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Behaviour of a Reinforced Sand during Triaxial Loading

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Introduction

Reinforced soil is the soil interbedded with reinforcement. Earlier attempts consisted of using metallic reinforcements primarily consisting of foils and discs. The emergence of polymer based geosynthetics in the form of geotextiles, geogrids, geomembranes and geocomposites as reinforcing elements has revolutionised the soil reinforcement techniques. Reinforced soil is used in embankments on soft soils, earth retaining structures, foundations and pavements.

The analysis and design of reinforced soil structures requires the understanding of the behaviour of reinforced soil. This paper deals with the behaviour of a reinforced soil during triaxial loading.

Review

Reinforced soil consists of two different materials, viz., soil and reinforcement. A scientific approach was proposed first by Vidal (1966) to use reinforcement in the soil. Since then, several studies have been conducted for understanding the behaviour of reinforced soil. In majority of the studies, conventional triaxial tests (CTC) have been conducted.

A complete review of the studies conducted on the behaviour of reinforced soil has been given by Soni (1996). Herein a brief review has been summarised in Table 1. In this paper attention is focussed on the effect

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Table 1
Literature on Triaxial Tests on Reinforced Sand

S.No.	Author	Year	Reinforcement Used	Placement of Reinforcement	Stress-Path	Remarks on the Study
1	2	3	4	5	6	7
1.	Yang	1972	Woven fibre glass netting	Horizontal layers	CTC	Strength of rainforced soil as a function of confining pressure and number of layers.
2.	Long et al.	1972	Aluminum foils	Horizontal layers	CTC	Strength envelope of reinforced soil can be interpreted by Mohr Coulomb criterion.
3.	Hausmann and Vagnoron	1977	Aluminum foils	Horizontal layers	CTC	Two models known as tau model and sigma model were suggested for strength prediction based on results of Yang (1972).
4.	Saran et al.	1978	Aluminum foil and sheets	Horizontal layers	CTC	The behaviour of reinforced soil is found to be brittle. Strength was observed to be function of spacing of reinforcement
5.	McGown et al.	1978	Aluminum foil mesh and fabric	Horizontal layers	CTC	Soils with relatively inextensible inclusions may have rupture strains lower than the soil. Extensible reinforcement may have rupture strains larger than the soil.
6.	McGown et al.	1985	Geogrid	Randomly distributed mesh	CTC	Mesh improves the strength of soil
7.	Gray and Al-Rafeai	1986	Woven, non-woven fabrics and fibres	Horizontal layers and randomly oriented fibres	CTC	Continuous oriented (layers) fabric inclusions increase the ultimate strength and axial strains at failure. Discrete randomly distributed fibres increase both the ultimate strength and stiffness of reinforced soil

Table 1 Continued.......

1	2	3	4	5	6	7
8.	Rao et al.	1987	Woven geotextiles	Horizontal layers	CTC	Hausmann's model is applicable for reinforced soils
9.	Mandal and Agarwal	1989	Nylon fibres and woven fabrics	Horizontal layers	CTC	Introduction of reinforcement in soil fabric increases the strength and failure strains
10.	Chandransekharan et al.	1989	Non-woven and woven fabrics	Horizontal layers	CTC	Mobilized friction resistance along soil fabric interface is non-uniform
11.	Rao et al.	1989	Woven and non-woven fabrics	Horizontal layers	CTC	Hyperbolic relation holds good for rainforced soils
12.	Varadarajan et al.	1992	Non-woven geotextiles	Horizontal layers	CTC. TC & RTC	Stress-strain and volume change behaviour of reinforced soil is stress path dependent
13.	Baykal et al.	1992	Non-woven and woven geotextiles	Horizontal layers	CTC & TC	Stress-strain behaviour of reinforced soil is stress path dependent
14.	Shamsher	1992	Non-woven and woven geotextiles	Horizontal layers and randomly distributed	CTC	Strength of reinforced soil can be predicted from Hausman's model and hyperbolic relation is valid for reinforced soils
15.	Atmatzidis and Athanasopoulos	1994	Non-woven and woven geotextiles	Horizontal layers	CTC	Triaxial tests appear feasible alternative to conventional pullout and direct shear tests to determine coefficient of interface friction
16.	Rao et al.	1994	Non-woven, woven geotextiles and geogrids	Horizontal layers	CTC	Strength of reinforced soil increases with number of layers. Also bearing capacity improves due to reinforcement but marginal variation in settlement

Note: CTC, TC, RTC, HC, RTE, TE and CTE are defined in text (Fig. 1) of locally manufactured reinforcement on the soil under various stress paths hitherto not adopted under triaxial loading.

Scope

The scope of the present study is to conduct drained triaxial tests on natural and reinforced sand using various stress-paths in both compression and extension sides to investigate the effect of type of reinforcement manufactured in India and the number of layers of reinforcement on the stress-strain volume change behaviour.

Materials Used

Ennore sand procured from the coastal area of southern part of Indian subcontinent near Chennai has been used in the study. This sand is also known as the Indian standard sand and has the following properties:

specific gravity = 2.64,

uniformity coefficient = 1.63,

effective size, D_{10} = 0.40 mm

median size, D_{50} = 0.60 mm,

maximum dry unit weights = 18 kN/m^3 and

minimum dry unit weights = 16 kN/m^3.

The soil particles are derived from quartz and are sub-rounded to rounded shape. For reinforcement, needle punched nonwoven and woven geotextiles have been used. The properties of the geotextiles are presented in Table 2.

Table 2
Characteristics of the Non-Woven and Woven Geotextiles

Type	Non-woven needle punched	Woven
Colour	White	White
Material	Polypropylene	Polypropylene
Thickness at 2 kPa	2.8 mm	0.66 mm
Average tensile strength in machine direction	10.77 kN/m	19.75 kN/m
Average tensile strength in cross-machine direction	12.53 kN/m	20.10 kN/m

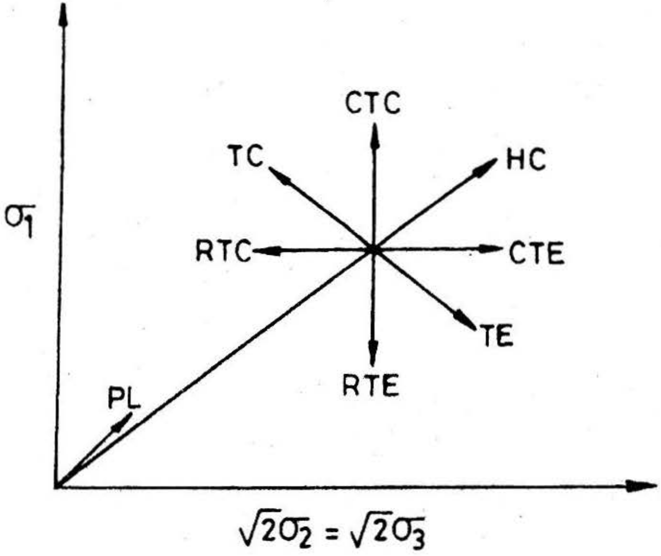

FIGURE 1 : Schematic Representation of Stress-Paths

Experimental Programme

Drained triaxial tests have been conducted on 3.81 cm dia. and 7.62 cm long cylindrical samples. Four series of tests have been conducted on

(i) natural sand

(ii) reinforced sand using single reinforcement layer of nonwoven geotextile at the mid height of sample designated as R1NW,

(iii) reinforced sand with two horizontal layers of nonwoven geotextile at one third and two thirds heights of the sample referred as R2NW and

(iv) same as in (iii) but with woven geotextile referred as R2W.

Six stress-paths, three on compression side and three in extension side as shown in Fig. 1 in addition to hydrostatic compression path have been adopted for testing. The stress-paths are:

(i) Conventional Triaxial Compression Test, CTC in which axial stress σ_1 is increased while radial stress σ_3, is kept constant

(ii) Triaxial Compression Test, TC, in which σ_3 is decreased and σ_1 is increased so that the average mean stress $(\sigma_1 + 2\sigma_3)/3$ is constant,

(iii) Reduced Triaxial Compression Test, RTC, in which σ_3 is decreased while σ_1 is kept constant,

(iv) Conventional Triaxial Extension Test, CTE in which σ_3 is increased while keeping σ_1 constant,

(v) Triaxial Extension Test, TE in which σ_1 is decreased and σ_3 is increased so that $(\sigma_1 + 2\sigma_3)/3$ is constant and

(vi) Reduced Triaxial Extension test in which σ_1 is decreased while keeping σ_3 constant.

Confining pressures in the range of 100-300 kPa have been applied during consolidation stage.

Experimental Set-up

Computer controlled triaxial apparatus has been used for testing. The details of the equipment are given in the manuals. The salient features of the equipment are presented herein. The equipment consists of a triaxial cell, three digital pressure controllers, a desk top computer, and a graphics plotter.

The triaxial cell comprises of two chambers, the upper chamber where the test specimen is set up and the lower chamber where the axial force is generated. The two chambers are separated by an actuating piston sealed by bellofram rolling diaphragms into the chamber at each end. Axial load is exerted on the test specimen by means of the piston fixed to the movable base pedestal. The top cap of the test specimen is fixed in position by an adjustable rod passing through the top of the cell.

For extension test, an extension device is fitted to triaxial cell to allow axial stress to be reduced below radial stress.

Digital pressure controller is a microprocessor controlled hydraulic actuator for precise regulation and measurement of liquid pressure and liquid volume change. It is used to measure axial, cell and back pressures and volume change. The device has its own computer interface and can be controlled directly from a computer.

The desk top computer is used to (i) conduct stress/strain controlled drained/undrained tests under various stress-paths, (ii) acquire data and (iii) produce results in tabular/graphical form.

Experimental Procedure

Cylindrical samples have been prepared under saturated condition using

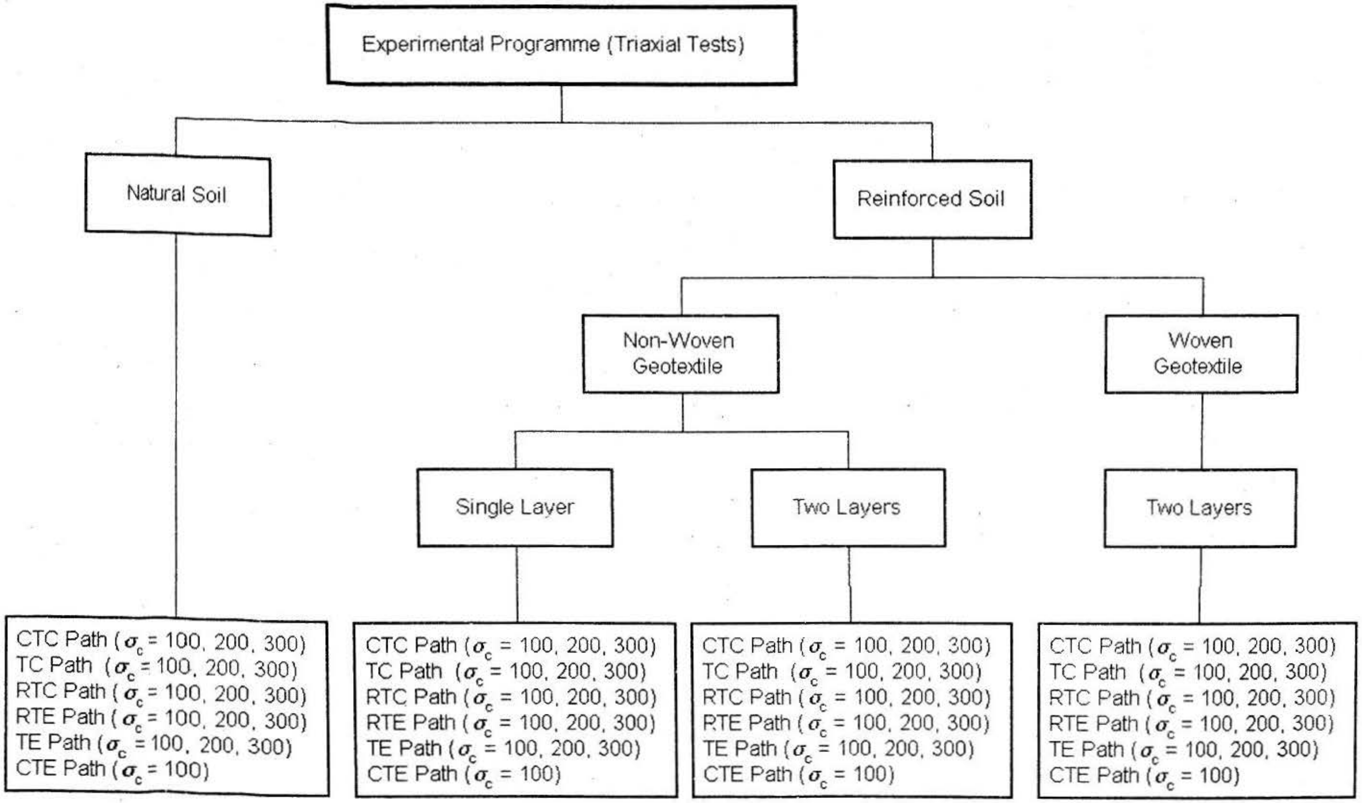

FIGURE 2 : Experimental Testing Programme

split mould (Bishop and Henkel) A uniform system of tamping has been adopted to obtain a relative density of 70% for all the samples. Nonwoven and woven geotextiles have been cut in the form of circular discs and placed in the soil samples at the required location during sample preparation.

The samples have been subjected to hydrostatic compression to the required pressure and then sheared to failure under various stress-paths under drained condition. Strain-controlled loading has been adopted for CTC and RTE paths with a strain rate of 0.38 mm/min. For other stress-path tests stress-controlled loading has been used. The tests have been conducted using the computer program GDSTTS and the computer program, GDSFBP has been used for data reduction. In all 62 tests have been conducted. The details are shown in Fig. 2.

Results and Discussion

Mean stress (σ_m) – volumetric strain (ε_v) relationship of natural and reinforced soil samples are shown in Fig. 3. It is found that

i) reinforced soils exhibit higher strains than natural soil at all stress levels (Table 3).

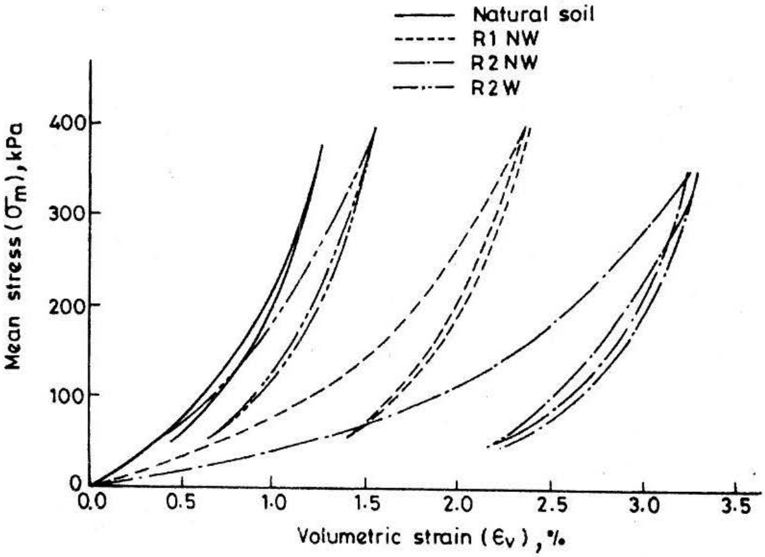

FIGURE 3 : Mean Stress-Volumetric Strain Relationship for Natural and Reinforced Soils for HC Path

Table 3
Volumetric Strains at σ_m = 100 kPa for HC path

Type of Series of Tests	Total strain %	Non-recoverable strain, %
Natural Soil	0.61	0.08
R1NW	1.25	0.42
R2NW	1.90	0.70
R2W	0.66	0.26

ii) volumetric strain increases with number of reinforcement layers.

iii) soil with nonwoven geotextile reinforcement shows higher volumetric strains than the soil with woven geotextile reinforcement.

iv) reinforced soils show large recoverable strains on unloading (Table 3). The non-recoverable strains increase with number of reinforcement layers. Nonwoven geotextile reinforced soils exhibit higher non-recoverable strains than woven geotextiles. Natural soil show very small non-recoverable strains.

v) The difference in stress-strain responses between unloading and reloading is insignificant for natural as well as reinforced soil.

It is observed that the variation in strain during unloading is negligible for all the three cases of reinforcement. This behaviour of reinforced soil is explained as follows. When the geotextile is compressed, rearrangement of soil particles takes place and the soil particles get locked in the geotextile. This locking-in of the particles depends on the size, shape and gradation of the soil and the characteristics of the geotextile. After locking-in of the particles, the reinforcement behaves as an integral part of the soil. On unloading, the geotextile does not regain its original position due to locking-in of the soil particles.

The stress-strain volume change behaviour of all the tests have been presented in Soni (1996). Herein the stress-strain-volume change relationships of limited tests for natural and reinforced soil samples have been presented. Figures 4 to 7 show stress-strain-volume charge relationship for TC and TE stress-paths for natural and reinforced soil samples, R1NW. It is observed that (i) the axial strains are higher for TC paths than TE paths and (ii) TC paths show volume expansion whereas TE paths show volume contraction near failure. Similar behaviour was observed for reinforced soil samples R2NW and R2W.

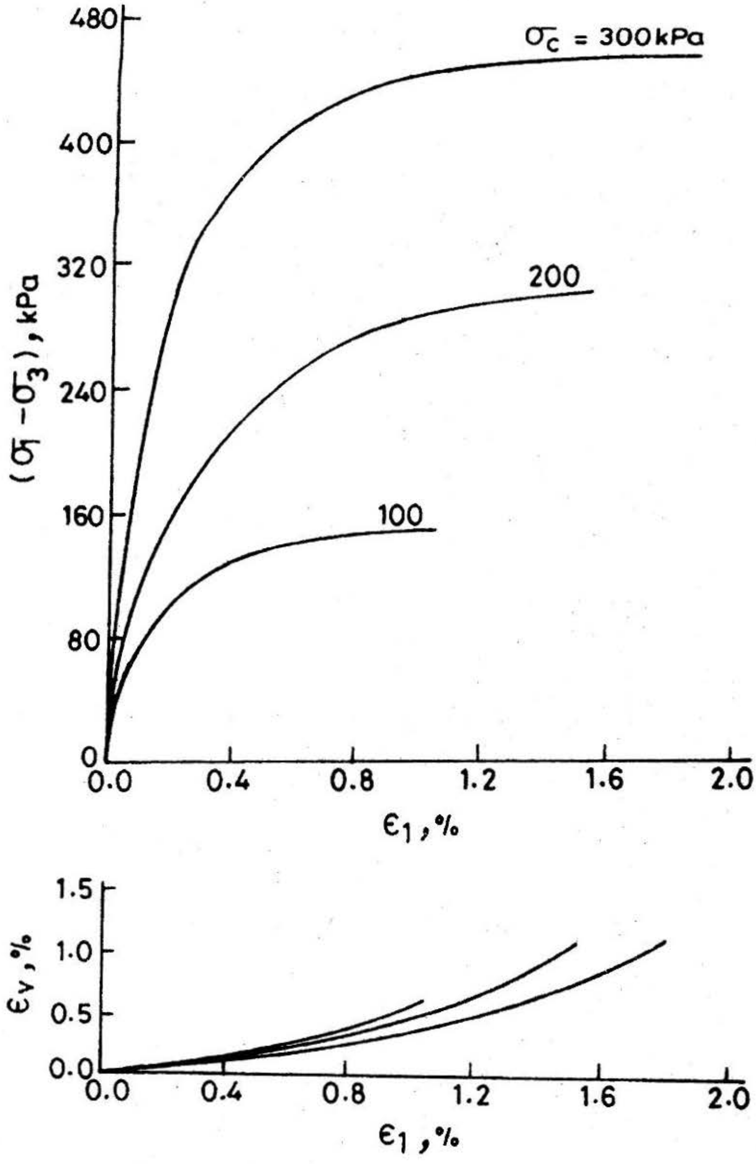

FIGURE 4 : Stress-Strain-Volume Change Relationship for Natural Soil for TC Path

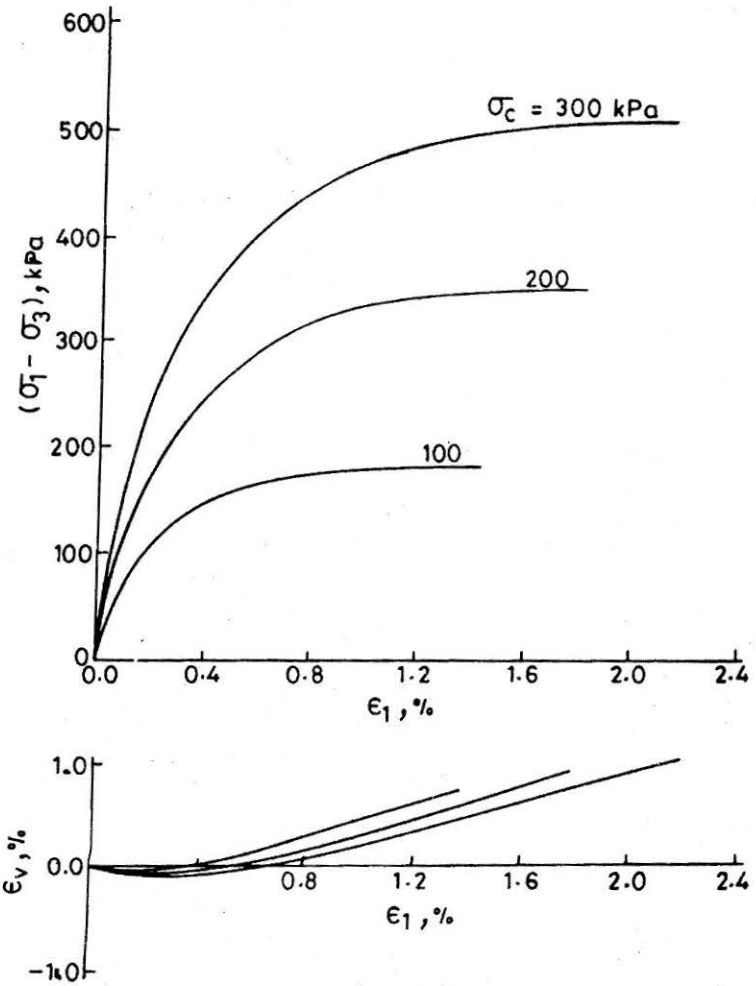

FIGURE 5 : Stress-Strain-Volume Change Relationship for Natural Soil for TC Path

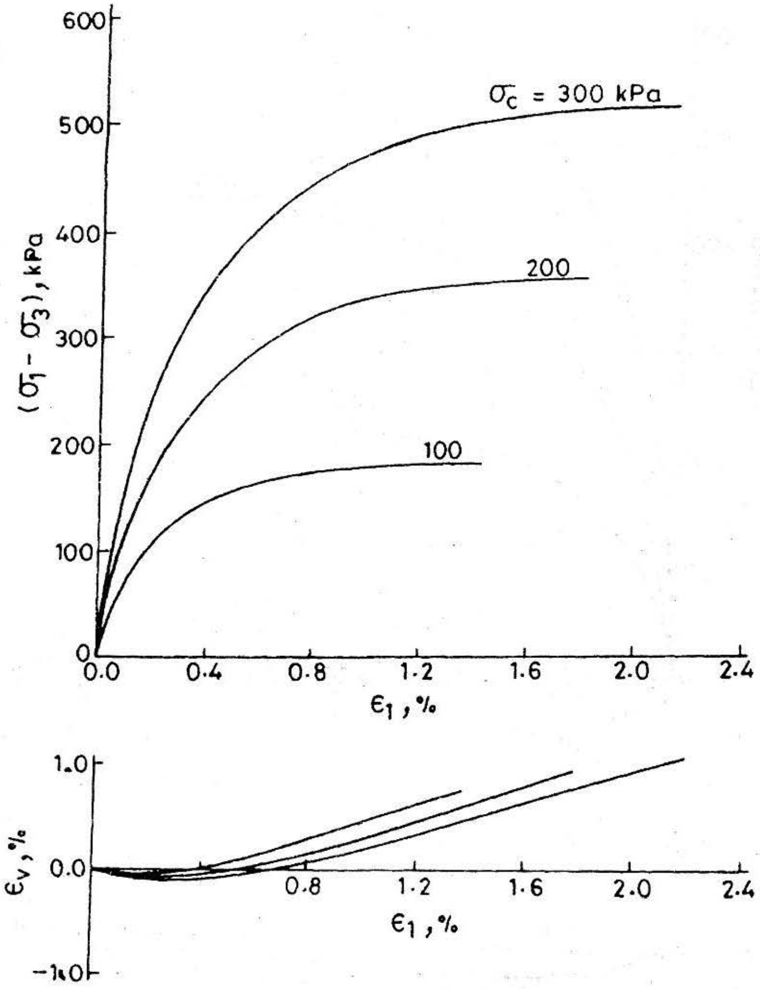

FIGURE 6 : Stress-Strain-VolumeChange Relationship for R1NW Soil for TC Path

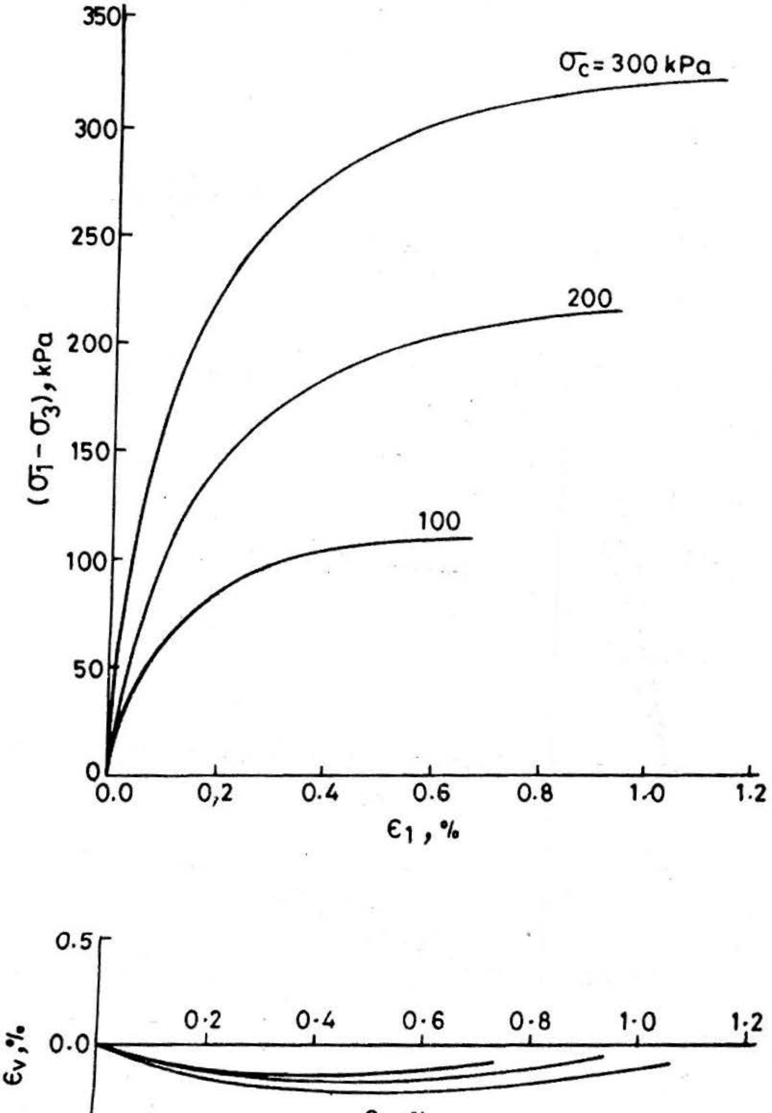

FIGURE 7 : Stress-Strain-Volume Change Relationship for R1NW Soil for TE Path

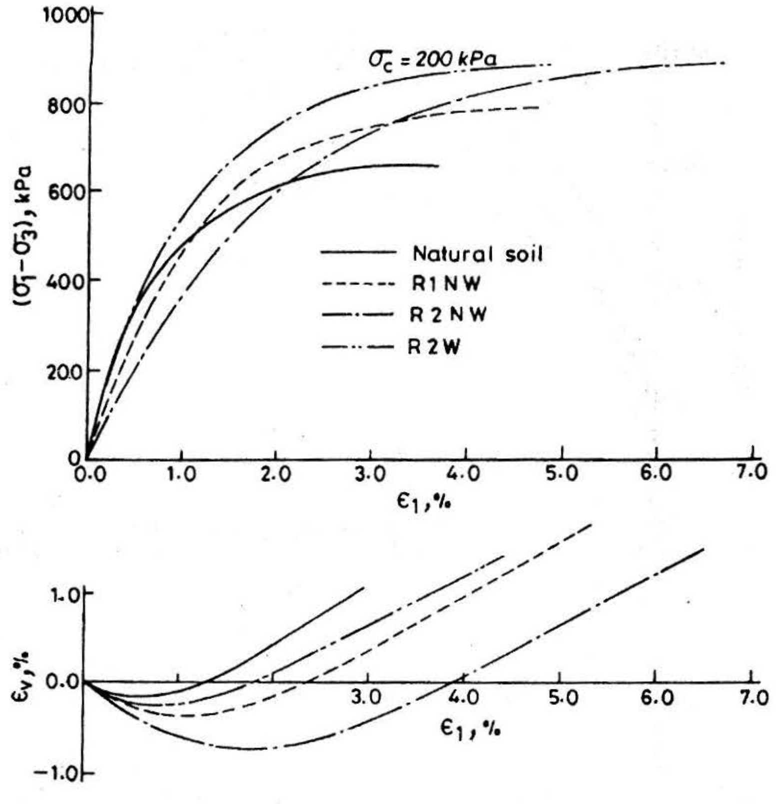

FIGURE 8 : Comparison of Stress-Strain-Volume Relationship for Natural and Reinforced Soil for CTC Path at σ_c = 200 kPa

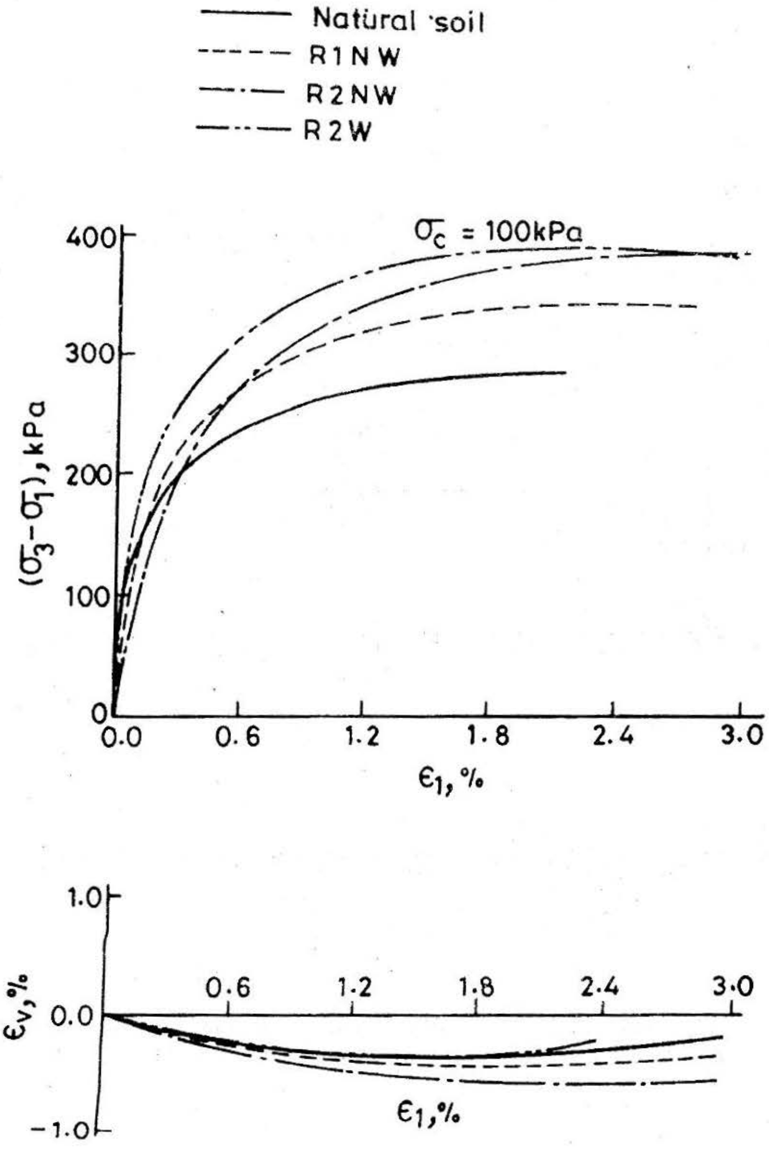

FIGURE 9 : Comparison of Stress-Strain-Volume Relationship for Natural and Reinforced Soil for CTE Path at σ_c = 100 kPa

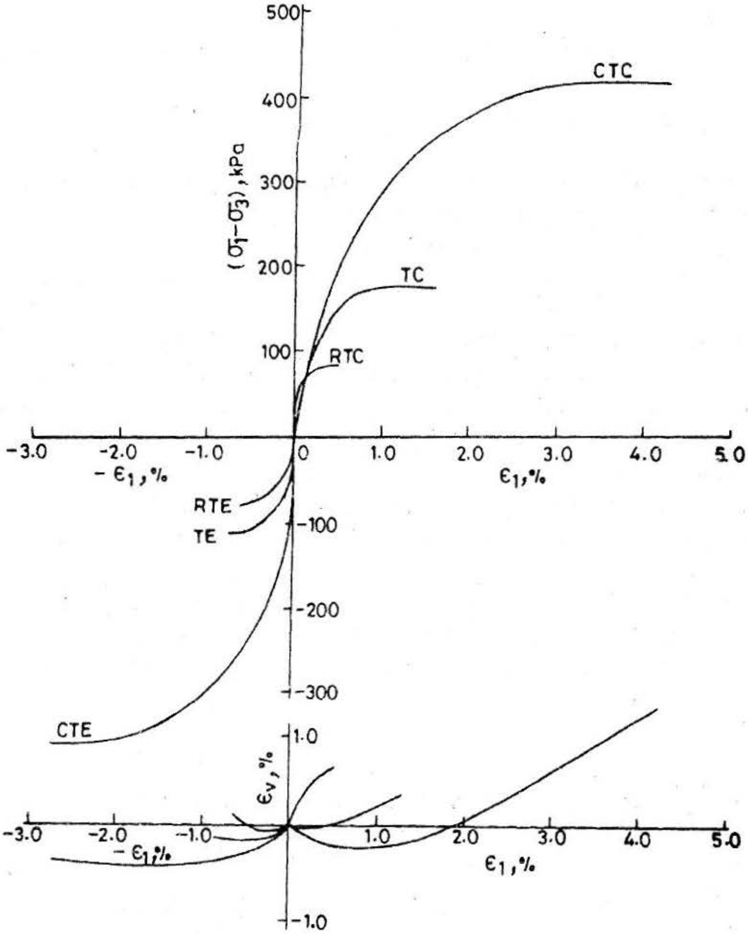

FIGURE 10 : Stress-Strain-Volume Change Relationship for R1NW Soil for various Stress Paths at σ_c = 100 kPa.

Figures 8 and 9 show comparison of stress-strain-volume change responses for natural and reinforced soil samples for CTC and CTE paths. As would be expected, reinforced soil samples show higher strength. Increase in number of layers gives more strength. Nonwoven geotextile produces flatter stress-strain curve. Similar findings have been reported by other investigators (for example Mandal and Agarwal, 1989; Rao et al., 1994).

Volume contraction increases with reinforcement as well as number of layers. Nonwoven geotextile shows more volume contraction than woven geotextile because of their higher compressibility.

The effect of reinforcement for other stress-path tests are similar in nature though the magnitudes are different.

In Fig. 10 is shown the stress-strain volume change relationships of reinforced soil, R1NW for various stress-paths at $\sigma_c = 100$ kPa. On the compression side, CTC path shows largest axial strain and volumetric contraction whereas RTC path shows smallest axial strain and volume expansion. On the extension side, CTE path exhibits largest axial strain and volume contraction whereas RTE path shows lowest volume contraction. The behaviour is similar in nature for other reinforced soils as well as natural soil. The failure of samples in the compression side is characterised by bulging and that in extension side is depicted by stretching.

Table 4 gives the failure strains for natural and reinforced soils for various stress paths. The effect of reinforcement results in considerable increase in the axial strains. The percentage increase, in general, is the same

Table 4
Comparison of the Strains at Peak Deviator Stress

Stress paths	σ_0 kPa	Natural soil	R1NW		R2NW		R2W	
		Failure, strain, %	Failure strain,	% Over Natural soil	Failure	% Over Natural soil	Failure	% Over Natural soil
CTC	200	3.00	4.00	33	6.50	116	4.00	33
TC	200	1.50	2.00	33	3.00	100	2.00	33
RTC	200	0.45	0.60	33	0.85	89	0.60	33
RTZ	200	0.50	0.65	39	0.90	80	0.65	30
TE	200	0.75	0.95	27	1.50	100	1.00	33
CTE	100	2.10	2.70	28	3.00	43	2.70	28

Table 5
Comparison of the Strength of Natural and Reinforced Soils

Stress paths	σ_0 kPa	Natural soil kPa	R1NW		R2NW		R2W	
			Strength kPa	%age increase over natural soil	Strength kPa	%age increase over natural soil	Strength kPa	%age increase over natural soil
CTC	200	650	800	23.08	865	33.07	850	30.08
TO	200	300	345	15.00	360	20.00	356	18.67
RTC	200	152	161	5.92	165	8.55	164	7.99
RTE	200	150	158	5.33	160	6.67	160	6.67
TH	100	202	218	7.92	220	8.91	220	8.91
CTE	100	295	350	18.64	330	3.22	380	28.01

for all stress-paths. The strain increases with the number of layers. Nonwoven geotextile causes more strain than woven geotextile since nonwoven geotextile is more compressible than woven geotextile.

In Table 5 is presented the strength of natural and reinforced soils for various stress-paths at the same σ_c values. It is observed that (i) the strength increases with number of layers (ii) nonwoven and woven geotextiles provide almost the same increase in strength (iii) the increase in strength varies with stress-path, the highest being for CTC path (iv) stress-paths on the compression side show higher increase in strength than the stress-paths on the extension side, the highest difference being between TC and TE paths.

It appears that increase in strength due to reinforcement is a function of average mean stress σ_m. As the value of σ_m increases (from RTC to CTC and from RTE to CTE) the effectiveness of reinforcement also increases in providing higher strength. The effectiveness of reinforcement is higher for strain-paths on compression side than those on extension side.. A comparison of increase in strength of TC and TE paths in which average mean stress is constant clearly reveals that the outward stretching of the reinforcement (additive to that caused during isotropic compression) in TC path is more effective than the inward stretching of the reinforcement (subtractive to that caused during isotropic compression) in the TE path.

The effectiveness of reinforcement decreases with confining pressure as shown in Fig. 17 for CTC path. Similar effect has been noted for other stress-paths.

Table 6
Comparison of the Angle of Internal Friction of Natural and Reinforced Soils

Series of test	Angle of internal friction, degree		Increase in the angle of internal friction of reinforced soil over natural soil, degree	
	Compression	Extension	Compression	Extension
Natural soil	37.6	36.4	–	–
R1NW	41.8	41.6	4.2	5.2
R2%	43.7	41.8	6.1	5.4
R2W	43.4	41.8	5.8	5.4

Table 6 presents angles of shearing resistance for natural and reinforced soils. It is noted that (i) as would be expected angle of shearing resistance ϕ increases with the inclusion of reinforcement (ii) the ϕ values for compression side increase with number of layers whereas the increase in ϕ value for extension side is very small and (iii) nonwoven and woven geotextile give almost the same values.

Conclusions

Hydrostatic compression tests show that the effects of reinforcement and number of layers of reinforcement are to increase volumetric strains during loading and unloading. The samples with nonwoven geotextile/ reinforcement undergo larger strains than those with woven geotextile reinforcement.

Under triaxial loading, the effect of reinforcement is to increase axial strains, volume contraction and strength; this effect increases with the increase in number of layers. The effect of nonwoven geotextile reinforcement is high on axial and volumetric strains but the effect on strength is nearly the same for both the reinforcement types.

The effect of stress-path on strain and strength for reinforced soil is very significant. The effect is more pronounced for compression than for extension paths.

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