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Effect of Polypropylene Planar Reinforcement on the Unconsolidated Undrained Behavior of Black Cotton Soil

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Abstract. Black cotton soil is very compressible and cohesive with extremely low bearing ca- pacity. This study's objective is to enhance the shear parameters such as the internal friction angle and cohesion of black cotton soil, thereby enhancing the bearing capacity of the soil. For the present study, soil sampling has been carried out near Kollegal, Karnataka. The coordinates of the site are 12°08'21.0" N and 77°04'59.0" E. The undisturbed and representative soil samples have been extracted from three different geographical locations at different depths. A detailed experimental study has been carried out to determine the physical, index, and engineering prop- erties. Cohesion and the internal friction angle determined for the soil under consideration were 0.05 N/mm^2 and 0° respectively. To increase the internal friction angle, polypropylene planar reinforced soil. Reinforcements were introduced. Unconsolidated Undrained (UU) triaxial tests were conducted on planar reinforced soil. Reinforcements were introduced in the soil specimen with one, two, and three individual layers, and results demonstrate that cohesion was increased marginally to 0.057 N/mm^2, 0.059 N/mm^2, and 0.061 N/mm^2, and the internal friction angle wasincreased to 2.7°, 4.2°, and 6.6° respectively.

Keywords: Black cotton soil, Shear parameters, Unconsolidated undrained triaxial test

1 Introduction

In the field of construction, black cotton soil is a challenging type of soil due to its poor shear behaviour. It is a cohesive, highly compressible soil. Because of the presence of montmorillonite mineral in clay, it loses its tensile strength in the wet state but exhibits high strength in dry state. This has been difficult for the construction industry to work with these soils because of their poor bearing capacity, excessive swelling, and shrinkage characteristics. Heavy shrinkage, cracking, and unevenness are some of the major issues with black cotton soil in the construction industry, which can lead to the development of cracks of varying depths in roads and other structures. Numerous stabilization procedures, including cement stabilization, chemical stabilization, and mechanical stabilization, have been utilized to improve the engineering properties of soil in the construction industry. Recently, a lot of researchers have focused on the study of reinforced soil to stabilize expansive soils, such as natural fiber reinforcement like jute, coconut fibers, etc., and geosynthetic fiber reinforcement like geogrid, geotextile, geonet, etc.

The soil's varied engineering properties are enhanced by the addition of reinforcing materials, such as fibers (natural or synthetic), metal strips, soil nails and anchors, and micro piles. The basic concept of ground improvement with geosynthetics is that reinforcing materials absorb tensile or shear stresses inside the structure, preventing failure due to shear or excessive deformation. The engineering properties of the soil improves with the use of reinforcements mainly due to two reasons. One, due to the friction that develops at the soil-reinforcement interface. On the other hand, the passive resistance that results from the development of bearing-type stresses on transverse reinforcement surfaces in a direction normal to the relative movement of soil reinforcement is also a reason for the enhancement.

Soil reinforcements can be introduced in two different ways, namely planar and randomly distributed fibers. In planar reinforced soils, the fibers are laid layer by layer. Reinforcement layers are arranged in order and all the layers are placed in the same orientation (i.e., the layers of reinforcement are parallel to each other). Sheets, strips, bars, and other forms of continuous fibers are used systematically in this type of arrangement. The reinforcements used for planar reinforced soils are geo-grids, geotextiles, geo-cells, etc. Randomly distributed reinforced soil has discrete fibers distributed randomly in the soil mass. The mixing of reinforcement with the soil is done until they form a homogeneous mixture. Reinforcements used for preparing randomly distributed reinforced soil are polypropylene fiber, Recron fibers, basalt fibers, etc.

Geogrid is a geosynthetic material used as soil reinforcement. Geogrid is a polymeric, planar product that resembles a mesh and is comprised of intersecting ribs that are connected at the junctions. Uniaxial and biaxial geogrids are the two primary varieties of geo-grid. Regularly perforated polymer sheets are longitudinally stretched to form uniaxial geogrid. They have substantially greater longitudinal tensile strength than transverse tensile strength. Regularly perforated polymer sheets are stretched longitudinally and transversally to create biaxial geogrids. Both the longitudinal and transverse tensile strengths of these are equivalent. The openings known as the apertures between the longitudinal and transverse ribs are large enough to facilitate interlocking with the nearby soil particles. The apertures are either rounded squares, elongated ellipses, near-squares, rectangles, or squares [1].

The behaviour of reinforced soil has been the subject of numerous studies in the past, a few of which have been studied. The reactivity of reduced scale geocell-reinforced soil to contributing elements such as loading plate size, soil grain size, and geogrid apertures was examined by Gh Tavakoli Mehrjardi et al [3] in 2019. It was determined that geocell reinforcements show great promise as a reliable way to increase the foundation bearing capacity. Additionally, geocell reinforcement could render the unreinforced backfill stiffer up to 5.24 times with the right choice of effective parameters.

In order to assess the shear strength of root-geomat reinforced soil (RMS), Huiming Tana et al. (2019) [4] used soil samples that had been cultivated with Bermuda grass and three-dimensional geomats. The test findings demonstrated that the combined root-geomat mutual interlocking effect significantly enhanced the soil's shear strength and cohesion, but the friction angle was negligible. Both the soil's shear strength and cohesiveness were noticeably improved as a result of the reduction in water content and increase in the root or geomat content.

Lihua Li et al (2020) [5] investigated the impact of polypropylene fiber length and quantity on the mechanical characteristics of municipal solid waste incineration

(MSWI) by conducting triaxial experiments on clay soil that has been combined with bottom ash (BA). The results indicate that as compared to the original soil and pure BA-mixed soil, the resistance to deformation and strength of polypropylene reinforced soil is enhanced. The internal angle of friction of the reinforced soil increases little as the number of fiber rises, whereas the cohesiveness of the reinforced soil rises significantly. When the control polypropylene fiber length and content are 2.5 cm and 0.3%, respectively, the sample can attain its maximum strength and have the optimal reinforcement effect.

Yuan-shun Shen et al (2021) [14] stated that undrained shear strength for plain soil and soil treated with cement consistently rises with increasing fiber content at a given confining pressure. The specimen treated with cement displayed higher values of c and u than the specimen treated with lime at the same fiber content. Comparing soil that has been treated with lime or cement to untreated soil with the same percentage of polyester fiber, a considerable improvement in unconfined compressive strength was observed.

Shixin He et al (2021) [16] investigated the tensile strength properties of soil reinforced with polypropylene (PP) fibers with various fiber dispersion, quantity, and aspect ratios. The study revealed that whether the distribution was discrete or random, an increase in fiber content led to an increase in tensile strength. Under various fiber mix patterns, the degree to which the tensile strength increased varied with the increase in fiber aspect ratio.

Amr M. Morsy et al (2021) [8] described the process through which strain and shear fields in a unit cell of reinforced soil evolve as shear stresses are created at the soil-reinforcement contact. Results indicated that as reinforcing tensile strain and ver- tical spacing rise, the variation in lateral earth pressure changes as vertical stress in- creases and reduces.

2 Methodology

For experimental studies, soil samples have been taken from Kollegala, Karnataka. Undisturbed and representative samples of the soil have been taken out from three different locations in the same geographical area. Sampling has been done at three different depths. Experimental analysis of the physical, index, and engineering characteristics of the soil has been carried out in the laboratory. Experiments on physical properties like water content, specific gravity, dry density and bulk density, index properties such as Atterberg limits, plasticity index, liquidity index, grain size distribution, differential free swell, etc., and engineering properties through triaxial and unconfined compressive strength (UCS) test have been carried out. A triaxial test has been carried out on undisturbed samples without reinforcement and representative samples with one, two, and three layers of reinforcement. Unconfined compressive strength (UCS) test has been carried out on a representative sample with three-layer reinforcement. A synthetic reinforcement material called geo-grid has been used for experimental purposes.

3 Test design

3.1 Preparation of specimen

The Black cotton soil taken from the water treatment plant site was dried and sieved on a 425µ IS sieve. The ideal moisture content of the soil was determined to be 19% through the standard proctor experiment. Water content equal to the optimum moisture content was mixed with the soil in order to obtain maximum uniformity and reach the max dry density.
The geogrid fiber used was cut on a circular shape of 35 mm diameter with negligible thickness. The prepared soil sample was compacted on the cylindrical mold of diameter 35 mm and a height of 85 mm. Geogrid fibers were placed in a specified number of layers.

3.2 Triaxial test

The triaxial test has been conducted for both undisturbed and representative samples. The undisturbed sample was extracted from the site using a UCS mold. The prepared specimen was inserted into a rubber membrane and placed in the pressure chamber of the triaxial testing machine and all the accessories and valves were fitted tightly. The water was filled and pressure was provided to the chamber. The soil sample was extracted from the UCS sampling tube (in case of undisturbed soil sample) or compacted to its maximum dry density (in case of representative samples) and the sample was made airtight with the rubber membrane and placed in a triaxial testing machine. The cell is put together and filled with enough water to create a 5 N/cm^2 confining pressure. The compression machine's loading plate form is elevated to bring the ram into an interface with the loading cap. The dial gauge is adjusted to zero to account for the load brought on by piston friction and cell pressure. Set the strain dial gauge to zero just as the ram touches the sample cap. Readings are taken of the proving ring at an interval of 50 divisions (0.5 mm) till the sample fails or 20% strain is achieved. The readings are tabulated and the stresses are calculated for every 0.5mm deformation. Mohr's circle is plotted considering the major and minor principal stresses obtained. Failure envelop is drawn for the Mohr's circle to determine the c and ϕ values of the sample. The displacements were measured using a strain gauge. The displacements obtained through experimental and numerical analysis (carried out in the SIGMA/W window of the Geo Studio tool) were compared.

Fig. 1: Reinforcement used

4 Behaviour of planar reinforced soil

4.1 Effect of reinforcement

The reinforced soil shows that there is a significant improvement in the internal friction angle and the cohesion of the black cotton soil as the layers of the reinforcement are increased. The effect of reinforcement shows that as the number of layers is increased from 1 to 3 the internal friction angle increases from 2.7^0 to 6.6^0 and cohesion increases from 0.057 N/mm² to 0.061 N/mm² with planar reinforcement improvement in the internal friction angle was even more evident than the increase in cohesion. These results have been verified with the UCS testing machine for samples with three layers of reinforcement.

5 Results

5.1 Results of laboratory tests

The main objective of the experimental study is to identify the engineering properties of the black cotton soil sample collected from a site in Kollegala and to study the effect of the different number of layers of reinforcement on the shear behavior of the soil. Physical and index properties of the soil were also identified. The deformed sample before and after the conduction of the triaxial test are shown in Fig. 2, Fig. 3, and Fig. 4. The results of the experiments conducted in the laboratory are tabulated below:

Table 1: Physical properties of soil

Parameter	Water content (%)	Bulk density (kN/m^3)	Dry density (kN/m^3)	Specific Gravity
Value	26.31	19.61	15.43	2.72

Table 2: Index properties of soil

Parameter	Atterberg Limits							
	Liquid limit (%)	Plastic limit (%)	Shrinkage limit (%)	I_p (%)	I_l (%)	I_c (%)	I_f (%)	I_t (%)
Value	51.2	15.21	12.07	36.22	30.65	69.35	26.15	1.39

Table 3: Index properties of soil

Parameter	Hydrometer Analysis				Differential free swell (%)	Free swell Index (%)
	Clay (%)	Silt (%)	Sand (%)	Gravel (%)		
Value	60	32	08	0	90.9	130

Table 4: Engineering properties of soil (Triaxial test)

Sample condition	Cohesion (N/mm^2)	Internal friction angle
Undisturbed sample	0.050	0°
Compacted sample (No reinforcement)	0.054	0°
1 Layer Reinforcement	0.0575	2.7°
2 Layer Reinforcement	0.059	4.2°
3 Layer Reinforcement	0.061	6.6°

Fig. 2: Sample Before Test

Fig. 3: Deformed Sample

Fig. 3: Deformed Sample

Table 5: Engineering properties of soil (UCS test)

Parameter	Failure angle (α)	q (max) N/mm^2	Cohesion N/mm^2	Friction angle
Value	48.52°	0.13	0.065	7.035°

5.2 Results obtained from triaxial UU test.

The readings of triaxial tests on undisturbed soil samples without reinforcement and representative soil samples with zero, one, two, and three layers of reinforcement have been tabulated and Mohr's circle has been plotted. The UU triaxial test was conducted on three samples but the Mohr's circle of one of the sample in each case did not coincide with the failure envelop. Hence, only two samples were considered for plotting the Mohr's circle. The results plotted after conducting the triaxial test in the laboratory have been shown below:

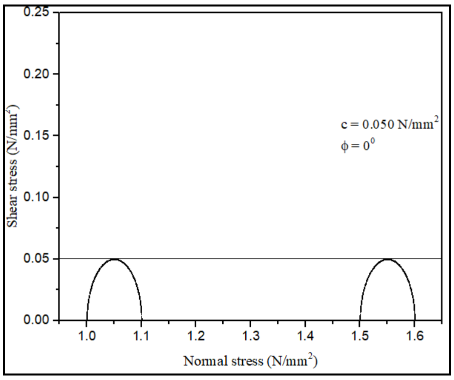

Fig. 5: Mohr circle obtained for Undisturbed sample from the UU Triaxial test

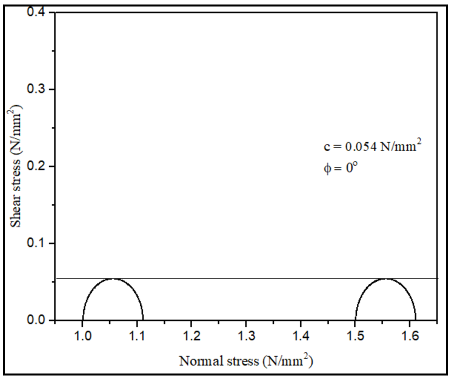

Fig. 6: Mohr circle obtained for the Compacted sample without reinforcement from the UU Triaxial test

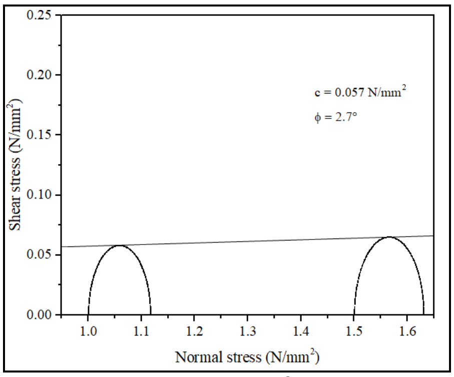

Fig. 7: Mohr circle obtained for Compacted sample with one layer reinforcement from the UU Triaxial test

Fig. 8: Mohr circle obtained for Compacted sample with two-layer reinforcement from the UU Triaxial test

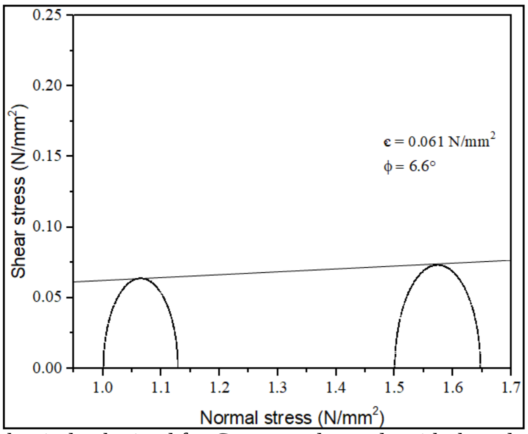

Fig. 9: Mohr circle obtained for Compacted sample with three-layer reinforcement from the UU Triaxial test

From the figures, it can be seen that with the increase in number of layers of reinforcements, there is a slight increase in the shear parameters of the soil. This increase is due to the interlocking effect of the soil reinforcement. The c value increased from 0.054 N/mm^2 for compacted soil sample without reinforcement to 0.061 N/mm^2 for a compacted sample with three layers of reinforcement. The ϕ values increased from 0° for compacted soil sample without reinforcement to 6.6° for compacted sample with three layers of reinforcement.

5.3 Results of UCS test

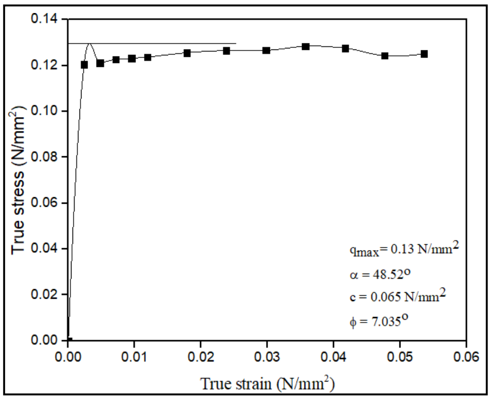

Fig. 10: UCS test result

For the three-layer reinforced soil sample, the c and ϕ values obtained through the UCS test were 0.065 N/mm^2 and 7.035° respectively, and those obtained through the triaxial test were 0.061 N/mm^2 and 6.6° respectively. The values of shear parameters obtained through the UCS test and triaxial test are almost equal. The analysis has been carried out by conducting UU triaxial and UCS tests in the laboratory. The results of three layers of geogrid shows no significant practical improvement probably due to non-anchorage effect of geogrid. Hence, from practical point of view, anchorage can be checked in further research.

5.4 Comparison of displacements obtained from experimental analysis and numerical simulation

The displacements obtained in representative samples with zero, one, two and three layers of reinforcements are compared with the displacements obtained during the numerical simulation of soil model (carried out in the SIGMA/W window of the Geo Studio tool) with zero, one, two and three layers of reinforcement respectively. The comparison figures plotted for the displacements obtained in experimental and numerical analysis are shown in the Fig. 11 to 14.

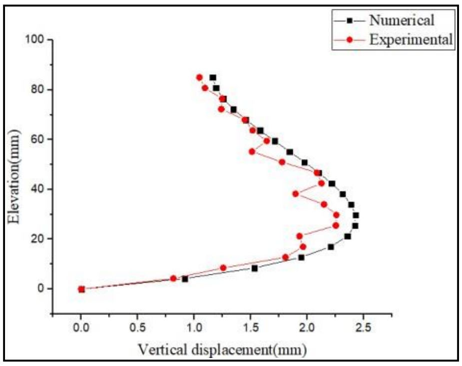

Fig. 11: Without reinforcement (Left side)

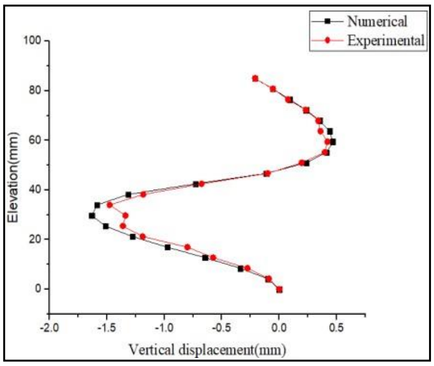

Fig. 12: One layer reinforcement (Left side)

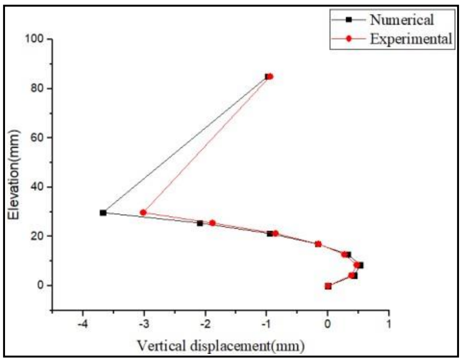

Fig. 13: Two-layer reinforcement (Left side)

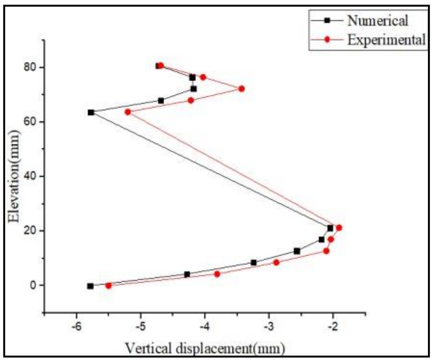

Fig. 14: Two-layer reinforcement (Left side)

The deformations have been taken along the vertical axis on the edges of the soil sample. The positive deformation indicates bulge of the sample outwards and the negative deformation indicates the convex deformation of the sample. From the figures 11 to 14, it can be observed that the displacements obtained through both numerical simulation and experimental analysis are almost the same through the length of the sample. Hence, the experimental results are validated through numerical simulation. The displacement results obtained for the left and right side of the sample were same due to the symmetry of the soil model.

6 Conclusions

The main objective of the study was to examine the effect of planar reinforcement on the shear behavior of black cotton soil. The effect of the number of layers of reinforcement is also intended to be studied. Tests on the index, engineering, and physical properties of the soil were conducted in the laboratory. Mainly, triaxial tests on black cotton soil were carried out to study the shear parameters of the soil. Triaxial tests were conducted on both undisturbed samples without reinforcement and representative samples with zero to three layers of reinforcement. The results were experimentally validated by conducting a UCS test on a representative soil sample with three-layer reinforcement.

The experimental results showed an increase in the shear parameters of the soil with the inclusion of soil reinforcements. With the increase in the number of reinforcement layers, there was an improvement in the shear parameters i.e. there was an improvement in the internal friction angle and cohesion of the soil. The UCS test result for three-layer reinforced soil validates the triaxial results for three-layer reinforced soil. The numerical displacements of soil models with zero to three layer reinforcements correlate with those obtained through experimental analysis. Hence, experimental results are validated through numerical analysis.

This study shows that soil reinforcements are useful in improving the shear behavior of soils. Increasing the number of layers of planar reinforcements can increase the effectiveness of soil reinforcements to certain extent. Hence, soil reinforcements can be used in areas with weaker soils.

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