International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:11, No:3, 2017

Anisotropic Shear Strength of Sand Containing Plastic Fine Materials

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***Abstract*—**Anisotropy is one of the major aspects that affect soil behavior, and extensive efforts have investigated its effect on the mechanical properties of soil. However, very little attention has been given to the combined effect of anisotropy and fine contents. Therefore, in this paper, the anisotropic strength of sand containing different fine content (F) of 5%, 10%, 15%, and 20%, was investigated using hollow cylinder tests under different principal stress directions of $\alpha = 0°$ and $\alpha = 90°$. For a given principal stress direction (α), it was found that increasing fine content resulted in decreasing deviator stress (q). Moreover, results revealed that all fine contents showed anisotropic strength where there is a clear difference between the strength under 0° and the strength under 90°. This anisotropy was greatest under F = 5% while it decreased with increasing fine contents, particularly at F = 10%. Mixtures with low fine content show low contractive behavior and tended to show more dilation. Moreover, all sand-clay mixtures exhibited less dilation and more compression at $\alpha = 90°$ compared with that at $\alpha = 0°$.

***Keywords*—**Anisotropy, principal stress direction, fine content, hollow cylinder sample.

I. Introduction

ANISOTROPY refers to the directional dependence of the mechanical properties of soil [1]. It can be one of the most important factors that affect soil characteristics, potentially causing serious problematic issues in the design of geotechnical structures. As a consequence, numerous studies have investigated this feature. However, most of these efforts were focused on pure sand or fine soil with very few studies examining sand-fine mixtures.

To investigate the anisotropy effects, tilted bedding plane samples were tested using a triaxail test, and direct shear test, in addition to loading test. Hollow cylinder samples were efficiently used for these investigations. It was found that the anisotropic strength decreased steadily and achieved the lowest value when the major principal stress direction became aligned with the horizontal bedding plane [2]-[5]. The whole spatial arrangement, grain shape, loading boundary condition, and packing density affect the degree of anisotropy [3], [6], [7]. The reduction in the deviator stress and dilatancy rate, caused by the rotation of principal stress direction toward the horizontal plane, was more conspicuous in a plane strain test than a triaxial test [4]. Similar results were recently obtained using a modified direct shear device where the sample can be prepared with a tilted bedding plane. For example, 20% difference between the maximum and minimum strength due to anisotropy was found by [8].

The hollow cylinder sample offers a great opportunity to study anisotropy under different conditions of stress path. This apparatus has been employed by many researchers (e.g. [9]-[15]). It was found that the rotation of the principal stress direction had a strong effect on the stress-strain characterization where it resulted in a significant decrease in strength and increase in the induced strains [16].

Sand mixtures with fine materials such as clay, silt or other fine material are more commonly found in nature than pure sand and can be used as a mechanical stabilization in earth structures. Therefore, there is a necessity to explore these sand mixtures, particularly as most studies have concentrated on pure sand. A study of sand-fine mixtures by [17] discovered that the peak strength of sand decreased with increasing Kaolinit content up to 20%, and therefore, some increasing happened although it was still less than the strength of pure sand. A mixture with bentonite exhibited a similar trend but the lowest strength was observed at 5% content. The deviator stress under undrained conditions tended to decrease with increasing silt content up to 50% and then increased [18]. A similar trend in undrained strength was observed by [19] but the threshold was 30%. The strength of sand-fine mixture is a controversial subject where [20] found that fine materials with contents ranging from 5% to 95% resulted in increasing strength.

In view of the aforementioned, the anisotropic strength of sand with fine contents has reasonable importance, and therefore, this study is a part of an ongoing study at Curtin University to study the effect of both fine material and anisotropy on the behavior of sand.

II. Materials Used

A. Sand

Poorly graded clean sand (SP) was used in this study. This sand was from the city of Perth in Western Australia. This soil had a coefficient of uniformity (Cu) and coefficient of curvature (Cc) of 1.5 and 1.04, respectively. Their minimum and maximum void ratios were 0.549 and 0.826, respectively. The specific gravity of this sand was 2.65.

B. Kaolinit

The fine material used in this study was Kaolinit which was produced by Sibelco (Australia). This material consisted of 93% Kaolinite and 7% quartz. It had a specific gravity, liquid limit, plastic limit, and plastic index of 2.66, 58%, 31%, and 27%, respectively.

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III. Apparatus

Large hollow cylinder apparatus HCA600 was used in this study with a sample of 600 mm height, 300 mm outer diameter and 150 mm inner diameter. This apparatus enabled axial load, torque, outer cell pressure, and inner cell pressure to be independently controlled. As a consequence, the direction of principal stress could be controlled. In this study, two directions of principal stress were chosen: vertical with α = 0° and horizontal with α = 90°. The saturation stage was executed and controlled automatically under constant initial effective stress of 30 kPa until the target value (0.95 in this study) for Skempton's B value was reached. Isotropic consolidation was then achieved by increasing the effective inner and outer pressure to 100 kPa. Samples were then sheared under drained conditions where b = 0.5 and p′ = 100 kPa. In this study, samples of sand with varying content of Kaolinite (5%, 10%, 15%, and 20%) were prepared for 70% relative density and tested under two different directions of principal stress of 0° and 90°.

IV. Results and Discussion

Figs. 1–4 show the relationship between the deviator stress and the deviator strain of sand mixtures that can be calculated as:

$$q = \left[1/2\left\langle(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right\rangle\right]^{1/2} \quad (1)$$

$$\varepsilon_q = \left[2/9\left\langle(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right\rangle\right]^{1/2} \quad (2)$$

The peak deviator stresses were plotted against the fine contents in Fig. 5 for both directions of principal stress 0° and 90°. For principal stress direction of α = 0°, the behavior shows that the strength decreases as the fine contents increases from 10% to 20%. However, the fine content of 5% gives the lowest peak deviator stress, where q decreased from 106 kPa at F = 10% to 98 kPa and 94 kPa for F = 15% and F = 20%, respectively.

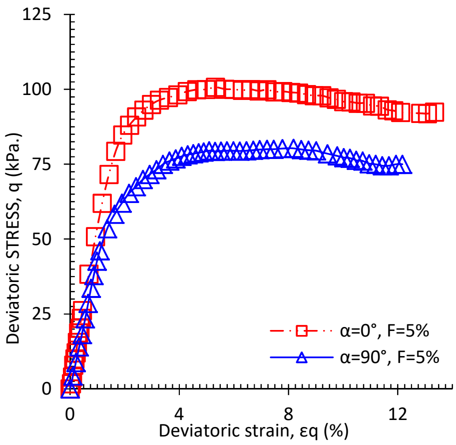

Fig. 1 Deviator stress-strain relationship for 5% fine content for α = 0° and α = 90°

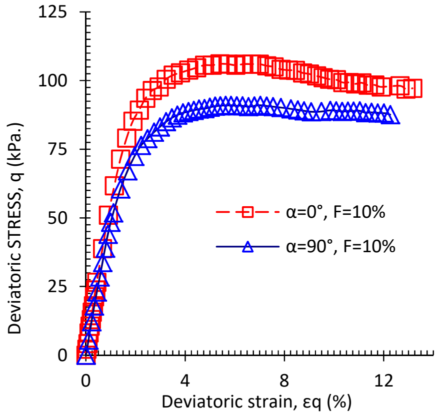

Fig. 2 Deviator stress-strain relationship for 10% fine content for α = 0° and α = 90°

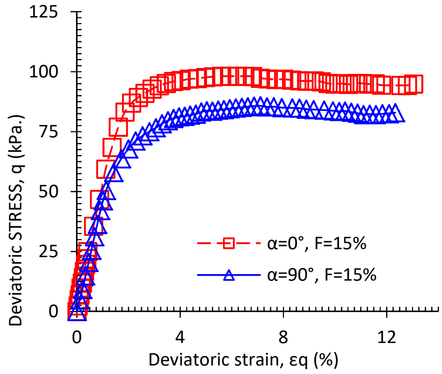

Fig. 3 Deviator stress-strain relationship for 15% fine content for α = 0° and α = 90°

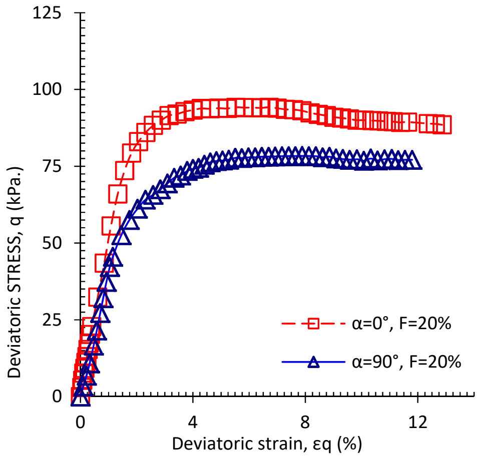

Fig. 4 Deviator stress-strain relationship for 20% fine content for α = 0° and α = 90°

A similar trend was observed for α = 90°, where q increased from the lowest value of 80 kPa at F = 5% to 91 kPa at F = 10%, followed by decreasing to 84 kPa and 78 kPa for F = 15% and 20%, respectively. This indicates that the fine content generally contributes to decrease the peak deviator stress. This decrease was more significant for α = 90° than α = 0°. However, the strength at α = 0° was greater than the strength at α = 90° for all mixtures. It is obvious that 5% fine content displays the lowest deviator stress while 10% fine content exhibits the largest value of q followed by less deviator stress. This decrease along with increasing fine content is consistent with the findings of [21], [22], and others, and can be explained by their interpretations. For low fine content, the particles of fine materials come between the contact of sand particles and work as lubrication. With this lubrication, it is easy for particles to move, slide and/or rotate, and thus, easier for the mixture to deform and fail.

With increasing fine content, the fine materials work as a bond and are also located inside the voids, providing less opportunity for deformation. However, further increase in the fine content will result in fewer contacts between sand particles and decrease its contribution to carry the applied load. In this investigation, the strength of pure sand was not tested and thus comparison is only with these fine content mixtures.

Figs. 1–5 show that for each mixture there is a clear anisotropic response to loading. The difference ratio between the deviator stresses at α = 0° and α = 90° was 20% for 5% fine content. With increasing fine content, anisotropy represented by the ratio of the difference in deviator stresses decreased to 14.1%. A similar trend was observed for the 15% fine content where the difference in q becomes 14.3%. This difference due to the directional dependence increased to 17% as fine content increased to 20%. These anisotropy findings can be explained based on the microstructure reported by [1], among others, where the preferred horizontal alignment of particles create a weak plane of deformation in the horizontal plane, and thus, exhibits lower strength compared with the vertical plane. With low fine contents of 5%, this weak plane became weaker as this low fine content worked as lubrication, and therefore, gave high anisotropy. However, with higher fine contents of 10% and 15%, anisotropy tended to decrease and this may be attributed to the contribution of this fine material as a support material to resist the deformation in the horizontal plane. The horizontal plane may have lost some of its weakness as the fine material is located in voids and works against the failure plane.

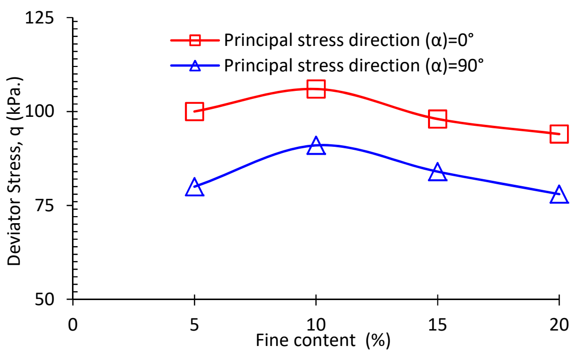

Fig. 5 Effects of fine content and principal stress direction on the peak deviator stress

Figs. 6 and 7 show the volumetric strain of the sand-clay mixture at α = 0° and α = 90°. It can be seen that mixtures with low fine content show low contractive behavior and tended to show more dilation. Moreover, all sand-clay mixtures exhibited less dilation and more compression at α = 90° compared with that at α = 0°. This is related to that previously mentioned: the weakening of the bedding plane due to the preferred horizontally alignment of particles which can exhibit poor interlocking and easy deformation. These results shed a light on the anisotropic behavior of sand that contains plastic fine material with contents of 5% to 20% where the sand dominated the behavior of the mixture. It contributes useful information that can be taken into consideration in the design of geotechnical structures.

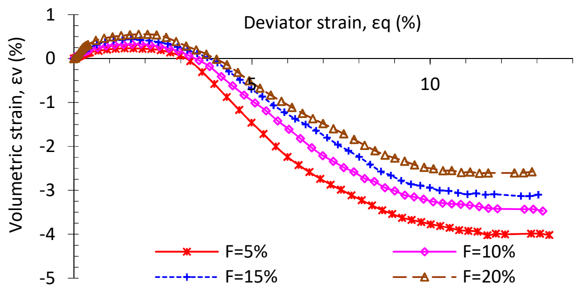

Fig. 6 Volumetric strain-deviator and strain relationship for different fine contents for α = 0°

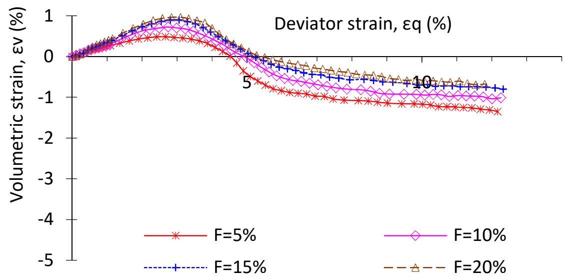

Fig. 7 Volumetric strain-deviator and strain relationship for different fine contents for α = 90°

V. Conclusion

Drained hollow cylinder triaxial tests were carried out on large scale samples to investigate the anisotropic stress-strain characterization of sand-plastic fine materials with different fine contents. Several conclusions can be drawn from this research. Irrespective of fine contents, sand-clay mixtures exhibited a clear anisotropic response to the principal stress direction. Fine contents of 5% resulted in a maximum difference ratio (20%) in the deviator stress due to anisotropy, while 10% fine content led to minimal difference ratio (14.1%). Increasing the fine content resulted in decreased peak deviator stress, where 5% fine content led to the lowest value as a result of acting as lubrication between sand particles.

ACKNOWLEDGMENT

Alaa Hussein Jassime Al-Rkaby is grateful for the PhD scholarship awarded by the Higher Committee for Education Development in Iraq (HCED) for his studies at Curtin University.

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