Shear Strength Behaviour of Desiccated Soils

by

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Introduction

The widespread existence of arid and semi-arid areas on the Earth's surface necessitates an enhanced understanding of their geotechnical behaviour. The soils met with in these areas may be described as desiccated soils. Seasonal changes in temperature and humidity affect these soils to considerable depths and may therefore influence their geotechnical behaviour.

A study of literature indicates that changes in colour, acid soluble constituents and the gain and loss of certain constitutents occur when soil is excavated, transported and replaced in areas of different climatic conditions (Lipman and Wayrick 1916). Soil exhibits a tendency to gain in iron and lose in alumina constituents when exposed to arid conditions. Soil acidity changes from *pH* 7.8 in the semi-arid regions to *pH* 5 2 in the semi-humid regions (Jenney and Leonard 1934). Sources of organic and mineral acids present in soils have been well documented by various investigators, notably Stephenson (1919, 1921) and Mirasal (1920). Studies on the chemical action of water on minerals and rock reveal that solution, hydrolysis and decomposition of soil compounds takes place (Dracher (1933), Grant (1974)). Water initially soluble salts which are extracted even when the ratio of water to soil is small. Under different conditions, the soil may unite with acidic and basic groups resulting in the regeneration of the soil. Leaching has been found to reduce *pH* values. A similar effect occurs on heating (Huberty and Haas 1940). Alternate wetting and driving, resulting in the build up and breakdown of soil granules, is reported to be partly responsible for a continuous increase in the percentage of water stable aggregates (Alderfer 1946). The extent to which discrete or elementary non-aggregated soil particles are grouped to form or less stable aggregates is a function of several factors like the grain size distribution, amount of clay, type of clay mineral present, nature of the saturating cation populations, presence and solubility of excess entities as well as organic decomposition, and organic cementing agents (Arca and Weed (1966), Watson and Stojanvic (1965), Gupta and Sen (1962)).

Individual clay particles can be linked into larger particles by hydrogen and potassium ions, naturally occurring cementing agents like carbonates, iron oxides, silicates, aluminates and certain organic matter (Lambe 1960) Seed *et. al.* (1960), Kenney *et. al.* (1967)). Particle cementation is added by drying which brings the particles closer together and precipitates

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cementing agents. Chemical attack by suitable regents on the majority of soil components is capable of forming covalently bonded macrolatticed compounds possessing considerable potential strength. Under suitable conditions, this is the end result of alternate wetting and drying cycles Ingles (1962).

Clay rewetted after severe desiccation exhibited an irreversible and significant increase in shear strength, which was attributed primarily to an increase in true cohesion and a small increase in the true angle of shearing resistance. These changes were attributed to an irreversible change in the void ratio produced by desiccation moisture stresses, Blight (1966). Repeated wetting and drying of a lateritic gravel resulted in a significant increase in unconfined compressive strength which was attributed to aluminium oxide bonding in the earlier stages and re-crystallization of ferric oxide in the later stages, Grant (1974). Subjecting a natural soil to repeated wetting and drying has been found to result in greater shear strength and brittleness. The cohesion has been found to increase and this has been attributed to the generation of chemical bonds in the soil by the wetting and drying process, Allam and Sridharan (1981). A study of the volume change behaviour of natural desiccated soils has shown that these soils possess reduced compressibility and greater permeability in their undisturbed state. Cementing agents of Ca, Mg, Al and Fe have been detected and it has been shown that their presence marks the presence and action of non-expanding or expanding lattice structured clay minerals in the soil fines, Sridharan and Allam (1962).

In this study the shear strength behaviour of desiccated soils has been investigated and the role played by the chief effects of climatic changes in influencing strength characteristics of the soil is examined.

Theoretical Considerations

From the above it can be inferred that climatic changes, particularly in the form of repeated wetting and drying, are capable of bringing structural and mineralogical changes in a natural soil. The soil particles can be expected to be linked together by a network of covalently bonded macrolatticed compounds so that they are cemented together. These compounds can be expected to increase the strength of the soil.

When the shear strength and stiffness of a soil are examined from the viewpoint of the modified effective stress concept, Sridharan and Rao (1973) which defines the contact stress as the effective stress controlling shear strength and volume change, it is clear that any increase in net interparticle attraction (intrinsic effective stress*), due to the introduction of

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* The conventional effective stress equation has been modified by Sridharan and Rao (1973) as

$$\bar{C} = \sigma - u + A - R$$

where $\bar{C}$ = contact stress which controls the shear strength and volume change behaviour of soils. The term (A-R) which represents the net attractive force resulting from various sources of attraction and repulsion between fine particles, is defined as the intrinsic effective stress. For all factors like dielectric constant, ion concentration, valency, etc., remaining same, changes in particle orientation ie. fabric, can result in changes in value of (A-R). Cementation forces (bonds) can also contribute to the amount of (A-R) present in a soil.

cementing bonds at particle contacts or due to changes in the pore fluid properties, will increase the effective stress and hence the stiffness and shear strength of the soil. Thus it can be anticipated that undisturbed natural desiccated soils possess an effective stress, imparted to them as a result of fabric changes and the deposition of cementing materials at particle contacts brought about by climatic changes. which enhances their resistance to shear and deformation. Remoulding these soils should result in loss of strength and stiffness as this additional effective stress is destroyed when fabric changes and rupture of interparticle cementing bonds take place. Comparison of the strength and stiffness possessed by such soils in their undisturbed and remoulded states is thus a measure of the contribution of climatic changes to the intrinsic effective stress present in them. Since climatic changes also generate cementation between particles, removal of cementing agents by chemical treatment, eg. by circulating EDTA solution (disodium salt of ethylene diamine tetracetic acid), which does not alter soil fabric should also result in some loss of strength and stiffness. Further, the shear strength behaviour of natural desiccated soils should be similar to that of a soil in which a network of cementing bonds has been introduced, e.g. iron hydroxide bonds. To verify this an experimental investigation has been conducted on a cemented soil prepared in the laboratory.

The desiccated soil having a stiffer fabric should also fail at lower strain levels and possess greater incompressibility. The pore pressure parameters A and B should be significantly different for the undisturbed and remoulded states of the soil. The greater stiffness of the desiccated soil should result in the soil fabric supporting a larger proportion of externally applied pressure (i. e. yield lower B values) and hence it should be possible to obtain ϕ values from $\overline{UU}$ shear tests on such soils.

The shrinkage stresses while bringing the particles closer together and thus increasing the dry density of the soil also produce fissures and microcracks. While the permeability of the undisturbed soil is thus increased, Sridharan and Allam (1982) it can be expected that the angle of shearing resistance of the soil is less than for the remoulded soil since it has been reported that fissured clays Lo (1970) yield a shear strength value between that for the intact material and that for failure along the fissures. Treatment with EDTA solution which removes cementing compounds of Al, Fe, Mg and Ca without altering the soil fabric should result in a loss of shear strength similar to that occurring on remoulding but yield an angle of shearing resistance similar to that of the undisturbed soil.

The study reported here examines the strength behaviour of some typical natural desiccated soils in their undisturbed and remoulded states in the light of the above predictions.

Experimental Work

To obtain data on the shear strength behaviour of desiccated soil, four typical desiccated soils sampled at depths varying between 2 and 3m in and around Bangalore, South India were subjected to conventional isotropically consolidated undrained shear tests in their saturated undisturbed and remoulded conditions. The chemical composition of these soils varied between the following limits (percentage by dry weight) :

Silica (SiO_2) — 60-70 per cent
Alumina (Al_2O_3) — 14-20 per cent

Ferric Oxide (Fe_2O_3) — 0.5-8 per cent

Potassium Oxide (K_2O) — 1.0-5 per cent

Calcium Oxide (CaO) — 0.5-4.5 per cent

Magnesium Oxide (MgO) — 0.5-1.5 per cent

The soils can be described as non-lateritic for the silica to alumina ratio is in excess of 3.0. The index properties of the soils range between : liquid limit, 38 to 53 per cent, plastic limit, 18 to 33 per cent, sand fraction, 46 to 70 per cent, silt and clay fraction 30 to 52 per cent.

For one soil, treatment with saturated EDTA (disodium salt of ethylene diamine tetracetic acid) solution, which was done by circulating the solution under a pressure of 13.78 kPa through triaxial test specimens initially consolidated to 34.45 kPa, was found to extract an average of 60 mg of Fe, 60 mg of Al, 20 mg of Ca and 80 mg of Mg from the specimens. Since the natural soils of Bangalore contain as much as 70 per cent sand with kaolinite as the dominant clay mineral and contain upto 8 per cent Fe_2O_3 by weight, it was decided to prepare an artificially cemented soil in the laboratory composed of 66 per cent sand passing through ASTM No. 40 sieve and 34 per cent kaolinite by weight. The higher percentage of sand was primarily chosen in order to have higher permeability. This mixture has LL = 21 per cent, PL = 15.5 per cent, and G = 2.61. Ferric chloride was added to the water used for remoulding so that the soil contained 2 per cent ferric chloride by weight in the dry state. The remoulding water content was 18 per cent and the triaxial test specimens prepared by hand remoulding were cured in an atmosphere of ammonia in order to precipitate iron hydroxides in the soil pores and thus cement the soil particles. Curing was done for a month in order to ensure complete precipitation. The specimens thus prepared were subjected to conventional isotropically consolidated undrained and unconsolidated undrained shear tests. After testing the cemented specimens, they were dried, broken down and remoulded specimens were prepared using an initial water content of 18 per cent. These remoulded specimens were subjected to similar tests. A strain rate of 0.08 per cent per minute was adopted for all the tests reported in this investigation.

For examining the influence of repeated wetting and drying on a natural soil, triaxial test specimens prepared from a disturbed quantity of soil 4 were subjected to repeated wetting and drying in the laboratory. Details of this study have been reported elsewhere Allam and Sridharan (1981) and and the findings have been used in this study for interpreting the exprimental data collected.

Results and Discussion

The Stress-Strain Response :

Fig. 1 shows typical results obtained $\overline{UU}$ and $\overline{CIU}$ shear tests on desiccated soils. It is obstrved that the disturbed soil exhibits larger

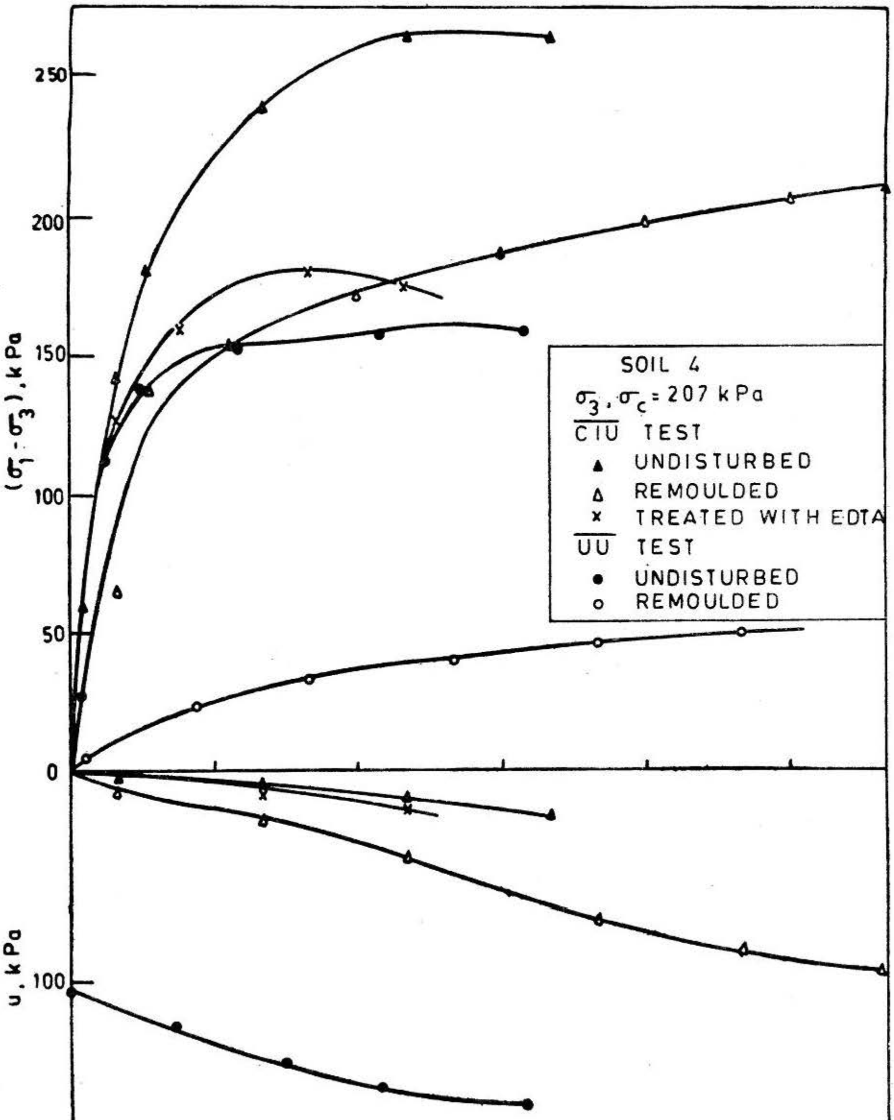

FIGURE 1 Typical Stress-Strain and Pore Water Pressure-Strain Curves for Soil 4

shear strength and a stiffer stress-strain response. Further, the strain at failure is more for remoulded soil, and this is more pronounced in the $\overline{UU}$ test. This is as predicted in the theoretical considerations. The average strain at failure for $\overline{UU}$ and $\overline{CIU}$ tests is given in Table-1. The reduction in shear strength and stiffness on remoulding is greater in case of $\overline{UU}$ as compared to $\overline{CIU}$ tests. Fig. 2 presents the stress-strain response of the cemented in the laboratory from which it is seen that identical changes in strength, stiffness and failure strain (Table-2) occur on remoulding. Since these changes can be attributed to the iron bonds introduced in the cemented soil it can therefore be concluded that similar bonds exist in the desiccated soil. The shear strength of the cemented soil is greater than that of the desiccated soil (Figs. 1 and 2). This can be attributed to the presence of more and/or better bonds in the cemented soil as they were generated under controlled conditions. Fig. 1 also shows the stress-strain behaviour of desiccated soil wherein EDTA solution was circulated to remove and chemical bonds present. The noticeable reduction in shear strength occurring on treatment indicates that the bonds present in desiccated soils are possibly chemical in nature as an analysis of the spent EDTA solution showed that quantities of Ca, Mg, Al and Fe had been removed from the soil.

For disturbed natural soil subjected to repeated wetting and drying, it was reported Allam and Sridharan (1981) that the soil gained progressively in strength and stiffness. Significant reductions in shear strength and noticeable reductions in stiffness were also reported when, after having undergone many cycles of wetting and drying, EDTA solution was circulated prior to consolidating and shearing. This was attributed to the soil by the process of wetting and drying, and these bonds were considered to be chemical in nature. The similarity of the stress-strain behaviour of desiccated soil to the reported behaviour of soil subjected to wetting and drying Allam and Sridharan (1981) suggests that perhaps desiccation bonds are induced by repeated wetting and drying.

In all cases it was found that the deviator stress-strain curves obtained could be transformed into rectangular hyperbolae Sridharan and Rao (1972) and the initial tangent modulus (ITM) was computed from the transformed relationships. Fig. 3 presents typical ITM-confining/consolidation (σ_3/σ_c) pressure curves obtained for desiccated soils (Soil 4) and Fig. 4 presents those obtained for the cemented soil. The ITM is found to increase significanty with σ_3 and σ_c for undisturbed soil, and also significantly with σ_c while the increase is only marginal with σ_3 for the remoulded soil. It is also seen that the ITM decreases on remoulding, the decrease being quite drastic for the $\overline{UU}$ test. For the $\overline{CIU}$ test it is seen that the decrease in ITM when the soil is treated with EDTA is less than that occurring on remoulding. Since only bonds are disrupted by EDTA while the soil fabric remains unchanged, it can be concluded that the ITM largely depends on fabric (or the intrinsic effective stresses due to the net attractive forces between particles) and remoulding (which alters the fabric) brings about larger reductions in the ITM. For undisturbed desiccated soil, the ITM vs. σ_3 variation obtained from the $\overline{UU}$ test is essentially same as the ITM vs. σ_c variation obtained from the *CIU* test. This is attributed to the external stresses (σ_3) being carried by the soil skeleton whose rigidity is

TABLE 1

Summary of Test Results For Desiccated Soils

Soil	1		2		3		4	
Soil State	UND	REM	UND	REM	UND	REM	UND	REM
Sand (per cent)	53.0		51.9		48.3		70.0	
Clay and Silt (per cent)	47.0		48.1		51.7		30.0	
Liquid Limit (per cent)	49.0		53.2		50.6		38.0	
Plastic limit (percent)	25.0		32.6		31.0		18.0	
Specific Gravity, G	2.63		2.63		2.68		2.60	
Void Ratio, e	0.80	0.75	0.63	0.65	0.68	0.62	0.69	0.62
Pore Pressure Parameter B	0.63	0.93	0.72	0.85	0.78	0.82	0.60	0.91
$\overline{UU}$ Shear Tests :								
c_{uu} (kPa)	38.9	15.5	39.8	29.3	32.8	27.6	24.5	17.2
ϕ_{uu} (deg)	13.4	1.7	5.5	2.5	4.5	3.0	11.0	2.5
c'_{uu} (kPa)	8.0	0.0	0.0	0.0	8.3	0.0	22.8	3.9
ϕ'_{uu} (deg)	30.6	35.2	31.4	31.4	25.8	35.2	25.1	29.9
$\overline{CIU}$ Shear Tests								
c_{cu} (kPa)	36.9	28.6	57.9	28.52	39.3	31.8	32.8	14.5
ϕ_{cu} (deg)	21.0	15.5	17.8	15.3	15.0	13.4	19.3	16.7
c'_{cu} (kPa)	23.4	0.0	47.5	0	32.8	0	22.8	3.9
ϕ'_{cu} (deg)	27.8	31.3	19.6	27.8	19.0	23.8	25.1	27.5
Average Failure $\overline{UU}$	11.7	15.6	13.2	18.3	13.6	18.0	11.3	23.5
Strain (per cent) $\overline{CIU}$	11.8	14.8	11.8	14.8	13.1	16.0	14.6	16.3

UND = Undisturbed REM = Remoulded

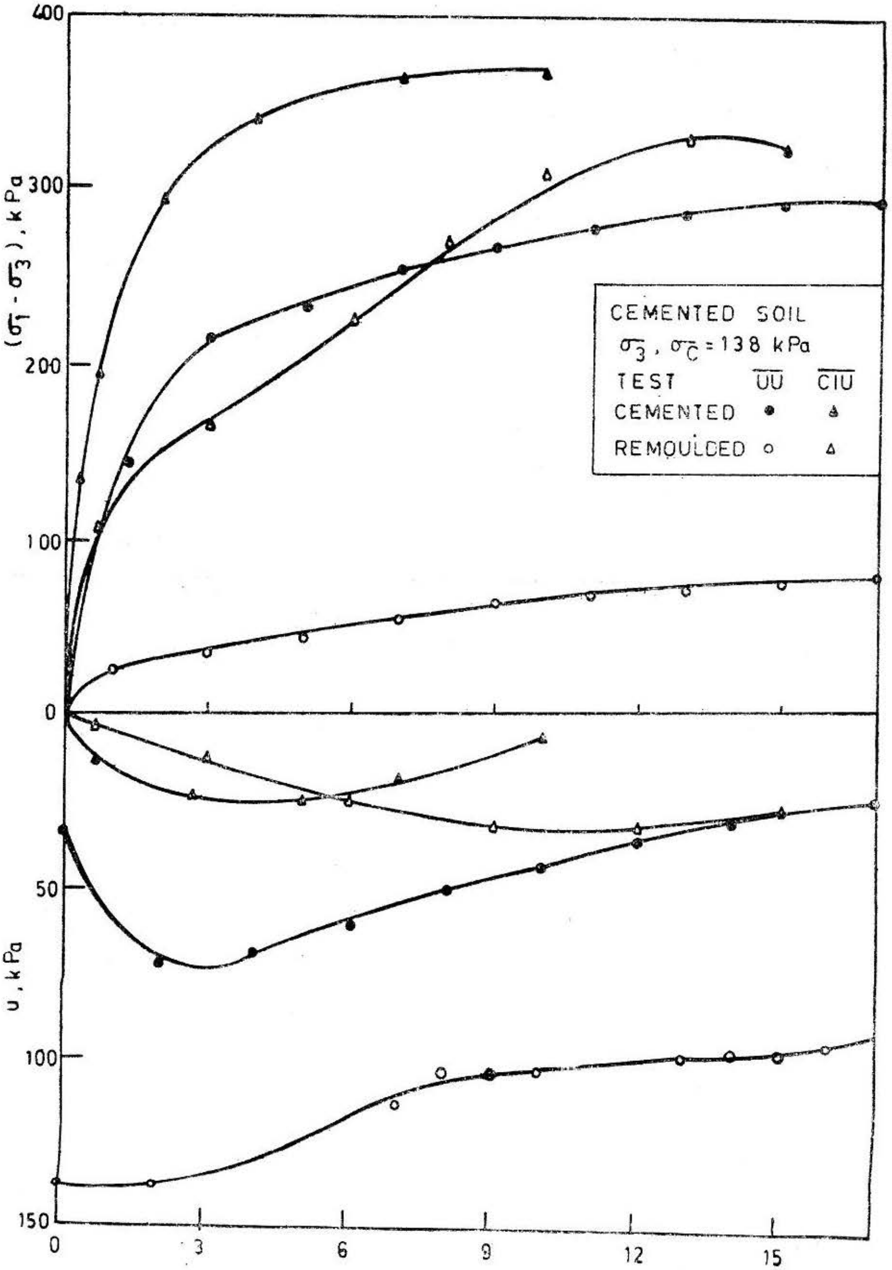

FIGURE 2 Typical Stress-Strain and Pore Water Pressure-Strain Curves for Cemented Soil.

TABLE 2

Summary of Test Results for Cemented Soil

Soil State	Cemented	Remoulded
Void Ratio	0.470	0.468
Degree of Saturation Sr, (per cent)	100	100
Pore pressure Parameter-B	0.37	0.96
$\overline{UU}$ Shear Test		
c_{uu} (kPa)	71.2	24.1
ϕ_{uu} (deg)	14.4	3.0
c'_{uu}(kPa)	16.5	4.2
ϕ'_{uu} (deg)	33.7	35.2
$\overline{CIU}$ Shear Test		
c_{cu} (kPa)	38.9	26.7
ϕ_{cu} (deg)	27.8	25.8
c'_{cu} (kpa)	16.5	8.3
ϕ'_{cu} (deg)	33.7	33.7
Average Failure		
Strain (per cent) $\overline{UU}$	14.4	17.3
$\overline{CIU}$	13.7	15.5

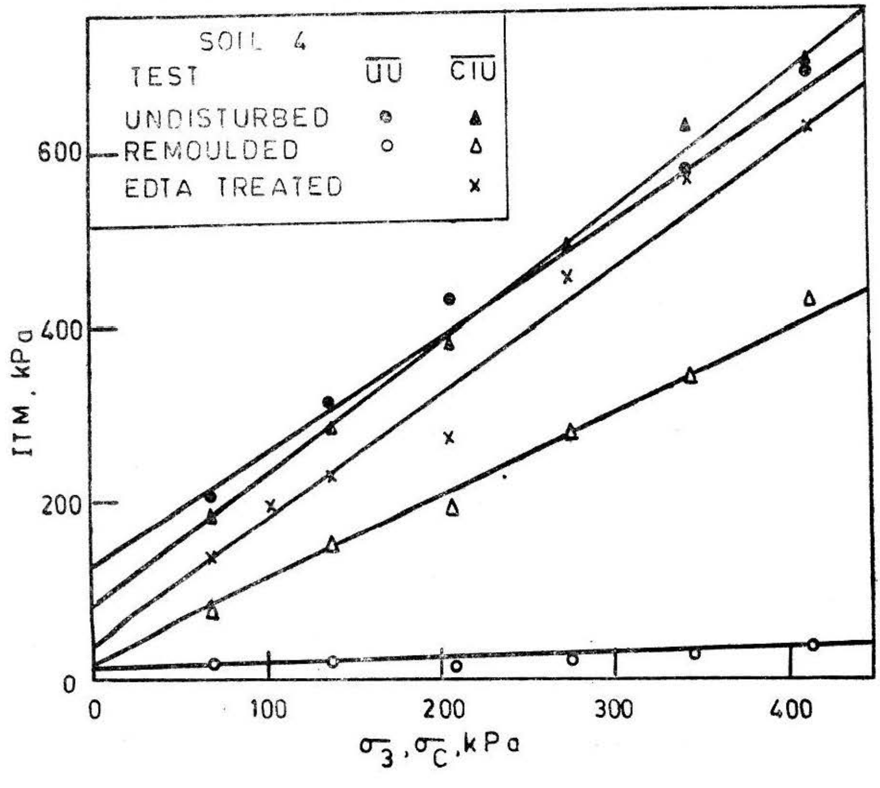

FIGURE 3 Initial Tangent Modulus-Confining, Consolidation Pressure Curves for Soil 4

enhanced by the intrinsic effective stress contributed by desiccation bonds.

For cemented soil, it is seen from Fig. 4 that remoulding has the same effect on the ITM values as was seen in the case of desiccated soil. The ITM values for cemented soil ($\overline{UU}$ and $\overline{CIU}$ tests) are larger than those for desiccated soils, and this can be attributed to stronger bonds. The ITM values from $\overline{UU}$ test on cemented soil are however, unlike those for desiccated soil, less than those obtained from $\overline{CIU}$ tests, but exceed those obtained from $\overline{CIU}$ tests on the remoulded soil. The sample preparation in case of cemented soil was such as to yield quite identical fabric structures for both cemented and remould samples. In this case it can thus be concluded that the ITM was more largely dependent on the presence of the bonds (i.e. the intrinsic effective stress contributed by the bonds).

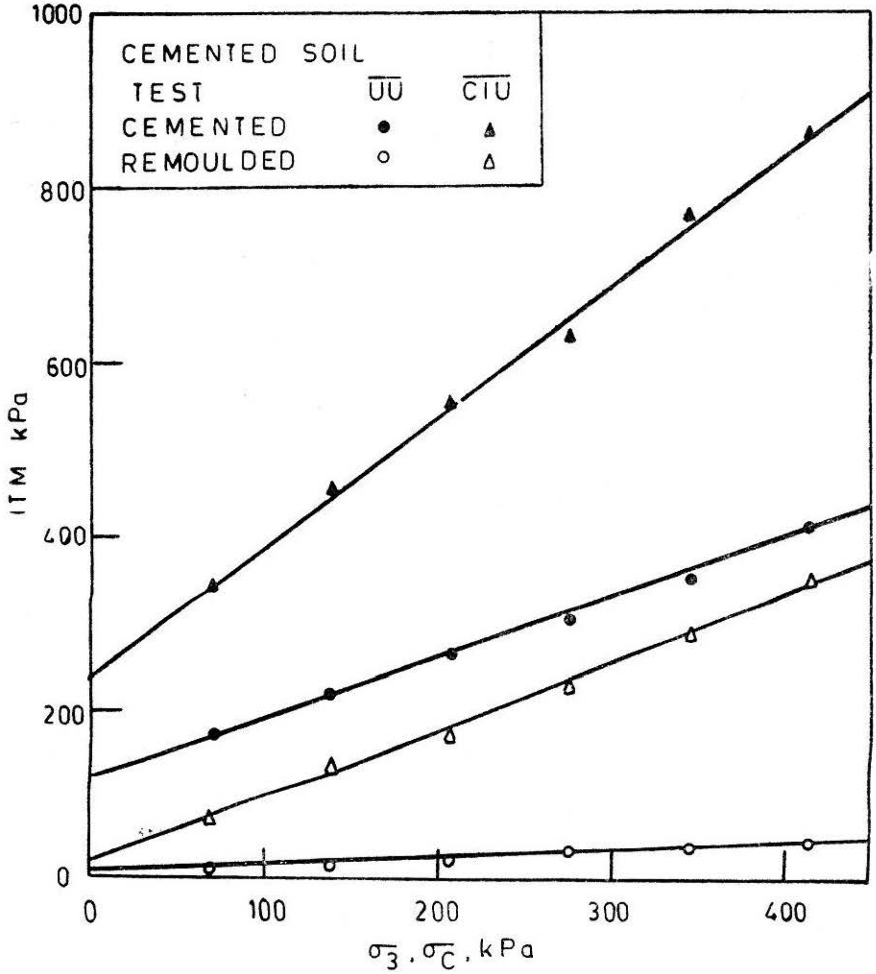

FIGURE 4 **Initial Tangent Modulus-Confining, Consolidation Pressure Curves for Cemented Soil.**

The $\overline{CIU}$ test on remould soil yielded lower ITM values compared to the $\overline{UU}$ test on cemented soil for the reason the intrinsic effective stress contributed by the iron bonds was larger than that imparted by the external consolidation pressure to the remoulded soil.

The $\overline{UU}$ test on remoulded desiccated soils (Fig. 3) and cemented soil Fig. 4) yielded very low values of ITM for the reason that remoulding lowered the soil skeleton rigidity by reducing the intrinsic effective stress contributed by fabric and bonds in the case of desiccated soils and that by bonds alone in the case of cemented soil.

The changes in ITM values on remoulding have been represented as the ratio of ITM undisturbed/remoulded and have been plotted against σ_3 and σ_c in Figs. 5 and 6 for desiccated soils and for the cemented soil.

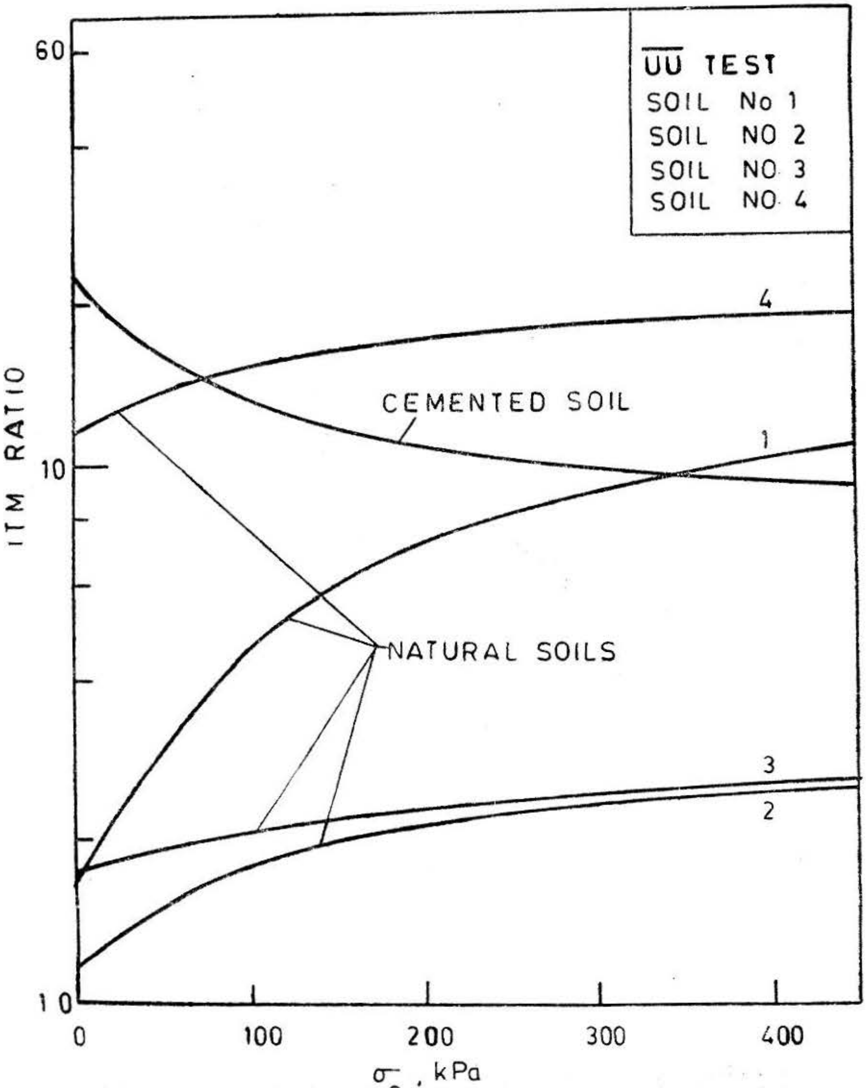

FIGURE 5 ITM Ratio-Confining Pressure Curves for Desiccated Soils and Cemented Soil.

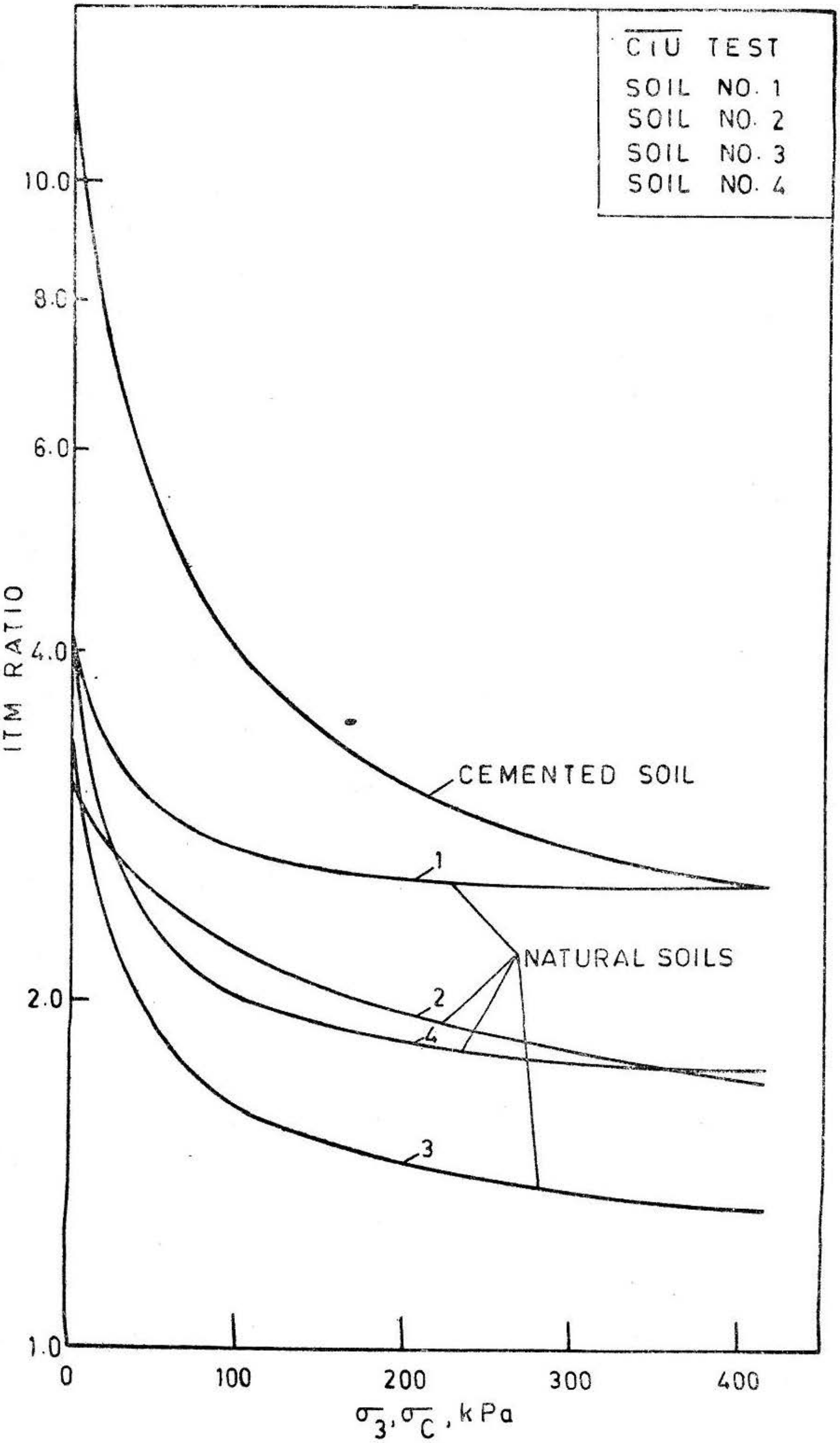

FIGURE 6 ITM Ratio-Consolidation Pressure Curves for Desiccated Soils and Cemented Soil.

The ITM ratios for desiccated soils vary between 2.5 to 18.5 ($\overline{UU}$ test) and 3.0 and 4.0 ($\overline{CIU}$ tests). For the cemented soil, ITM ratios of 23 and 11.5 and were obtained from $\overline{UU}$ and $\overline{CIU}$ tests respectively. These higher values may be attributed to the better bonding induced under laboratory conditions. The values of the ITM ratio reported for the soil subjected to wetting and drying Allam and Sridharan (1981) are closer to those obtained for desiccated soils (5.65 to 8.85 for number of rewetting cycles ranging between 25 and 60). Compared to the large increase brought about by repeated wetting and drying, the reported reduction on treatment with EDTA Allam and Sridharan (1981) is compartively small. The resemblance to desiccated soils is striking.

It has been reported Allam and Sridharan (1981) that the ITM increased when a soil was subjected to repeated wetting and drying and this was attributed to both fabric changes and bonding brought about by the repeated wetting and drying process. Further, treatment of the specimens with EDTA prior to consolidation and shearing resulted only in small reductions in the ITM values (which exceeded those for specimens not having undergone repeated wetting and drying). This behaviour was attributed to fabric changes (and hence changes in the intrinsic effective stress) predominating over chemical bonds produced by the repeated wetting and drying process. In the light of these reported findings it can be conoluded that the ITM values for desiccated soils are largely dependent upon fabric contributed net interparticle attraction and less on chemical bonds. For the cemented soil, wherein fabric was not significantly affected by remoulding because of the sample preparation procedure itself, the ITM is mainly dependent on the presence of bonds. The observed stiffness characteristics of desiccated soils are thus in accordance with the predictions made in theoretical considerations.

The Pore Pressure Parameters

The B parameter for desiccated soils is much less than unity particularly for the undisturbed state (Table 1). Remoulding the soils brought about an increase in B values. A similar effect occurred for the cemented soil (Table 2). It was earlier understood that the B parameter Bishop and Henkal (1962) was unity for saturated clays and values less than unity were indicative of signs of unsaturation. Subsequent investigations (Bishop (1973), Lee *et. al.* (1969) have shown that for incompressible porous media B values less than unity are not proof of unsaturation. Where interparticle contact is accepted as feasible, the results of investigations on the shear strength of granular material Sadasivan and Raju (1977) suggest that for unisize particles, the shear strength of the assembly depends only on the particle arrangement and interparticle friction-the particle size has no influence. If clays are considered analogus to cohesionless granular masses, the principal difference being particle size, it can be argued that the non-unity values of B reported for saturated sands Lee *et. al.* (1969) are also likely to occur for consolidated clays. In other words, the clay skeleton also possesses an incompressiblity which is enhanced by the presence of bonds.

A low B value for saturated soil is thus indicative of the presence of an intrinsic effective stress which contributes to the incompressibilty of the soil fabric. The lower B values for desiccated soils thus indicate the presence of desiccation bonds and confirm the prediction made in the theoretical considerations. The *B* values have been reported to decrease when a soil is subjected to repeated wetting and drying as a result of bonding occurring during the process, Allam and Sridharan (1981).

Fig. 7 presents some typical curves showing the variation of the pore pressure parameter at failure, A_f, with confining/conslidation pressure for desiccated soil. For $\overline{CIU}$ tests it is seen that A_f values are lower in the undisturbed state as compared to the remoulded state indicating the greater resistance possessed by the undisturbed soil to shearing forces. This may be chiefly due to the intrinsic effective stresses contributed by the fabric since the values of A_f for EDTA treated specimens are also generally lower than those for the remoulded specimens. Since EDTA removed bonds without affecting fabric, the above conclusion is thus justified. Fig. 1 also shows that lower pore pressures are mobilized by the undisturbed desiccated soil during the $\overline{CIU}$ test clearly exhibiting the greater resistance to shearing possessed by them. The pore pressure

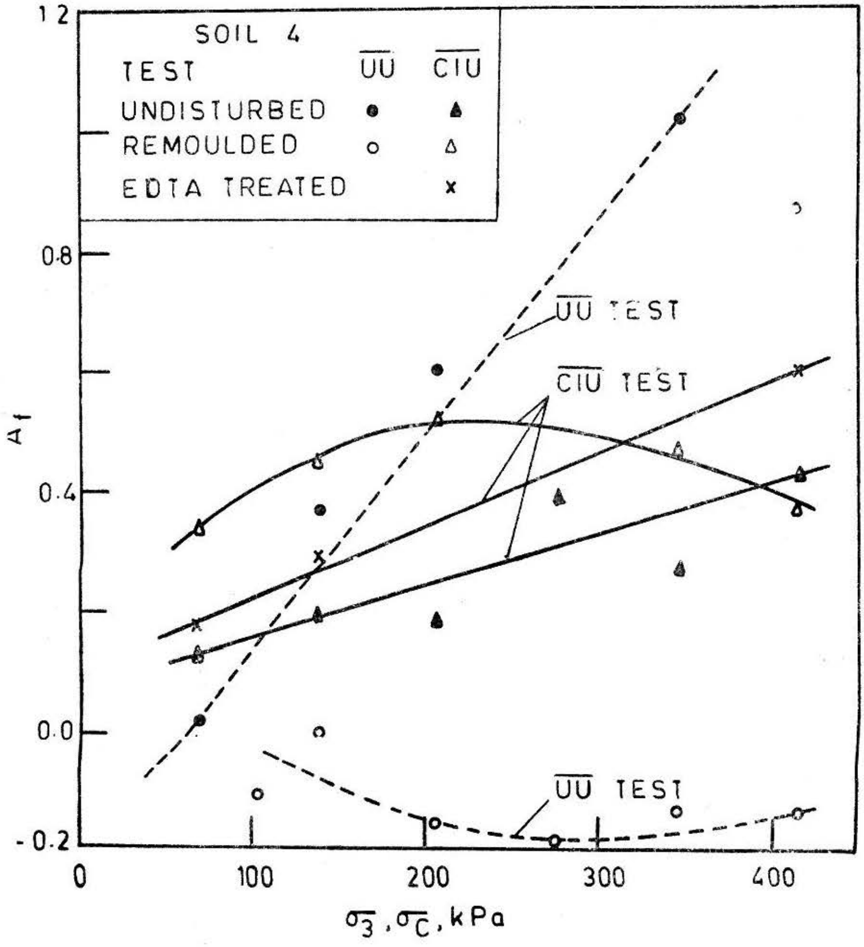

FIGURE 7 ***A_f*-Confining, Consolidation Pressure Curves for Soil 4.**

responses obtained from $\overline{UU}$ tests are different compared to those obtained from the $\overline{CIU}$ test. While pore pressures at failure are larger than the initial for the undisturbed state, thus yielding positive A_f values, the final pore pressures for remoulded soils are less than the initial values thus generally yielding negative A_f values. This is generally because the remoulded soil develops initial pore pressures nearly as large as the applied confining pressure and during shearing the pore pressure either reaches the value of the confining pressure or decreases if the soil exhibits a tendency to dilate at large strains. For the soil subjectcd to wetting and drying, it was reported that A_f values generally decreased and even where EDTA treatment was done A_f was generally lower than the initial value at higher σ_c Allam and Sridharan (1981). The response of desiccated soils in thus quite similar to that of soil subjected to wetting and drying. It can thus be concluded that the larger resistance to shear possessed by desiccated soils is chiefly due to the fabric differences it has compared to the remoulded state.

Influence of Remoulding on the Shear Strength

Fig. 8 presents typical shear strength-confining/consolidation pressure curves obtained for desiccated soil. Fig. 9 shows the corresponding data obtained for the cemented soil. The relative parallelness of the curves in the case of $\overline{CIU}$ tests shows that fabric differences between undisturbed and remoulded specimens do not play as large a role in influencing shear strength particularly at the large strain levels involved unlike their effect on the soil stiffness. Further, unlike what has been observed regarding the ITM, the difference in shear strength obtained from $\overline{CIU}$ and $\overline{UU}$ tests on the undisturbed and also cemented soil is considerable. The shear strength of the cemented soil is also larger than that of the desiccated soil further confirming that better bonding was achieved in the laboratory. Interestingly enough, the cemented soil possesses a shear strength greater than that for its remoulded state. This is unlike the reported behaviour of silt cemented with lime Lambe (1960) or of natural cemented clay Loiselle *et. al.* (1971) where in the effect of bonds was evident only in the stiffness of the soil and contributed nothing to the shear strength at large strain levels. The mechanistic concept for the mobilization of shear strenth given by Lambe (1960) does not hold for the cemented soil containing iron hydroxide bonds prepared in the laboratory as they are not totally ruptured at the low strain levels as envisaged in the concept.

As predicted in the theoretical considerations, treatment with EDTA is found to yield shear strength values from $\overline{CIU}$ tests lower than those corresponding to the remoulded soil. These values are even lower than those obtained from $\overline{UU}$ tests on undisturbed soils at low σ_c values. The $\overline{UU}$ test values of shear strength for cemented soil are likewise more than the $\overline{CIU}$ test values on the remoulded soil. This suggests that the strains taking place during consolidation apparently disrupt some bonds and thereby reduce the total pre shear effective stress inspite of the contribution provided by consolidation pressures. The data corresponding to $\overline{CIU}$ tests on remoulded and EDTA treated desiccated soil indicate that while both remoulding and EDTA treatment may

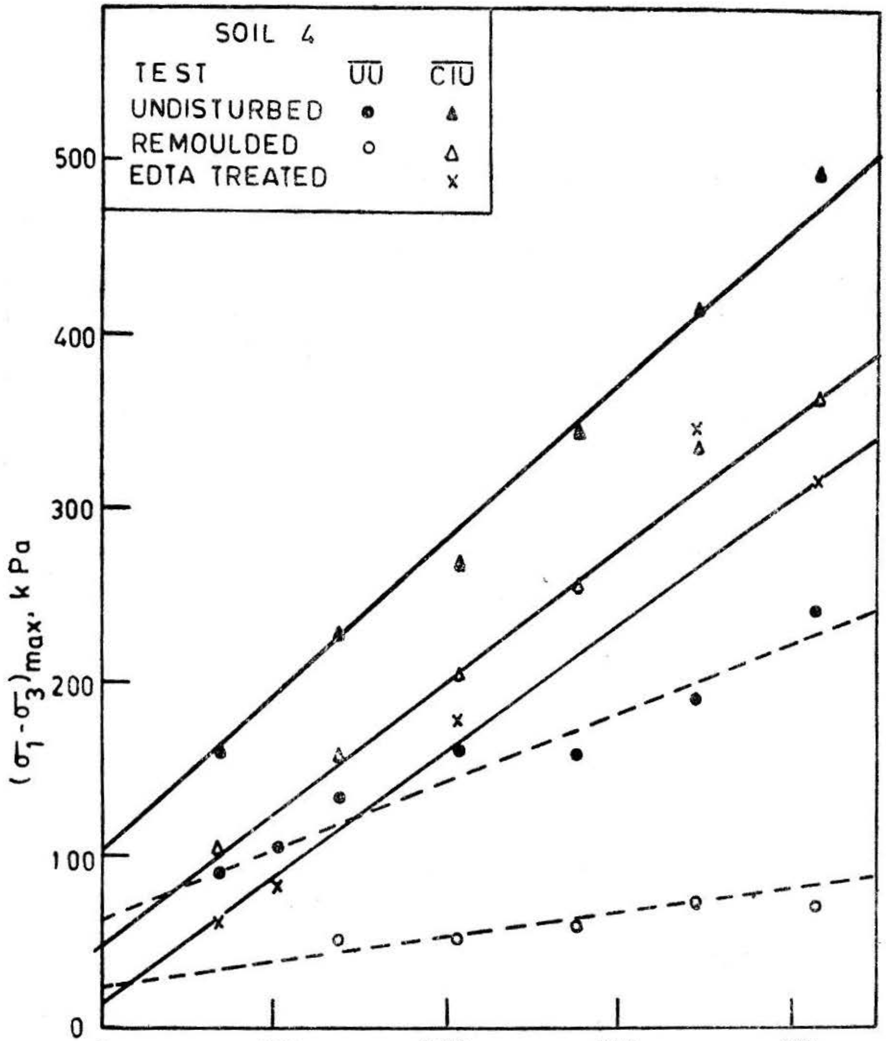

FIGURE 8 Shear Strength-Confining, Consolidation Pressure Curves for Soil. 4.

disrupt all the desication bonds, the remoulded sample is more homogeneous and free from structural defects (e.g. shrinkage cracks and therefore possesses more shear strength than the EDTA treated sample.

Figs. 10 and 11 present the sensitivity ratio (defined as shear strength undisturbed to remoulded in case of desiccated soils and as that for cemented to remoulded in case of cemented soil) variation with σ_3/σ_c. It is seen that sensitivity ratios between 1.75 and 5.5 are obtained from $\overline{UU}$ tests and between 1.57 and 2.37 from $\overline{CIU}$ tests on desiccated soil. The corresponding values for cemented soil are 4.85 and 1.82 from $\overline{UU}$ and

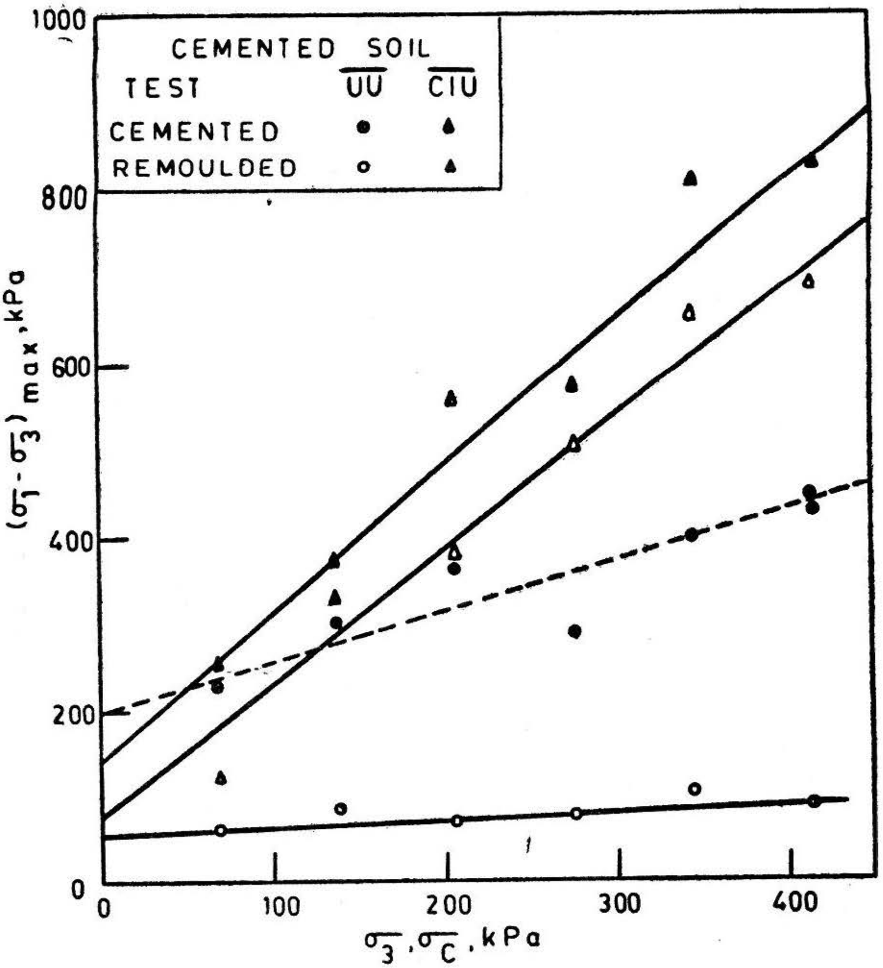

FIGURE 9 **Shear Strength-Confining, Consolidation Pressure Curves for Cemented Soil.**

$\overline{CIU}$ tests. These values are indicative of the resemblance in behaviour of desiccated soils to cemented soil. A sensitivity ratio as large as 1.64 has been reported from $\overline{CIU}$ tests on soil subjected to repeated wetting and drying, Allam and Sridharan (1981). This is also within the range of values observed for desiccated soils and is indicative of the similarity of desiccation bonds to wetting and drying bonds.

Mobilization of the Shear Strength Parameters with Strain

The shear strength parameters obtained for desiccated soils in their undisturbed and remoulded states are presented in Table 1, while Table 2 presents the values obtained for the cemented soil. It is observed that the undisturbed desiccated soil possesses greater cohesion (both in terms of total and effective stresses) than the remoulded soil. The same is observed

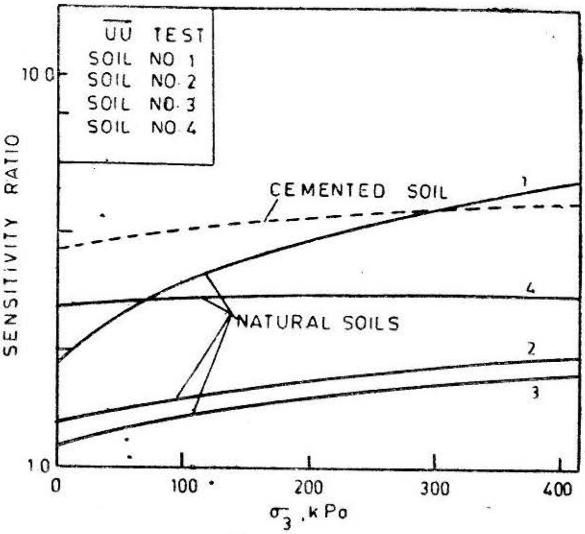

FIGURE 10 Sensitivity Ratio-Confining Pressure Curves.

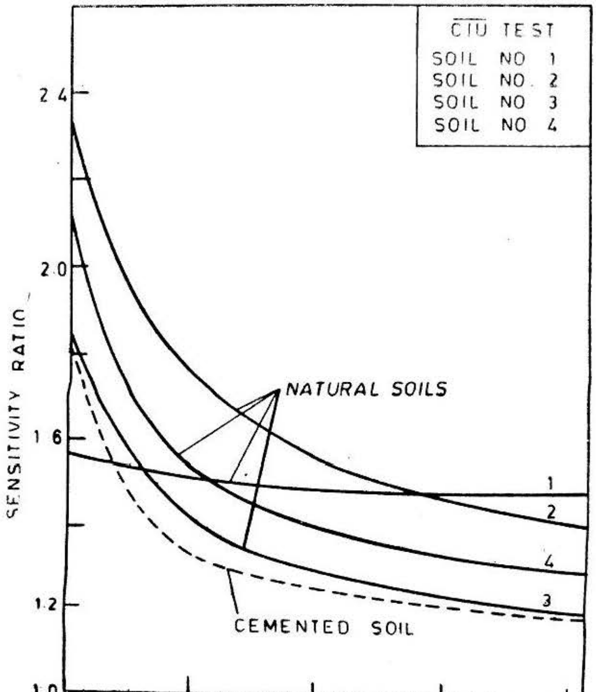

FIGURE 11 Sensitivity Ratio-Consolidation Pressure Curves.

for cemented soil. This is attributable to that part of the intrinsic effective stress which is imparted to the soil by desiccation bonds and fabric effects and by the iron hydroxide bonds in the cemented soil. The presence of cohesion also demonstrates that the influence of bonds is not limited to small deformations in the case of desiccated soils and the cemented soil of this investigation, unlike the cementation bonds present in Outardes clay, Lee *et. al.* (1969) and the behaviour predicted by Lambe (1960). This is clearly seen from Figs. 12 to 15 which present the mobilization of effective cohesion and angle of shearing resistance as obtained from $\overline{UU}$ and $\overline{CIU}$ shear tests on a typical desiccated soil and on the cemented soil. Pronounced peaks in the effective cohesion-axial strain curves are obtained for the undisturbed and cemented states. The effective cohesion at failure for cemented soil is found to be 30 to 17 per cent

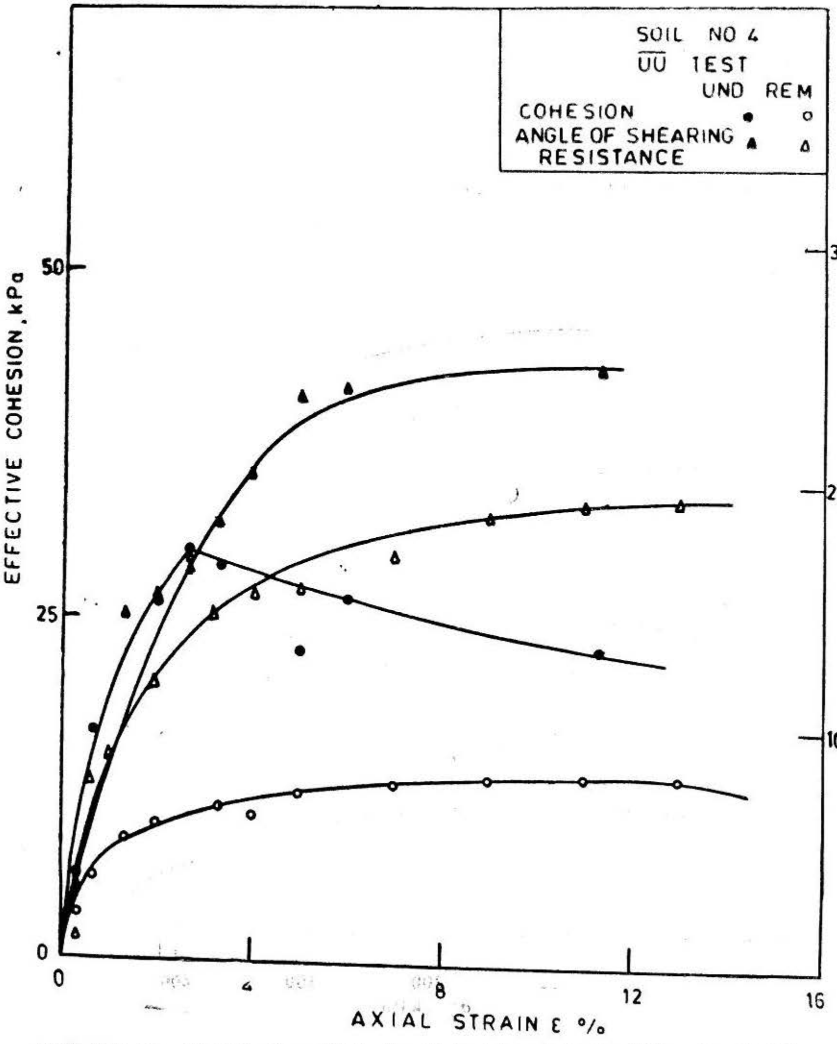

FIGURE 12. Mobilization of Effective Cohesion and Angle of Shearing Resistance for Soil 4 from $\overline{UU}$ Tests.

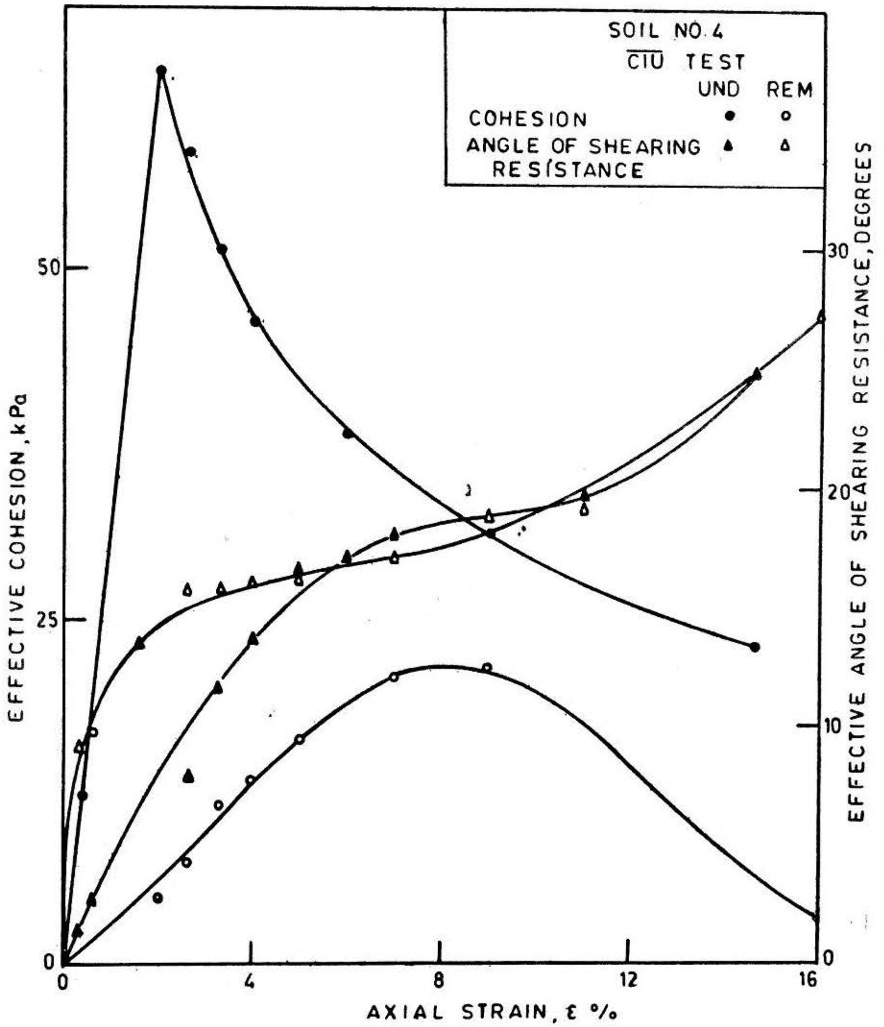

FIGURE 13 **Mobilization of Effective Cohesion and Angle of Shearing Resistance for Soil 4 from $\overline{CIU}$ Tests.**

of its peak value and 400 to 200 per cent of the remoulded failure value from $\overline{UU}$ and $\overline{CIU}$ shear tests respectively.

From Figs. 12 to 15 it is also seen that the frictional component of strength is mobilized more rapidly at small strains for the remoulded state irrespective of the type of test. This can be attributed to the greater homogenity and density (for desiccated soils) occuring in the remoulded specimens, as well as to the lower stiffness (in particular for the cemented soil) which calls for greater participation by the friction and interference aspects of strength mobilization due to the absence/reduced influence of cohesion.

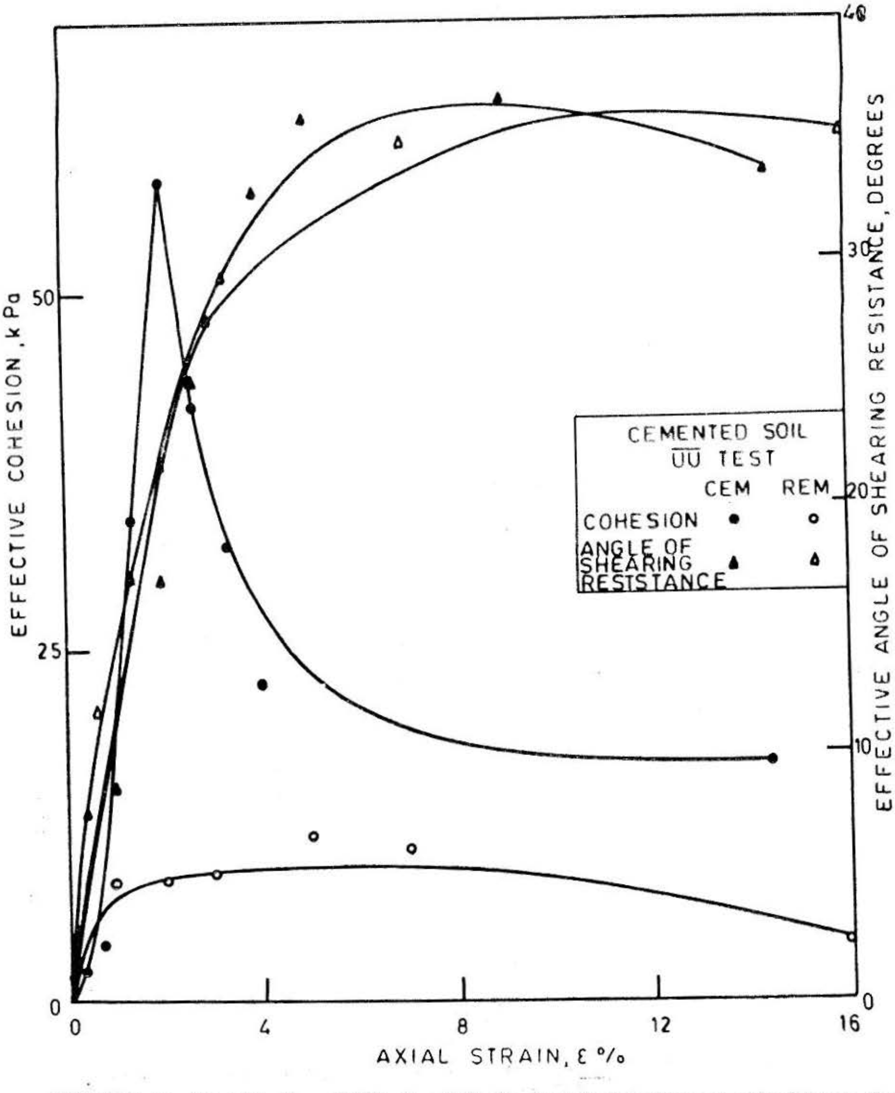

FIGURE 14 Mobilization of Effective Cohesion and Angle of Shearing Resistance for Cemented Soil from $\overline{UU}$ Tests.

The data in Tables 1 and 2 also show that the $\overline{UU}$ shear tests on the soils (particularly undisturbed and cemented soil) yield angles of shearing resistance both in terms of total and effective stresses. This is because the intrinsic effective stress imported by the bonds increases the incompressibility of the soil so that the soil supports significant proportions of the applied all round stress under no volume change conditions. Consequently the shear strength varies linearly and significantly with change in confining pressure so that the failure envelope possesses a non-zero slope. For the remoulded soil, the absence of bonds implies reduced effective stress inspite of the lower void ratios and hence a more compressible fabric which supports only a small proportion of the applied confining pressure as

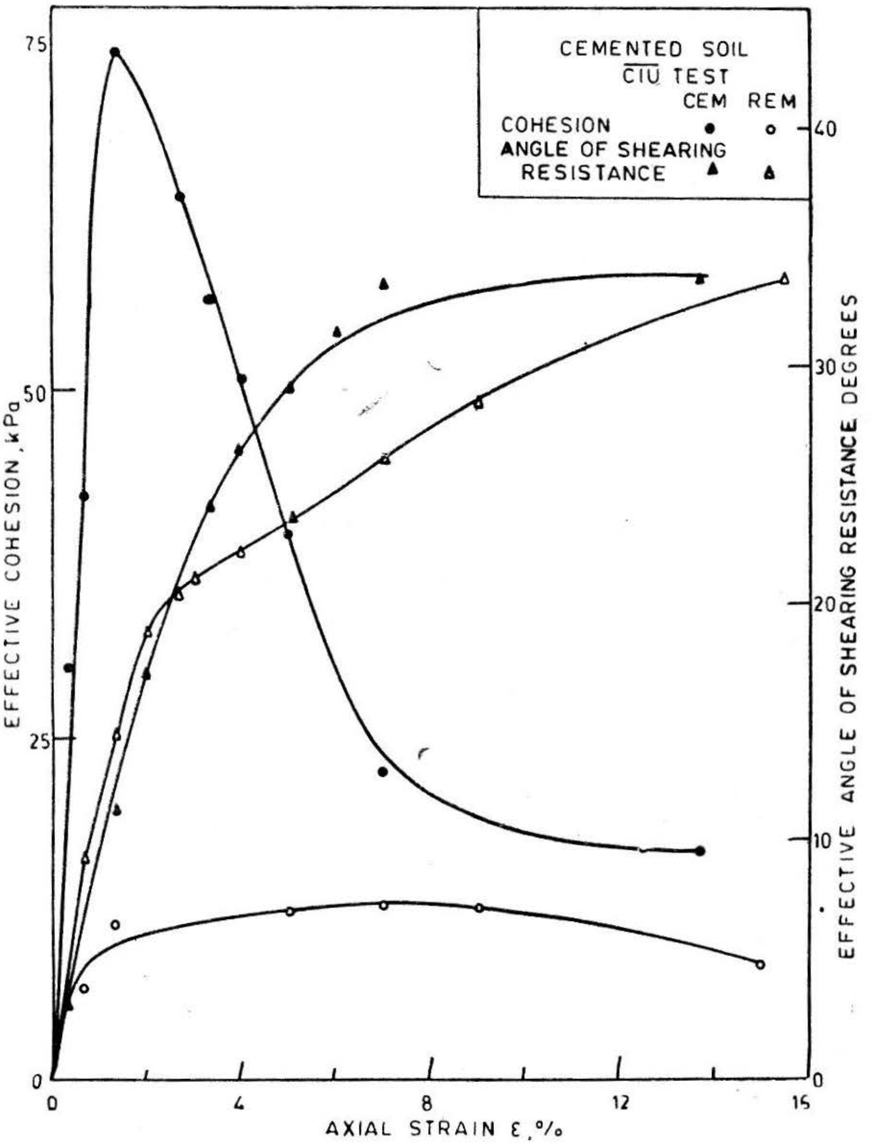

FIGURE 15 **Mobilization of Effective Cohesion and Angle of Shearing Resistance for Cemented Soil from $\overline{CIU}$ Tests.**

compared in the pore fluid. For this reason the change in shear strength with respect to change in σ_3 is small and the failure envelope is, as a result, flatter.

Fig. 16 shows some typical failure envelopes obtained for desiccated soils from $\overline{UU}$ shear tests and Fig. 17 presents the corresponding envelope obtained for the cemented soil. It is seen that effective stress angles of shearing resistance can be easily obtained from $\overline{UU}$ shear tests on undisturbed or cemented soils as a result of their greater incompressibility as

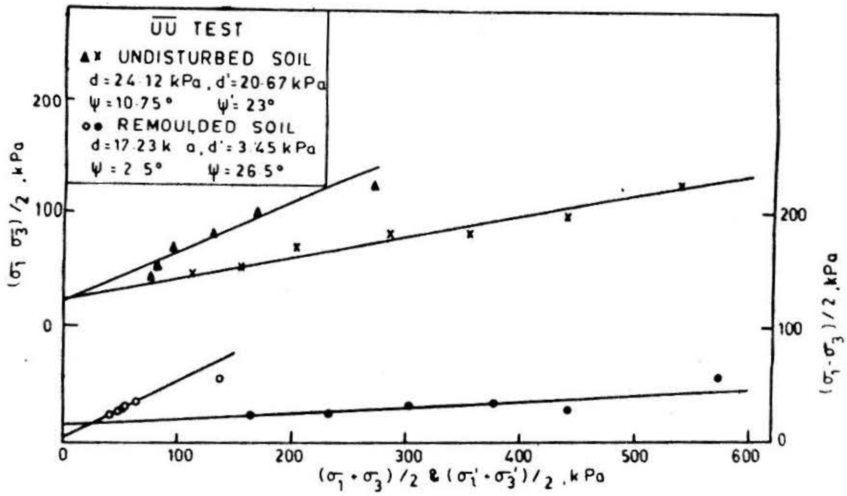

FIGURE 16 Mohr-Coulomb Failure Envelopes from $\overline{UU}$ Tests-Soil 4

compared to remoulded soils. This is an anticipated in the theoretical considerations. Remoulded soils also yield effective stress angles of shearing resistance without much difficulty.

It is also observed that the desiccated soils possess larger effective stress angles of shearing resistance from both $\overline{CIU}$ and $\overline{UU}$ shear tests in their remoulded state as compared to the undisturbed state. This is as anticipated in the theoretical considerations and can be attributed to the more homogenous and structural defect free specimens obtained by remoulding. This is confirmed by the value obtained for EDTA treated Soil 4 specimens (Table 3) which yielded a ϕ'_{cu} value closer to the undisturbed value than the remoulded value. The EDTA treatement removes bends but leaves the soil fabric and structural defects unaltered. A similar finding has been reported for soil subjected to repeated wetting and drying, Allam and Sridharan (1981).

TABLE 3

$\overline{CIU}$ Shear Test Results of Soil 4 for Undisturbed, Remoulded and EDTA Treated Conditions

Soil State	UND	REM	Treated with EDTA
c_{cu} (kPa)	32.8	14.3	5.4
ϕ_{cu} (deg)	19.3	16.7	16.7
c'_{cu} (kPa)	22.8	3.9	0.0
ϕ'_{cu} (deg)	25.1	27.5	24.5

UND = undisturbed REM = remoulded

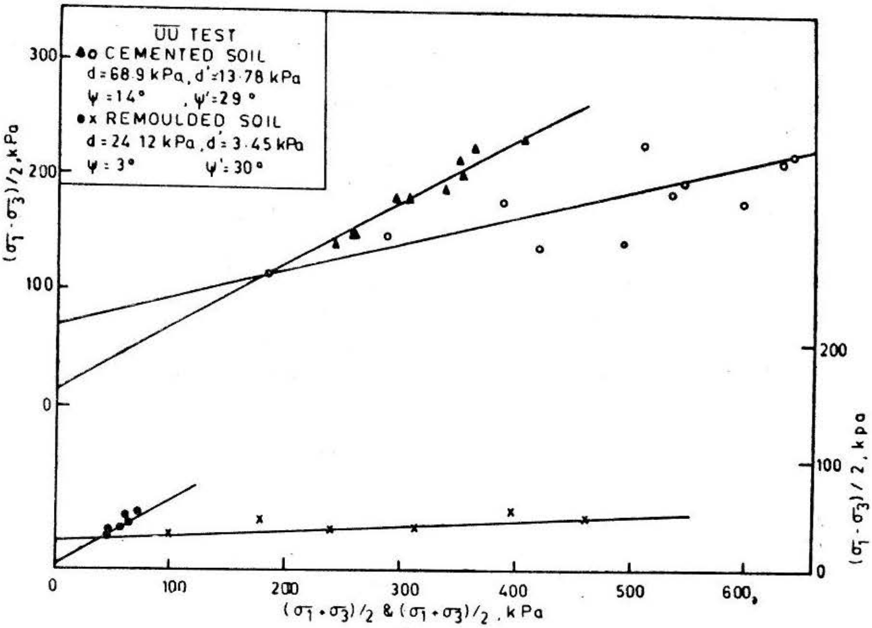

FIGURE 17 Mohr-Coulomb Failure Envelopes from *UU* Tests-Cemented Soil

In the case of the cemented soil it is observed that the effective angles of shearing resistance are the the same for cemented and remoulded states indicating that the specimen preparation technique yielded similar fabric in both states.

The $\overline{UU}$ shear tests are founded to yield larger effective stress angles of shearing resistance as compared to $\overline{CIU}$ shear tests. This is because, while changes in effective stress occur in $\overline{UU}$ shear tests without significant volume changes, this is not the case in $\overline{CIU}$ shear tests. The volume changes occuring during consolidation bring about a re-orientation of soil particles and hence lower effective angles of shearing resistance.

From Tables 1 and 2 it is also seen that $\overline{UU}$ shear tests generally yield smaller cohesion values than $\overline{CIU}$ shear tests. This may be because the greater particle spacing in the former gives lesser net attractive forces between particles as the intensity of interparticle attraction is inversely proportional to the spacing between particles.

Conclusions

1. Desiccated soils possess a stiffer stress-strain response and brittleness in the undisturbed state which is largely due to [fabric effect and partly due to the presence of desiccation bond which by imparting an additional intrinsic effective stress improve the rigidity of the structure.

2. Desiccation bonds are chemical in nature and can be destroyed either by remoulding or by chemical treatment (Viz. EDTA).

3. The shear strength is greater for desiccated soils in their undisturbed state. Sensitivity ratios as high as 5.5 ($\overline{UU}$ shear test) and 2.37 ($\overline{CIU}$ shear test) have been obtained. These values are less than the corresponding values for cemented soil and this is attributed to better and more bonds occuring in the latter. The sensitivity ratios exceeding unity shows that the generally understood concept of the cohesion component of shear strength vanishing at low strains does not apply to these soils.

4. The presence of desiccation bonds and fabric differences result in the undisturbed desiccated soil possessing larger initial tangent moduli. In case of the cemented soils this wholly due to the presence of bonds in the cemented state. Both aspects can be also viewed as contributors to the intrinsic effective stress present in a soil system.

5. The results of $\overline{CIU}$ and $\overline{UU}$ shear tests also indicate that some bonds are disrupted during consolidation strains.

6. While mobilization of cohesion reaches a maximum in the early stages of a shear test, a considerable proportion of the peak value survives the deformation strains and contributes significantly to the shear strength of undisturbed desiccated and also cemented soils. This is less evident in remoulded soils.

7. Undisturbed desiccated soils showed lesser A_f values in $\overline{CIU}$ shear tests when compared with the remoulded soils corroborating the presence of bonds.

8. The $\overline{UU}$ shear test yields larger effective angles of shearing resistance in case of desiccated soils than the $\overline{CIU}$ shear test.

9. It is also generally observed the $\overline{CIU}$ shear tests yield larger effective cohesion values than the $\overline{UU}$ shear tests.

10. The total and effective stress cohesion values are larger for undisturbed and cemented soil as compared to remoulded soils and this clearly shows that desiccation and cementing bonds influence shear strength even at large strains.

11. It can be concluded that the fabric changes produced by climatic changes play a larger role in determining the stiffness characteristics of desiccated soil while the cementation effects predominate in the strength mobilization.

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