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EFFECTS OF GEOGRID AND NON-WOVEN GEOTEXTILES ON THE SHEAR BEHAVIOR OF SOIL

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ABSTRACT: Geosynthetic reinforcement plays a significant role in construction projects by stabilizing and enhancing the bearing capacity of soil. However, the complex interactions between soil and geosynthetic materials are open for investigation. This study aims to elucidate interactions by examining the effects of various geosynthetic materials, specifically nonwoven geotextile and geogrid, on the shear strength of fractional sand. Direct shear tests were performed on sand specimens incorporating geosynthetics arranged in multiple configurations to assess their influence on soil strength properties. The test results showed that the soil friction angle changed from 29° to 38°, which is the advantage of geogrid in improving soil properties. The use of non-woven geotextile increased the cohesion from 8 kPa to 15kPa. The methodology of the test using the location of the reinforcing material also has its peculiarities, which are summarized in the discussion of the results obtained. The findings of this research contribute to a deeper understanding of how the type and characteristics of geosynthetic materials affect soil performance to refine the design and application of reinforcement strategies in construction engineering. The results can be applied in the design of roadways and foundations, where enhanced soil stability is crucial for structural integrity and to the formulation of effective erosion control strategies in civil engineering projects.

Keywords: Soil, Geosynthetic, Strength, Cohesion, Position

1. INTRODUCTION

Soil reinforcement is a set of measures aimed at improving soil's physical and mechanical properties to ensure building structures' stability and durability. Different soil reinforcement methods are used depending on the soil type, geological conditions, and project requirements [1].

Today, physical, mechanical, and chemical soil reinforcement methods are widely used [2]. Mechanical soil reinforcement methods involve utilizing physical actions to enhance the properties of soil. These methods of improving soil are without changing its chemical composition [3-4]. Features of mechanical methods include the use of various machines, equipment, and technologies to achieve the desired results.

The main mechanical methods of soil strengthening are compaction (loading, vibrating, tramming, explosions), using geosynthetic material (geotextiles geogrid, geogrids, geometric) [5], using randomly distributed fibers (natural, artificial, mineral), and piles (bored, vibro-tamped, drillable, sandy). Each of the presented methods has its peculiarities. Vibrating compaction employs vibratory plates or rollers to induce vibrations into the soil, which helps rearrange soil particles and reduce voids, leading to increased density and strength [6]. Compared to other methods like explosions, vibrating compaction produces significantly less noise, making it suitable for urban environments where noise restrictions are in place. The equipment used for vibrating compaction is generally user-friendly, allowing operators to achieve effective results without extensive training. Vibrating compactors can easily navigate tight spaces, making them ideal for projects with limited access. However, variations in soil density can occur at different depths, which may result in inconsistent compaction levels and potential weak spots in the structure.

Tramming is a straightforward soil strengthening method that utilizes a heavy vehicle to compact soil through repeated passes. It is particularly effective for large, flat areas where rapid compaction is required. However, the efficiency of tramming diminishes in very wet conditions, where soil may become too soft to compact effectively.

Explosive compaction involves using controlled explosions to compact soil quickly and can achieve significant density increases in a short amount of time, making it useful for projects with tight schedules. The disadvantage of this method is that excessively dry or wet soils can lead to suboptimal results. The explosive work is restricted near buildings and sensitive structures, posing safety and regulatory challenges [7].

Mostly compaction methods are used for subsidence, swelling, technogenic, highly compressible, organic, loose sandy soil, and loamy soils.

Natural, artificial, mineral method of soil strength characterized by an isotropic increase in strength of soil composite without plane of least resistance, a wide range of materials used but lack of standards, difficulty in controlling the homogeneity of the mixture [8]; pile – it is impossible to control the monolithic and density of concrete over the entire height of the pile, the unhardened concrete may be eroded by groundwater [9-10].

The use of geosynthetics for soil reinforcement offers several key advantages over other methods [11-12]. These advantages stem from the properties of geosynthetics and their effectiveness in various conditions [13-14]. Therefore, research in the application of geosynthetics is extensive. Studying two conditions helps understand the performance and effectiveness of the reinforced soil structure under different stress orientations [15]:

- shear force parallel to the reinforcement layer. This condition evaluates how the soil and reinforcement behave when shear forces are applied along the plane of the reinforcement layer. This typically involves assessing the frictional resistance and load transfer capabilities between the soil and the reinforcement material [5].
- shear force normal to the reinforcement layer. This condition examines the behavior of the soil-reinforcement system when shear forces act perpendicular to the reinforcement layer. This involves understanding how the reinforcement resists pullout forces and maintains stability under shear stress acting across the reinforcement plane [16].

Also, the results of many studies show the changes in the strength and deformation properties of soil and deformation properties of soil reinforced with geosynthetic materials at different degrees of water saturation [17-18]. The test results are also significantly influenced by the specimen preparation procedure for the shear test, especially for the mixed samples. The studies noted that the dry pluviation method cannot guarantee a homogeneous and saturated specimen of sand–clay mixture or well-graded sand [12]; the wet pluviation cannot be used for well-graded soil or sands containing fine particles because of the particle segregation[19]; dry tamping sample preparation can successfully avoid the honeycomb structure [20-21] induced by the capillary forces, but it enhances the heterogeneities and uncertainty of physical properties in the sand-clay mixture specimens due to the possible segregation effect; consolidation of the sand-clay mixture slurry on the interface direct shear device may result in soil leakage. Therefore, the study of additional parameters that influence soil testing results using the direct shear test is ongoing. This study presents the influence of changes in the strength properties of soil reinforced with geosynthetic materials, which were obtained with different geotextile positions in the soil during the conduction of direct shear tests.

2. RESEARCH SIGNIFICANCE

Soil reinforcement with geosynthetic materials is one of the key areas in geotechnical construction. The shear strength parameters determine the soil's load-bearing capacity, and an important parameter is the angle of internal friction and the geotextile-soil interaction coefficient. The study presents the investigation of the effect of reinforcement by geotextile and geogrid and proves a positive effect on soil properties. Direct shear test results showed the dependence of the change in the soil's shear strength depending on the reinforcing material's location. By demonstrating the benefits of applied materials, the study contributes to safer and more resilient infrastructure, potentially reducing the risk of failure in engineering structures.

3. MATERIALS AND METHODS

3.1 Methodology of Experiment

Soil tests were conducted in the “ENU-Lab” laboratory of L.N. Gumilyov Eurasian National University. The methodology of the direct shear experiments is presented in Fig. 1. Tests were conducted with conventional direct shear equipment, where the soil is made to slide along a horizontal failure plane at a constant displacement rate. In contrast, a constant load is applied perpendicular to the plane of relative movement. The shear box in setup was circular, divided into an upper and a lower half. The soil sample is placed inside this box. A vertical normal load was applied to the soil sample through the upper half of the shear box, simulating the overburden pressure. This load was applied using a loading frame with weights. The lower half of the shear box was moved horizontally at a constant displacement rate, while the upper half remained fixed.

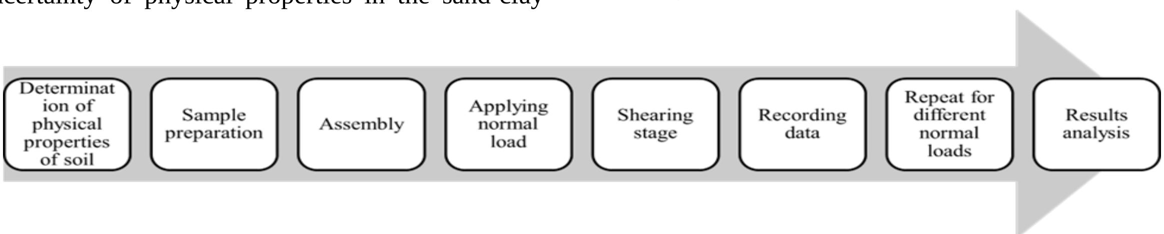


Fig.1 Methodology of experiment

This movement simulates the shear force acting on the soil. Instruments were used to measure the applied shear force, normal load, and horizontal displacement. The direct shear device is presented in Fig. 2. Load cells and displacement transducers were used for these measurements.

Fig.2 Direct shear device

To set up load cells designed for measuring applied stresses, a calibration and sensitivity check has been performed. This process involves comparing the output data with known weights or other reference measuring instruments to ensure the accuracy of the measurements. The load cells were installed and secured to minimize distortion of results from external influences or installation errors. As for the displacement transducers used to measure ground deformations during the testing process, their sensitivity was verified, and their proper fixation on the ground surface was ensured.

The equation for calculating the shear stress of geosynthetic reinforced soil composites is represented in the equation [22-23]:

$$\tau = \sigma \cdot \tan\varphi + c \qquad (1)$$

where τ – shear stress, kPa;
σ – normal stress, kPa;
φ – friction angle of geosynthetic reinforced soil,°;
c – cohesion of the soil, kPa

This equation on the Coulomb failure criterion describes that a material fails (experiences shear failure) along a particular plane when the shear stress on that plane reaches a critical value determined by the normal stress and the material's inherent properties, specifically cohesion and the friction angle [15]. When studying friction angle in single direct soil shear, it is important to consider various aspects, including the construction of the slope angle, which plays a key role in determining the shear resistance and overall stability of the soil mass. The slope angle characterizes internal friction as a fundamental parameter in geotechnical engineering. The first step in the analysis is defining the slope angle concept in single plane shear. This angle represents the maximum angle at which a soil layer can shear without failure (Fig.3). It depends on the internal friction of the soil, which in turn is determined by the nature and condition of the soil, moisture content, stress state, and other factors [24]. When the friction angle increases, the soil's shear resistance increases, which positively affects its bearing capacity and stability.

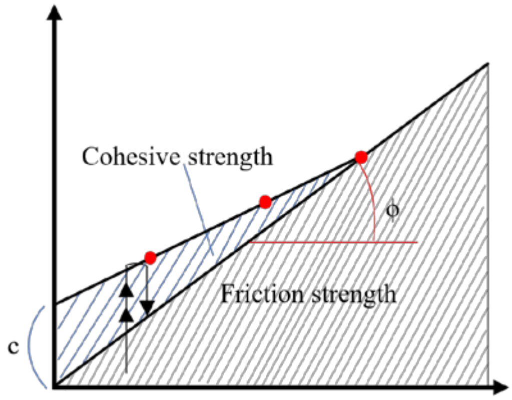


Fig.3 Concept of friction angle [25]

The slope angle of internal friction may vary depending on the type and condition of the soil.

3.2 Testing Procedure

Sieve, hydrometer, liquid, and plastic limit analyses were conducted to classify the soil, and the results of this analysis are represented in Table 1. The soil sample was classified as sand with fine friction.

Table 1. Physical characteristics of the soil

Soil characteristic	Value
Specific gravity, g/cm^3	2.538
Maximum dry density, g/cm^3	2.031
Optimum water content, %	10.194
Sand sized fraction (75µm-2mm), %	60.794
Silt sized fraction (5-75µm), %	19.193
Clay sized fraction (<5µm), %	15.607
Liquid limit, LL, %	23.251
Plastic limit, PL, %	1.190
Plasticity Index, PI, %	22.061

The stage of sample preparation included preparing the soil sample to the desired moisture content and density and placing the soil sample into the shear box, ensuring it was evenly distributed and compacted. The soil mass amounted to 231.48 grams. The selected normal stresses were 50 kPa, 75 kPa, and 100 kPa. For each stress level, three samples were tested (3 samples at 50 kPa, 3 at 75 kPa, and 3 at 100 kPa). Similarly, three samples were tested for each stress level with geosynthetic reinforcement. In total, 27 samples were tested. This amount allows achieve more accurate results. Samples were prepared without reinforcement and reinforced with geosynthetic materials according to the standard test ASTM [26]. Non-woven geotextile and woven geogrid were chosen as reinforcement, the physical and mechanical characteristics of which are presented in Tables 2-3.

Table 2. Physical and mechanical characteristics of non-woven geotextile

Name of indicators	Non-woven geotextile
surface density, g/m^2	400
tensile strength, no less, kN/m	13.0
relative elongation at break length/width, %	55-130

Table 3. Physical and mechanical characteristics of geogrid

Name of indicators	Woven geogrid 35/35
surface density, g/m^2	270
tensile strength, kN/m not less longitudinal/ transverse	35/35
relative elongation in the longitudinal direction/transverse direction, %	12/12

The nonwoven geotextile used in the experiment is a high-strength fabric made of polypropylene fibers bonded by needle-punching with subsequent thermal bonding. This manufacturing method ensures a durable fabric capable of withstanding various environmental conditions and mechanical stresses. This material is used to prevent the intermixing of contacting layers of pavement, construct drainage systems, reinforce soil bases, and stabilize slopes [5].

The selected type of geogrid is polyester with polymer impregnation which is used for reinforcing bearing layers in road construction, reinforcing weak foundations, and building retaining walls [27]. The polyester used in the production of geogrids has excellent resistance to mechanical damage and chemicals [28].

In experiments, reinforcement materials were placed horizontally and perpendicular to the failure plane (Fig.4). The position is parallel with the sliding direction, and testing is performed at intervals of one, two, and three layers. Conversely, if the position is perpendicular to the sliding direction, a single layer is sufficient for each geosynthetic material [5, 29].

When placing the nonwoven geotextile and geogrid for the single plane ground shear tests, several technical requirements were followed to ensure the accuracy of the results, the safety of the process, and the efficiency of the materials [30-31]. These requirements include proper surface preparation for installation. The soil was level and compact to eliminate possible distortion of the data during the testing process. The geotextile and geogrid were installed on a clean surface with no foreign materials or contaminants that could affect the quality of the bond and test results. The soil was placed in layers at the bottom of the box, each layer being thoroughly compacted to avoid voids and ensure uniformity. The box cover was installed after all soil layers had been placed and compacted [32].

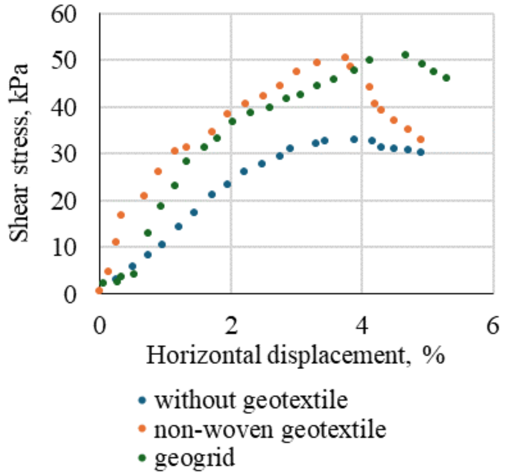
The cutting speed was 0.1 mm/min. The shear force was increased in small, controlled steps. This approach helps in accurately capturing the soil's response to increasing shear stress and ensures the data collected is precise. Throughout the shearing stage, the deformation of the soil specimen was closely monitored. Both horizontal displacement (shear deformation) and vertical displacement (change in specimen height) are recorded. These measurements were crucial for determining the shear strength parameters of the soil [33-34]. The shearing was continued until the soil specimen reached failure, which is indicated by a peak in the shear stress versus horizontal displacement curve or by a large horizontal displacement with no further increase in shear stress [35-36]. The point of failure provides the maximum shear stress that the soil can withstand under the given normal load. Data on shear force, and horizontal, and vertical displacement was continuously recorded during the shearing stage. This data was used to plot and calculate the shear stress versus horizontal displacement curve.

a b c

Fig.4 Placing of different reinforcement materials

4. RESULTS AND DISCUSSIONS

Shear stress versus horizontal displacement curves were plotted for all tested specimens (Fig.5). Fig. 5a shows the curves for unreinforced specimens and specimens reinforced with different materials in a horizontal position (σ,50 kPa). In graphs, horizontal displacement represents how much the specimen has deformed horizontally relative to its initial thickness.



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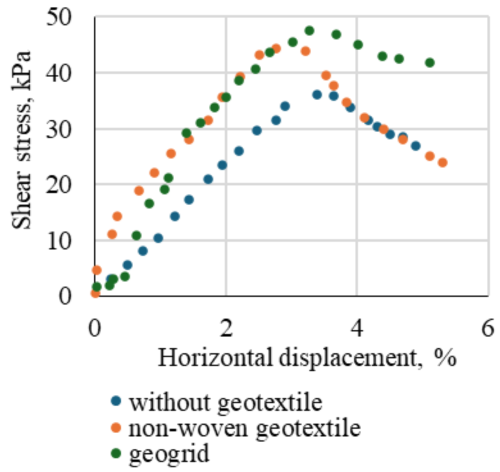
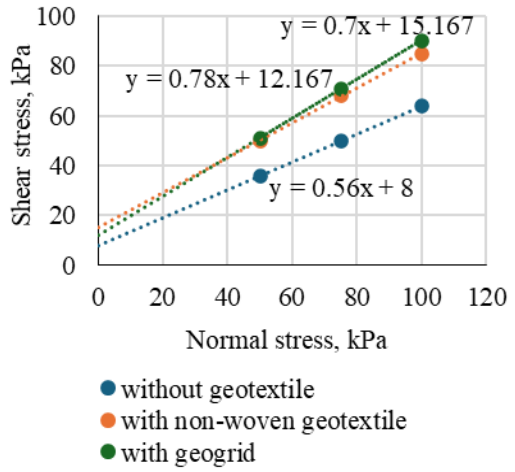


b

Fig.5 Shear behavior for normal stress 50kPa: a) horizontal position reinforced material; b) perpendicular position reinforced material

Fig. 5b shows the curves for specimens without reinforcement and specimens reinforced with geosynthetic materials arranged perpendicularly (σ,50 kPa). The results show that when the soil is tested at different normal stresses, the shear stress increases to a peak, increasing the shear strain up to a certain value and then gradually decreasing. The peak shear stress occurs at a strain between 3% and 5% for the tested soil. This observation is critical in understanding the behavior of soil under stress, as it highlights the point at which the soil transitions from an elastic state to a plastic state. In the elastic state, the soil deforms but returns to its original shape when the stress is removed. However, once the peak shear stress is reached, the soil exhibits plastic behavior, meaning it undergoes permanent deformation.

The obtained experimental points were approximated by a straight line, and this line's slope angle characterizes the soil's internal friction (Fig.6). The displacement of the line in the vertical direction represents the cohesion. The equation in the diagram near the trend line shows how the soil tangent stress varies as a function of the applied normal stress.



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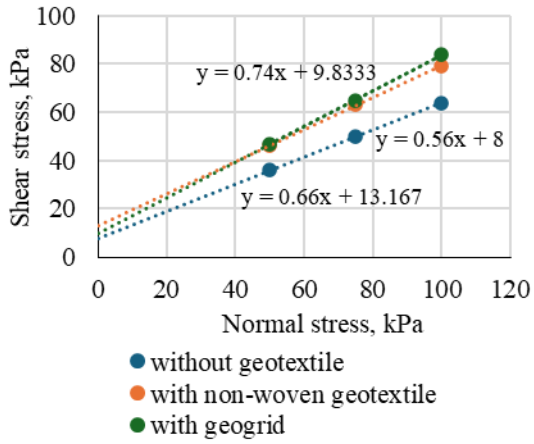
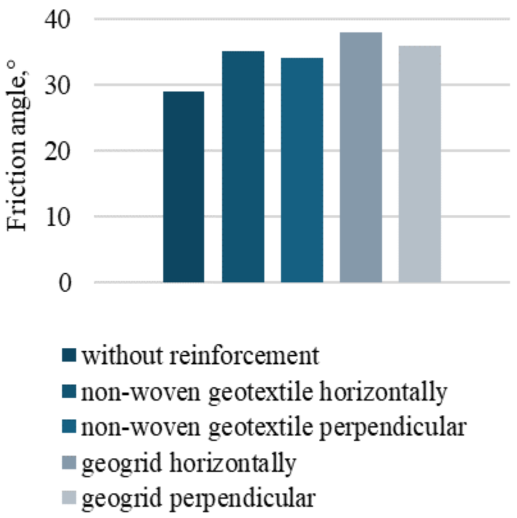


b

Fig.6 Results of direct shear test: a) horizontal position reinforced material; b) perpendicular position reinforced material

Results in Fig. 6 showed that the soil reinforced with geosynthetic materials had a higher value of shear stress, indicating enhanced mechanical properties and improved soil stability. These materials provide additional tensile strength to the soil, helping to distribute loads more effectively and reduce deformations. Better results for shear stress in soil are obtained for the samples reinforced with geogrid in horizontal and perpendicular testing positions. The values of the shear angle and cohesion are presented in Fig. 7.



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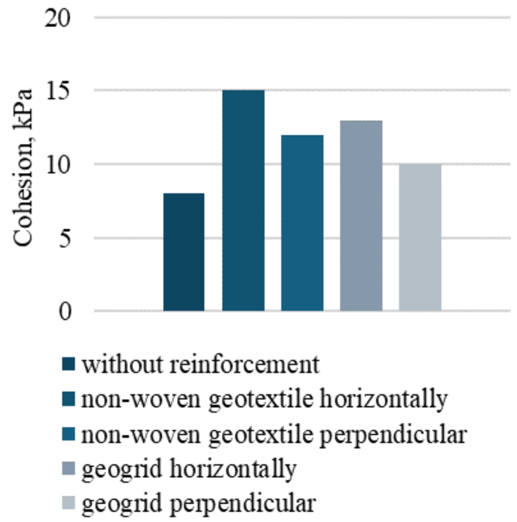

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Fig.7 Results: a) friction angle, b) cohesion

Cohesion measures the internal molecular attraction between soil particles, contributing to the soil's overall shear strength. Analyzing the results of Fig.7b showed that due to its structure, nonwoven geotextile creates strong bonds between soil particles, significantly increasing its cohesion.

Statistical analysis was applied to analyze the results, which include various key metrics that provide insights into the data set. The primary focus was on understanding trends, variances, and correlations among different variables.

One of the significant findings was the calculation of the average data, which helped identify the central tendency. Additionally, the standard deviation was obtained which offered insights into the dispersion of the data. The average values of the friction angle and adhesion after reinforcement were 35.75° and 12.5 kPa, respectively. The standard deviation was calculated according to the formula:

$$\sigma = \sqrt{\frac{\Sigma(x_i-\mu)^2}{n-1}} \quad (2)$$

where x_i – each value; μ - average value, n- number of samples.

The coefficient of variation was calculated using the formula:

$$CV = \frac{\sigma}{\mu} \cdot 100\% \quad (3)$$

where σ - standard deviation; μ - average value.

The obtained values of standard deviation and coefficients of variation are presented in Table 4.

Table 4. Results of the statistical analysis

Name	σ , standard deviation	CV, coefficient of variation, %
φ, friction angle, °	1.71	4.78
c, cohesion, kPa	2.08	16.64

The statistical analysis showed that the variability of adhesion between samples was higher than the variability of friction angle. Geosynthetic reinforcement increased the friction angle value by 31%. Cohesion values increased from 8 kPa to 15 kPa when geosynthetic reinforcement was used—an increase in friction angle after geotextile application indicates improved soil stability. Geotextile materials help to distribute loads evenly and provide additional resistance to shear stresses due to their tensile strength, which helps to anchor soil particles and reduce their displacement under load.

The present study using small reinforcement in a small box doesn't fully replicate real field conditions because the scale of the reinforcement relative to the soil particle size, as well as the scale of the interaction, is different. However, small-scale tests allow parameters such as geosynthetic type, strain rate, soil type, and pressure to be easily varied. This makes them suitable for investigating the effects of different factors on reinforcement performance and provides a fundamental understanding of how each affects the overall behavior of the structure. They provide valuable data on the basic behavior of the soil-reinforcement system, providing a cost-effective and operational approach to assessing the performance of geosynthetics in construction.

5. CONCLUSION

The following results were obtained from the study:

1. Using geosynthetics in the soil improved the shear strength and the geogrid-reinforced

specimen showed maximum shear strength values and an increase of 31% over the unreinforced soil.

2. The location of the reinforced material influenced the results obtained, while the shear strength results at the horizontal position of nonwoven geotextiles increased by 3 % and geogrid by 5% respectively.
3. The location of the reinforced material influenced the results obtained, while cohesion at the horizontal position of nonwoven geotextiles increased by 20% and geogrid by 24% respectively. These results depend on material characteristics. The nonwoven geotextiles are typically manufactured using synthetic fibers that are mechanically or thermally bonded together. This manufacturing process creates a fabric with a random fiber arrangement and high internal friction between fibers. As a result, nonwoven geotextiles exhibit a higher cohesive strength, meaning they can resist the movement of soil particles more effectively under shear stress conditions.
4. The interaction of geosynthetics with the soil is a complex process. The behavior of geosynthetically reinforced soil composites is determined by the properties of both the geosynthetic and the soil. For other types of geosynthetic-soil composites, additional research is required.
5. The statistical analysis of the results showed changes in the mechanical properties of the reinforced soil. The correlation of higher adhesion values knowledge can guide the selection of appropriate reinforcement techniques and materials based on the specific requirements of a project.

The direction of research into the effect of geosynthetic materials on soil strength properties is diverse. In this study one of the types of soils is considered, in the prolongation of the study is an interesting question and influence of geosynthetic materials on mixed soil where different types of soils are combined with geosynthetics to explore how these materials interact and affect the overall mechanical behavior of the composite material. These mixes can include variations in grain size, mineral composition, organic content, and other soil characteristics.

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