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Effect of the fines content and its characteristic grain shape on the undrained strength of loose silty sands

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ABSTRACT
Static liquefaction of loose saturated granular soils has caused several catastrophic failures of earth fills, tailings storage facilities and waste dumps. It is well known that the liquefaction potential strongly depends on state parameters. However, the influence of grains' intrinsic properties has attracted less attention. In this paper, comprehensive experimental work on non-plastic silty sands is presented. The main objective is to study the effects of the characteristic grain shape of the fines content (FC) on the undrained behavior of loose cohesionless silty sandy materials. Samples of Ottawa sand mixed with varied amounts of fines were prepared, to obtain the common FC scenarios of underfilled, transitional and overfilled packings. Two types of fines were used: glass beads and mine tailings. Constant volume and constant stress ring shear tests were carried out at large shear strains of around 100%. The results show that transitional cases exhibit higher residual strength under constant volume conditions. Moreover, data on mixtures indicate that angular fines content significantly increases the critical friction angle, while it decreases when rounded FC are used. The same trend is observed in the undrained (i.e., constant volume) peak and critical strengths. The results help to understand the effect of intrinsic characteristics of soils on static liquefaction potential. The main application is the assessment of the undrained behavior of granular mixtures that can drastically vary their properties in industrial processes, such as mine waste production.

RÉSUMÉ
La liquéfaction statique de sols granulaires lâches et saturés a provoqué plusieurs défaillances catastrophiques de remblais, de parcs à résidus miniers et de terrils. Il est bien connu que le potentiel de liquéfaction dépend fortement des paramètres d'état. Cependant, l'influence des propriétés intrinsèques des grains a été moins étudiée. Dans cet article, des travaux expérimentaux sur des sables silteux non plastiques sont présentés. L'objectif principal est d'étudier les effets de la forme caractéristique des grains de la teneur en fines (FC) sur le comportement non drainé de matériaux sableux limoneux lâches. Des échantillons de sable d'Ottawa mélangés à diverses quantités de fines ont été préparés, pour obtenir les scénarios typiques de FC correspondant aux empilements sous-remplis, transitoires et sur-remplis. Deux types de fines ont été utilisés : des billes de verre et des résidus miniers. Des essais de cisaillement annulaire à volume constant et à contrainte constante ont été réalisés à des déformations de cisaillement de 100 %. Les résultats montrent que la teneur en fines angulaires augmente significativement l'angle de frottement critique, tandis qu'elle diminue avec l'utilisation de fines arrondis. La même tendance est observée pour les résistances au pic et critiques non drainées. Les résultats aident à comprendre l'effet des propriétés des sols sur le potentiel de liquéfaction statique. La principale application est l'évaluation du comportement non drainé des mélanges granulaires dont les propriétés peuvent varier considérablement dans les procédés industriels, tels que la production de déchets miniers.

1 INTRODUCTION

To achieve the goal of stable Tailings Storage Facilities, the mechanical properties of tailings need to be evaluated by means of in-situ and laboratory tests. Currently, there are many approaches to evaluate these properties for design purposes. However, the heterogeneity of the materials can pose significant challenges (Aubertin et al., 2002; Bussière, 2007). Tailings can be composed of mixtures of materials from diverse geological origins, varied grinding and comminution processes, and different metallurgical treatments. Thus, the grains within these mixtures can largely vary in size, morphology and mineralogy. It is well known that these properties strongly impact the mechanical behavior of granular materials (Carrasco et al., 2025; Cho et al., 2006; Lakkimsetti & Latha, 2023; Yang & Luo, 2015; Yang & Wei, 2012). However, the combined effects of mixtures of polydisperse particle sizes and shapes with varying fines content (FC) on the mechanical behavior of granular materials have not been deeply studied (Carrasco et al., 2023). Motivated by these challenges, this paper proposes a comprehensive experimental study on granular mixtures taking into account the effects of the characteristic grain shape of the fines content on the mechanical behavior of silty sands.

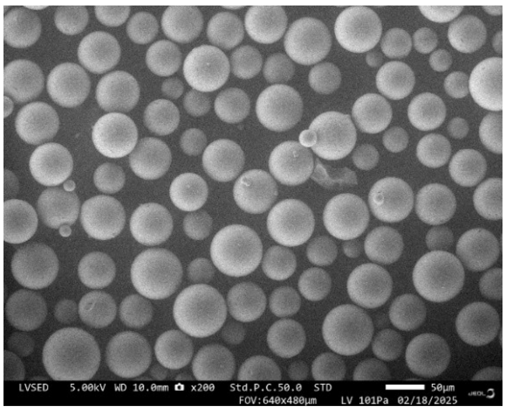
2 EXPERIMENTAL METHODS

2.1 Granular materials

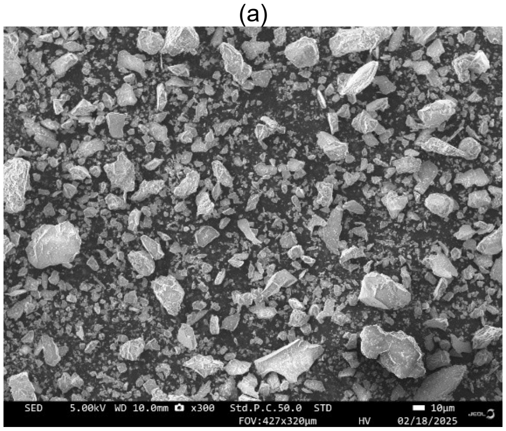
The granular materials used in the experimental work are Ottawa sand (OS), glass beads (GB) and hard rock Malartic tailings (ML). Ottawa sand is a poorly-graded sand without fines (FC=0), maximum particle diameter d_{max}=0.85 mm, mean grain size d_{50}=0.39 mm and specific gravity of 2.65. The maximum and minimum void ratios of OS are 0.752 and 0.548, respectively. GB and ML are non-plastic fine materials used to prepare mixtures with OS with varied

FC. The grain size range of both GB and ML is restricted to 0.038 mm and 0.075 mm; i.e., passing the standard sieve no. 200 and retained in sieve no. 400. The specific gravities of GB and ML are 2.52 and 2.72, respectively.

Scanning Electron Microscope (SEM) was used to characterize the particle shape of GB and ML. The SEM images of GB and ML are shown in Figure 1a and b, respectively. The image of OS is shown in Figure 1c. It can be seen that the particle shapes of GB are perfect spheres, whereas ML shows angular and subangular shapes. The grain shape of OS can be visually described as subrounded to subangular.



(a)



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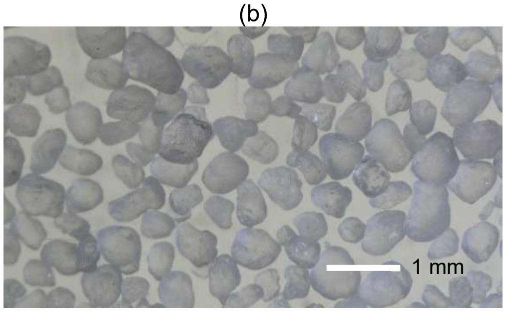


(c)

Figure 1. SEM images of (a) GB, (b) ML and (c) OS.

To study the effect of FC and particle shape on the mechanical behavior of granular mixtures, OS was mixed with different percentages of FC from GB and ML, ranging from 0% to 100%. The PSDs of the combined mixtures are presented in Figure 2.

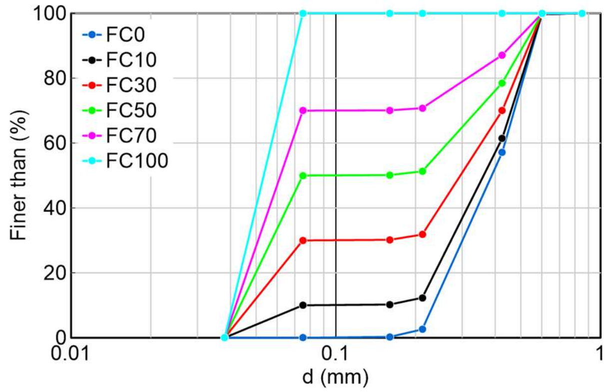


Figure 2. PSDs of mixtures of OS with varied FC.

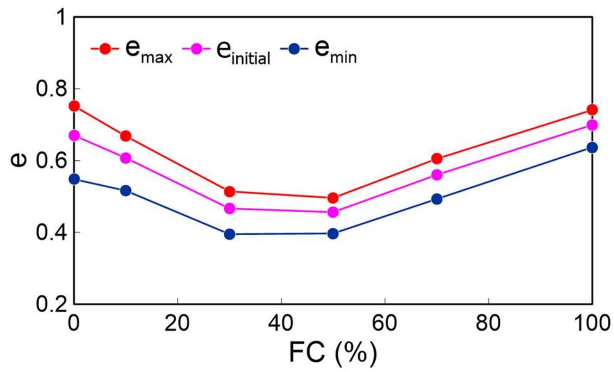


Figure 3. Variation of void ratio with FC for OS-GB mixtures.

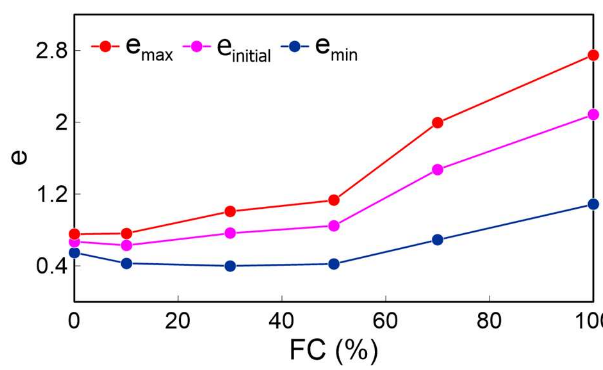


Figure 4. Variation of void ratio with FC for OS-ML mixtures.

The variation of the maximum void ratio (e_{max}) and the minimum void ratio (e_{min}) with the FC for the mixtures of OS with GB and ML are presented in Figure 3 and Figure 4, respectively. As FC increases, e_{min} shows a decreasing trend until a FC threshold, indicating the densest condition. After that, e_{max} and e_{min} show an increasing trend up to FC=100%. The profile of these trends strongly depends on the characteristic particle shape of the fine fraction (Biarez and Hicher, 1997). Namely, the more angular the particle shape, the higher the difference between e_{max} and e_{min}. As expected, Figure 3 shows that when OS is mixed with GB fines (OS-GB), e_{max}-e_{min} is smaller than the mixtures OS-ML (see Figure 4).

In Figure 3, low values of GB fines (FC=0-20%) produce loose packings. This is known as the underfilled condition (Thevanayagam et al., 2002), characterized by fines rattling within the voids between coarse grains. In this case, fines have negligible contribution to the intergranular force network, which is mainly supported by coarse particles (Yamamuro & Lade, 1997). As FC increases, there is a gradual reduction in the reference void ratios until FC=30-50%, where GB fines fill the voids and the material reaches a denser condition; here, fines and coarse grains have both crucial roles in the force transmission of the soil skeleton. After exceeding FC=50%, fines start to overfill the voids and, at high FC, coarser OS particles are surrounded by GB fines and a loose packing is formed; this condition is known as overfilled (Thevanayagam et al., 2002).

In Figure 4, the overfilled and underfilled transition is less evident in OS-ML mixtures. While e_{min} shows a FC threshold at FC=30%, while e_{max} systematically increases with FC between 0% to 100%.

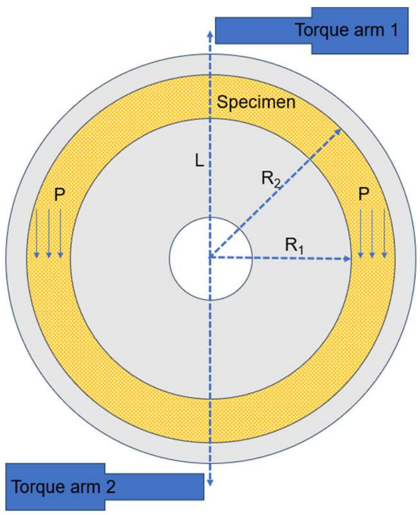


Figure 5. Schematic diagram of the ring shear test.

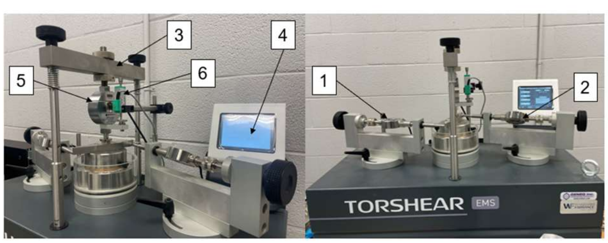


Figure 6. Ring shear device: (1-2) 1 kN shear horizontal load cell, (3) crossbeam (4) touch-screen display, (5) 5 kN vertical load cell and (6) 10-mm vertical displacement sensor.

2.2 Ring shear tests

A ring shear test device was used to carry out constant volume (CV) and constant stress (CS) tests on dry specimens of OS, GB, ML and their mixtures. An advantage of the ring shear test is that it can reach large shear deformation so that the critical state can be reached, compared to other conventional laboratory tests whereby the critical state cannot be always determined. Figure 5 shows the schematic diagram of the ring shear test.
The annular ring soil specimens have 20 mm in height, an inner radius of 35 mm and an outer radius of 50 mm, so the width of the specimen is 15 mm. The test can described as follows: a vertical consolidation pressure (σ'_v) is applied on the specimen. After completion of the consolidation stage, the specimen is sheared by turning the base of the mold. The mobilized shear stress of the specimen is measured by two torque arms. Interpretation of the test data is carried out in accordance with the standard ASTM D6467-21.

Figure 6 shows the ring shear test equipment used in this experimental work. The capacity of the horizontal load cell is 1 kN and that of the vertical load cell is 5 kN. A vertical displacement sensor with a 10 mm travel distance is used for monitoring the vertical deformation during consolidation and shearing.

All specimens were prepared by pouring dry material into the annular mold and ensuring homogeneity. Mixtures of OS with GB and ML were prepared at an initial void ratio ($e_{initial}$), corresponding to a density index of $I_D = 0.4 = (e_{max} - e_{initial})/(e_{max} - e_{min})$. The void ratios of the specimens are shown in Table 1 for both mixtures OS-GB and OS-ML. Before shearing, a vertical consolidation pressure was applied to consolidate the specimens; σ'_v = 50, 100 and 200 kPa were used. After consolidation, the specimens were sheared under CV or CS conditions. CV is achieved by controlling vertical load to keep constant specimen height upon shearing. On the contrary, vertical load is kept constant during shearing under CS. All of the specimens were sheared up to 100% of shear strain. Since the specimens were dry, all the stresses measured correspond to effective ones.

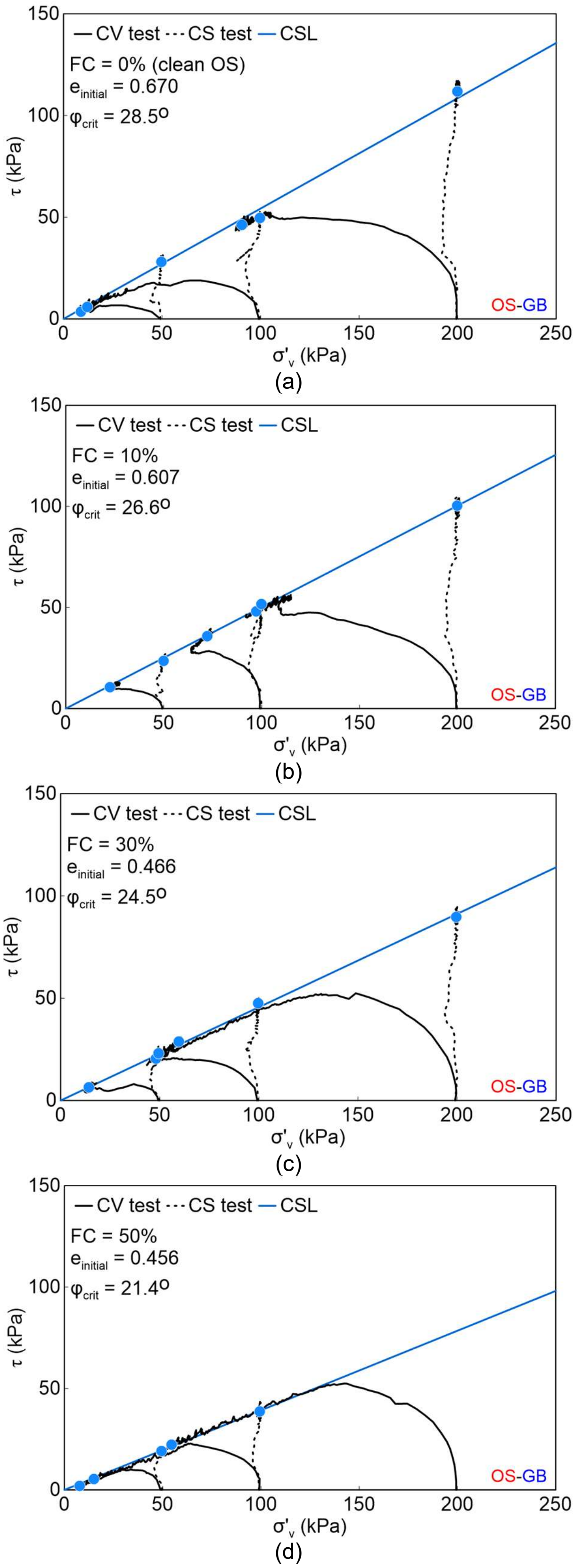
Table 1. Physical characteristics of tested mixtures

FC	OS-GB			OS-ML		
(%)	e_{max}	e_{min}	$e_{initial}$ (*)	e_{max}	e_{min}	$e_{initial}$ (*)
0	0.752	0.548	0.670	0.752	0.548	0.670
10	0.668	0.516	0.607	0.761	0.428	0.628
30	0.514	0.395	0.466	1.006	0.399	0.763
50	0.496	0.397	0.456	1.130	0.421	0.846
70	0.605	0.493	0.560	1.995	0.689	1.473
100	0.741	0.637	0.699	2.750	1.085	2.084

(*) Before consolidation, density index I_D=0.4.

3 RESULTS

The stress paths and the critical state line (CSL) in the τ - σ'_v space (τ is the shear stress) of all the tests performed are presented in Figure 7 and Figure 8 for the mixtures OS-GB and OS-ML, respectively. It can be observed that the specimens tested under CV behaved contractively, exhibiting peak and critical (or residual) strengths.



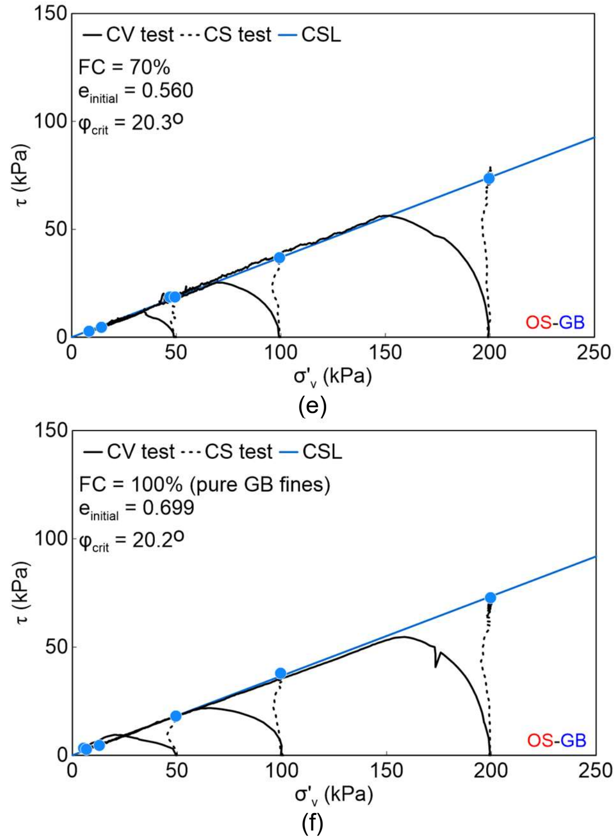
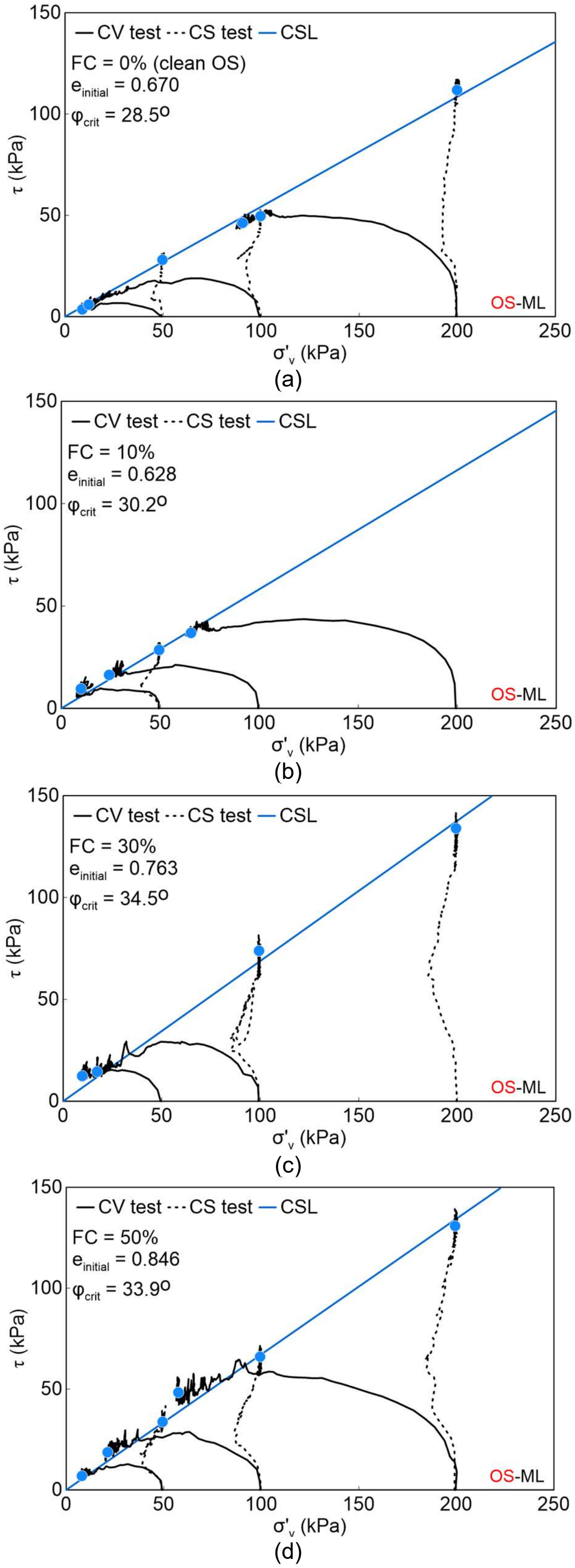


Figure 7. Stress paths for mixtures of OS and GB with (a) FC=0%, (b) FC=10%, (c) FC=30%, (d) FC=50%, (e) FC=70% and (f) FC=100%; all the specimens were prepared at D_r=0.4.

Figure 9 presents the evolution of the effective internal critical friction angle φ_{crit} for all the mixtures, where $\tan(\varphi_{crit})=\tau/\sigma'_v$ at critical state. As FC increases in OS-GB mixtures, there is a decreasing trend in φ_{crit} until a value for pure GB (FC=100%) of 20º, which is a well reported value for glass beads (Cantor & Ovalle, 2025). Rounded GB fines filling the voids of subangular OS might reduce the interlocking effect between subangular particles of OS, thus reducing the shear strength. Moreover, Figure 9 shows that φ_{crit} of OS-ML mixtures increases with FC, since angular fines provide high interlocking, even if the void ratio is significantly higher than OS-GB at high FC. At FC>30%, the OS-ML mixtures stabilize at φ_{crit}=34º, which is a typical value of hard rock mine tailings (Aubertin et al, 2002).



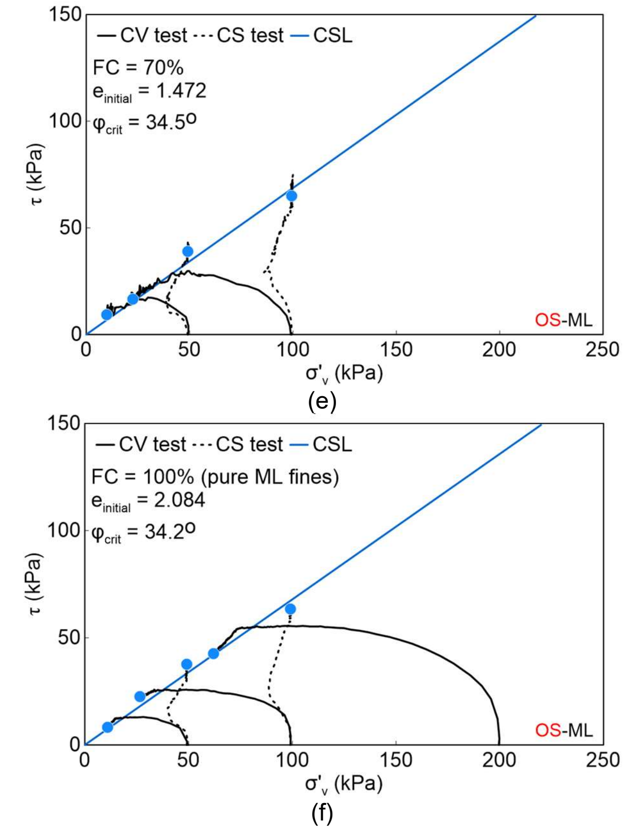


Figure 8. Stress paths for mixtures of OS and ML with (a) FC=0%, (b) FC=10%, (c) FC=30%, (d) FC=50%, (e) FC=70% and (f) FC=100%; all the specimens were prepared at I_D=0.4.

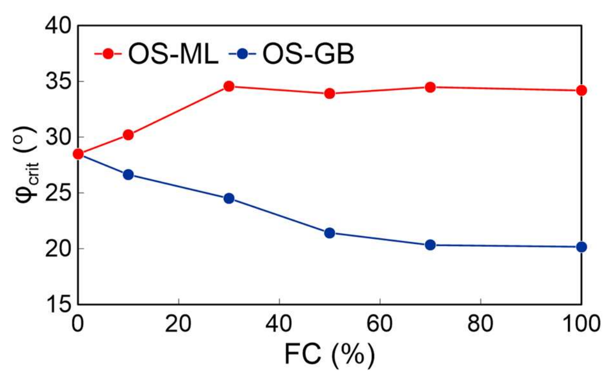


Figure 9. Variation of φ_{crit} with FC for mixtures of OS with ML and GB.

Figure 10 shows the variation of peak undrained (i.e., constant volume) shear strength (Su_{peak}) and critical residual shear strength (Su_{crit}) for the mixtures OS-GB. The results are derived from CV tests carried out at different vertical consolidation pressures of 50 and 100 kPa. It can be noted that Su_{peak} shows an increase from FC=0% to 10%. After that, it shows rather constant values with further addition of FC. On the other hand, Su_{crit} also increases in the same FC range, but shows a rapid decrease at FC>10%, down to constant values of about 5 kPa between FC=50 to 100%.

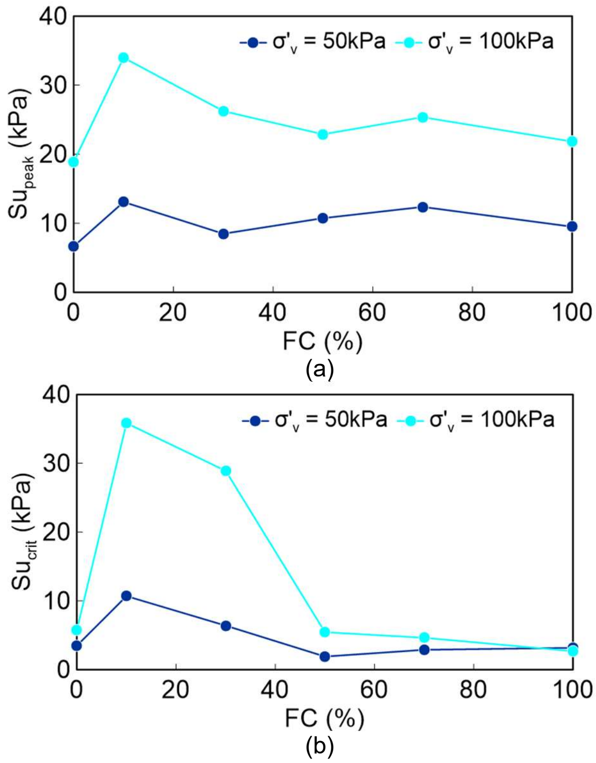


Figure 10. Variation of (a) Su_{peak} and (b) Su_{crit} with FC for mixtures of OS with GB.

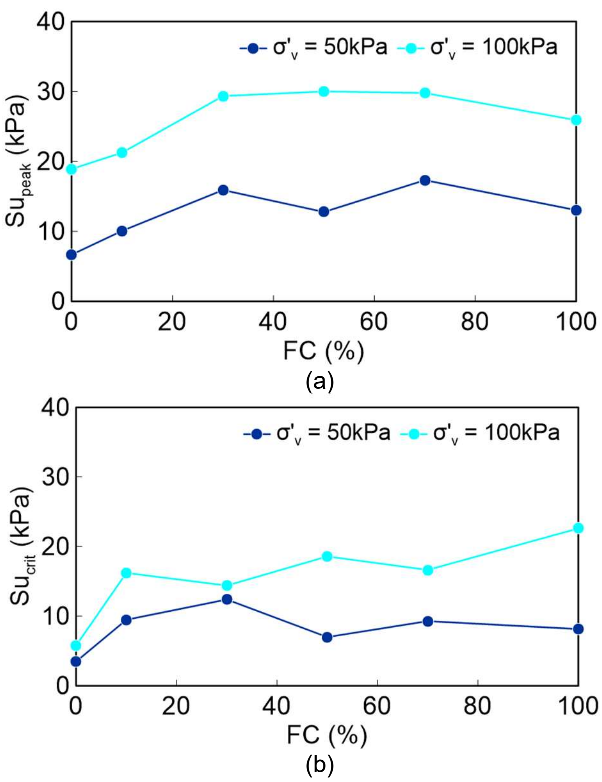


Figure 11. Variation of (a) Su_{peak} and (b) Su_{crit} with FC for mixtures of OS with ML.

Figure 11 shows the variation of Su_{peak} and Su_{crit} for the OS-ML mixtures, after tests at σ'$_v$ = 50 and 100 kPa. Su_{peak} shows an increase with adding fines until FC=30%. Thereafter, the values are relatively constant between FC=30 to 70%, and slightly decrease at FC=100% (pure ML tailings). Su_{crit} increases with FC until FC=30%, and shows negligeable changes up to FC=100%.

Even if the particle size distribution of a given FC value is always the same, regardless of the nature of the fines (GB or ML), the trend of the residual strengths is remarkably different. On the one hand, GB fines reduce φ_{crit} of OS and promote static liquefaction with low residual strength at high FC. On the other hand, adding angular fines to OS increases φ_{crit} and does not reduce the residual strength at high FC content.

3 CONCLUSIONS

This study presented an experimental investigation into the role of fines content (FC) and their characteristic particle shape on the drained and undrained shear strength of loose granular mixtures. Specimens were prepared by systematically mixing Ottawa sand (OS) with two types of non-plastic fines: rounded glass beads (GB) and angular hard rock Malartic tailings (ML). Ring shear tests under constant volume (CV) and constant stress (CS) conditions were carried out at various consolidation pressures (50-100-200 kPa), reaching large shear deformation to ensure critical state conditions.

It was found that FC played an important role in the packing configurations of the studied granular mixtures. Despite similar particle size distributions for a given FC mixed with OS, the specimens exhibited significantly different mechanical responses depending on the fines' particle shape. Mixtures of OS with rounded GB fines showed a reduction in critical friction angle with further addition of fines, until reaching the value of pure GB of about φ_{crit}=20°. Also, adding GB fines generated greater susceptibility to contractive behavior and static liquefaction. In contrast, mixtures of OS with angular ML fines demonstrated higher drained strength with further addition of fines, until reaching the value of pure ML of about φ_{crit}=34°. Also, adding ML fines results in enhanced residual critical strengths at constant volume.

It has been largely recognized that drained behavior of granular soils is particularly influenced by the degree of interlocking between particles, which is promoted by angular shapes in ML fines, whereas it is relegated by rounded GB fines. The results of this study showed that angular fines can enhance both peak and critical strength values under constant volume, thereby reducing the potential for static liquefaction. These trends hold true even when the void ratios are significantly higher in OS-ML mixtures, compared to OS-GB, highlighting the compensating effect of particle angularity vs. density.

From a geotechnical engineering standpoint, the findings in this study are particularly relevant to the design and stability assessment of structures constructed with mixed granular materials, such as earth fills and tailings dams. In industrial operations where materials of varying grain shapes and FC are routinely generated, overlooking the influence of fines morphology could lead to underestimating liquefaction risks.

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