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Strength enhancement of geogrid-reinforced flyash-modified soil: an experimental study

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Abstract

Research in soil reinforcement is essential for enhancing the stability and load-bearing capacity of civil engineering structures, cost-efficiency, and innovation. RTPS (Raichur Thermal Power Station) generates about 1.5 million tons of flyash annually, which causes environmental problems. Interface shear tests, foundation model tests, etc… are used to study the effect of reinforced soil, which are costly, complex, time-consuming, and require expertise. So, an attempt is made in the present study to confirm that the introduction of RTPS's flyash provides a significant improvement in soil properties through a small-scale UCS test (specimen diameter is 36 mm) as compared with untreated soil and to determine the optimum position and performance of geogrid-reinforced flyash-modified soil through large-scale UCS (specimen diameter is 100 mm) and CBR tests with three different types of geogrid. An experimental study shows that RTPS's flyash is non-pozzolanic flyash and belongs to classification "F." Also, this is a stable material, and we can satisfactorily use it as a filler material with soil. The UCS and CBR values for the reinforced case are higher compared to all unreinforced combinations, with increased elastic modulus values affecting the stress-strain behavior of the soil. Compared to the CBR-unsoaked condition, the CBR-soaked condition shows higher performance ratios with the flyash addition. By considering the geogrid aperture size, the soil-reinforcement interface (more in a smaller aperture geogrid) is as important as the strength of the geogrid.

Keywords: *Flyash, Geogrid, small-scale & large-scale UCS tests, CBR test.*

1. Introduction

Research in soil strength enhancement is of paramount importance in the field of geotechnical engineering. Soil serves as the fundamental support for all type of structures, making its strength a critical factor. By enhancing soil strength, engineers can optimize foundation designs, reduce settlement, and increase load-bearing capacity. This not only ensures the safety and longevity of structures but also leads to cost savings and efficient land use [1]. In the context of infrastructure development, particularly in urban areas, where available land is limited, geotechnical research is essential for sustainable growth. Improved soil strength can support taller buildings, transportation networks, and underground structures, making more efficient use of valuable urban space [2].

The soil reinforcing technique is widely adopted in construction areas where the ground needs improvement. The widely used reinforcement material in the construction field is geosynthetics. Among them, geogrids are mainly used for reinforcing work in the construction of roadways to stabilize and strengthen the subgrade soil [3]. Geosynthetics can be defined as planar products manufactured from polymeric material, which are used with soil, rock, or other geotechnical engineering-related material as an integral part of a manmade project, structure, or system [4]. Among the various functions of geosynthetics, the reinforcement function plays the primary role in enhancing the load-carrying capacity [5]. The interaction due to the geogrid interlocking with aggregate minimizes aggregate particles' lateral movement and reduces the vertical subgrade deformations [6]. The geogrid placement depth in the CBR test was studied, and it is found that geogrid can be placed at the middle of the height of the specimen or the upper one-third layer and the middle layer [7]. Geogrid with higher tensile strength provided better performance compared to the lesser one [8]. The engineering performance of different

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soil types was studied for using geogrid as reinforcement and found that CBR value increases for reinforced case compared with the unreinforced case for both the laboratory and field investigations [9]. Likewise, when geotextile was used as reinforcement, the migration of subgrade fines into the subbase has been reduced [10]. Using geogrid as a single layer of reinforcement has reduced the potential swell behavior of expansive clays [11]. When the layers of geogrids are increased from single to two or multiple improvements in the soil strength, higher bearing capacity has been achieved [12]. Using the geosynthetics such as geogrids and geotextiles has enhanced pavement life and reduced the rut depths [13]. The findings indicate that there is a considerable amount of increase in strength of subgrade soil reinforced with geosynthetics and the amount of increase depends on the properties and type of geosynthetics, depth and number of reinforcement layers, and mechanisms involved [14].Flyash is an industrial by-product generated during the combustion of coal in thermal power plants. It is generated in large amounts in many countries [15]. Over 65% of the produced flyash is disposed of in landfills [16]. If the flyash, as a waste material, is not managed well, it can lead to serious environmental and health problems [16,17]. However, many characteristics of flyash such as low compressibility, high shear resistance, high strength and pozzolanic characteristics offer it an important role in improving the properties of soil in geotechnical applications [5].

2. Problem findings

RTPS is a coal-fired electric power station located at Yadlapur D(Shaktinagar) in the Raichur district of the state of Karnataka, India. The power station was commissioned during various periods from 1985 and it accounts for about 70% of the total electricity generated in Karnataka. RTPS uses coal for generation of electricity. Its daily requirement of coal is about 20,000 metric tons, when running at full capacity. RTPS generates about 1.5 million tons of flyash annually which causes environmental problems. The fly-ash which gets generated during the burning of coal disperses into the air and hence pollutes the atmosphere. This gets deposited on the surrounding land, thereby making the land infertile. The fly-ash may also cause breathing problems for humans. The fly-ash is disposed of by converting it into wet slurry and dumping it into vacant tracts of land (which become what are known as ash-ponds). This is not environmentally friendly [18].

Interface shear test, Foundation model test, etc…are some laboratory tests carried out to determine performance of Geosynthetic reinforced soil. These tests are costly, complex, Time-consuming, large areas, and require expertise [19]. And also most of the time, it is not possible to achieve MDD of the respective OMC for soil towards more fines and cohesiveness. The unconfined compressive strength (UCS) and California Bearing Ratio (CBR) tests are essential tools in the field of geotechnical engineering, primarily used to assess and understand the mechanical and physical properties of soil. The UCS test provides valuable information for construction and foundation design with Simplicity, speed, cost effective, direct measurement and widely accepted standards. This helps engineers make informed decisions about soil suitability for various projects. On the other hand, the CBR test measures the strength and load-bearing capacity of soil, particularly when it's used as a subgrade material for road construction.

Based on the literature review and problem findings, the following objectives are drawn for the present investigation

- To confirm that the introduction of RTPS's flyash provides a significant improvement in soil properties as compared with untreated soil.
- To evaluate the engineering properties of flyash-modified soil, the optimum percentage of flyash is to be found.
- To determine the optimum position and performance of Geogrid-reinforced flyash-modified soil through UCS and CBR tests.

3. Materials and Methods

A. Soil

The soil sample were collected from the site Bengaluru university, Jnanabharathi campus, Bengaluru, to conduct various laboratory tests. The soil sample is collected in polythene bags, it is then oven-dried and the properties of the soil are determined as per IS code provisions. The grain size distribution curve of soil is presented in Figure 1. Soil is classified as intermediate compressible clay (CI) as per the Indian Standard classification system (ISCS).

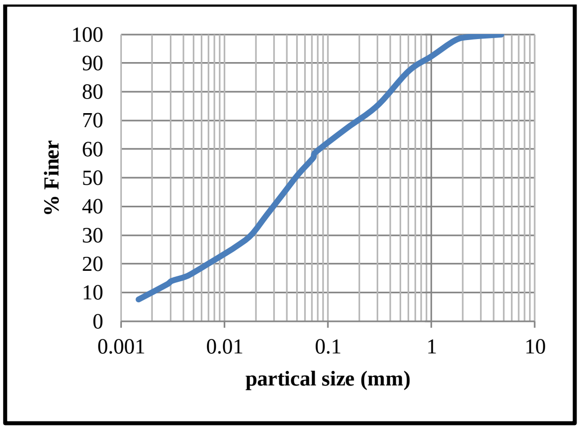

Figure 1: Particle size distribution curve of soil.

B. Flyash

The flyash used in the present study was collected from Raichur Thermal Power Station, Karnataka. This flyash is directly collected from open, dry dumps. It is a non-plastic was a specific gravity of 2.02 and flyash belonging to classification “F” according ASTM C618-12a. Chemical analysis reveals that the free lime content in flyash are very low hence, it behaves toward non-pozzolanic flyash. Table 1 and Table 2 summarizes the results of the physical and chemical properties the soil and flyash respectively.

Table 1: Physical properties of soil and flyash

Description	Soil	Flyash
Color	Red	Gray
Specific gravity	2.65	2.02
Liquid limit (%)	37.0	25.26
Plastic limit (%)	21.3	00
Shrinkage limit (%)	14.0	--
Free swell index	No swell seen	No swell seen
Sand size fraction (%)	41.3	17.1
Silt and clay size fraction (%)	58.7	82.6
Soil classification	CI	--
OMC (%)	16.5	18.11
MDD (kN/m^3)	17.46	13.73
UCS (kPa)	308	59.5

Table 2: Chemical composition of soil and flyash in % by weight

Constituent	Soil	Flyash
Silica (SiO2)	63.56	64.75
Titanium Oxide (TiO2)	0.42	0.50
Alumina (Al2O3)	16.31	23.23
Iron Oxide (Fe2O3)	8.19	6.60
Calcium Oxide(CaO)	3.06	2.37
Magnesium Oxide (MgO)	0.56	0.39
Sodium Oxide (Na2O)	0.61	0.75
Potassium Oxide (K2O)	0.46	1.18
Loss of Ignition(LOI)	6.63	0.12
Manganese oxide(MnO)	0.091	--

C. Geogrids

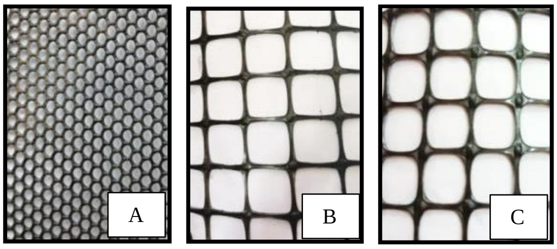

Figure 2: Different types of Geogrid used in study are, A.TG-4, B.TG-20 and C.TG-40

Table 3: Properties of geogrids used in this study.

Reinforcement type		TG-4	TG-20	TG-40	Unit
Structure		Biaxial Oriented			
Material		Polypropylene			
Aperture shape		Oval	Rectangle	Rectangle	
Aperture size	MD	8	38	38	mm
	CD	6	38	38	mm
Rib thickness	MD	2	2.4	4.3	mm
	CD	2	2.3	3.3	mm
Ultimate strength	MD	4	20	40	kN/m
	CD	4	20	40	kN/m

Figure 2 shows three types of Polypropylene-Biaxial-Geogrids (A.TG-4, B.TG-20 and C.TG-40) used in the current study of different tensile strengths and apertures size and the properties of the geogrids are shown in Table 3 as given by manufactured company (M/s. Geotech Industries Pvt Ltd, Gujarat).

Sample preparation of geogrid-reinforced flyash-modified soil

Figure 3: Materials used to prepare geogrid-reinforced flyash-modified soil

Large-scale UCS and CBR tests were conducted with unreinforced as well as reinforced soil specimens. For the reinforced soil specimen, reinforcements were cut in the form of a circular disc slightly smaller than the diameter of mould i.e., 100 mm. The numbers of reinforcing layers varied from 1 to 2 and they were placed in the specimen at the depths of H/2, H/3, H/4 and 2*H/4 respectively. For compacting the soil into the mould, first determine the required quantity of oven-dried soil, flyash and water based on the maximum dry density and optimum moisture content obtained from the standard proctor test.

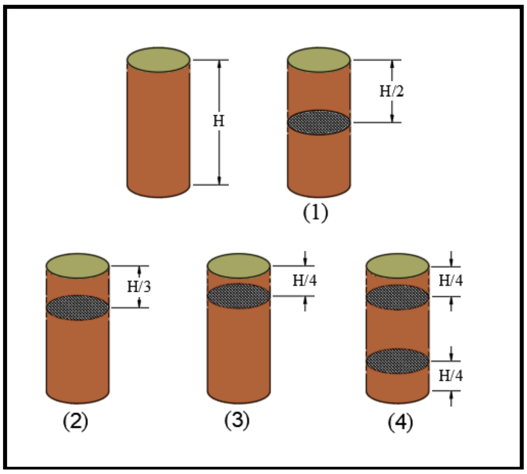

Figure 4: Different combinations of geogrid placement

Figure 5: Mould used for Large-scale UCS specimen preparation of 100 mm in diameter and 20 mm in height

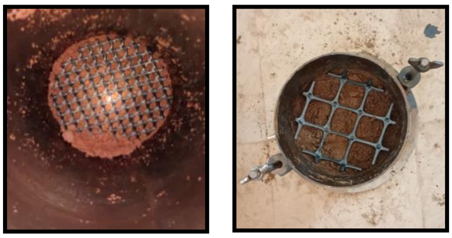

Figure 6: Geogrid placement in UCS and CBR mould while sample preparation

Figure 7: Arrangement of compaction and extraction of large-scale UCS specimen mould.

At first, the calculated amount of soil and flyash is mixed thoroughly as a dry-homogeneous mix. The required amount of water corresponding to the optimum moisture content was then added to the dry mix and thoroughly mixed. Now separate the wet soil mix into even parts of the required numbers. The soil required for filling the portion of the mould below the reinforcing layer was then poured into the UCS mould and pressed evenly and scratched over it to avoid layer formation. Figure 4 shows the different combinations of geogrid placements. After filling the soil in the lower portion of the mould, reinforcement was placed inside the mould at the specified position, as shown in figure 6 and then the required amount of soil was poured over it. The process was repeated for other layers as well, until all the layers were placed in position within the specimen and finally the soil was compressed with arrangement, extract the UCS specimen from mould carefully. As such, prepare the CBR specimen using a standard rammer for compaction. Arrangements . static load application. Using the sample extruder made for the compaction and extraction of large-scale UCS specimen mould shown in Figure 7.

Table 4: UCS test notations adopted for different combination of Geogrid type and Geogrid position

Unreinforced UCS test combinations			
Soil	Su		
Soil+FA	SFu		
Reinforced UCS test combinations			
Reinforcement type	**TG-4**	**TG-20**	**TG-40**
Soil+FA+ G(H/2)	SFu1*	SFu1**	SFu1***
Soil+FA+ G(H/3)	SFu2*	SFu2**	SFu2***
Soil+FA+ G(H/4)	SFu3*	SFu3**	SFu3***
Soil+FA+ G(2*H/4)	SFu4*	SFu4**	SFu4***

Table 5: CBR test notations adopted for different combination of Geogrid type, Geogrid position and soaking conditions.

Unreinforced CBR test combinations			
Test condition	**Unsoaked**	**Soaked**	
Soil	Su	Ss	
Soil+FA	SFu	SFs	

Reinforced CBR test combinations						
Geogrid type	**TG-4**		**TG-20**		**TG-40**	
Test condition	Unsoaked	Soaked	Unsoaked	Soaked	Unsoaked	Soaked
Soil+FA+ G(H/2)	SFu1*	SFs1*	SFu1**	SFs1**	SFu1***	SFs1***
Soil+FA+ G(H/3)	SFu2*	SFs2*	SFu2**	SFs2**	SFu2***	SFs2***
Soil+FA+ G(H/4)	SFu3*	SFs3*	SFu3**	SFs3**	SFu3***	SFs3***
Soil+FA+ G(2*H/4)	SFu4*	SFs4*	SFu4**	SFs4**	SFu4***	SFs4***

Where,
G : *Geogrid.*
FA : *Flyash of optimum amount.*
G(H/2) : *1st combination of geogrid placement .e., H/2 from top surface of specimen.*
Ex,
SFu3* : *Soil, Flyash, unsoaked condition/ Immediate, 3th combination of geogrid placement and GT-4.*
SFs4** : *Soil, Fly ash, soaked condition, 4th combination of geogrid placement (i.e., double layer reinforcement) and GT-40*

4. Results and Discussion

To determine the optimum flyash content in soil, different combinations of flyash and soil were set and UCS tests were performed with the OMC and MDD of the respective combination, which were determined by the standard Procter compaction test. Then reinforced flyash-modified soil was tested for large scale UCS and CBR tests by considering the different numbers, positions and types of geogrids. Performance ratio used to evaluate the performance of geogrids-reinforced flyash-modified soil. Table 4 and table 5 shows the UCS CBR test notations adopted for different combination of Geogrid type and Geogrid position respectively.

4.1 Determination of optimum flyash content in soil

4.1.1 Compaction characteristics of soil with addition of flyash

Table 6: CBR test notations adopted for different combination of Geogrid type, Geogrid position and soaking conditions.

Combination	OMC (%)	MDD (g/cc)
Soil	16.5	1.78
Soil+2%Flyash	16.8	1.68
Soil+4%Flyash	16.8	1.67
Soil+6%Flyash	17.22	1.68
Soil+8%Flyash	17.27	1.68
Soil +10%Flyash	17.47	1.71
Soil+12%Flyash	17.91	1.68
Soil+14%Flyash	17.96	1.69

Table 6 shows the changes in moisture content with dry densities for the soils with varying water content and flyash amounts. From this table, it can be inferred that as the amount of flyash increases up to 10% replacement with soil, MDD goes on increasing and after 10% replacement with soil; MDD goes on decreasing for the corresponding OMC. But by comparing all flyash replacement combinations, soil alone exhibits a higher MDD and a lesser OMC. The inclusion of low-weight flyash in local soil can make the mixed samples comparatively decrease the overall weight. The significance of these changes depends on the amount of ash added and the chemical composition of the clay minerals and ash [20].

4.1.2 UCS characteristics of soil with addition of flyash

Small-scale UCS test specimens (specimen diameter is 36 mm) are prepared for MDD and corresponding OMC), which are determined by standard Procter compaction test results. Figure 8 shows the UCS strength of different combinations of flyash replacement in soil. From this Figure, it can be inferred that as the amount of flyash replacement in soil increases from 0% to 10% (i.e., from 308 kPa to 387 kPa), UCS goes on increasing, and after 10% to 14% replacement with soil, UCS goes on decreasing (i.e., from 387 kPa to 314 kPa). The UCS of flyash-modified soil is greater than the UCS of natural soil, although strain at the ultimate UCS value is also high. Hence, we can understand that the inclusion of flyash in soil makes the soil more ductile, which is desirable for all geotechnical applications. Fly ash particles, by filling voids in the soil structure result in improved compaction and shear strength. Additionally, fly ash can modify the soil's microstructure by reducing the size of voids in the soil mass and enhancing the bond between them, thereby improving mechanical properties. Hence, 10% flyash replacement with soil is considered optimal for further study.

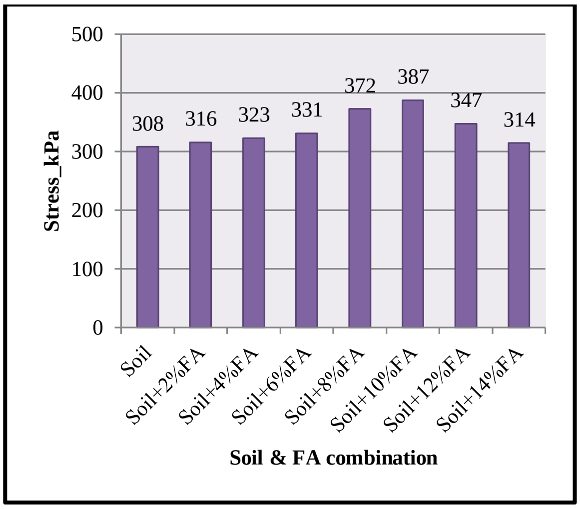

Figure 8: UCS strength of different combinations of flyash replacement in soil.

4.2 Large scale - UCS test results

A total 14 combinations of large scale UCS specimens were arranged to study the unreinforced and reinforced soils by varying the different types of geogrid, numbers and their positions. The geogrids taken in this study have an aperture size of 38mm, so placing these geogrids in a conventional size UCS test specimen (specimen diameter is 36 mm) will not be possible to study the effect of reinforcement. This is because in this study, large-scale UCS test specimen (specimen diameter is 100 mm) were selected. All UCS test specimens are tested immediately after specimen preparation, with a strain rate of 0.89 mm/min and a normal load that corresponds to a constant strain interval noted. Studied of all unreinforced and reinforced soil combinations by collecting knowledge from the stress versus strain curve pattern, Young's modulus and UCS strength, which are obtained from large-scale UCS test discussed below.

Elastic modulus

Table 7 shows the elastic modulus of all reinforced and unreinforced UCS test combinations in MPa. The elastic modulus was determined by calculating the gradient (axial stress divided by axial strain) of the linear portion of the stress versus strain curves of the UCS test results. In all UCS test combinations, the stress versus strain curve initially exhibits a nearly linear elastic portion with a slope (elastic modulus or stiffness). But all stress strain curves of

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single-layer reinforcement do not overlap on each other also elastic modulus value is not same. It confirms that there is an optimum position for Geogrid to get a higher UCS of reinforced soil.

Table 7: Elastic modulus in MPa

Unreinforced UCS specimens			
Soil	8.6		
Soil+FA	10.0		
Reinforced UCS specimens			
Reinforcement type	**TG-4**	**TG-20**	**TG-40**
Soil+FA+ G(H/2)	12.5	19.0	19.6
Soil+FA+ G(H/3)	12.0	18.6	15.3
Soil+FA+ G(H/4)	11.2	18.4	14.3
Soil+FA+ G(2*H/4)	18.0	20.0	21.6

UCS value

The peak value of the stress versus strain graph of the UCS test is considered the UCS value for the respective specimen. From Table 8 it can be seen that the UCS value of all reinforced soil combinations is greater than the UCS value of unreinforced soil, it has been known that if reinforcement layers are placed in the soil during the application of forces, the stress required to cause failure will increase, and the soil will show a tendency toward greater ductility. It is because of the reinforcement that within the specimen the load is distributed over a large area; hence the capacity to withstand deformation becomes greater. During application of the load, the stresses that develop within the sample are transferred to the geogrid layers in the form of tension via frictional force owing to the interlocking and bonding that exists between the soil particles and the geogrid material [21][22].

Table 8: Large scale-UCS test results in kPa.

Unreinforced UCS test results _kPa			
Soil	82		
Soil+FA	95		
Reinforced UCS test results _kPa			
Geogrid type	TG-4	TG-20	TG-40
Soil+FA+ G(H/2)	136	168	178
Soil+FA+ G(H/3)	128	160	170
Soil+FA+ G(H/4)	110	155	159
Soil+FA+ G(2*H/4)	186	181	194

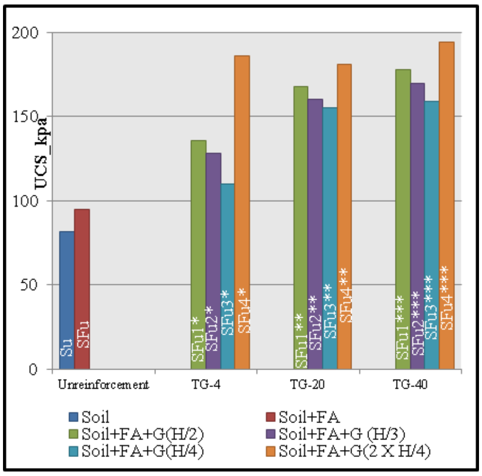

Figure 9: Large scale-UCS test results in kPa.

4.3 CBR test results

Load-penetration curves obtained from the CBR tests conducted with both unreinforced and reinforced specimens with varying numbers of reinforcing layers, reinforcement position, soaked and soaked. From the load-penetration curves, CBR values for each case were calculated for penetrations of 2.50 mm and 5.0 mm, and it was observed for all the cases that the CBR value corresponding to 2.50 mm penetration is higher than that obtained for 5.0 mm penetration. Therefore, the CBR values reported in table 9 are those of 2.50 mm penetration.

Table 9: CBR test results in %.

Unreinforced CBR test results_%						
	Unsoaked		Soaked			
Soil	4.7		1.4			
Soil+FA	6.7		2.5			
Reinforced CBR test results_%						
Geogrid type	**TG-4**		**TG-20**		**TG-40**	
Test condition	Unsoaked	Soaked	Unsoaked	Soaked	Unsoaked	Soaked
Soil+FA+ G(H/2)	14.4	9.8	14.4	9.8	14.9	9.8
Soil+FA+ G(H/3)	17.2	10.7	15.4	10.7	15.8	11.0
Soil+FA+ G(H/4)	21.0	12.2	18.2	11.6	19.1	12.1
Soil+FA+ G(2 X H/4)	22.6	13.5	20.5	12.8	21.0	13.3

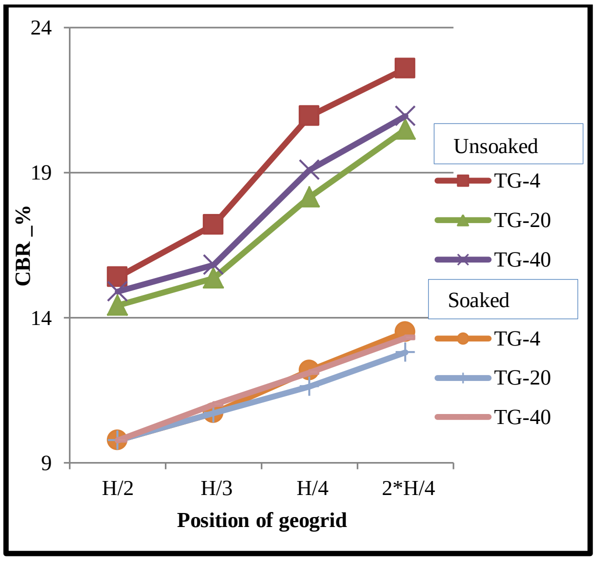

Figure 10: CBR test results in % for reinforced specimens for Unsoaked and soaked conditions.

CBR Performance ratios:

The improvement in CBR with reinforcement is measured in terms of performance ratios. The performance ratio is a ratio of the CBR value of reinforced flyash-modified soil to that of unreinforced flyash-modified soil. These ratios are indicative of the geogrid contribution towards increasing CBR for a given soaked condition, position, and type of geogrid [9].Table 10 shows performance ratio of unsoaked and soaked CBR tests. From this table, the flyash-modified soil exhibits a higher CBR value compared to the soil alone; both in unsoaked and soaked conditions. And compared to the CBR-unsoaked condition, the CBR-soaked condition shows higher performance ratios of the optimum flyash addition. Further the presence of a reinforcing layer within the specimen has a marked influence on its CBR performance ratio. Further, it is observed that the piston load at a given penetration is higher in all cases of reinforced specimens as compared to that of unreinforced specimens, and the amount of increase in the piston load depends on the number of reinforcing layers within the specimen as well as the reinforcement type. Expected, the CBR of soil samples is greatly affected by soaking; however, a notable improvement is noticed due to reinforcement. The presence of reinforcement is found to be advantageous for CBR results [21][22].

Table 10: Presentation of performance ratio for CBR results.

Unsoaked test combinations	Performance ratio		Soaked test combinations	Performance ratio
SFu/Su	1.42		SFs/Ss	1.78
SFu1* /SFu	2.15		SFs1* /SFs	3.92
SFu2* /SFu	2.56		SFs2* /SFs	4.28
SFu3* /SFu	3.13		SFs3* /SFs	4.88
SFu4* /SFu	3.37		SFs4* /SFs	5.4
SFu1** /SFu	2.15		SFs1** /SFs	3.92
SFu2** /SFu	2.30		SFs2** /SFs	4.28
SFu3**/SFu	2.71		SFs3**/SFs	4.64
SFu4**/SFu	3.06		SFs4**/SFs	5.12
SFu1***/SFu	2.22		SFs1***/SFs	3.92
SFu2*** /SFu	2.36		SFs2*** /SFs	4.4
SFu3***/SFu	2.85		SFs3***/SFs	4.84
SFu4*** /SFu	3.13		SFs4*** /SFs	5.32

A. Effect of specimen size

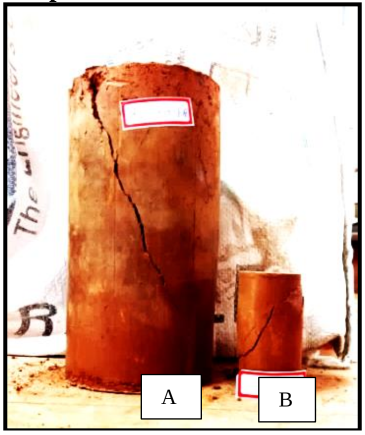

Figure 11: Failure pattern of UCS specimens for combination Soil+10%FA (A) Large-scale, (B) Small-scale

In this study, soil and flyash-modified-soil specimens of both small-scale and large-scale UCS specimens were considered and tested with same MDD, respective OMC, aspect ratio i.e., two and strain rate. Table 11 shows the UCS value in kPa for different dimensions of unreinforced specimens. The UCS value is varied with a high difference. Figure 11 shows the failure pattern of UCS specimens for combination Soil+10%FA (a) Large-scale, (b) Small-scale

The results of this study indicated a significant decrease in UCS, with an increase in the specimen diameter size. This can be attributed to an increase in heterogeneity and inherent weakness agents such as porosity, micro fissure, etc. due to an increase in the specimen diameter; these in turn influence the values of UCS [23]. This is expected owing to the small volume of specimen which provides the decreased number of micro-cracks and pores in the homogenous matrix as compared with the larger specimen sizes [24].

Table 11: The UCS values in kPa of Small-scale and Large-scale specimens for the unreinforced condition.

Combination	Small-scale specimen	Large-scale specimen
Soil	308	82
Soil+10% FA	387	95

B. Effect of position of reinforcement

The effect of the position of reinforcement in large-scale UCS test specimens of geogrid-reinforced flyash-modified soil was studied by considering all nine single-layer reinforced specimen combinations. The combination of specimens that have a reinforcement at H/2 position, i.e., SFu1*, SFu1**, and SFu1***, exhibits a higher UCS value, although strain at UCS is also exhibiting a high value with a better elastic modulus value compared to H/3 and H/4 positions, i.e., SFu2*, SFu2**, SFu2***, SFu3*, SFu3**, and SFu3***. The UCS value from positions H/2 to H/4 varies from 136 kPa to 110 kPa, 168 kPa to 155 kPa, and 178 kPa to 159 kPa for TG-4, TG-20, and TG-40, respectively.

The effect of the position of reinforcement in CBR test specimens of geogrid-reinforced flyash-modified soil was studied by considering all nine unsoaked single layer reinforced specimen combinations. The combination of specimens that have a reinforcement at H/4 position, i.e., SFu3*, SFu3**, and SFu3***, exhibits a higher CBR value, although strain at load is also exhibiting high compared to H/2 and H/3 positions, i.e., SFu1*, SFu1**, SFu1***, SFu2*, SFu2**, and SFu2***. The CBR value from positions H/4 to H/2 varies from 21% to 14.4%, 18.2% to 14.4%, and 19.1% to 14.9% in unsoaked conditions, and 21.2% to 9.8%, 11.6% to 9.8%, and 12.1% to 9.8% for TG-4, TG-20, and TG-40, respectively.

Figure 12 shows the failure patterns of UCS specimens for single layer reinforcement combinations of TG-20 geogrid. In all H/3 and H/4 reinforcement position failure plane extended from bottom to nearly center of specimen only. It is because of reinforcement is placed from top of H/3 and H/4. Hence, which may have caused the strength of soil in the top portion of the sample to be higher compared to the bottom section, which in turn could have let to the top section not affected to more strain during the UCS test. Moreover in H/2 single layer reinforcement combinations, failed specimens shows an inconsistency in the failure pattern in between the top and bottom portions of the sample. This could be attributed to the non-uniformity experienced during compaction for sample preparation, which may have caused the density of soil in the top portion of the sample to be higher compared to the bottom section, which in turn could have let to the top section not affected to more strain during the UCS test [25].

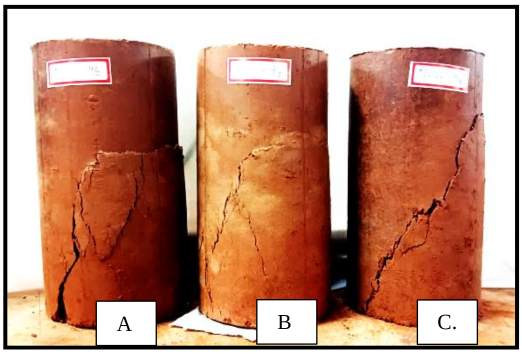

Figure 12: Failure pattern of UCS specimens for combinations of (A) SFu1**,(B) SFu2** and (C) SFu3**

In general, in UCS test specimen the majority of the tensile stress and strain occur in the middle section of the sample, compared to the top and bottom sections. Radial strain in particular typically originates from the

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sample's center and distributes outward from the center, lowering the strain as it reaches the end of the sample [25]. In H/2, the geogrid layers were placed nearer to the origin of stress and strain that likely occurred at the center of the sample, compared to H/3 and H/4, which could have led to higher extraction of tensile stress by the geogrid layers and consequent provision of greater reinforcement to the sample as compared to the rest of the samples. H/4 resulted in the lowest UCS value, most likely because its reinforcement layers were located the furthest from the center of the specimen, where the majority of the stress developed during the loading compared to the other samples. But in CBR test mould the majority of the deformation occurs at the top of the specimen while testing, compared to the sections at the bottom. Strain in particular typically originates from the sample's top by a CBR plunger and distributes downward from the top, the strain lowering as it reaches the bottom of the sample as shown in Figure 13 (A).

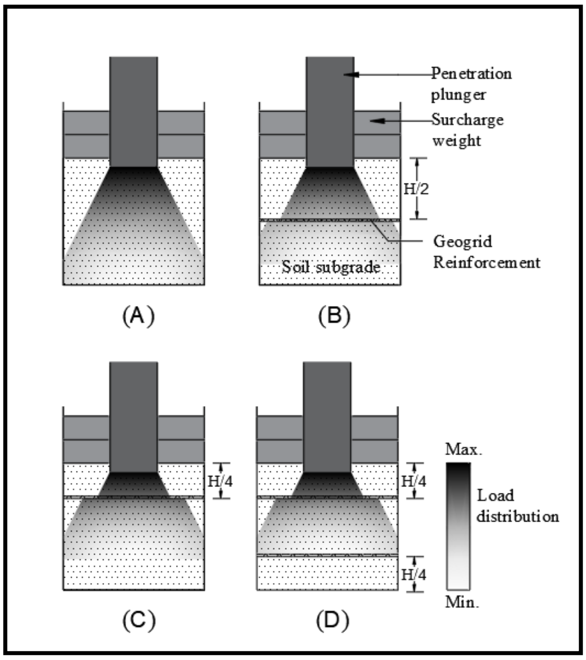

Figure 13: Load distribution phenomenon of unreinforced and reinforced soil on CBR testing, (A) Unreinforcement, (B) Single layer reinforcement at H/2 position, (C) Single layer reinforcement at H/4 position, and (D) Double layer reinforcement conditions.

In H/4, the geotextile layers were placed nearer to the origin of stress and strain that likely occurred at the top of the sample, compared to H/3 and H/2, which could have led to higher extraction of tensile stress by the geogrid layers and consequent provision of greater reinforcement to the sample as compared to the rest of the samples as shown in Figure 13 (C). H/2 resulted in the lowest CBR value, most likely because its reinforcement layers were located the furthest from the top of the specimen, where the majority of the stress developed during the loading compared to the other samples as shown in Figure 13 (B).

C. Effect of number of geogrids

All specimens of two-layer reinforcement systems and the optimum position in a single-layer reinforcement system, i.e., H/2 from the top of the specimen, were chosen for the comparison. It was observed from the Figure 9 that with an increasing number of geogrid layers, the UCS of double-layer reinforced soil is greater than the UCS of single-layered reinforced soil, although strain at the UCS is also exhibiting a high elasticity value. That is, SFu4*, SFu4**, and SFu4*** exhibit a higher UCS value compared to a single-layer reinforcement system, i.e., SFu4*, SFu4**, and SFu4***. The UCS value from positions H/2 to 2*H/4 varies from 136 kPa to 186 kPa, 168 kPa to 181 kPa, and 178 kPa to 194 kPa for TG-4, TG-20, and TG-40, respectively. Figure 14 shows failure pattern of UCS specimens for combination (A) SFu1* and (B) SFu4*, i.e., H/2 and 2*H/4 positions of reinforcement for TG-4. The failure plane for 2*H/4 is very different from the H/2 position. We can see that in the 2*H/4 position, the failure plane intercepts from both the upper and bottom portions of the specimen, but in the H/2 position, the failure plane intercepts from only one side, i.e., at the center. The study shows the resistance toward deformation is higher in the 2*H/4 position compared to H/2. But the origin of strain starts from the center of the specimen, and UCS strength improvement is also not significant when comparing these two combinations in all types of geogrids used. Hence, two-layer reinforcement systems can be used effectively by placing reinforcements at the origin of strain and in different reinforcement positions.

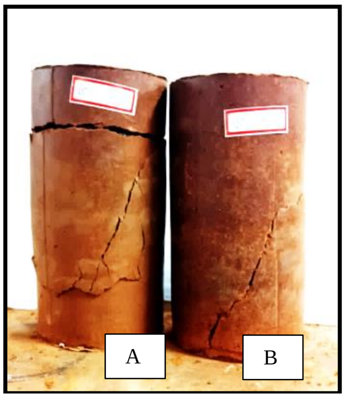

Figure 14: Failure pattern of UCS specimens for combinations of (A) SFu4* and (B) SFu1*

Figure 10 shows the change inflicted upon the CBR value of flyash-modified soil by increasing the number of reinforcement layers from 1 to 2 for different types of geogrids. Consequently, all specimens of two-layer reinforcement systems and the optimum position in a single-layer reinforcement system, i.e., H/4 from the top of the specimen, were chosen for the comparison. It was observed from the aforementioned Figure s that, with an increasing number of geogrid layers, the CBR value of double-layer reinforced soil is greater than the CBR value of single-layer reinforced soil. That is, SFu4*, SFu4**, and SFu4*** exhibit a higher UCS value compared to a single-layer reinforcement system, i.e., 21% to 22.6%, 18.2% to 20.5%, and 19.1% to 21.0% in unsoaked conditions, and 21.2% to 13.5%, 11.6% to 21.8%, and 12.1% to 13.3% for TG-4, TG-20, and TG-40, respectively.

The increase in both UCS and CBR values with an increasing number of reinforcement layers could be attributed to the corresponding rise in internal confinement provided to the solids by the geogrid layers. Moreover, the presence of a higher number of reinforcement layers increases the probability that the geogrid will intercept the deformation of the sample and lead to an even distribution of the stresses within the soil as shown in Figure 13 (D), increasing the overall strength of the corresponding sample. Hence, the joint interception of a vital failure plain by multiple reinforcement layers could explain the substantial delay in the failure of the double-layer sample as opposed to the specimen arrangements with single layers [25] [26].

D. Effect of Geogrid type

Figure 9 shows UCS test results in kPa for different positions and types of geogrid for the immediate test. Among all these three types of geogrids, the TG-4 geogrid exhibits higher strength, i.e., 136 kPa in the single layer and 186 kPa in the double layer, compared to the other two types of geogrids, i.e., TG-20 and TG-40, in both the single layer and the double layer reinforcement systems. Further Figure 10 shows the effect of the number of reinforcements on the CBR test. In this comparison, the optimum position of geogrid specimens in a single layer combination was chosen, i.e., H/4 from the top of the mold. Here also TG-4 exhibits higher strength, i.e., 21.0% and 22.6%, compared to TG-20 and TG-40, i.e., 19.1% and 22.6%, in both the single layer and the double layer reinforcement systems, respectively.

The increase in UCS and CBR value in TG-4 reinforcement can be observed even after its tensile capacity is lower compared to others. It is because the soil-reinforcement interface is more common in TG-4, which has a smaller aperture compared to the other two types of geogrids. Therefore, the combination of an appropriately strong geogrid with a well-designed shape can significantly enhance the UCS of soil, making it more stable and better suited for various engineering applications. After the termination of each UCS and CBR tests, the geogrid layers were separated from the specimen to carry out a visual inspection for deformation (rupture) of the reinforcement layers. It was noted that none of the geogrid layers ruptured. Therefore, it could be presumed that failure of the reinforced samples during the conduct of UCS experiments was not caused by any inadequacy of tensile strength provided by the geogrid layers [26].

5. Conclusions

Based on the results and detailed discussions presented the following conclusions can be deduced from the present study.

- RTPS’s flyash is non-pozzolanic flyash and belongs to classification "F". Also, this is a stable material, and we can satisfactorily use it as a filler material with soil.
- A small-scale UCS test shows that 10% of RTPS’s flyash exhibits the optimum flyash amount in the soil sample taken, and the incorporation of this into the soil significantly improves the strength and stiffness.
- When soil is tested for both small-scale and large-scale UCS with the same MDD, OMC, and aspect ratio, the observed trend is a decrease in strength as the diameter of the UCS specimen increases.
- Compared to the CBR-unsoaked condition, the CBR-soaked condition shows higher performance ratios with the optimum flyash addition i.e., 1.42 times in unsoaked condition and 1.72 times in soaked condition.
- The UCS and CBR values for the reinforced case are higher compared to all unreinforced combinations with increased elastic modulus values, affecting the stress-strain behavior of the soil. This was partly attributed to the additional apparent cohesion and confining pressure introduced to the soil grains by geogrid layers.
- The UCS values decreased continuously as the reinforcement layers were located away from the center of the specimen. Thus, the CBR values decrease continuously with the increase in the depth of geogrid in the mold. This was associated with the assignment of geogrid layer locations in the soil that experienced the maximum stress, strain, or displacement, which proved to be more effective compared to random placements.
- The optimum depth of placement for the single reinforcement in the UCS specimen is at H/2, and in the CBR specimen, it is at H/4 from the top of the specimen, which shows a higher UCS and CBR value than the other positions.

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- The UCS and CBR values of the soil increase significantly with an increase in the number of reinforcing layers and their relative positions within the soil. As evident from the elastic modulus values, the stress-strain behavior of soil improved considerably for the different cases considered in the study.
- The increase in strength in TG-4 reinforcement can be observed even after its tensile capacity is lower compared to others. The soil-reinforcement interface is as important as the strength of the geogrid. And also, large-aperture reinforcement inclusion in UCS and CBR tests does not exhibit better results because of the small test specimen size.

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