (4 mm) was identified, which led to the best enhancement in the performance of samples.

1. Introduction

Many areas in the world consist of poor cohesive soils that are inappropriate for construction projects. However, these soils can be reinforced by using different natural and synthetic materials, making them acceptable for construction [1]–[8]. Soil reinforcement utilizing geosynthetic materials has various benefits due to its great capacity to differential settlement with no structural distress, cost effectiveness and ductility. The fast acceptance of soil reinforcement can be ascribed to a variety of factors, including aesthetics, cost-effectiveness, simple construction methods, and adaptability to various conditions of the site [9], [10]. Geotextiles are one of the most popular geosynthetic materials employed to reinforce soil. The primary role of these elements is to redistribute stresses, which involves transferring load from strongly unreinforced parts to the reinforced ones, hence preserving equilibrium through stress redistribution within the soil mass. As a result, the internal stability of reinforced soil structures will be improved [11]. Mirzababaei et al. [12] performed unconfined compression tests on reinforced clay and found that incorporating reinforcement into clay increases soil strength, limits post-peak strength loss, and alters failure performance from brittle to ductile. Nguyen & Yang [13] stated that the California

Bearing Ratio (CBR) value significantly increases for samples reinforced with layers of nonwoven geotextile under soaked and unsoaked conditions. Fındık & Keskin [14] examined the effect of geotextile reinforcement on clay features, including settlement and sliding resistance parameters. They displayed how single-layered and double-layered geotextiles improve bearing capacity and reduce settlement in various moisture conditions. Lakshmi & Lakshmi [15] reported that the improvement in CBR strength of subgrade soil reinforced with geotextiles leads to the reduced pavement thickness, leading to a cost-effective construction. Dienta & Bağriaçik [16] expressed that using geotextiles improved soil strength. In addition, they found that geotextiles have a good potential to be applied in highway and road construction, resulting in a longer lasting and more durable infrastructure.

The improved behavior of reinforced soil is attributed to the stress transmission at the interface between soil and reinforcement. In order to occur such a process, it is important to ensure that the soil and reinforcement interact properly. Because the interfacial strength is low, the interface collapses before the entire strength of the reinforcement can be mobilized. As a result of the interface failure, the strength of the reinforcement may not be significantly employed [17], [18]. The shear failure at the interface may possibly stem from the high shear stresses close to the reinforcement, based on experimental findings by Jewell & Wroth [19], Milligan et al. [20], and Sridharan et al. [21]. They expressed that the maximum shear stresses occur in the vicinity of the reinforcement and diminish rapidly as it moves farther away. Therefore, it is advantageous to surround the reinforcement with thin layers of high-strength granular soil while using poor backfill for construction in order to withstand the high shear stresses close to the interface. Due to the enhanced interface features, this will improve the mechanism of stress transmission.

The technique known as sandwich or sand cushion involves the arrangement of sand layers on both sides of the reinforcement within the reinforced clay. Sandwich layers, according to Sridharan et al. [21], considerably increase the ability of geogrids embedded in poor soils to be pulled out. Sreekantiah & Unnikrishnan [17], by conducting tests on model retaining walls, stated that sandwich layers improved the response of these walls. Utilizing triaxial tests (Unnikrishnan et al. [22]), direct shear tests (Abdi et al. [23]), and pullout tests (Sridharan et al. [21], Abdi & Arjomand [24], Abdi & Zandieh [9]), researchers have examined the effect of adding thin sand layer sandwiching on either side of the reinforcement inside the clay on the deformation and strength characteristics of reinforced clay. Unnikrishnan et al. [22] conducted tests on the reinforced clay with layers of sand (around the reinforcements) and found that adding sand improves the strength properties of reinforced clay. Abdi et al. [23] studied the improvement of strength caused by providing layers of sand on both ends of the geogrid (sandwich technique) inside the clay sample through performing large-scale direct shear tests. They concluded that incorporating a layer of sand in the vicinity of the reinforcement substantially increases the clay strength.

Li et al. [25] developed an enhanced vacuum preloading technique along with a sand sandwich structure (SSS) to make easier the consolidation of dredged clay-slurry fills and original soft marine clay for land reclamation. They found that the combination of the SSS and the enhanced vacuum preloading method led to more favorable consolidation outcomes. Balakrishnan & Viswanadham [26] conducted research on the efficacy of incorporating geogrid layers within thin sand layers to improve the deformation characteristics of vertical reinforced soil walls made with marginal backfills. It was discovered that these walls outperformed those without the sand-cushioned geogrid layers. In order to control the frost impacts in vulnerable soils, Nourmohamadi et al. [27] employed an innovative sandwich geocomposite structure, consisting of geotextile-soil-nano silica aerogel-geotextile liners. Various combinations of soil and aerogel were used to create geotextile soil-aerogel liners, which were then placed between two layers of geotextiles. These liners were designed to function as thermal insulators on the soil surface. Tabarsa & Hajiesmaeilian [28] showed that the sandwich technique is an effective method of stabilizing clay slopes for engineers given the acceptable development of a factor of safety. Cui et al. [29] demonstrated that embedding geogrids in sand layers enhances ductility and peak strength, with significant improvements in apparent cohesion and internal friction angle under varying confining pressures (CP).

2. Research Significance

Considering the weak interaction between clay and geotextile, it is necessary to investigate the effect of adding thin layers of sand around the geotextile for improvement of the interface. Therefore, in this research, the enhancement of strength caused by providing sand layers around the geotextile in reinforced clay has been evaluated. This research analyzes different aspects of the sandwich mechanism using a series of triaxial tests. A considerable number of unconsolidated undrained (UU) triaxial tests were carried out by altering the thickness of sand layers around the geotextile, CP value, and number of geotextile layers. The findings of this research can be utilized for assessment of the effect of a coarse material sandwich method on the behavior of geotextile-reinforced clay.

3. Materials and Methods

In the present research, clay with low plasticity (CL) and poorly-graded sand (SP) were collected from regions in Aliabad and Babolsar cities, respectively, both located in north of Iran. The gradation curves of clay and sand are illustrated in Fig.1. The CL had liquid limit, specific gravity, plastic limit, optimum moisture content (OMC), plasticity index and maximum dry unit weight (MDUW) of 30%, 2.72, 19%, 22.7%, 11% and 15.7 kN/m^3, respectively. In addition, SP had specific gravity of 2.61, coefficient of uniformity of 5.75, coefficient of curvature of 0.78, minimum dry unit weight of 14.1 kN/m^3 and MDUW of 16.8 kN/m^3. A commercially available nonwoven geotextile was employed. The characteristics of the geotextile are illustrated in Table 1.

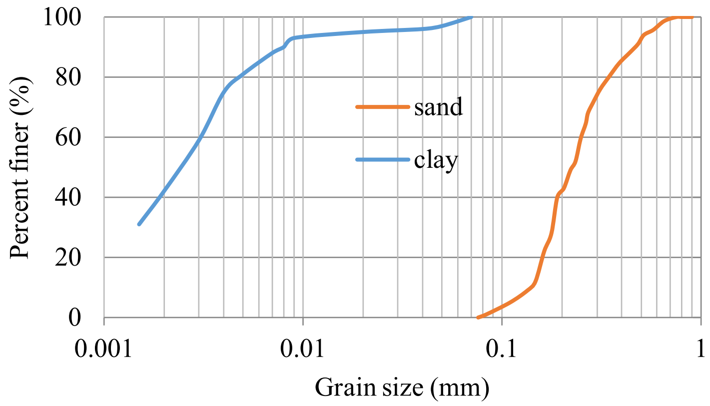

Fig. 1 *Particle size distribution of soils*

Table 1 *Properties of the geotextile used in the experiments*

Parameter	Value
Type	Non-woven
Unit weight	250 g/cm^2
Elongation	50 %
Static puncture resistance	2500 N
Tensile strength	13 kN/m

Wet mass of natural clay was placed in an oven at 110°C ± 5°C for at least 24 hours before being crushed and ground into the dry powder. The OMC and MDUW of clay were determined through conducting standard proctor compaction tests (ASTM D698 [30]). In order to achieve a uniform dispersion of moisture in the soil, certain quantities of soil and water, based on the OMC, were blended together. This mixture was then placed in a temperature-controlled chamber inside a plastic bag, and tightly sealed for a minimum of two days. All the samples had a cylindrical form, measuring 50 mm in diameter and 100 mm in height. In the case of the specimens without reinforcement, clay was compacted in five layers through the utilization of a static compaction method. The split mold was filled with clay in various layers for the reinforced samples, taking into consideration the organization of the geotextile layers. Before adding the next soil layer and the underlying geotextile to each clay layer, the clay surface was leveled and scarified to provide a suitable interface bonding between geotextile and clay. Following the horizontal placement of the geotextile, the clay for the subsequent layers was poured and compacted. Until the specimen preparation was finished, this procedure was repeated. Clay was placed inside a stretched rubber membrane within a split mold to create the sandwich samples. To prepare the specimen, a rubber membrane was stretched by applying vacuum pressure between the mold and the membrane. The prescribed amount of sand was incorporated and compacted with a tamper to achieve the required thickness after leveling and compacting the clay to the desired height. Following that, the geotextile was inserted above sand, and then the remaining amount of sand and clay soil was placed, respectively, using the aforementioned process. Fig. 2 shows the arrangement of geotextile and sand layers in different samples.

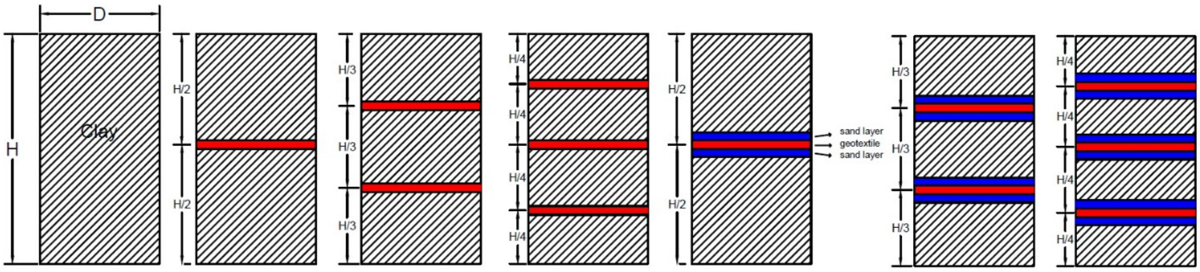

Fig. 2 *Arrangement of geotextile and sand layers*

4. Experimental Program

UU conditions simulate the performance of soils exposed to rapid loading (compared to the period needed for the dissipation of pore water pressure in cohesive soils) following construction. Soil has the lowest shear strength under this type of loading [17], thus it was utilized in the present investigation to explore the impact of sandwich layers on soil performance. The variables of tests were CP (100, 200, 300, 400 kPa), the number of geotextile layers (one, two, and three layers), and thickness of sand layer (zero, two, four, and six mm) sandwiching the geotextiles. The axial load-measuring device shall be a load ring, electronic load cell, hydraulic load cell, or any other load-measuring device capable of measuring the axial load to an accuracy of 1% of the axial load at failure and may be a part of the axial loading device. The vertical deformation of the sample is usually found from the travel of the piston acting on the top of the sample. The piston travel is measured by a deformation indicator with a range of at least 20% of the initial height of the sample and an accuracy not to exceed 0.25 % of the initial sample height. The deformation indicator is commonly a linear variable differential transformer (LVDT) or other measuring device meeting the requirements for accuracy and range [31].

Based on ASTM D2850 [31], UU triaxial tests were performed on samples at a constant axial strain rate of 1 mm/min. Since all of the samples exhibited ductile characteristics, there was no evident peak on stress-strain curves. The tests were carried out until the strain levels of the samples approached 15%, at which point the strain level was designated as the failure strain. UU triaxial tests were carried out on unreinforced clay, clay reinforced with geotextile, and clay reinforced with geotextile surrounded by thin layers of sand (known as sandwich samples). To ensure the validity of tests, three identical samples were tested at the same conditions for each combination of variables. As an acceptance criterion, the individual strength values of three samples should not differ from the mean value by more than 5%. Fig. 3 indicates a view of the triaxial test performed on one of the samples.

Fig. 3 *A view of the triaxial test*

5. Results and Discussion

5.1 Impact of Geotextile Layer

Fig. 4 depicts the stress-strain curves of unreinforced and reinforced samples under a CP of 200 kPa. At a certain CP, the reinforced clay samples had greater peak shear strengths than the unreinforced soil sample, indicating that reinforcements are able to efficiently enhance the undrained shear strength of clay. As the amount of geotextile layers and CP increased, there was a noticeable increase in the maximum shear strength. This finding suggests that the bond between clay and geotextile is more robust when the geotextiles are placed closer together. Unnikrishnan et al. [22] and Indraratna et al. [32] found similar outcomes. According to Hassan et al. [33], the shear strength of soil rises as the number of reinforcement layer increases. This can be ascribed to the greater internal confinement, the enhanced shear resistance at the interface between reinforcement and soil, and the formation of tensile forces in the geosynthetic reinforcement. Nguyen [34] conducted a series of CBR tests to examine the bearing capacity and failure mechanism of clay reinforced with nonwoven geotextile. They reported that the incorporation of nonwoven geotextile layers enhances the CBR of the reinforced clay samples by approximately 49.5%. Based on Noorzad & Mirmoradi [35], the geotextiles have the capacity to intercept the failure plane within the sample, evenly distribute the generated stresses throughout the soil, and consequently enhance the shear strength of the reinforced soil. Tiwari et al. [36] exhibited that the geotextile's tensile capacity plays a chief role in reducing the swell pressure. Furthermore, it contributes to the enhancement of in-plane drainage conditions. The interaction between the soil and geotextile at their interface was found to improve shear strength. Table 2 displays the maximum deviatoric stresses corresponding to various CPs. In addition, the rate of increase in the maximum deviatoric stress of reinforced samples compared to the unreinforced one was presented. For example, at CP=100 kPa, for non-sandwich specimen with one, two and three geotextile layers, the maximum deviatoric stress is 30, 51 and 74% higher than the unreinforced specimen, respectively. Besides, the clay-geotextile interaction is greater under higher CP, leading to the increase of the shear strength. The application of reinforcement layers hinders the occurrence of sample failure, promotes a uniform distribution of pressures within the soil, and enhances the strength of the soil.

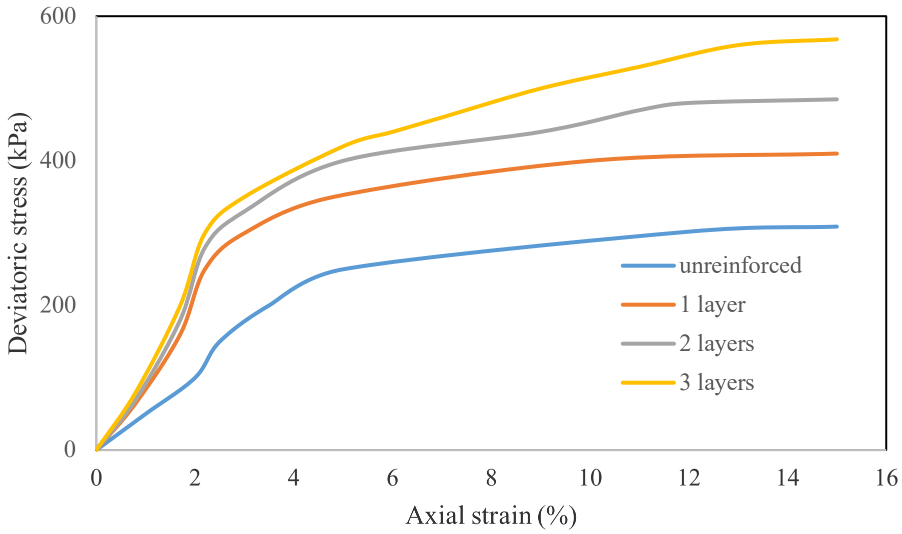

Fig. 4 *Stress-strain curve for unreinforced and reinforced clay samples (confining pressure = 200 kPa)*

Table 2 *Values of maximum deviatoric stresses (kPa) for non-sandwich specimens*

Number of geotextile layers	CP =100 kPa	Increase rate (%)	CP =200 kPa	Increase rate (%)	CP =300 kPa	Increase rate (%)	CP =400 kPa	Increase rate (%)
0	270		309		363		432	
1	351	30	410	32	504	38	591	36
2	410	51	485	56	613	68	626	44
3	472	74	568	83	711	95	734	69

5.2 Effect of Sand Layer

Fig. 5 indicates the stress-strain curves of sandwich samples with one layer of geotextile under a CP of 200 kPa, where t represents the thickness of the sand layer. It can be detected that as the sand-layer thickness grows, the shear strength of the sandwich sample increases. As demonstrated, adding a thin layer of sand around geotextile can improve the shear behavior of reinforced clay. In fact, the incorporation of thin sand layer causes an enhancement in the clay-geotextile interface interaction, increasing the shear strength of the reinforced clay.

Nguyen [37] concluded that the addition of a geotextile material and a thin layer of sand had a substantial positive impact on the clay's CBR value. Moreover, Thanh & Minh [38] showed that the sandwich sand layer enhanced the CBR of the reinforced clayey soil. Maximum deviatoric stresses for sandwich samples are presented in Table 3.

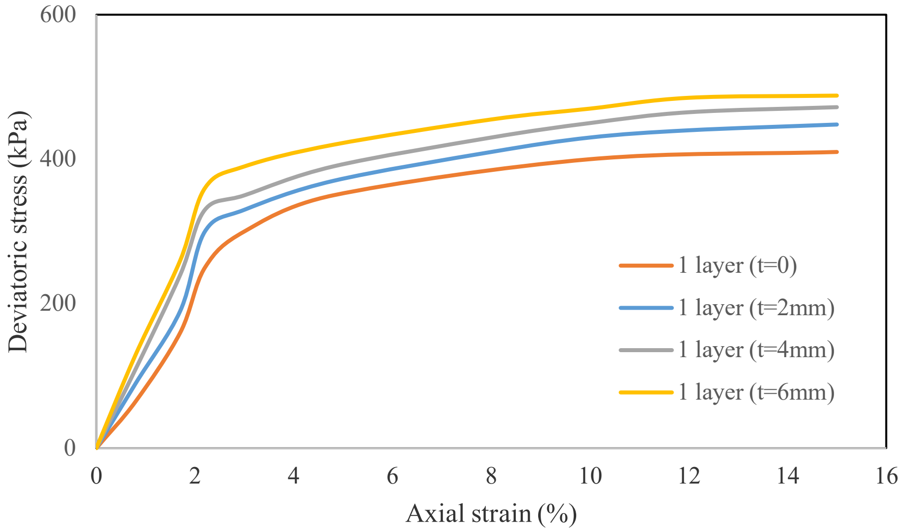

Fig. 5 *Stress-strain curve for reinforced and sandwich specimens (confining pressure = 200 kPa)*

Table 3 *Values of maximum deviatoric stresses (kPa) for sandwich specimens*

Number of geotextile layers	Thickness of the sand layer (mm)	CP = 100 kPa	CP = 200 kPa	CP = 300 kPa	CP = 400 kPa
1	2	401	448	500	550
	4	426	472	540	580
	6	438	488	565	599
2	2	441	525	605	618
	4	531	550	648	679
	6	546	565	667	713
3	2	463	614	682	710
	4	611	639	738	757
	6	624	651	757	772

The stiffness of the sandwich samples increased dramatically at low strain levels and exceeded that of the reinforced sample because sand is stiffer than geotextile. The sandwich method offers advantages in reinforcement purposes like pavements, in situations where the typical level of strain is usually not very high. Incorporation of sand layers can aid drain and avoid buildup of pore water pressure, in addition to enhancing clay performance. According to Thuo & Yang [39], the sand cushions play important roles in improving the drainage of water within the slope system, thereby increasing the overall stability of the system. The results also indicate that the reinforcement has a greater impact at lower CPs. The reason for this is that the rise in additional confining stress caused by reinforcement is greater at lower CPs. At high CPs, the influence of geotextile is substantially reduced because of the low relative movement between the soil and the geotextile.

Figs. 6–9 show the variations of the increase rate of the maximum deviatoric stress (compared to the unreinforced sample) versus thickness of the sand layer. As seen, reinforcement improves the strength characteristics of the samples. In other words, by reinforcing the sample, its maximum deviatoric stress increases, and this issue is more obvious for higher number of geotextile layers. Several researchers such as Noorzad & Mirmoradi [35] and Yang et al. [40] have reported similar results. This is attributed to the fact that although the rate of conducting tests is such that it is assumed to be undrained, but due to the presence of geotextile with proper permeability, the created pore water pressure is partially drained, and as a result, the strength increases. The nonwoven geotextile might be regarded as a permeable material because its permeability is several orders of

Int. Journal of Integrated Engineering Vol. 17 No. 1 (2025) p. 232-246

magnitude greater than that of the clay. Adding permeable reinforcements can greatly enhance the shear strength of clay when subjected to undrained loadings [20].

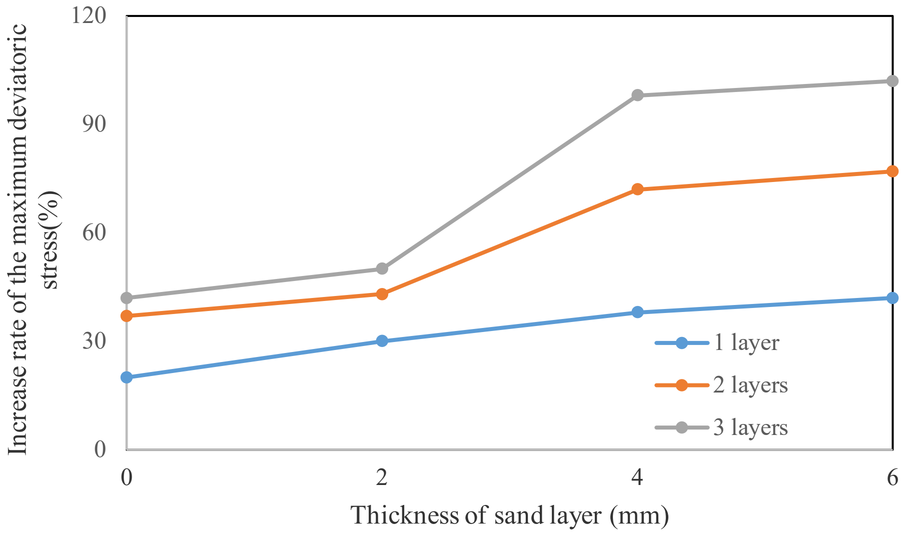

Fig. 6 *Variation of the increase rate of the maximum deviatoric stress with thickness of the sand layer for different number of geotextile layers under the confining pressure of 100 kPa*

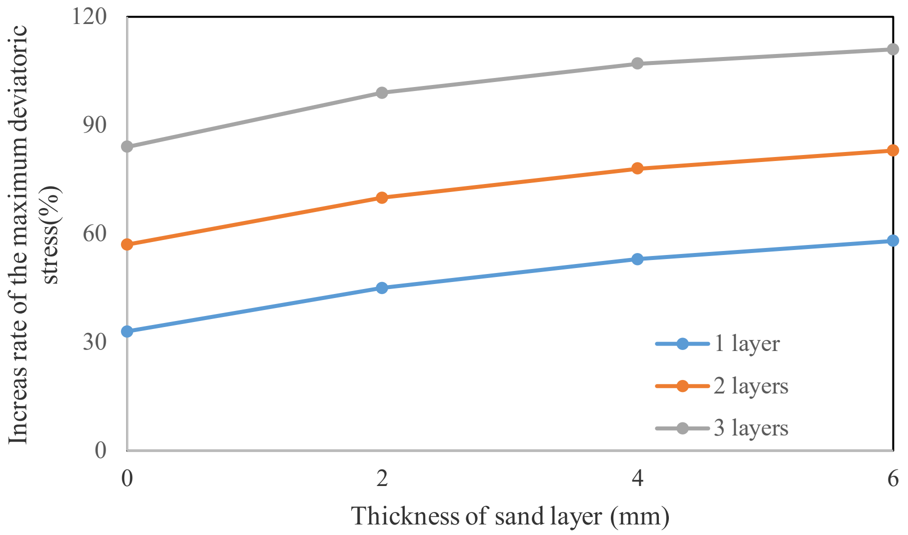

Fig. 7 *Variation of the increase rate of the maximum deviatoric stress with thickness of the sand layer for different number of geotextile layers under the confining pressure of 200 kPa*

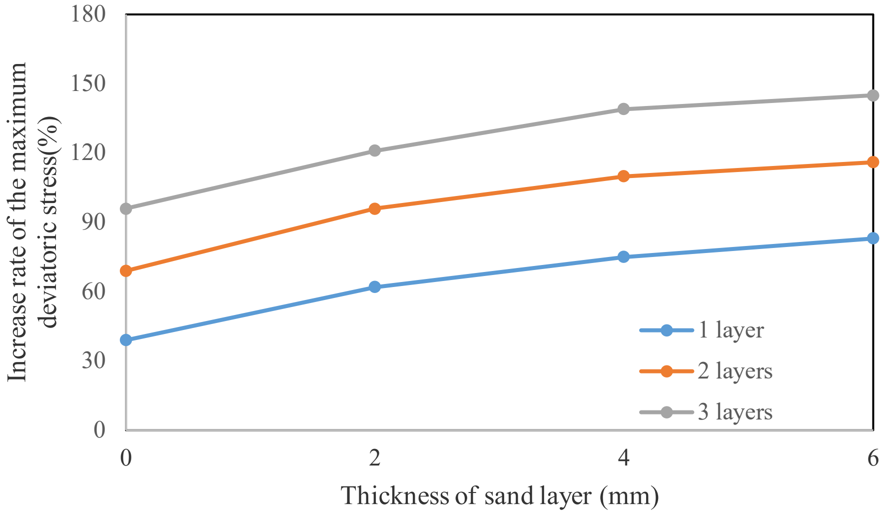

Fig. 8 *Variation of the increase rate of the maximum deviatoric stress with thickness of the sand layer for different number of geotextile layers under the confining pressure of 300 kPa*

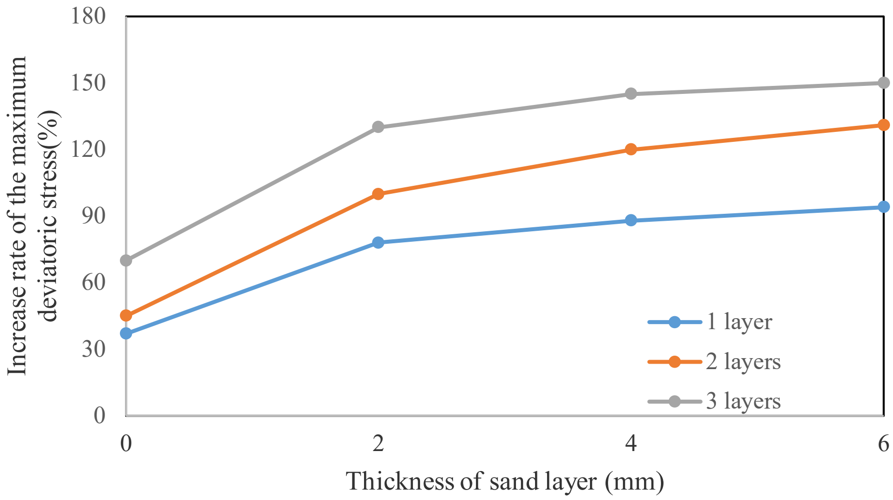

Fig. 9 *Variation of the increase rate of the maximum deviatoric stress with thickness of the sand layer for different number of geotextile layers under the confining pressure of 400 kPa*

Ingold & Miller [11] found that the presence of permeable reinforcements in reinforced clay can enhance its shear strength. This improvement occurs because the reinforcements facilitate the dissipation of excess pore water pressure that builds up during undrained loadings. The pore water pressure is able to migrate radially from the soil into the reinforcement. The reinforcement mechanism is ascribed to the activated tensile strength in geotextile layers due to the interaction between soil and reinforcement. Nguyen et al. [41] and Yang et al. [42] discovered that there is a direct relationship between the enhancement of shear strength in reinforced soil and the mobilized reinforcement tensile load/strain. They expressed that the nonwoven geotextile has substantial permeability, which decreases the vertical drainage path within the sample and promotes pore water dissipation. In this way, excess pore water pressure will be dissipated to a greater extent, and as a result, a higher increase in strength will be observed. Moreover, it can be found that with rising the thickness of sand layers around the geotextile, the maximum deviatoric stress increases. For example, for the sample reinforced with two layers of reinforcement under CP of 100 kPa, the increase rate of maximum deviatoric stress increased from 37 to 77% with increasing the thickness of the sand layer from 0 to 6 mm. The reason is that the reinforced sample acquires its superior behavior through the stress transfer from the soil to reinforcement at the interface. Therefore, a suitable interaction at the interface of the soil with the geotextile will cause such a behavior. In reinforced clay, the strength at the interface is low and thus, failure occurs at the interface before the reinforcement strength reaches its ultimate capacity. In this case, a large amount of the reinforcement strength is not utilized in the failure phase of the sample [13]. According to experimental findings, the incorporation of layers of sand improves the shear strength of the reinforced clay by increasing the interface interaction between the geotextile and clay. Additionally, the sand serves as a layer of lateral drainage to release excessive pore water pressure caused by shearing. Raisinghani & Viswanadham [43] displayed that the utilization of sandwich technique can enhance the mechanical effectiveness of a soil-geotextile system and accelerate the dissipation of pore water pressure in reinforced soil. Additionally, it can reduce the occurrence of long-term clogging in nonwoven geotextile drains, as observed by Lin & Yang [44]. Zimbu [45] showed that the introduction of sand layers provides drainage and strength functions, thus improves the performance of red coffee soils (RCS) embankments.

Sand around the geotextile layer improves drainage and can lower the development of pore water pressure during loading. In comparison to simple reinforced sample, sandwich samples have more strength and stability. The thin sand layer can offer more drainage and higher frictional strength for the weak clay-geotextile interface. The cost will also be substantially cheaper than entirely using expensive and high strength sand material in the projects. As previously stated, one of the roles of geotextiles is stress redistribution; however, this function is heavily dependent on the properties of soil strength. The stress transfer usually occurs at the soil-geotextile interface, which is a weak plane when cohesive soils are utilized. When such reinforcing materials are provided, the use of cohesive soils becomes highly undesirable. For appropriate soil-geotextile interface characteristics, supplying a thin layer of sand near the geotextile will be a better and more effective approach. Therefore, the sandwich method is a good strategy for increasing strength that is also cost effective [46]. The results show that providing thicker sand layers more than 4mm will not result in the further enhancement in system performance. Unnikrishnan et al. [19] reported similar findings by studying the performance of reinforced clay under cyclic and monotonic loads. Ouria et al. [47] detected that the interface's ability to withstand shear forces grew with the rise of the sandwich layer's thickness up to a certain threshold, after which it maintained a steady state. Xie et al. [48] depicted that the maximum pullout resistance of the geosynthetics–sand–clay layered reinforced (GSCLR) structure did not consistently improve as the sand layer's thickness increased. Instead, an optimum thickness for the sand layer was found.

5.3 Shear Strength Parameters

Table 4 presents the shear strength parameters (internal friction angle and cohesion) for different samples. As seen, with increasing the number of geotextile layers, cohesion increases. Furthermore, with rising the thickness of sand layer, the cohesion decreases but internal friction angle increases. This is in line with the findings of Yang et al. [42]. By improving the friction angle of reinforced samples, the sandwich approach enhances shear strength. Adding apparent cohesion to the unreinforced soil explains how reinforcement contributes to the improvement of shear strength parameters [49]. Based on the concept of apparent cohesion, the primary factor behind the improvement of shear strength by nonwoven geotextile is the rise in the clay's undrained cohesion. The addition of the sand layer improves the interaction at the geotextile-clay interface. The enhancement of clay's shear strength mainly arises from the growth of the internal friction angle when employing the sandwich technique.

Table 4 *Values of shear strength parameters*

Number of geotextile layers	Thickness of sand layer (mm)	Cohesion (kPa)	Internal friction angle (degree)
0	0	59	15
	0	190	17
1	2	181	20
	4	173	21
	6	162	22
	0	241	15
2	2	230	19
	4	212	21
	6	207	22
	0	311	12
3	2	287	18
	4	268	20
	6	252	22

5.4 Stiffness and Ductility

Table 5 displays the values of stiffness and ductility for different samples. Stiffness is defined as the ability to withstand deformation when a force is applied [50]. Stiffness is found by calculating the slope of the stress-strain curve in its initial linear portion [51]. As observed, with rising the thickness of sand layer, the stiffness increases. This depicts the efficiency of sand layer addition not only for the improvement of strength but also for the stiffness of samples.

Table 5 *Values of stiffness and ductility for various samples*

Number of geotextile layers	Thickness of sand layer (mm)	CP (kPa)	Stiffness (MPa)	Ductility
0	0	100	5	10.8
		200	6.5	10.5
		300	8.8	10.3
		400	9.6	10
	0	100	6.2	13.4
1		200	7.5	13.2
		300	9.7	13
		400	11.1	11.7
	2	100	7.3	12.5
		200	7.9	12.3
		300	13.3	11.1
		400	15	10.7
	4	100	8.3	11.2
		200	8.6	11
		300	15.1	10.7
		400	15.4	10.6
	6	100	10	10.2
		200	12.2	10.1
		300	12.6	10
		400	15.7	9.9
	0	100	6.5	13.9
2		200	8	13.2
		300	10.3	12.5
		400	13.7	11.3
	2	100	7.5	12.9
		200	9.7	12.3
		300	14	12.1
		400	17.7	11.4
	4	100	9.3	11
		200	13.1	10.8
		300	16.2	10.3
		400	17.7	10.1
	6	100	12.5	9.9
		200	14.2	9.6
		300	15.5	9.4
		400	20.4	9.3
	0	100	12.3	14.7
3		200	14.2	13.7
		300	16.6	12.8
		400	18.1	11.6
	2	100	12.5	12.3
		200	13.2	11.7
		300	16.1	11
		400	20.3	10.3

4	100	10.4	11
	200	14.2	10.8
	300	16.5	10.5
	400	17.9	10.4
6	100	15.1	10.3
	200	15.6	10.1
	300	20.5	10
	400	25.3	9.9

It can also be seen that the stiffness increased by adding geotextile layers. This is related to the fact that as the stiffness of a composite material depends on the stiffness of the materials generating it, the inclusion of a stiffer material (geotextile) into the sample matrix causes a larger increase in stiffness. In other words, as the stiffness of the geotextile is higher than that of clay, the stiffness of the mixture is increased by the inclusion of stiffer materials to the samples. Several researchers [52], [53] also have stated a increase of the stiffness of soils by adding geosynthetic reinforcements.

Ductility in soil refers to its ability to undergo significant deformation without failure. This property is crucial in geotechnical engineering, particularly in assessing how soils respond to various stresses during events such as earthquakes or construction activities [54], [55]. The ratio of the area below nonlinear part (the energy absorbed by the material during plastic deformation) of the stress-stain curve to the area under linear part (the energy absorbed during elastic deformation) of this curve provides a measure of ductility, indicating how much energy a material can absorb before failing. The larger the area under the nonlinear part relative to the linear part, the more ductile the material is considered to be [56], [57]. The ductility can be found using Eq. (1) where A and A' are the area under nonlinear part and the area under linear part, respectively:

$$\text{Ductility} = \frac{A}{A'} \tag{1}$$

This relationship inidicates that materials exhibiting high ductility will have a significantly larger area under the nonlinear portion of their stress-strain curves compared to less ductile materials. As seen, the addition of geotextile layers improves ductility. Geotextiles act as reinforcement within the soil matrix, distributing loads more evenly and preventing excessive deformation. This contributes to a material's ability to deform plastically rather than fracturing under stress, thereby increasing its ductility. With increasing the thickness of sand layer, ductility reduces. As the thickness of the sand layer increases, the stress distribution within the layer changes. Thicker layers can lead to more pronounced stress concentration, which may exceed the material's capacity to deform plastically, resulting in a more brittle failure [58]. Besdies, as CP increases, ductility reduces and samples exhibit a more brittle behavior. At lower CP, samples demonstrate more ductility, allowing them to deform significantly before failure. However, at higher CP, the stress-strain curves often show less deformation capacity and a more abrupt failure, indicating reduced ductility [59].

6. Conclusions

Using fine-grained soils with low hydraulic conductivity that are found locally has become a common alternative to costly granular soil. This not only reduces transportation expenses but also minimizes the environmental consequences of disposing of the excavated soil. The performance of the system during rainfall infiltration may be compromised by the insufficient draining capacity of fine-grained materials, as pore water pressures tend to accumulate. This research proposes the utilization of nonwoven geotextile drains and a thin layer of sands as potential solutions to enhance both the drainage capacity and strength of fine-grained soils. Therefore, a set of UU triaxial experiments were carried out to examine the performance of clay samples reinforced with nonwoven geotextiles and clay samples reinforced with geotextiles embedded in a thin layer of sand (sandwich method). The main findings from this study can be summarized as follows:

1- The reinforced clay and sandwich specimens effectively enhanced the maximum shear strength of the clay. The shear strength rose in conjunction with the number of geotextile layers and the thickness of the sand layer.

2- The presence of geotextile layers in reinforced clay increased its shear strength due to the lateral constraint. As the number of geotextile layers increased, the shear strength of the reinforced clay also increased. For example, at CP=100 kPa, for non-sandwich specimen with one, two and three geotextile layers, the maximum deviatoric stress is 30, 51 and 74% higher than the unreinforced specimen, respectively. An interesting finding was that applying thin layers of sand over the geotextile enhanced the clay's response through interfacial improvement. The enhancement is due to the more effective interconnecting of sand with geotextile.

3- Introduction of non-woven geotextile has led to the improvement of the apparent cohesion in the interface of soil and geotextile, thereby boosting its effectiveness. When employing the sandwich technique, the shear strength experiences a growth owing to the presence of the sand layer. This is ascribed to an increase in the friction angle of the reinforced samples. Furthermore, the optimum sand layer thickness (4 mm) was discovered to result in the greatest enhancement.

Although the sandwich technique can be more economical than using high-strength materials, the need for high-quality sand and geotextiles may still contribute to increased project costs, especially if these materials are not readily available locally. Moreover, to accurately assess the performance of geotextile-reinforced systems, detailed studies of the clay-geotextile interface are necessary. This includes determining the coefficient of friction and understanding the failure mechanisms, which can complicate the analysis and design processes. It should be noted that placing and compacting the sand layers uniformly on both sides of the geotextile can be challenging, particularly in large-scale projects or under difficult site conditions. Any inconsistencies in the sand layer thickness or compaction can lead to uneven load distribution and localized weaknesses, potentially reducing the overall effectiveness of the reinforcement. These limitations highlight the need for careful consideration in design and implementation. Successful implementation requires careful material selection, proper design, and meticulous construction practices to mitigate these limitations. Finally, this study suggests that the presence of sand layers and small reinforcement spacing can efficiently enhance the interaction of geotextile-soil, increasing the shear strength of clay. Thus, in practice, fine-grained and low permeability soils can be utilized as backfill in reinforced structures by taking into account appropriate drainage. This can be carried out by applying construction methods that use permeable geotextile layers and also high-friction sand layers to surround geotextile. For future studies, conducting long-term field investigations to assess the durability and performance of applying sandwich technique under environmental conditions, including freeze-thaw and wet-dry cycles, is suggested.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Issa Shooshpasha, Ali Hasanzadeh;* ***data collection:*** *Ali Hasanzadeh, Vahidreza Salari;* ***analysis and interpretation of results:*** *Issa Shooshpasha, Ali Hasanzadeh, Vahidreza Salari;* ***draft manuscript preparation:*** *Ali Hasanzadeh. All authors reviewed the results and approved the final version of the manuscript.*

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