Anisotropic Behaviour of a Saturated Uniform Sand

Anisotropie sur le Comportement d'une Sable Uniforme Saturée

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SYNOPSIS The results of triaxial compression tests that were carried out on both frozen-thawed and unfrozen specimens, and of triaxial extension tests done on unfrozen specimens are presented in this paper. They refer to a fine and uniform river sand. The anisotropic behaviour of the sand, its influence upon the Young's modulus and on shear strength was studied. The latter is examined on the basis of the Rowe's dilatancy theory.

INTRODUCTION

The determination, for design purposes, of the geotechnical parameters which characterize granular deposits is usually done using theoretical, experimental or empirical relations to interpret the information given by in situ tests.
When the type or the importance of the structure to be designed also requires more complete investigation, laboratory tests are carried out on samples prepared at a relative density approaching the in situ density. This is often estimated on the basis of empirical relations.
The geotechnical parameters obtained from the above procedure allow the usage of theories which, in the majority of cases, refer to a homogeneous and isotropic half-space.
However, it is well known that natural deposits (Tanimoto, 1974) and samples prepared in laboratory as well are characterized by anisotropic behaviours. The results of anisotropy-effected parameters of a fine-uniform sand that was tested in the triaxial cell are reported in this paper. We also present results of the effect of freezing-thawing on the sand structure.

SOIL TESTED

A fine and uniform sand coming from the mouth of the Adige river was utilized to prepare the samples.
The sand, which has a mean grain size D_{50} of 0.36 mm, a specific gravity G of 2.70, and a uniformity coefficient C_u of 1.82, has the following mineralogic composition: 25% of quartz, 35% of feldspar, 15% of carbonatic elements and 25% of heavy minerals.
The grain size distribution is 100 percent finer than the size 20 sieve, 75 percent passing the size 40 sieve, 5 percent passing the size 80 sieve and 1 percent finer than the 200 sieve.
The particles are angular or subangular but some particles are platy.
According to ASTM-standard No. D 2049 procedure, the minimum and maximum densities have been determined and the following figures have been found: 13.52 and 16.07 kN/m^3 respectively.
Studies performed by Mazzucato (1980) have not indicated, for this sand, any appreciable particle crusing in triaxial compression tests for consolidation pressures up to 980.7 Pa.

TESTING PROCEDURES

Two series of triaxial tests were performed.
In the first one specimens with diameter of 3.7 - 3.9 cm and height of 7.5 - 8.3 cm, were forced to yield in drained conditions with either increasing (C.C.I.D.) or decreasing (E.C.I.D.) vertical stresses. The horizontal stresses were kept constant throughout the tests. The initial consolidation was of the idrostatic type. In order to evaluate the size effect, C.C.I.D. tests were also performed on larger specimens (diameter of 10 cm and height of 20 cm).
The minimum densities were obtained by gently pouring sand through a funnel into a mold filled with water. Higher densities were the result of compaction by vibration on the bases of the mold during the sedimentation (Bishop and Henkel, 1957; Lee and Seed, 1967).
The ranges of the initial relative densities were 0.48 - 0.46 (dry unit weight 14.61 - 14.71 kN/m^3), and 0.81 - 0.85 (15.59 - 15.69 kN/m^3), for the respective minimum and maximum values.
In the second series, the specimens underwent a process of freezing and thawing before being tested in the triaxial cell .
The aim of testing such samples was to investigate stress-strain behaviour, relating it to different sedimentation directions with respect to the specimen longer axis.
The specimens, which were subjected to compression triaxial tests isotropically consolidated and drained (C.C.I.D.), have their major axis parallel or perpendicular to the sedimentation direction.
The samples have been prepared by means of underwater sedimentation which took place inside a cubic iron box which has a side dimension of 170 mm. The box, the main geometrical characteristics of which are illustrated in fig. 1, was

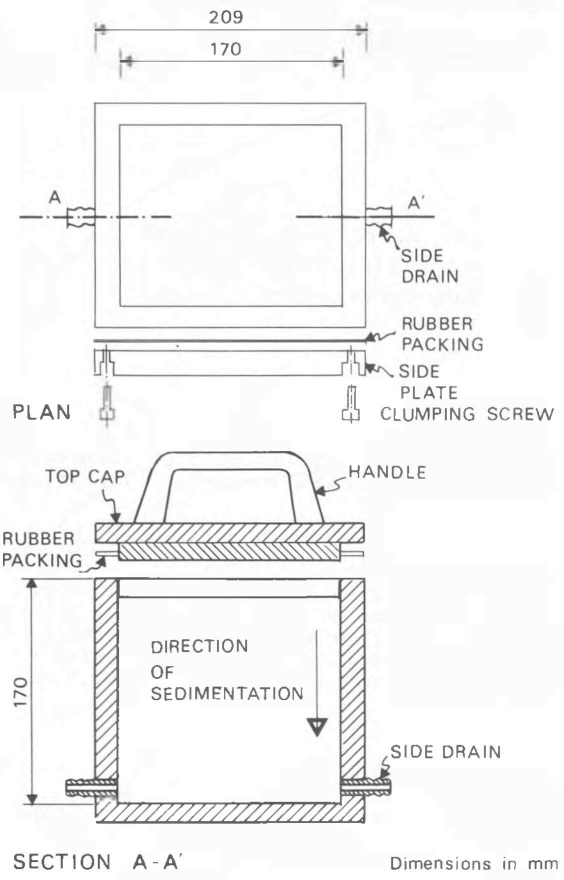

Fig. 1 Sedimentation cubic mold employed to freeze the sand sample

designed to allow the removal of the top cap and of two other parallel side-plates.
The following procedure was followed in order to prepare the specimens: after having produced the sedimentation process, thin wall brass samplers (inner diameter = 38 mm, outer diameter = 40 mm, height = 90 mm) were inserted by hand into the sample, both parallel and orthogonal to the sedimentation (pouring) direction. For this reason we will write of parallel and orthogonal specimens, adopting the convention given above, from now on.
After having fixed all sides of the box the bottom drains were connected to a rubber balloon. The box was frozen from the top to the bottom so that the excess of water, due to the freezing-process, could leave the sample from the bottom drains. In order to fulfil this task, the freezing process took place at -20° C. The iron cubic mold was submerged for half of its height in a basin filled with a water-alcohol mixture. The mixture was replaced every two hours by a new one at room temperature. Four replacements took place before leaving the mold inside the basin at - 20° C for the night.
Afterwards the frozen cubic sample was pushed out of the iron box and the specimens were extracted from the frozen sample, pushed out of the brass samplers and placed, following usual procedures, into triaxial cells to allow them to thaw.
The initial relative densities of the entire samples ranged from 0.23 to 0.62 (dry unit weight of 14.13 - 15.11 kN/m^3). The lowest density was obtained by sedimentation, pouring the sand inside the cubic mold filled with water, after dropping the grains in air from an height of about 15 cm. The highest density was the result of a similar procedure. Vibration caused by gentle strokes was applied to the box with a rubber hammer during and after the sedimentation process.
The dry unit weight of all samples was evaluated at the end of each triaxial test referring to its dry weight and to its initial dimensions. From now on, when compared, the specimens of the two series will be labelled "unfrozen" or "frozen", referring only to the stage of sample preparation.
The C.C.I.D. tests were conducted with a constant velocity of (0.07 - 0.08) mm/min. The E.C.I.D. tests were performed utilizing a controlled-stress path cell (Bishop and Wesley, 1975) in which the vertical stresses were generated by means of a step by step procedure with a mercury column lowering its values with a ratio $\Delta\sigma/\sigma = 0.05$.
The symbols adopted in all the figures are summarized in table I.

TABLE I

TYPE OF TRIAXIAL TEST		SIMBOLS	
		A	B
CCID	UNFROZEN	○	●
	FROZEN 1	Φ	**Φ**
	FROZEN 2	⊖	**⊖**
ECID	UNFROZEN	□	■

(1) Major axis of specimens // to pouring direction
(2) " " " ⊥ " " "

Column A refers to lower densities
" B " " higher "

TEST RESULTS

The simplest and most evident demonstration of the presence of inherent anisotropy is shown by the examination of volumetric and axial strains which occur in a triaxial cell during an idrostatic compression stage.
In this case, if an isotropic-behaviour hypothesis is accepted, it follows that there are equal principal strains, that is :

$$\varepsilon_v = \alpha \cdot \varepsilon_1 \tag{1}$$

where $\alpha = 3$.

The values of volumetric and axial strains, with regard to C.C.I.D. tests, measured after consolidation are shown in fig. 2. For the set of consolidation stresses examined, ranging from 49 to 490.5 Pa, α lays between 4 and 7 for the unfrozen specimens and between 1.4 and 2 for all the frozen-thawed specimens.

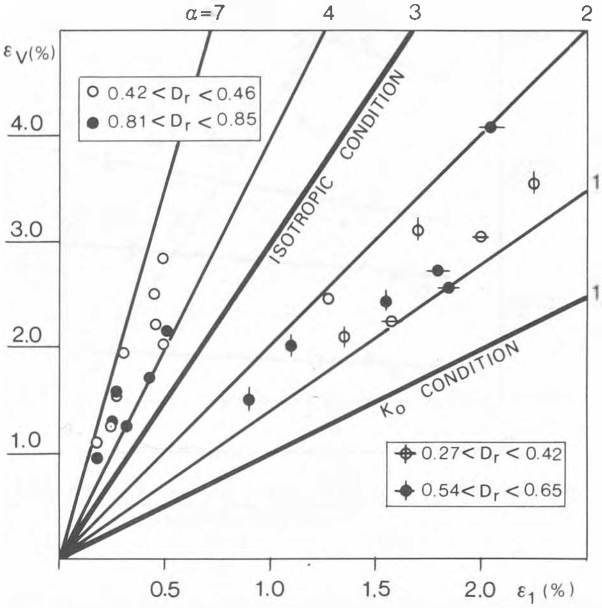

Fig. 2 Relations between volumetric and axial strains after consolidation for frozen or unfrozen specimens

Specimens (diameter = 10 cm, height = 21 cm) prepared by mean of pluvial sedimentation through air have also given values of α ranging from 4 to 7.
These results indicate that unfrozen specimens have a radial strain greater than the axial strain and that the values of α seem to be independent of the initial unit weight.
The specimens prepared by the previously described process have, on the other hand, an axial strain greater than the radial, with always lower than 3.
This last circumstance may be attributed to structural variation of the specimens during the freezing process.
We observe that there is a substantially similar behaviour both for the specimens parallel and orthogonal to the sedimentation direction. Such behaviour has to be put in relation with the forced strains of the specimens, which are contained by brass samplers. Thus they occur only in the direction of their major axis, while the freezing front advances in a direction parallel to the sedimentation direction.
The consolidation stage has allowed us to evaluate the presence of inherent anysotropy. The effects on stress-strain behaviour have been examined considering both the elastic moduli and the failure strength of the performed tests.
The evaluation of the elastic modulus was performed, during the C.C.I.D. tests, following the procedure proposed by Lade and Duncan (1975) for determining the modulus E_{ur}.
The unloading-reloading loop took place at an axial strain equal to 1 percent in order to reduce the inconveniences resulting from the interaction of loading ram, top cap, porous stones and specimen, and to avoid any great changes in the density of specimen after consolidation (Ricceri and Soranzo, 1980).
When frozen samples are considered, the elastic moduli of both series of specimens (parallel and orthogonal to the sedimentation direction) have about the same values.
In the field of relative densities ranging from 0.46 to 0.65, the values of K_{ur} in the relation

$$E_{ur} = K_{ur}\, p_a \left(\sigma_3 / p_a \right)^n \tag{2}$$

are

$$K_{ur} = 750 - 1200 \quad \text{and} \quad n = 0.51$$

For the same specimens, the secant modulus E_{50} (defined with stress and strain at 50 percent of failure strength) is greater for parallel than for orthogonal specimens.
The experimental values of E_{50}, within the field of relative density examined, are bounded by two parallel lines, as defined by equation (2), in the plane log E_{ur}-log σ_3, in which n=0.71 and K = 77 and 115 respectively.
The ratio

$$\frac{1}{R_s} = \frac{(\sigma_1 - \sigma_3)_V}{(\sigma_1 - \sigma_3)_H} \tag{3}$$

between failure resistance of parallel and orthogonal frozen specimens, which underwent C.C.I.D. tests, is presented in fig. 3 as a function on the consolidation stresses.

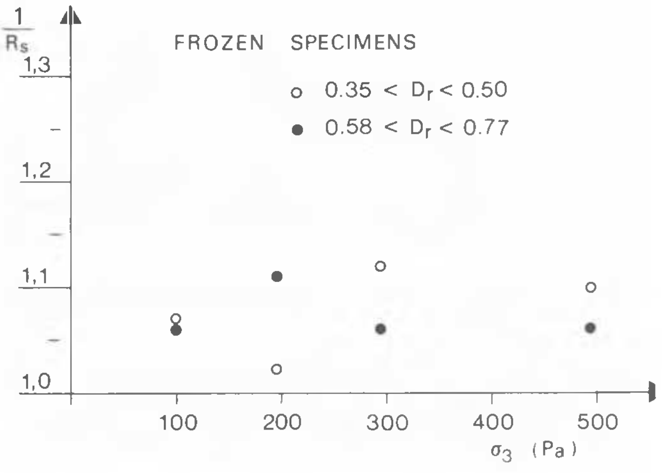

Fig. 3 Ratio of deviatoric stresses at failure of parallel and orthogonal specimens as function of confining stresses

Such ratio has a mean value of 1.08 indicating a greater resistance of the specimens sampled parallel to the sedimentation direction. This is a consequence of the anisotropic behaviour which affects the soil strength.

On the other hand from the comparison of the values of E_{ur} and $(\sigma_1 - \sigma_3)_f$ pertinent to - C.C.I.D. tests performed on unfrozen and frozen specimens, with major axis parallel to the pouring direction, which are reported in fig. 4 and 5 respectively, we can observe that the freezing -thawing process does not produce evident effects on such parameters. These are shown in the figures in which all results are reported as function of relative densities.

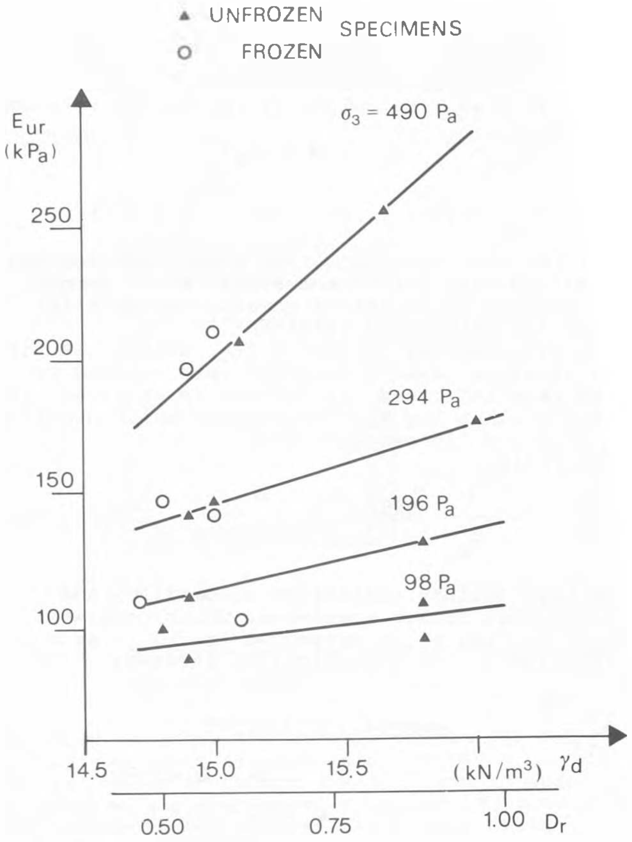

Fig. 4 Variation of the elastic modulus E_{ur} with the relative density for both frozen and unfrozen specimens

It follows that the soil structure after consolidation seems to be substantially similar for both series of samples.

In this sense we may consider that the considerably different strains recorded during consolidation, for the frozen and unfrozen specimens, are necessary to bring the unstable structure of frozen specimens disturbed by the advancing freezing front back to the original state.

The effect of structural anisotropy upon the strength of a granular material can be better understood by comparing triaxial extension and compression tests.

The stress dilatancy theory (Rowe, 1962; Rowe et Al., 1964) considers the strength of a granular material as formed by :

- sliding friction
- particle reorientation effect
- dilatancy effect.

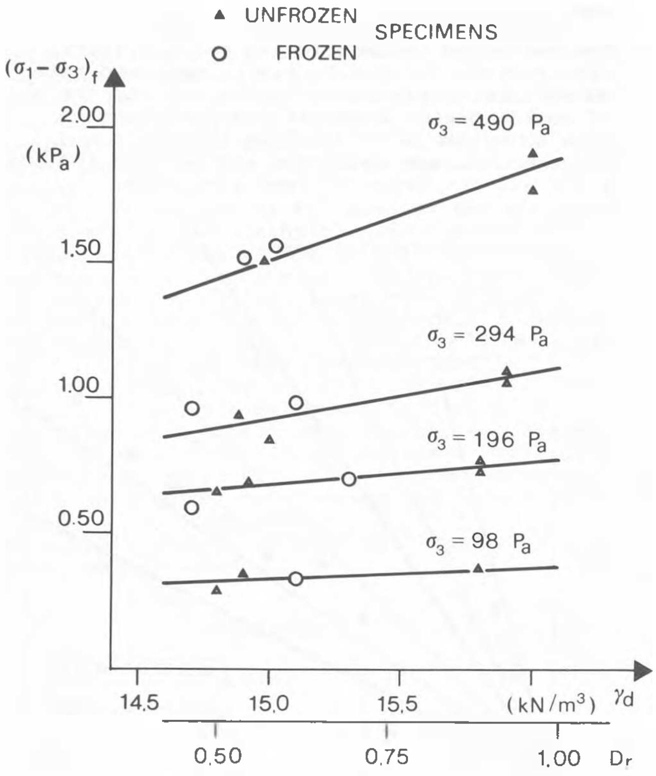

Fig. 5 Variation of the failure strength with the relative density for both frozen and unfrozen specimens

Deducing the dilatancy effect, for the axisymmetric deformation, it is possible to have to sum of the first two contributes of the strength which are given by a relation of the type:

$$\frac{\sigma_1}{\sigma_3} = \tan^2 (45 + \Phi_f/2) \cdot D \qquad (4)$$

where:

$$D = D_c = (1 - \frac{\varepsilon_v}{\varepsilon_1}) \qquad (5)$$

in triaxial compression tests

$$D = D_E = 1/(1 - \frac{\varepsilon_v}{\varepsilon_3}) \qquad (6)$$

in triaxial extension tests.

In fig. 6 the ratios σ_1/σ_3 for all tests are reported as function of D_c and D_E, defined by (5) and (6).

The straight line:

$$\sigma_1/\sigma_3 = 2.95\ D \qquad (7)$$

separates the C.C.I.D. tests from the E.C.I.D.

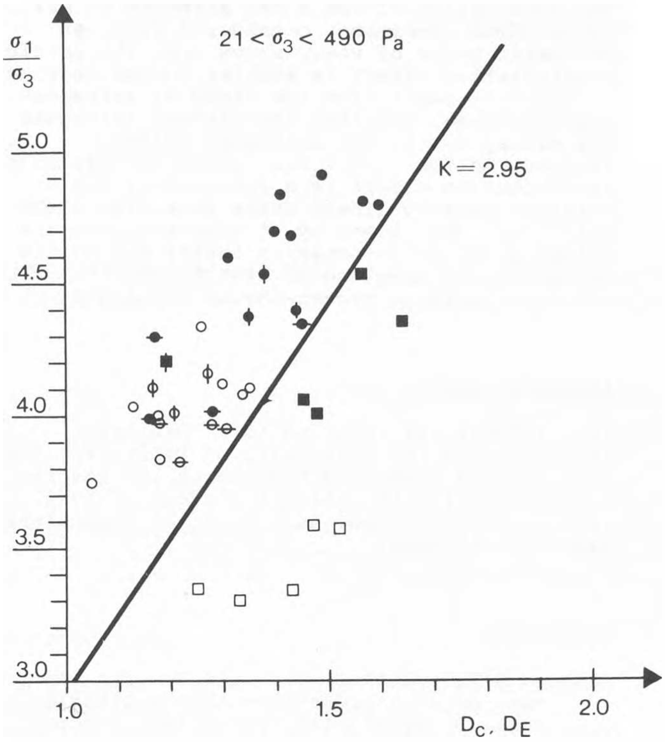

Fig. 6 Principal stress ratios as functions of dilatancy factors

tests. If the strength mobilized by frictional resistance is a property of the examined soil, then it does not depend upon the type of test. It follows that the strength developed by energy required to rearrange and reorient soil particles is lower for E.C.I.D. tests than for C.C.I.D. tests. The peak friction angle Φ and Φ_f are reported as functions of the minor principal stress in fig. 7, 8 and 9. These refer to

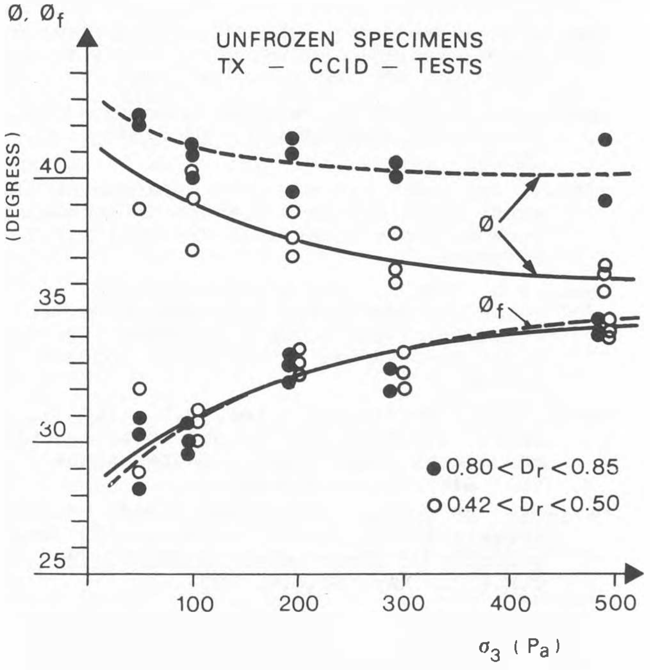

Fig. 7 Effect of the minor principal stress on the friction angles Φ and Φ_f for the unfrozen C.C.I.D. tests

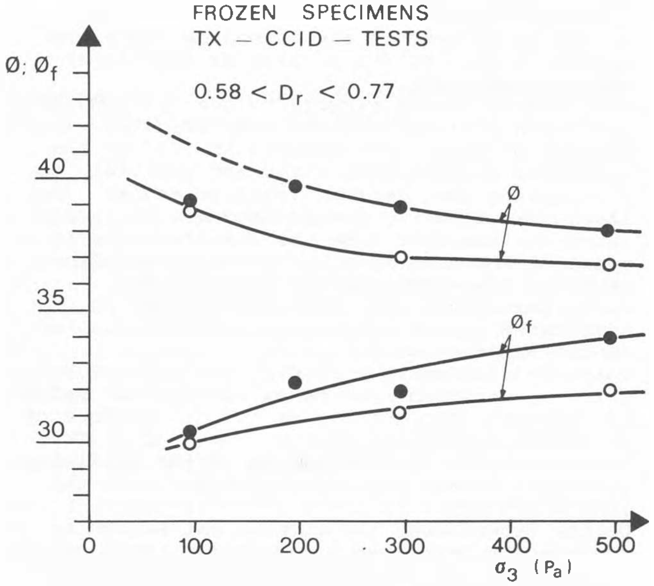

Fig. 8 Effect of the minor principal stress on the friction angles Φ and Φ_f for the C.C.I.D. frozen tests

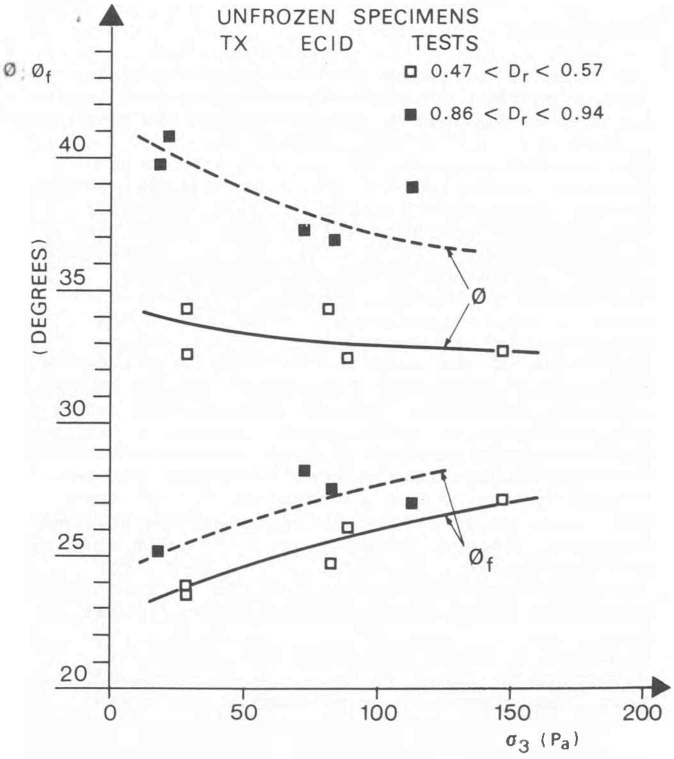

Fig. 9 Effect of the minor principal stress on the friction angles Φ and Φ_f for the E.C.I.D. unfrozen tests

triaxial tests of the following types: C.C.I.D. unfrozen, C.C.I.D. frozen and E.C.I.D. unfrozen respectively.

When the friction angle Φ_f of the triaxial C.C.I.D. tests summarized in fig. 7 is considered, we find values which do not seem to be affected by the relative density which, as it is well known, conditions the peak friction angle .

On the other hand in the extension tests presented in fig. 9, Φ_f is greater for higher density specimens.

With regard to the results of the C.C.I.D.tests performed on frozen-thawed samples, (the results of which are reported in fig. 8) the specimens sampled with direction parallel to the pouring one, exhibit friction angles Φ_f lower than those of the orthogonal specimens. Since in this last case the results refer to tests of the same type performed on specimens at about the same relative density, the different values of Φ_f and Φ must be attributed to the anisotropic characteristics of the material.

Comparing the results of C.C.I.D. and E.C.I.D. tests on unfrozen specimens, the highest values of the peak friction angles are a consequence of higher dilatancy effects ($\Phi - \Phi_f$).This decreases with the increasing of the confining principal stress and grows together with the sample density.

On the other hand, the greater values of D (defined by equations 5 and 6) for equal values of σ_1/σ_3 of the E.C.I.D. triaxial tests indicate greater dilatancy effects for these tests.

CONCLUSIONS

The results presented in this paper confirm that specimens of granular soil prepared in the laboratory exhibit a characteristic anisotropic behaviour.

The strains measured at the end of the isotropical consolidation stage of triaxial tests give a first confirmation of such behaviour. The strains recorderd during this stage are a consequence of both the type of soil structure, and of the method of sample preparation.

The freezing-thawing process, adopted to be able to sample specimens in two directions perpendicular to each other, alters the soil structure of the sand bounded inside a sampler. However it seems that the consolidation stage, with its different induced strains, can bring the sand back to its original state.

In fact the values of both the Young's modulus and the failure-resistances of frozen and unfrozen specimens are substancially the same.

The anisotropic characteristics of the studied material produce effects upon the peak strength which is higer, by about 8 percent for specimens sampled parallel to the sedimentation direction, than those sampled perpendicular to it.

Equation 4, which considers the effect of dilatancy at yield in the form as proposed by Rowe, has proved to be extremely useful in interpreting the physical component of shear strength at failure. It has allowed to separate the behaviour of the compression and extension tests as well as, among each series of tests, to consider the effect of the sample-densities.

The examination of the shear strength of all the studied specimens, considered from an energetic point of view, shows that the particle reorientation effect is similar for the unfrozen C.C.I.D. tests, for the field of stresses and densities, and that the highest strengths are mainly due to the dilatancy effect.

Instead, in the -E.C.I.D. tests the particle reorientation effect is a function of the relative density (these tests have also given values of Φ_f lower by 4° compared with the values given by compression tests) and of the direction of sampling as seen in the C.C.I.D. tests on frozen-thawed specimens.

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