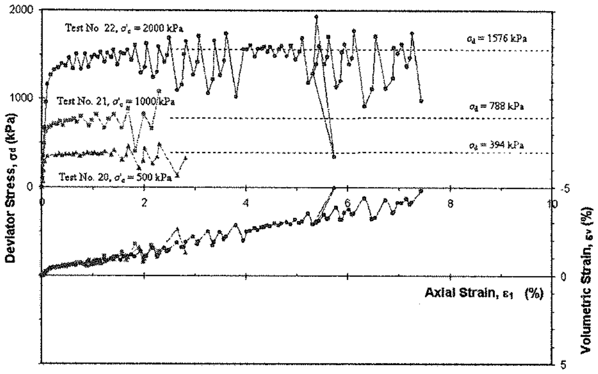

Figure (7) Triaxial compression test results at constant σ'_1 for specimens with fixed caps.

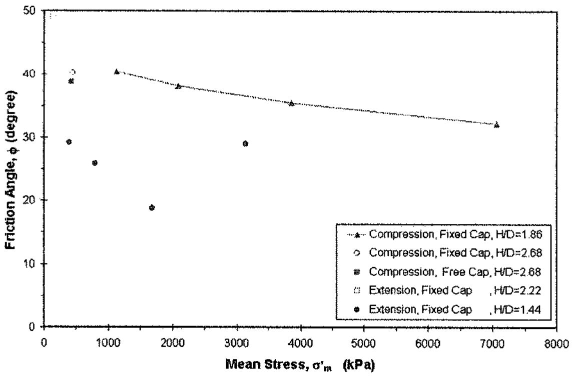

Figure (8) Influence of end conditions or H/D on strengths in triaxial compression or extension tests.

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Contrary to results of compression tests, the friction angles determined in extension tests scatter considerably and do not form a reasonable pattern that can be interpreted meaningfully

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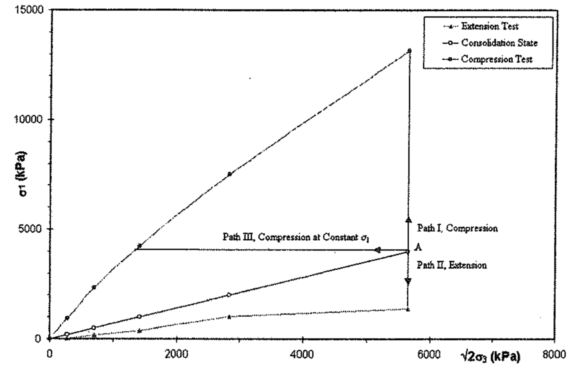

Figure (1) Different stress paths on Triaxial plane.

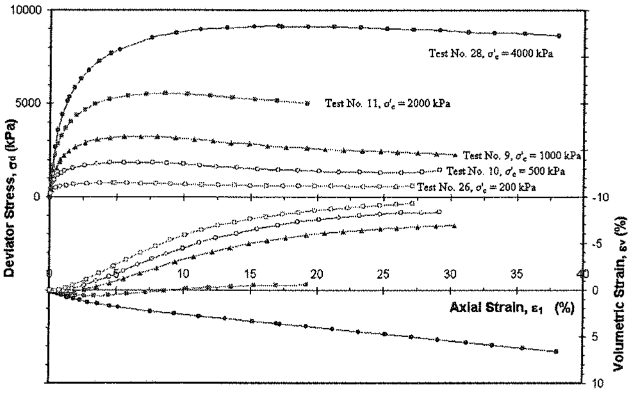

Figure (2) Triaxial compression test results for specimens with fixed caps.

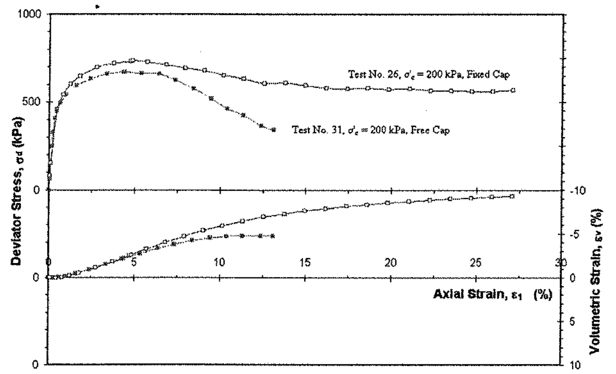

Figure (3) Influence of end conditions in triaxial compression tests on tall specimens (H/D=2.68).

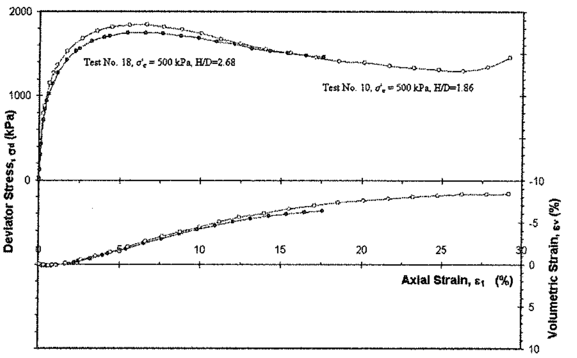

Figure (4) Influence of H/D in triaxial compression tests at σ'_c =500 kPa .

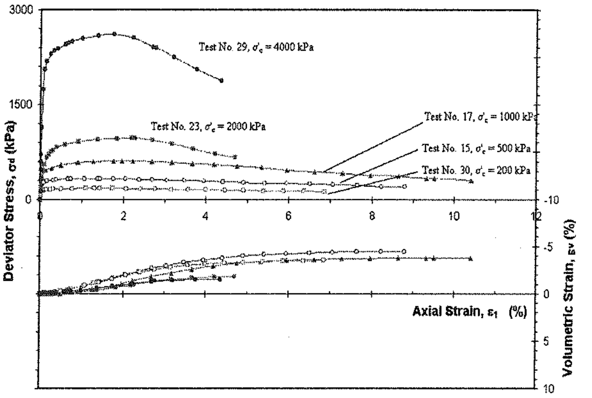

Figure (5) Triaxial extension test results for specimens with fixed caps.

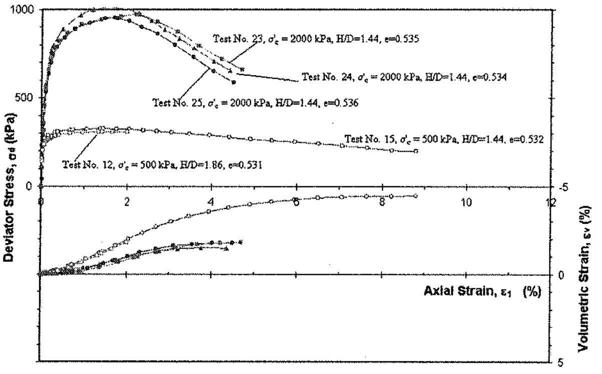

Figure (6) Influence of density or H/D in triaxial extension tests.

- The friction angle decreases with increasing confining pressure.
- The strain-to-failure increases with increasing confining pressure.
- The strength increases with decreasing height-to-diameter ratio for specimens without free or lubricated ends.
- The maximum rate of dilation occurs at the failure point.
- Specimens with restrained or fixed ends exhibited higher strengths than specimens with free or lubricated ends.
- More meaningful and reasonable results are obtained from compression tests, in which shear planes develop after peak failure, than from extension tests, in which shear planes develop before peak failure.

However, other findings in compression tests, such as the mode of failure, appear to have been influenced seriously by the boundary conditions. All specimens with restrained ends failed by bulging with no indications of shear plane developments. In tests on similar specimens but with free cap, shear planes with clear inclinations were fully developed.

From the results of the previous studies on fine sands as well as the present study on coarse sand, it appeared that the difference between failure modes in tests on fine sand and tests on coarse sand, under comparable boundary conditions, corresponded to the difference in thickness of shear planes mobilized inside the specimens. This thickness, which has been shown theoretically and experimentally to be proportional to particle size, is not pronounced in tests on fine sands. In tests on coarse sands the thickness is relatively large, and development of shear planes requires relative displacements of caps and bases in the horizontal direction. If the necessary displacements are allowed, the specimens will produce shear planes after peak failure. Otherwise, bulging failures are produced, and these change the stress-strain and volume change characteristics noticeably as:

- Steeper stress-strain curves after failure are obtained in tests that allow shear planes to develop.
- Volume change termination occurs at much smaller strains in tests with shear planes.

In extension tests, all specimens failed by development of shear planes either in the mid-section of the specimens in tests at low confining pressures (less than 1000 kPa) or under the cap in tests at higher confining pressures (more than 1000 kPa).

For tests at low pressures, the shear planes were clearly observable at the early stages of tests but as the tests were continued, the shear zones were deformed gradually so that the failure modes at the ends looked much more like necking than shearing.

For tests at high pressures, the developed shear planes under the cap were not clearly visible. The volume changes in these tests were terminated at much smaller axial strains than those in extension tests at low confining pressures.

Comparison of results from the extension tests shows that:

- The strain-to-failure in extension tests is smaller than that in compression tests.
- The stress-strain curves after failure in extension tests become steeper as the confining pressures increase, and their rates of stress decrease are much higher than those in compression tests.
- The strain-to-failure increases as the confining pressure rises up to 1000 kPa, and thereafter, it decreases irregularly.

The thickness of shear bands in compression tests appeared to be in better agreement with an average of those proposed in the literature.

The inclinations of shear bands were considerably different from theoretical predictions either according to equilibrium considerations or to compatibility considerations. The reason for this discrepancy was not definitively identified, but the anisotropic fabric in the specimen was considered to be one of the factors, which could have influenced the shear band inclinations in compression and extension tests.

proportional to the size of particles over a range from l0d to 20d. In a theoretical development [10] it has been shown that the thickness of shear bands in compression should be close to 16d in which d is the average diameter of particles. This means that the coarser the grains are, the thicker the shear plane will be.

If the displacement at the cap or base or both were possible, the specimen would deform gradually and adjust itself until the desired displacement would be achieved and a shear band be fully developed. With fixed ends the specimen would start changing its failure path gradually from dilation only in shearing zone to expansion in the entire specimen until it fails in bulging.

It might be suggested to use a very tall specimen with the same fixed ends as an alternative for the specimen with free ends in order to facilitate the creation of shear bands at the middle height. This may cause another problem, because as the height of the specimen increases, the occurrence of buckling becomes more likely, and this changes the failure mode completely. In the range of appropriate height-to-diameter ratios (H/D=2-3), effects of end conditions on the mode of failure are still present, as can be seen from the results of tests on short and tall specimens with restrained ends.

The shear band results indicate that an average of the two above predictions for thickness of the shear plane is more reasonable and comparable to that observed in the actual tests.

The appearance of a shear plane in test 31 was detected at about 7-8% axial strain. This means that the shear plane became visible after peak failure. This observation is similar to that made before in compression tests on fine sands [12]. The only difference was that in the test on coarse sand the shear plane appeared closely after peak failure, but in the tests on fine sand the shear planes occurred after considerable straining beyond the peak failure point.

Extension Tests

The type of failure modes observed at the end of all extension tests was some sort of necking with no clear indications of shear bands. In tests with effective confining pressures higher than 1000 kPa, the failure zones developed below the cap, whereas for tests at lower pressures they developed close to the mid-section of the specimens.

The shear band angle, however, can be measured when the first view of the slip surface is marked. This was possible only in test 30 in which a Lucite cell wall was used. The shear band angle measured in this test with respect to the major principal stress direction was about 15 degrees. The shear band was detected at about 8% axial strain.

Calculations for the orientation of the shear band based on theoretical considerations [8, 13] in both compression and extension tests do not agree with the measurements and predict higher values. However, the anisotropic fabric may play an important role in shear band orientation, and this is not accounted for in theoretical formulations.

Based on previous studies on fine sands [12], the shear bands in extension tests were observed closely after peak failure and accompanied by a sudden and considerable drop in sustained stress difference. But for coarse sand, the results of test #30 in Fig. 4 showed that the shear band became visible at about 7% to 8% axial strain which is rather far beyond the failure point (3.67%). Besides, the shape of the stress-strain curve after failure is almost flat with only a slight decrease in stress difference after peak failure.

CONCLUSIONS

The following observations regarding the strength and volume change characteristics of sands under comparable conditions in compression tests appear to be generally valid independent of the size and type of sand particles employed in the tests:

-The tendency for dilation decreases with increasing confining pressure.

failure are sound, but after failure, the specimens become very sensitive to adjustment of the cell pressure. This causes considerable change of deviator stresses in a short period of time. In order to produce satisfactory results in these tests, it is important to perform all readings, calculations and cell pressure adjustments as fast as possible. Thus, the elapsed time between two consecutive readings is an important factor in these tests. During some portions of the tests the readings and the cell pressure adjustments were conducted quickly and the corresponding parts of the stress-strain curves are relatively steady. Further, these steady sections of the curves correspond to strengths that compare well with the strengths obtained from the failure envelope in Fig. 1. This is indicated by the values of deviator stress and the horizontal lines on Fig. 7.

All three specimens dilate during the tests and the amount of volume change before failure is not affected too much by the magnitude of confining pressure.

STRENGTH CHARACTERISTICS

The strength results obtained in all compression and extension tests are presented in Fig. 8 in terms of friction angle versus mean stress at failure. The effects of height-to-diameter and end conditions is exhibited more clearly in this Fig.. The friction angle values for all short specimens (H/D=1.86) in the compression tests follow a reasonable pattern. They indicates that the magnitude of the friction angle reduces as the mean stress or confining pressure increases. But, the friction angles corresponding to tall specimens (H/D=2.68) represent smaller strengths than those obtained for short specimens under equal mean stress conditions. The effect of free cap used in test 31 also results in a smaller friction angle (38.8) than that of test 26 (40.3) in which a fixed cap was employed.

The results of the extension tests, however, do not demonstrate a reasonable pattern that can be interpreted meaningfully as shown in Fig. 6. This behavior is due to development of shear planes, which according to theoretical considerations (Peters et al. 1988) usually occur before peak failure in extension tests. These shear planes initiate and propagate through the specimens in response to local nonuniformities and stress concentrations; consequently, they result in erratic behavior. In comparison, shear planes in compression tests develop after peak failure, and they do not have any influence on the strength in compression. It should be mentioned, however, that in the extension tests performed in this study the shear planes became visible at a point beyond the peak failure. Regarding the strengths calculated for the extension tests at 500,1000, and 2000 kPa effective confining pressures, it should be mentioned that these strengths are questionable because there was uncertainty about the correct load cell calibration constants used in the vertical load calculations.

CHARACTERISTICS OF SHEAR PLANES

Compression Tests

Except test 31, in which a free horizontally translating cap was provided for the specimen, all compression tests performed on tall or short specimens and under various minor principal stresses did not exhibit any shear planes. All specimens in these tests failed as they bulged considerably in the middle and exhibited almost zero lateral strain at the ends. In test 31, however, a shear band was allowed to develop clearly as a result of the horizontal cap displacement. The amount of displacement in the horizontal direction at the end of the test was about 1.65 cm, and the thickness of the shear band was about 19 mm. The shear band formed an angle with the major principal stress (vertical) of 45 degrees. It seems that the boundary conditions of different specimens employed in this study have had significant influences on the mode of failures.

Previous studies on granular materials [10, 11] show that the thickness of shear band is failure for identical specimens (i.e. same minor principal stresses) is much smaller in extension tests than in compression tests. Further, the stress-strain curves after failure are substantially steeper in extension tests than in the corresponding compression tests. The reason is most likely due to the development of shear planes and necking in extension tests, whereas all specimens in Fig. 2 failed in bulging. The strength decrease after failure in the extension tests becomes less pronounced as the confining pressure reduces from 4000 to 200 kPa.

It can be also seen in Fig. 5 that the major principal strain-to-failure increases from 1.3% to 2.0% as the confining pressure increases from 200 kPa to 1000 kPa, and then it varies irregularly at higher confining pressures. This behavior is also seen for the strain-at-end where the rate of dilation has decreased to zero. For tests up to 1000 kPa, it increases and lasts to high strains (ε_1 = 10.4%) but for the tests at 2000 and 4000 kPa, the axial strains-at-end diminish considerably to about 4.3%. The reason for this behavior may be due to development of shear planes in the different tests. Observations showed that the shear planes at 2000 and 4000 kPa confining pressures developed just below the cap with no clear inclinations, but for those at lower pressures the shear planes were observed in the middle sections of the specimens.

The amount of dilation in the extension tests also increases as the confining pressure decreases except in test 30 at 200 kPa. The rate of dilation in this test tapers off earlier than that in test 15 at 500 kPa. This may be because a tall specimen was used in test 30 and because a shear plane developed in both tests at about the same axial strain. The tall specimen had a larger volume than the short specimen in test 15 and the volumetric strain ($\varepsilon_v = dv/v$) consequently was calculated to be smaller beyond the point of shear plane formation. The rate of dilation is maximum at failure in all extension tests, and it decreases to zero in response to development of shear planes and necking in the specimens.

In order to examine whether it would be possible to produce shear planes in the mid-section of the specimens instead of beneath the cap, three extension tests were performed on identical specimens at 2000 kPa confining pressures. The results of the tests are shown in Fig. 6. All three specimens, however, exhibited necking under the cap. The results of two tests at 500 kPa confining pressures are also presented in this Fig.. Test 12, which was performed on a taller specimen than test 15, was stopped because there was not sufficient space in the cell for vertical extension.

These two sets of data are comparable with the following exceptions:

The strengths obtained at 2000 kPa confining pressure are functions of void ratio. It means that the higher strength corresponds to the denser specimen. But this relation is not seen for the results at 500 kPa. It should, however, be noted that the influence of density in these results is not quite distinct due to the minor differences between void ratios as well as deviator stresses; therefore, all specimens may practically be assumed to have identical density with minor strength differences that is acceptable. This argument may also be applied to the results of two specimens at 500 kPa in respect to the influence of the aspect ratio on the strength.

The strain-to-failure for test 23 is a little higher than those for the two other tests (#24, #25). Also, the shape of the stress-strain curve for test 23 is different from those of the two other curves (#24, #25). The reasons for these behavior are not clear.

Compression Tests at Constant σ'_1

In order to examine the influence of the stress path on the shear characteristics and strength behavior of triaxial specimens, some compression tests were conducted at constant major principal stresses. The results of three compression tests at 500,1000,2000 kPa confining pressures are plotted in Fig. 7. As seen in this Fig., the shape of the stress-strain curves up to

Compression Tests at Constant σ'_1

This series of tests was conducted only with short specimens and using initial effective confining pressures of 500, 1000, and 2000 kPa (Fig. 1, path III).

In these tests the cell pressure was adjusted after each reading to a new lower level such that the sum of the cell pressure and the deviator stress remained constant during the shearing.

STRESS–STRAIN AND VOLUME CHANGE CHARACTERISTICS

Compression Tests

The results of compression tests on short specimens (H/D=1.86) at various confining pressures as well as that of the tall specimen (H/D=2.68) at 200 kPa confining pressure are shown on Fig. 2. It is seen that all stress- strain curves have smooth curvatures and are gradually dropping after failure. This is due to the type of failure (bulging) caused by the restrained ends used in all specimens in this Fig..

As expected from past studies on sand [7], it is seen that the amount of dilation in each test decreases with increasing confining pressure and the volume change becomes compressive in tests at high confining pressures. The rate of dilation is highest at the failure point in each test. In test 28, the specimen is undergoing compression and this continues even at high axial strains (up to 36%). The rate of compression also shows a slight increase as the specimen is strained beyond 20%. The stress-strain curve of this test resembles that of a loose specimen at low confining pressure, which has also undergone compression [8]. The slope of the curve after failure is small compared to those of other tests in which the specimens dilate. The stress-strain behavior becomes more brittle as σ_3 reduces, and the strain-to-failure increases as higher confining pressure is applied. This behavior of sand also has been seen before [7].

Fig. 3 shows the result of tests on tall specimens with different end conditions. It is seen that the strength obtained for a specimen with regular rough cap (#26) is higher than that with a free cap. This is due to the end restraint, which acts as though a slightly higher confining pressure is imposed on the specimen as well as possibly an increased side friction along the loading piston. However, the initial modulus, strain-to-failure, and the amount of volume change up to failure in both tests remain nearly the same.

It is interesting also to realize that the stress-strain curves after failure in both tests start with identical initial slopes, and as the tests proceed, the curve of the first test gradually becomes flat due to bulging of the specimen. The curve of the second test becomes more brittle because of shearing until it reaches a constant slope when the shear band is fully developed. The volume change in the second test at the time of shear band formation decreases and has totally terminated at the end of the test. In comparison, the rate of volume change in the first test decreases slowly and the specimen keeps expanding with almost constant rate even at high axial strains (27%).

Fig. 4 shows the results of compression tests performed on short and tall specimens at 500 kPa confining pressures. Both specimens were restrained by rough caps, and no shear bands were observed. It is seen again that the strength obtained for the tall specimen is slightly less than those of the short specimen. This behavior is due most likely to the difference in specimen heights as reported by other investigators [9]. However, more tests on tall specimens are necessary to confirm this conclusion.

Extension Tests

Fig. 5 represents the stress difference and volume change results in terms of major principal strain (ε_1) in extension tests at different confining pressures. Comparing these curves with those obtained in the compression tests (Fig. 2), it is seen that the range of strain-to-

to H/D=2.68 was employed. Two different boundary conditions (restrained or free) were provided at the caps of the tall specimens. (b) In the second apparatus a relatively short specimen with restrained ends and typical height of 13.2 cm and a diameter of 7.1 cm corresponding to H/D = 1.86 was employed. The H/D ratios for triaxial extension apparatuses were 1.44 and 2.22 corresponding to high and low effective confining pressures respectively.

Three readings were recorded in each data set: the vertical load on the specimen either in compression or in tension, the vertical strain, and the volume change showing the amount of compression or dilation. Two corrections were made to the test results. The first and most important correction was made for membrane penetration into the specimen. A considerable amount of volume change was measured in the consolidation stage of each test due to membrane penetration. The method applied here was described by Frydman et al. [6] in which the amount of membrane penetration was basically dependent on the particle size and the effective confining pressure. The second correction was due to the strength of the membrane made to deviator stresses calculated for the extension tests.

The loading rate of the Wykeham Farrance machine was set at 0.003 inch/min. At this rate it was possible to record precise data at the beginning of each test and calculate a more correct initial modulus for the specimen. Moreover, this rate was appropriate for tests in which the major principal stress was maintained constant while changing the confining pressure after each reading. At this rate it was possible to perform the required calculations, and adjust the cell pressure during the time available between two consecutive readings.

EXPERIMENTAL PROGRAM

Three different series of drained triaxial tests were conducted on specimens consolidated under various effective confining pressures (200 - 4000 kPa). At the end of each test, photographs were taken of the specimen to display the mode of failure and any shear banding that might have occurred. Shear bands are defined as the localization of deformation in thin layers of intensively shearing material. For sand, a particular thickness of the band is visible; (about 15 times the particle size). In a clay material, such a thickness is invisible and the shear band, or rupture layer, is viewed as a slip line.

Compression Tests

The first series of tests was conducted as conventional triaxial compression tests as represented with path I in Fig. 1. This Fig. shows all examined stress paths on the triaxial plane (an octahedral plane in which $\sigma_3=\sigma_2$; therefore, the horizontal axis becomes $\sqrt{\sigma_3^2+\sigma_2^2}=\sqrt{2}\sigma_3$). All paths (tests) start from an identical condition (i.e. point A), which is the condition at the end of the consolidation stage. The compression tests were performed on both tall and short specimens. The tests on tall specimens were carried out at 200 and 500 kPa effective confining pressures, because the Lucite cell wall was not strong enough to withstand higher cell pressures. For tests at 200 kPa the two different end conditions (restrained and free cap) were employed in order to investigate their effects on the strength as well as development of shear planes. For short specimens, with restrained caps, the following effective confining pressures were applied: 500, 1000, 2000, 4000 kPa.

Extension Tests

As for the compression tests, two different apparatuses were used for the extension tests. Only one test with 200 kPa effective confining pressure was performed on a tall specimen (H/D=2.22). For tests on short specimens (H/D=1.44), the range of effective confining pressure was 500 - 1000 - 2000 - 4000 kPa, i.e. the same as those in the compression tests (Fig. 1, path II).

of 1.0 and 2.5 were investigated. In view of the results obtained, different conclusions were reached regarding the behaviour of cross-anisotropic soils. The behaviour depended on the boundary conditions or, nominally, the H/D-ratio of the triaxial specimens. The specimen with H/D = 2.5 exhibited distinct, but temporary drops in their pre-failure stress-strain curves, and the friction angles changed in a consistent pattern over a range of 5.5 degrees. In comparison, the specimens with H/D = 1.0 showed more smooth stress-strain behaviour and their friction angles were essentially constant with very little effect of initial grain orientation.

The study presented herein is, in part, a continuation of previous investigations on Cambria Sand and, in part, a preliminary study for a larger investigation of the behaviour of sand at very high confining pressures.

Test Materials

The soil used in this study was Cambria Sand, which has subrounded grains and particle sizes between 2.00 mm (NO. 10 U.S. Standard Sieve) and 0.84 mm (NO. 20 U.S. Standard Sieve). This grain size distribution was the same as those used in the previous investigations [3, 4] on this sand so that comparison of results would be possible. Moreover, in this range of grain sizes, the amount of particle crushing would be expected to be considerable. Therefore, a study of crushing and identification of the crushed grains would be possible. The specific gravity of this sand was measured to be 2.668 and the maximum and minimum void ratios were 0.80 and 0.51 respectively (see Ref. 2).

In all compression and extension tests, the rubber membrane carried some part of the vertical load, which, of coarse, was not very large. The elastic parameters of the latex rubber membrane, Young's modulus and Poisson's ratio, were 14 kg/cm^2 (1370 kPa) and 0.5, respectively. These values were required for corrections to the deviator stresses calculated in the compression and extension tests.

SAMPLE PREPARATION

Previous experiments on Cambria Sand [3] has indicated that, in order to prepare dense specimens with a void ratio between 0.54 and 0.53, the sand should be poured and shaken under water in the mold in 10 layers with one minute shaking for each layer. However, this subject was examined again because the size of specimens used in the present study was different from those in the previous studies. Several specimens were prepared with various numbers of layers and shaking time for each layer and their void ratios were measured. The results showed that the above condition (ten layers and one minute shaking per layer) was still applicable and could produce specimens with the desired range of void ratios. The prepared specimens also had anisotropic fabric due to the strong preferred grain orientations in vertical sections and almost completely random orientations in horizontal sections.

Depending on the range of applied confining pressures, one to three membranes were used to prevent membrane puncturing [see Ref. 5]. Although all specimens were produced under de-aired water, it was necessary to perform additional saturation procedures. The detailed saturation procedure has been presented elsewhere [5]. The degree of saturation was checked by measuring the B parameter. This value was in all cases below the acceptable level for full saturation unless a back pressure up to 60 psi was applied inside the specimen. B-values measured subsequently were between 0.96 and 1.00 for all specimens, thus indicating that full saturation had been achieved.

TESTING DEVICE AND MEASUREMENTS

Two different triaxial compression apparatuses were used in this study: (a) In the first apparatus a tall specimen with typical height of 19.0 cm and diameter of 7.1 cm corresponding

Triaxial Testing on Coarse Sand under Different Stress Paths

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ABSTRACT

A stress path triaxial testing study entailing compression, extension, and compression tests at constant major principal stress, was performed on coarse Cambria Sand prepared with cross-anisotropic fabric in cylindrical specimens. Height-to-diameter ratios of 1.44, 1.86, 2.22, and 2.68 as well as different end conditions were employed to study the sand behaviour in the range of applied effective confining pressures from 200 kPa to 4000 kPa. The compression test results were well comparable with those in the previous investigations as follow. 1) The tendency for dilation decreases with increasing confining pressure. 2) The friction angle decreases with increasing confining pressure. 3) The strain-to-failure increases with increasing confining pressure. 4) The strength increases with decreasing height-to-diameter ratio for specimens without lubricated ends. 5) The maximum rate of dilation occurs at the failure point. 6) Specimens with restrained ends exhibited higher strengths than specimens with free or lubricated ends. However, the mode of failure appears to have been influenced seriously by the boundary conditions, which in turn changes the stress-strain and volume change characteristics.

In extension tests, all specimens failed by development of shear planes either in the mid-section of the specimens in tests at low confining pressures (less than 1000 kPa) or under the cap in tests at higher confining pressures (more than 1000 kPa). Comparison of results from the extension tests shows that: 1) The strain-to-failure in extension tests is smaller than that in compression tests. 2) The stress-strain curves after failure in extension tests become steeper as the confining pressures increase, and their rates of stress decrease are much higher than those in compression tests. 3) The strain-to-failure increases as the confining pressure rises up to 1000 kPa, and thereafter, it decreases irregularly. 4) More meaningful and reasonable results are obtained from compression tests, in which shear planes develop after peak failure, than from extension tests, in which shear planes develop before peak failure.

Keywords

Sand, Triaxial Test, Shear Strength, Stress Path

INTRODUCTION

Natural in-situ sand deposits display fabric anisotropy due to parallel alignment of particles. Studies have shown that fabric anisotropy may have considerable influence on the stress-strain and strength behaviour of sand [1, 2]. Ochiai and Lade [3] studied the effect of cross-anisotropic fabric on the three-dimensional stress-strain behaviour and strength of coarse Cambria Sand (2.00 mm > d > 0.84 mm). Cubical specimens with lubricated ends were tested using triaxial compression, plane strain, and cubical triaxial equipments with independent control of the three principal stresses. The results indicated that the initial cross-anisotropic fabric affected prefailure stress-strain and volume change behaviour. Sufficient changes in the fabric had occurred at large strains to produce failure conditions, which resemble those observed for isotropic sands. In another study by Lade and Wasif [4], the stress-strain, volume change, and strength characteristics of the same Cambria Sand prepared with cross-anisotropic fabric in specimens with lubricated ends and height-to-diameter ratios