EXPERIMENTAL INVESTIGATION OF TIME-DEPENDENT EFFECT ON SHEAR STRENGTH PARAMETERS OF SAND–GEOTEXTILE INTERFACE[*]

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Abstract– The time-dependent behavior of soils has been investigated extensively using one-dimensional and triaxial tests. The phenomena associated with time effects in soils are creep, relaxation, strain rate and re-arrangement effects. The engineering properties of soil are often improved significantly with the elapse of time. The objective of this paper is to investigate the time-dependent effect on the shear strength parameters of sand–geosynthetic interface using large direct shear test apparatus. For this purpose, the geotextile layer was carefully adhered to a piece of rigid block with a thickness such that half of the shear test box is occupied. The other half of the box has been filled with sand and the test performed. Three normal stresses of 30, 45, and 60 kPa have been applied in all tests. The shear stress has subsequently been applied at different times to the failure stage. In all tests, the shearing velocity has been kept the same. The results of these experiments show that the stiffness and friction angle of the sand–geotextile interface increases up to 35% and 5.5% at 720 minutes after the sample is poured in the mold. These increases occur mostly in the first two hours following the normal stress application to the samples. The findings in this paper are interesting to consider in practice.

Keywords– Sand, geosynthetic, large direct shear test, aging, friction angle, sand–geotextile interface

1. INTRODUCTION

For the past three decades, the use of geosynthetics to reinforce soil mass has grown significantly. Nowadays, they are a well–accepted construction material. The use of reinforcement objects increases resisting forces in the soil mass through the tensile force provided by reinforcement elements, and consequently reducing the horizontal deformations and increasing the overall stability of the soil structure [1]. Therefore, the evaluation of soil-geosynthetic interface parameters, the interface friction angle, δ, and adhesion, c_a, is important for the design of reinforced soil structures.

There are some basic issues to be analyzed when designing soil geosynthetic reinforced structures such as the prediction of loads on the geosynthetics and the development of enough anchorage for the reinforcement (especially in retaining walls and slope reinforcement), the potential for embankment sliding along the reinforcement and etc [2]. If there is insufficient anchorage length, the failure will happen at the soil reinforcement interface above and below the reinforcement as the reinforcement is pulled out. This phenomenon is known as the "pull-out" mode. If the geomaterial–reinforcement interface strength is less than the shear strength of the soil alone, then the reinforcement represents a plane of weakness, and a "direct shear" mode failure occurs. The interface direct shear test was standardized by ASTM D 5321 which specified the use of a large conventional shear box machine (300×300 mm) after appropriate modification [3].

The soil–geosynthetic interaction parameters are influenced by a) interaction mechanism between geomaterials and geosynthetics (pull-out or direct shear), b) physical and mechanical properties of geomaterials (density, grain shape and size, grain size distribution, water content, and plasticity of clayey soils), and c) mechanical properties (tensile peak strength), shape and geometry of geosynthetics.

The effect of progressive failure on the measured shear strength of a textured geomembrane-geosynthetic clay liner interface has been investigated by Fox and Kim [4]. They have conducted all tests by large direct shear test using different specimen gripping/clamping systems to isolate the effects of progressive failure. Also, they indicated that progressive failure causes a reduction in measured peak shear strength, an increase in the displacement at peak, an increase in large displacement shear strength, and significant distortion of the shear stress-displacement relationship.

Although the shear strength of soil/geosynthetic interface has been investigated by conducting other tests such as tilt table tests [5] and torsional ring shear tests [6, 7], the direct shear test is still the most common testing method. For example, direct shear tests on interfaces between soil and geotextile have been performed by Alfaro et al., Bergado et al., Farsakh et al., Garg and Saran, Lafleur et al., Lee and Manjunath, Mahmood et al., Richards and Scott and Rowe et al. [8-16].

Studies involving interfaces between soil and geogrid have been conducted, for example, by Moghadas Nejad and Small, Bauer and Zhao, Bakeer et al., Cancelli et al., Cazzuffi et al., Jarret and Bathurst, Liu et al. [17-23]. The characteristics of soil-geomembrane interface under different degree of saturation and bentonite contamination can be found in Wu et al., Mitchell et al., Fishman and Pal, Hsieh and Hsieh, Fleming et al., Orman, Zabielska-Adamska and Vukelic et al. [5, 24-30]. The interface shear strength of soil to other types of reinforcement such as tire shreds, rubber chips, or geofoam is also investigated using direct shear tests [31, 32].

It is well established that time dependent property changes after deposition and/or densification occur in clean sand deposits in the field [33-36]. These changes, which may be significant over periods of days to weeks, include an increase in small strain stiffness and large strain strength, as reflected by increasing penetration resistance. Most published evidence of aging effects in sands comes from in situ tests like cone and standard penetration tests.

Daramola investigated the effects of aging on both the stiffness and shear strength of Ham River sand. Four consolidated drained tests on the sand were performed. The volumetric strain data that the axial strain at which the soil became dilatant decreased with increasing time. Daramola concluded that a 50% increase in modulus occurs for each log cycle of time. Despite the increase in modulus and dilatancy, there was no increase in the shear strength of the sand with time [37].

Denisov and Reltov studied the development of adhesion between sand grains and a quartz plate with time. An experimental program was developed which involved placing the grains on a vibrating quartz or glass plate and measuring the shear force necessary to move the grains. The results show that the shear force required to move the sand grains increased as the amount of time that the plate was submerged increased [38].

The strength-increase effects can also occur in clays over engineering aging time in the laboratory. Yasuhara and Ue found that there was an approximate 50% increase in undrained, direct shear strength with secondary aging times varying from 15 minutes to 30 days [39]. Most recently, Martin et al. stated that time-dependent changes in stiffness could be caused by bacterial growth [40].

This paper presents the results of a laboratory testing program to study the time-dependent effect on shear strength parameters of sand–geotextile interface using a large direct shear test apparatus. In addition, in these tests, the influence of variables such as moisture content of sand and thickness of geosynthetic on time-dependent effects has been investigated. The specific properties observed with time are the shear strength parameters and stiffness of sand–geotextile interface.

2. TEST DEVICE AND MATERIALS

A large direct shear apparatus with dimensions of 300×300 mm was used to carry out the tests according to the procedure described by ASTM. Three actuators recorded by computer facilitate the equipment movements. The horizontal actuator has a maximum load capacity of 50 kN and is connected to a 50 kN tension/compression load cell. The horizontal and vertical displacements are measured by digital indicators with outputs for data acquisition. All instrumentation data are digitally displayed with outputs for convenient interfacing with a personal computer. The normal stress is applied by a lever arm which is connected to a rigid plate with 300×300 mm of loading area. In this apparatus, the top half of the shear box is fixed, and the bottom half is moved.

The soil used in tests was dune sand, and its main characteristics are presented in Table 1. The shape of the sand grains was subangular with rounded edges. Also, the grain size distribution of the sand is shown in Fig. 1. The geosynthetic used for tests was a needle punched non woven geotextile. Table 2 presents the properties of the non woven geotextile provided by the manufacturer.

Table 1. Main characteristics of the sand

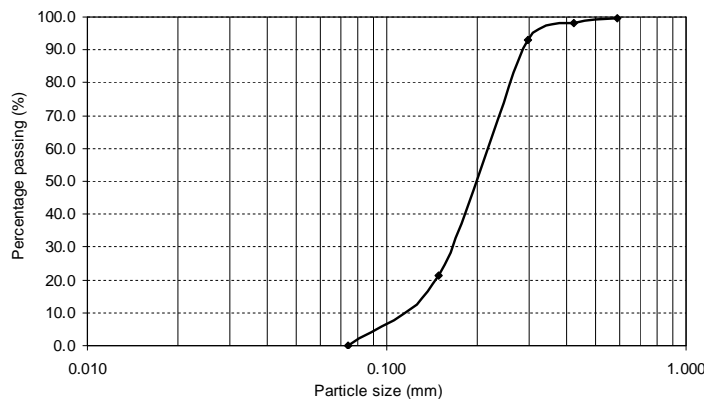| Property	Value
Minimum void ratio, e_{min}	0.636
Maximum void ratio, e_{max}	0.89
Specific gravity, G_s	2.65
Uniformity coefficient, C_u	1.87
Curvature coefficient, C_c	1.17

Fig. 1. Grain size distribution of sand

Table 2. Properties of nonwoven geotextile

Product name	Polymer type	Mass per unit area (g/m^2)	Thickness (mm)	Tensile strength (kN/m)	Grab elongation (%)
GTN.20	Polypropylene	200	1.80	14.1	>50
GTN.50	Polypropylene	500	3.80	27	>50

3. TESTING PROCEDURE

The interface shear tests were conducted at the Geotechnical Engineering Laboratory of K. N. Toosi University of Technology using a direct shear apparatus. A square base direct shear box (300×300 mm) split horizontally at a mid-height was used.

Various methods have been suggested for keeping geosynthetics in place during shearing including clamping [41] and gluing [42]. Clamping was avoided as it may increase the likelihood of a progressive failure, and thus reduce the measured peak interface shear strength [4, 41]. In the present study, two

procedures were evaluated for tests. In the first approach, the sand was poured in a half shear test apparatus box, and the geotextile layer was located on it and the rest of the half box was then filled with the same sand. In the second approach, the geotextile layer was carefully adhered to a piece of rigid block with a thickness such that half of the shear test box was occupied. The other box half was filled with the sand, and the test was performed. The test results indicated that the results of the two configurations of tests had a very small difference. Therefore, for simplicity and in order to minimize the potential for any movement of the geotextile during shearing, the geotextile specimen was glued to a rigid block. The authors believe that the glue does not influence the compressibility and internal shear deformation of the geotextile since the glue does not penetrate into the geotextile, and it only covers one side of the surface of the geotextile. The viscosity of the glue was such that it did not penetrate into the voids of GT. The rigid block with glued geotextile was kept under compressive stress for one hour to ensure a proper bonding. The application of compressive stress for one hour also helped to reduce elongation of the geotextile during shearing and encouraged a sliding type of failure.

The rigid block-geotextile assembly was mounted in the lower half of the shear box. The sand was poured in three layers into the upper half of the shear box immediately over the geotextile surface and compacted to a certain dry density which was 1500 kg/m^3. A 100×100 mm square tamper was used to compact the soil. Then the load plate was rested on the sand and the normal stress was applied and remained on the sand for various periods of time. These times were 0, 15, 60, 120, 180, and 720 minutes immediately after the normal stress was applied. After a certain mentioned elapsed time, the shear stress was applied and the test was continued to the failure stage. Fig. 2 shows the geometry of testing procedure.
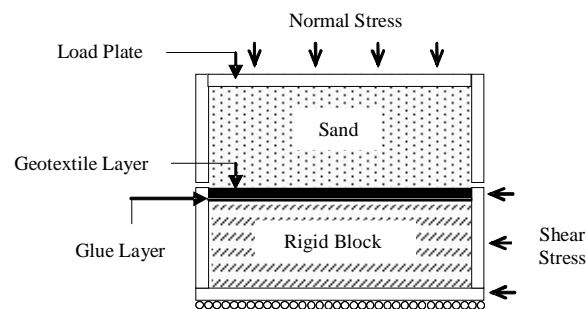

Fig. 2. Geometry of test procedure

All tests were performed for both dry and partly saturated sand with a moisture content of 7%. The soil dry density was 1500 kg/m^3 and for wet sand this was calculated from $\gamma=\gamma_d(1+\omega)=1500(1+0.07)=1605$ kg/m^3. For evaluating the influence of the thickness of geotextile, two types of geotextile were used. In all tests, the sand was compacted to a dry density of 1500 kg/m^3. Many researchers used a normal stress ranging from 10-90 kPa [4, 14, 27, 32, 43]. In this paper, three normal stresses of 30, 45, and 60 kPa were applied in all tests. The shear rate selected for all the tests was 0.85 mm/min. This is almost similar to the rate used by others [13, 14, 43-45]. In the present study, 120 tests were performed. Among them, main tests were 108 tests and 12 tests were undertaken to evaluate the repeatability of results. All samples were tested under the strain controlled condition.
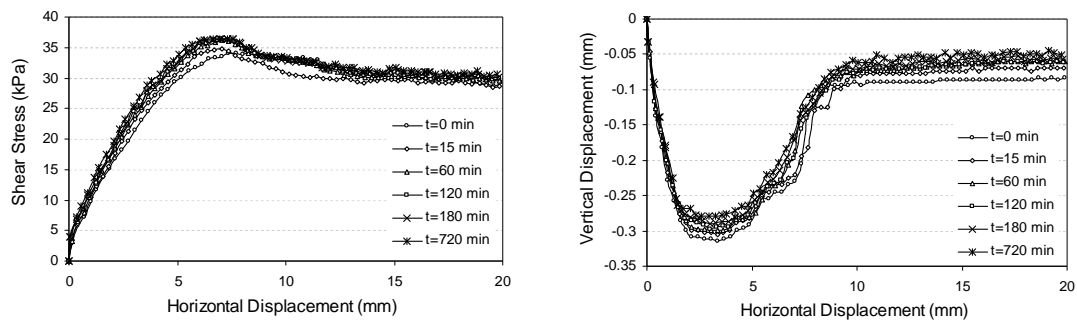
4. TEST RESULTS

The direct shear tests were conducted on unreinforced soil samples to evaluate shear strength parameters of the sand and geotextile-sand interface. The results of direct shear tests included the variation of shear stress–horizontal displacement and vertical displacement–horizontal displacement for the sand alone and the geotextile-sand interface at different normal stresses, moisture content, and elapsed times after

applying the normal stress. In the following sections, the results of dry and wet specimens with a moisture content of 7% are presented.

a) Dry samples

For example, the variation of shear stress–horizontal displacement and vertical displacement–horizontal displacement for dry sand-GTN50 geotextile for σ_n=45 kPa are presented in Figs. 3a and 3b, respectively.
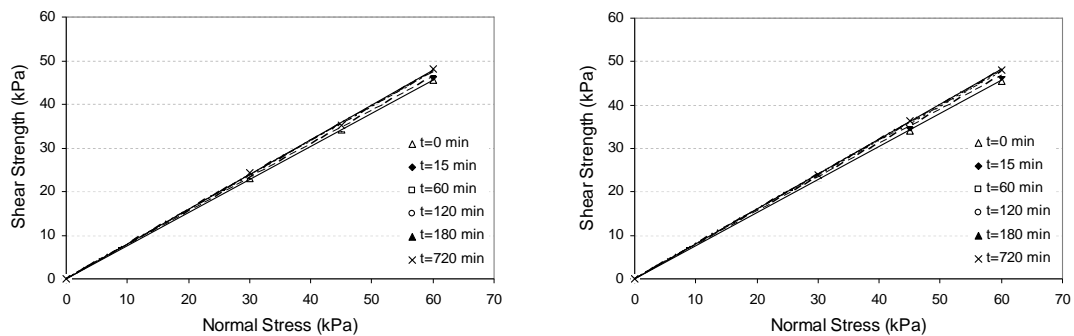

| a) Variation of shear stress versus horizontal displacement | b) Variation of vertical displacement versus horizontal displacement |

Fig. 3. Results of tests for interface of dry sand- GTN.50 geotextile at different elapsed times and for σ_n=45 kPa

As seen in Fig 3b, at the initial stage when the shear displacement is small, the geotextile reinforced sand undergoes a vertical contraction. Following this contraction, the vertical deformation behavior depends on the soil type. For dense sand used in this study, the test specimen exhibits dilatancy with increasing the shear displacement. For soils with expansion behavior, geotextile causes a decrease of dilatancy of soil specimen. This trend is similar to findings of Liu et al. [23].

Fig. 4 shows the variation of shear stress-normal stress for dry sand-geotextile at different times. It can be seen that the shear stress increases with time. Thus, the friction angle of sand-geotextile interface slightly increases with time.

| a) Sand- GTN.20 geotextile interface | b) Sand- GTN.50 geotextile interface |

Fig. 4. Variation of shear stress versus normal stress for dry sand-geotextile at different times

1. Friction angle: The values of friction angles of a dry sand and sand-geotextile interface at different elapsed times are summarized in Table 3.

The variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ with time for only dry sand and dry sand-geotextile interface is presented in Fig. 5, respectively. Here ϕ_t and $\phi_{t=0}$ denote the sand friction angle after elapsed time of t and that at no elapsed time, respectively. Characters δ_t and $\delta_{t=0}$ represent respectively, the sand-geotextile interface angle at an elapsed time of t and that at no elapsed time. As observed, the increase in values of

$\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ is significant for the first two hours. Beyond this, the variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ is very small. Also, the variation of $\delta_t/\delta_{t=0}$ with time for sand-geotextile interfaces is greater than that for the sand alone. As a whole, the values of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ increase up to 2.5%, 3.3% and 3.9% at 720 minutes after the sample is poured in the mold for dry sand, dry sand-GTN.20 geotextile, and dry sand-GTN.50 geotextile, respectively. In addition, the variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0\ in}$ with time for dry sand and sand-geotextile interface is shown in Fig. 6 in log scale. As seen, although beyond an elapsed time of 720 min the values of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ still slightly increase, such variations are insignificant. It should also be noted that for the first two hours, changes are significant.

Table 3. Values of friction angles of dry sand and sand-geotextile interface at different times

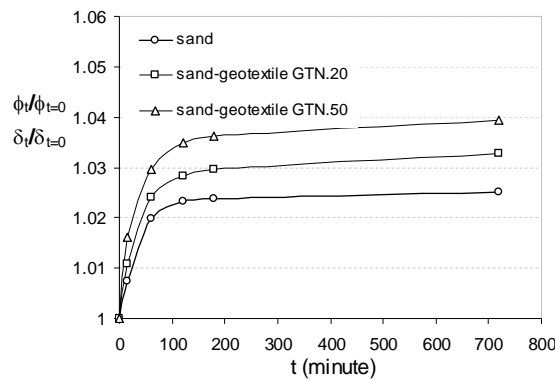| t (min)	Sand	Sand-geotextile interface	
		GTN.20	GTN.50
0	40.6^o	37.3^o	37.3^o
15	40.9^o	37.7^o	37.9^o
60	41.4^o	38.2^o	38.4^o
120	41.54^o	38.35^o	38.6^o
180	41.57^o	38.4^o	38.65^o
720	41.62^o	38.52^o	38.77^o

Fig. 5. Variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ with elapsed time for dry sand and sand-geotextile interface
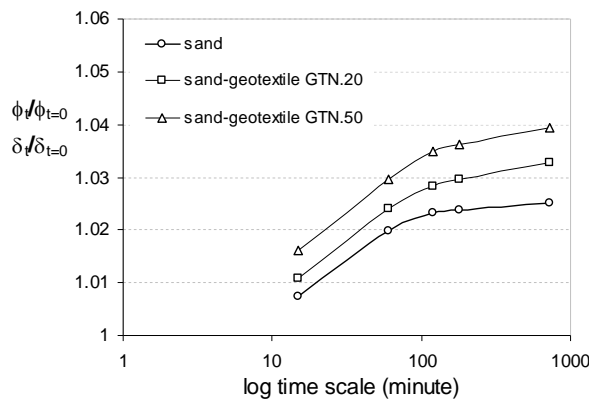

Fig. 6. Variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ with log time for dry sand and sand-geotextile interface

2. Stiffness: To determine the stiffness changes with time, a term k_{50}, which is proportional to the stiffness, is introduced. This term equals the slope of the line passing through the origin and corresponding to 50% of the maximum shear stress in shear stress-horizontal displacement curve.

The variation of $k_{(50)t}/k_{(50)t=0}$ with time for dry sand and dry sand-geotextile interface is presented in Fig. 7. The variation of $k_{(50)t}/k_{(50)t=0}$ with time is the same as the variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ and those are

important for about the first two hours. As a whole, the value of $k_{(50)t}/k_{(50)t=0}$ increases up to 6.7%, 11.8% and 12.6% at 720 minutes after the sample is poured into the mold for dry sand, dry sand- GTN.20 geotextile, and dry sand- GTN.50 geotextile, respectively.
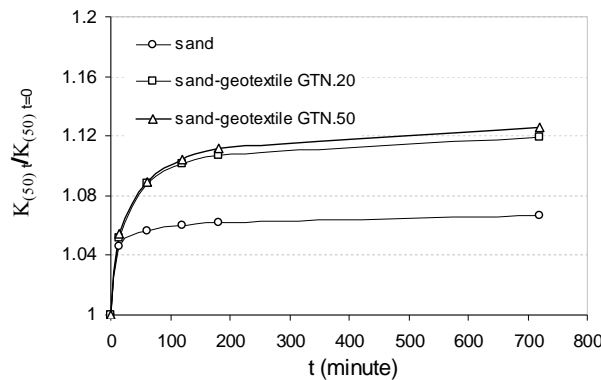

Fig. 7. Variation of $k_{(50)t}/k_{(50)t=0}$ with time for dry sand and sand-geotextile interface

b) Wet condition

In this condition, tests were performed on the sand with a moisture content of 7%. The variation of shear stress–horizontal displacement and vertical displacement–horizontal displacement for wet sand-GTN50 geotextile for σ_n=60 kPa are presented in Figs. 8a and 8b, respectively.

Figure 9 shows shear stress-normal stress variation for wet sand-geotextile at different times. It can be seen that the shear stress increases with time.
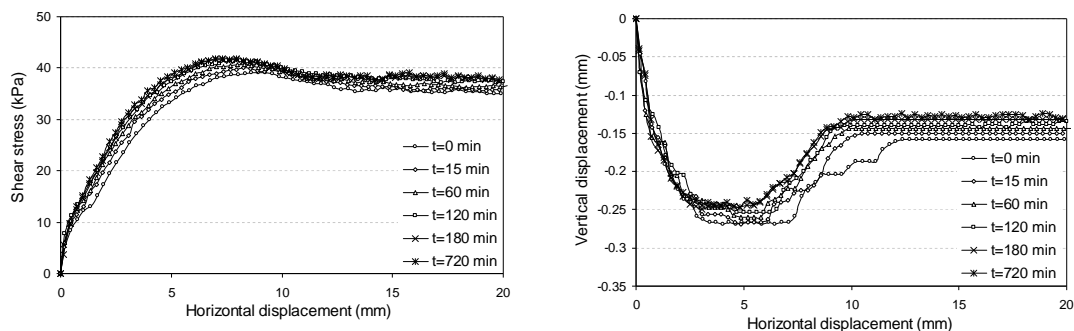
a) Variation of shear stress versus horizontal displacement

b) Variation of vertical displacement versus horizontal displacement

Fig. 8. Results of tests for interface of wet sand- GTN. 50 geotextile at different elapsed times and for σ_n=60 kPa
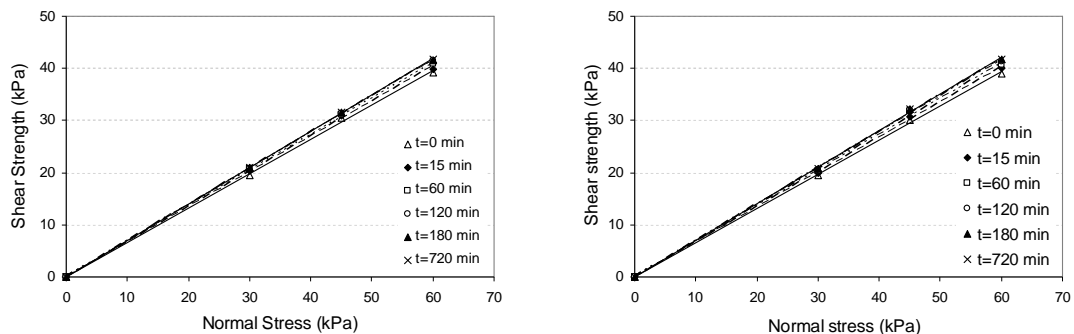
a) Sand- GTN.20 geotextile interface

b) Sand- GTN.50 geotextile interface

Fig. 9. Variation of shear stress versus horizontal stress for wet sand-geotextile at different times

1. Friction angle: The values of friction angles of wet sand and sand-geotextile interface at different times are summarized in Table 4

Table 4. Values of friction angles of wet sand and sand-geotextile interface at different times

t (min)	Sand	Sand-geotextile interface	
		GTN.20	GTN.50
0	36.2°	33.4°	33.2°
15	36.7°	33.9°	33.9°
60	37.3°	34.5°	34.5°
120	37.6°	34.75°	34.8°
180	37.62°	34.8°	34.9°
720	37.73°	34.95°	35.05°

The variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ with time for wet sand alone and wet sand-geotextile interface is presented in Fig. 10, respectively. As illustrated, the increase in $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ is significant for the first two hours. For other elapsed times, the variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ is very small, similar to dry condition. Also, the variation of $\delta_t/\delta_{t=0}$ for sand-geotextile interfaces is greater than those for sand. As a whole, the values of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ increase up to 4.2%, 4.6% and 5.5% at 720 minutes after the sample is poured in the mold for wet sand, wet sand-GTN.20 geotextile, and wet sand- GTN.50 geotextile, respectively. The variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ with time in log scale for wet sand and sand-geotextile interface is shown in Fig. 11. As seen, although beyond an elapsed time of 720 min the values of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ still slightly increase, such variations are insignificant. It should also be noted that for the first two hours, changes are significant.
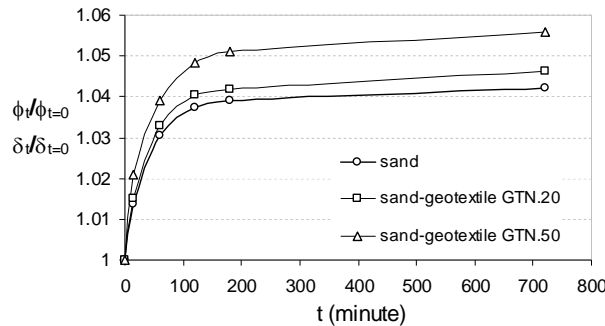

Fig. 10. Variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ with time for wet sand and sand-geotextile interface
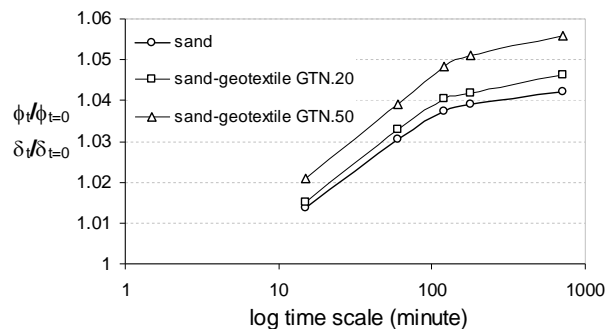

Fig. 11. Variation of $\phi_t/\phi_{t=0}$ or $\delta_t/\delta_{t=0}$ with log time for wet sand and sand-geotextile interface

2. Stiffness: The variation of $k_{(50)t}/k_{(50)t=0}$ with time for wet sand and wet sand-geotextile is presented in Fig. 12. The variation of $k_{(50)t}/k_{(50)t=0}$ with time is important for the first two hours. As a whole, the value of $k_{(50)t}/k_{(50)t=0}$ increases up to 24%, 31% and 35% at 720 minutes for wet sand, wet sand-TN.20 geotextile, and wet sand-GTN.50 geotextile, respectively.
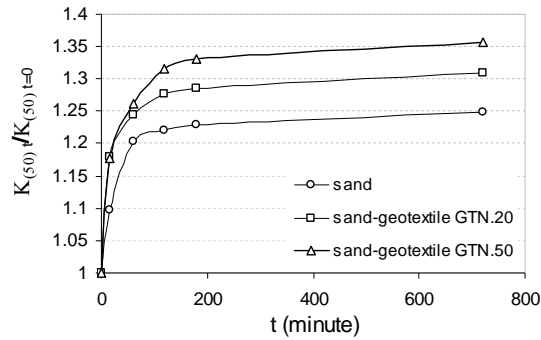
Fig. 12. Variation of $k_{(50)t}/k_{(50)t=0}$ with elapsed time for wet sand and sand-geotextile interface

5. DISCUSSION

Currently, there is uncertainty as to the underlying causes of aging phenomenon. Generally, hypotheses fall into two categories: mechanical mechanisms and chemical mechanisms. Mechanical mechanisms assume an increased frictional resistance developed during secondary compression, increased interlocking of particles and surface roughness, and internal stress arching [36, 46]. Chemical mechanisms focus on the dissolution and precipitation of silica or other materials such as calcium carbonate [47, 48]. Other mechanisms that have been proposed include blast gas dissipation following blast densification [49], biological activity [40], and pressure solution at particle contacts. Some field evidence and a limited number of laboratory test results have been presented to support specific hypotheses. However, there is no consensus or incontrovertible evidence to validate either hypothesis.

Schmertmann believes that during aging, small particle movements occur which lead to a more stable soil structure. These movements result in an increase in the stiffness and a decrease in the compressibility of the soil [36]. Mesri et al. state that the aging effect in sands is due to an increase of the frictional resistance that develops during secondary compression. This increasing resistance does not occur solely from the change in the density that occurs during drained secondary compression. Rather, it is due to a continued rearrangement of soil particles resulting in increased macro interlocking of particles and micro interlocking of the surface roughness. These mechanisms cause an increase in both stiffness and shear resistance [46].

A number of researchers, for example, Daramola and Martin et al., investigated the effect of aging on the soil stiffness. They concluded that the stiffness of sand increased with time [37, 40]. In the current research work, the effect of time-dependence is investigated on both stiffness and shear stress of a sand/geotextile interface.

As seen from the results, the shear strength, friction angle and stiffness of the sand and sand-geotextile mixture increase with time and the compressibility decreases slightly with elapsed time. However, the rate of increase and decrease of these values with time for the sand-geotextile mixture is more than those of the sand alone. This is because in sand-geotextile composite there are some pores in the geotextile, and sand grains can enter them and move easily inside the pores with time. This leads to a more rapid rearrangement and therefore, a more stable soil structure. Obviously, the existence of moisture content accelerates this rearrangement.

The results show that the increase in friction angle and stiffness of a wet sand and wet sand-geotextile interface is more than that of dry sand. This is because water around the sand particles facilitates a more relative movement and as a result, greater rearrangement of sand gains occurs.

As seen in Figs. 5, 7, 10 and 12, for sand-geotextile interface, a thicker geotextile (GTN.50) offers a greater interface friction angle and stiffness than thinner geotextile (GTN.20). This is because the thicker

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geotextile layer is more extensible than the thinner sheet, leading to greater sand grain movement, resulting in a better rearrangement for sand grains. In addition, the thicker geotextile provides deeper fine voids and thus more sand grains occupy these voids, so as a result, greater sand movements occur with time.

In general, it may be said that the increase in stiffness can reduce the soil deformation at elapsed times following the soil compaction. This may be considered in the real design. In current practice, no consideration is given to the aging effect. To account for this phenomenon in real situations, it is recommended that more investigation be done, especially on shape, size, and relative density of sands.

6. CONCLUSION

Extensive laboratory tests were performed to evaluate the variation of interface characteristics between sand and two types of geotextiles with time using a large scale direct shear apparatus. For sand alone and sand reinforced with geotextile, tests were conducted at a dry density of 1500 kg/m^3. To determine the elapsed time effects on shear strength parameters of the sand and sand-geotextile interface, normal stresses of 30, 45, and 60 kPa were applied at different times of 0, 15, 60, 120, 180 and 720 minutes after the sample was poured in the shear test mold. The effect of moisture content and thickness of geotextile were also investigated on time-dependent shear strength parameters and stiffness of the sand and sand-geotextile interface. The results show that the shear strength parameters of sand-geotextile vary with time. Within the scope of this research, the materials used, and the results obtained from the tests carried out in this study, the following general remarks may be cited:

1. The stiffness and shear strength parameters of sand alone and sand-geotextile interface generally increase slightly with time.
2. The compressibility of sand alone and sand-geotextile composite decreases slightly with the elapsed time.
3. The increase in friction angle and stiffness with time for sand-geotextile interface is more than those of the sand alone.
4. The thicker geotextile layer increases the shear strength parameters of a sand-geotextile interface more than thinner layer.
5. The moisture content has a more significant effect on shear strength and stiffness increase with time.
6. A 5.5% increase in the friction angle and 35% increase in the stiffness of sand reinforced with geotextile GTN.50 were achieved after 720 minutes.
7. The increase in stiffness and strength in both sand and sand-geotextile samples occurs mostly in the first two hours following the normal stress application.

It is generally concluded that the shear strength parameters of sand and sand-geotextile interface increase with time and a variation of shear strength parameters is very small with elapsed time. In addition, it may be said that, in practice, the strength of sand and sand-geotextile composite is gained soon after the construction stage. It is necessary to perform further experimental research and field tests to generalize the findings in this paper.

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