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Shear strength response of clay and sand column with different sand grain shapes

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Abstract. Sand columns in clayey soil are considered one of the most economical and environmentally-friendly soil-improving techniques. It improves the shear strength parameters, reduces the settlement, and increases the bearing capacity of clayey soils. The aim of this paper is to study the effect of grain shape in sand columns on their performance in improving the mechanical properties of clayey soils. An intensive series of consolidated-drained triaxial tests were performed on clay specimens only and clay specimens with sand columns. The parameters examined during the experimental work were grain shape in sand columns (angular, rounded, sub-rounded) and effective confining pressure (50 kPa, 100 kPa, 200 kPa). The results indicated that there is a significant improvement in the deviatoric stress and stiffness values of specimens with sand columns. Improving deviatoric stress values in the use of angular sand grains was found to be higher than those in the use of sub-rounded and rounded sand grains. A 187%, 159%, and 153% increment in deviatoric stress values were observed for the sand columns with angular, sub-rounded, and rounded grain shapes, respectively. The specimens were observed to be more contractive as the sand column was installed, and as the angularity of grains in the sand column was increased. Sand column installation improves significantly the angle of internal friction, and the effective angle of internal friction increases as the angularity of the sand grains increases.

Keywords: grain shape; local strain measurements; sand column; triaxial test

1. Introduction

The construction of sand and stone columns plays an important role in the treatment of soft clayey soils and gives many advantages for example soil reinforcing, increasing soil shear strength and bearing capacity, decrease consolidation periods of soft soils. In addition, it was considered as an economical and environmentally-friendly technique for soil treatment in the case of low-loading constructions. In general, the reinforcement of soft clay soils with embedded columns by materials is stiffer than soft clay, these materials as compacted sand or stone columns, and cement or lime columns (Alamgir *et al.* 1996). Sand column installation provides low consolidation and construction period for a structure like embankments on soft clay, while stone columns increase the bearing capacity of soft soils by replacement of the soft soils with high-bearing strength granular material (Najjar *et al.* 2010).

Several researchers investigated improving the response of soft clayey soil reinforced it with stone columns and sand columns, some of these studies used large-scale laboratory models, triaxial tests, and others made finite element models (Juran and Guermazi 1987, Sivakumar *et al.* 2004, 2007, Black *et al.* 2006, 2007, Ambily and Gandhi 2007, Murugesan and Rajagopal 2009, Rajagopal 2009, Shivashankar *et al.* 2010, Yoo 2010, Fattah *et al.* 2011, Jorat *et al.* 2013, Afshar and Ghazavi 2014, Indraratna *et al.* 2015, Kumar and Samanta 2020, Sohaib *et al.* 2020, Dinarvand and Ardakani 2022).

For example, Bergado *et al.* (1984) mentioned in their study the use of a single coarse-grained column, their results showed that the ultimate bearing capacity becomes high three times more than the bearing capacity of soft clay. Juran and Guermazi (1987) observed during laboratory investigation a significant effect of soil type, replacement area of sand columns, the permeability of column material, and the number of columns and their group effect on the deformation behavior of footing on soft soils with sand columns. Numerous researchers used single granular column installation and others used group of columns and they studied the effect of the number of columns, replacement area, and group effect on the performance of granular columns in improving the bearing capacity of soft soils (Munfakh *et al.* 1984, Hu 1995, Wood *et al.* 2000, Hanna et al. 2013, Ali *et al.* 2014, Frikha *et al.* 2015).

The responses of soft soil with sand columns in drained and undrained conditions were studied by several researchers, all soil specimens in these studies were first isotopically consolidated and then subjected to shear strain (Juran and Riccobono 1991, Sivakumar *et al.* 2004, 2007, Black *et al.* 2007, 2011, Andreou *et al.* 2008, Najjar *et al.* 2010, 2013, Frikha *et al.* 2015, Shamsi *et al.* 2019). Sivakumar *et al.* (2004) made an undrained triaxial test for kaolin soil specimens with fully and partially included sand columns, they used two types of loading conditions and two different techniques of sand column construction with area

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replacement of about 10%, and also, they investigated the effect of column length on its performance. Their results showed that sand column length has a significant effect on the bearing capacity and stiffness of soft clay. Also, they concluded that there is no increase in the bearing capacity when the sand column embedded length exceeds five times its diameter. Andreou *et al*. (2008) made a series of laboratory tests to study the effect of grain size, confining pressure, strain rate, and drainage condition using triaxial tests on the load crying response of kaolin clay. The results showed an improvement in load bearing and this improvement becomes high as the confining pressure increases. Najjar *et al*. (2010) conducted undrained triaxial tests on normally consolidated soft clay soil reinforced with sand columns. They considered the effect of column diameter, column length, and effective confining pressure.

They observed a decrease in excess pore water pressure with axial strain during shear and an improvement in the load-carrying capacity of the soft clay and sand column system. Also, the results indicated that shear strength parameters were not significantly affected by the inclusion of columns in case of an increase in Young's modulus. Furthermore, other researchers performed numerical models for soft clay and sand column systems using finite element analyses to examine the performance of sand columns inclusion within soft clay soil in increasing the load-bearing capacity of soft soils (Matsui *et al.* 2001, Murugesan and Rajagopal 2006, Ambily and Gandhi 2007, Hanna *et al.* 2013, Indraratna *et al*. 2013, 2015, Ngo *et al.* 2016, Demir *et al*. 2017, Ehsaniyamchi and Ghazavi 2019, Jaiswal and Kumar 2022). Most of the studies whether experimental or numerical indicated that the failure mode in soft clay and sand column systems is lateral expansion along the sand column (lateral bulging of sand columns) at the upper part of the column. According to several investigation results, numerous researchers suggested making the length of columns between four to eight times of column diameter, in order to reduce the bulging of columns and increase the bearing capacity of the system (Narasimha Rao *et al.* 1992, Muir Wood *et al*. 2000, McKelvey *et al.* 2004). On the other hand, several studies proposed to use of geogrid or geosynthetic materials to make a casing for sand columns.

These materials separate soft clay and sand column on one hand and provide lateral support from bulging failure on the other hand (Sharma *et al.* 2004, Sivakumar *et al.* 2004, Najjar *et al.* 2010, Tandel *et al*. 2014, Shamsi *et al.* 2019, Yoo and Abbas 2020). In addition, the length of the sand column embedded through soft soil and the diameter of the column (area replacement ratio) were studied by several researchers (Ayadat and Hanna 2005, Najjar *et al.* 2013, Black *et al*. 2011).

Very few researchers focus on their studies on the effect of the sand column material grain shape and size on the performance of the sand/stone column in improving the responses of soft clay and sad column system (Siahaan *et al.* 2018). Siahaan *et al.* (2018) studied the influences of grain size gradation and shape on the undrained shear response of soft kaolin clay. Two shapes of sand column material grains were used in the installation of the column, the first one angular igneous crushed rock particles of basaltic origin and the second one sub-rounded river pebbles. They concluded that the load-settlement response of the clay and sand column system was significantly affected by the shape and gradation of grains, in addition, well-graded sand column materials resulted in higher shear strength. An increase in the shear strength, and load-bearing capacity of soft clay and sand column system with sand angular sand grains and non-uniform grain size distribution. During the construction of projects in soft clay layers that needed the installation of sand columns to support the structure load, the material of sand columns was taken from borrowed areas which include grains of different sizes and shapes. In addition, the shear strength of these materials varied with their size and shape. As recorded by researchers the grains interlocking in angular-shaped grains are higher and produce higher shear strength than rounded-shaped grains, also, angular-shaped grains result in higher shear strength parameters (Cho *et al.* 2006, Guo and Su 2007).

The previous experimental researches and numerical analyses using finite element methods to examine the load caring capacity of sand columns consider the effect of column length, column diameter, area replacement ratio, grain size of column material, and group effect of sand columns. However, very few studies consider the influence of sand grain shapes on the performance of sand column in load-carrying capacity. In addition, previous researches did not consider the local strain measurements to study the response of the reinforced soft clay with the sand column at low strain. Therefore, this paper aims to study the influence of sand grain shape and effective confining pressure on load-carrying capacity and shear strength of soft clay with the sand column. During an extensive experimental work, a series of consolidated triaxial tests were conducted on clay only and clay with the sand column. Three different grain shapes were used to construct the sand columns (angular, sub-rounded, and rounded). All consolidated drained triaxial tests were performed under three different effective confining pressures

2. Experimental work

A series of isotropically consolidated drained triaxial tests were conducted on clayey soil specimens having a diameter of 70 mm and a height of 147 mm. Tests were performed on pure clay specimens and specimens with a single sand column. Sand column has a 20 mm diameter and was installed in predrilled holes in the center of the clay specimen. Three types of granular materials of the same size and different shapes were used to make the sand column and to study the effect of the sand grain shape on the performance of the sand column. All specimens were saturated under back pressure of 300 kPa and isotropically consolidated under effective confining pressures of 50 kPa, 100 kPa, and 20kPa.

2.1 Material properties

Clay: The soil used during the experimental study was clayey soil obtained from the Gaziantep University

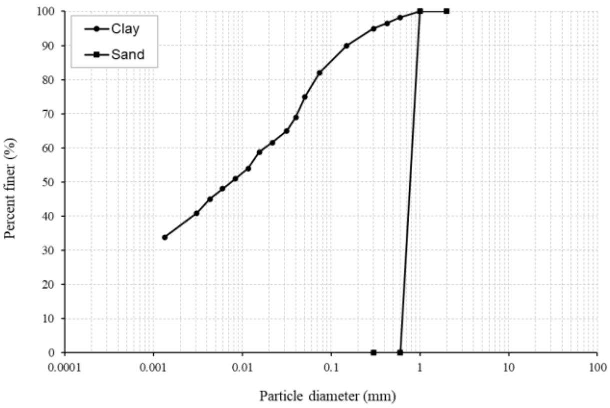
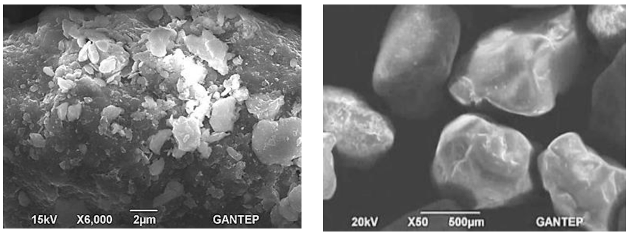
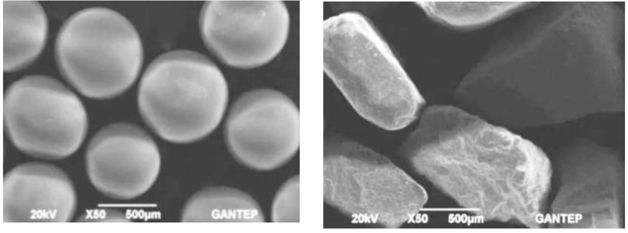


Fig. 1 Grain size distribution curves for pure clay and coarse materials used for the sand column

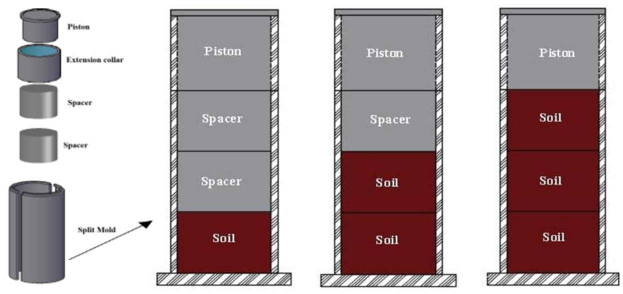


(i) Clay (ii) Leighton Buzzard sand



(iii) Glass beads (iv) Crushed sand

Fig. 2 Scan electronic microscope photos of pure clay and materials used for the sand column.



(a) (b) (c) (d)

Fig. 3 Compaction mold and soil specimen preparation steps.

Campus, Turkey. Clayey soil has a plastic limit and liquid limit values of 25 and 42, respectively. The clay particles have a specific gravity of 2.7. The grain size distribution of the clayey soil that has a particle size lower than 1 mm is presented in Fig. 1. According to these properties the soil was classified as CL based on the Unified Soil Classification System (USCS). The shape and size of the clay particles were evaluated using a Scanning Electron Micrograph (SEM) as shown in Fig. 2.

Coarse material: three different shapes and the same size of coarse materials were used during the experimental work as sand column materials. The size of the three materials falling between 0.6 mm and 1.0 mm were artificially selected by sieving them through standard sieves. Coarse materials were washed several times until it becomes clean and then dried to use in all tests. The grain size distributions of these materials were determined in accordance with the ASTM D422. The resulting grain size distribution curves are presented in Fig. 1. According to the grain size distribution curves of coarse materials, they are classified as poorly graded sand (SP) based on the Unified soil classification system (USCS). The first type of coarse material was crushed sand (CS) which is artificially made, the grain shape of crushed sand was classified as very angular shape, and the crushed sand grains have a specific gravity of 2.67. The second type of coarse material was Leighton Buzzard sand (LB), the grain shape of this type of sand was classified as a sub-rounded shape, and the specific gravity of this type of coarse material is about 2.6. The third type of coarse material was glass bead, the shape of grains of this type of coarse material is well rounded, the glass bead was ordered from a company in Turkey. The grains of the glass bead have a specific gravity of 2.5.

2.2 Sample preparation and test procedure

The triaxial test samples with sand column were prepared using a special design split mold (70 mm x 147 mm), soil samples were compacted inside the split mold under static compaction energy using a collar and piston as shown in Fig. 3. In order to distribute the compaction energy throughout the specimen, two compaction spacers were used (Diameter of 70 mm and height of 49 mm), in this case, the compacted soil specimens will have the same density throughout it. With the aim of obtaining soil samples near to soft state, we select water content for soil specimens on the wet side of the compaction curve. Therefore, to obtain this water content a series of compaction tests for pure clay samples were conducted using standard proctor energy, the results of compaction tests are presented in Fig. 4. A point in the compaction curve (wet side, 95% degree of saturation) was selected that has high water content and low dry unit weight (water content of 22% and dry unit weight of 16.7 kN/m3). It is expected that soil specimens in this water content and dry unit weight be workable and have low shear strength. At the beginning of sample preparation, the required amount of pure clay and water corresponds to the water content of 22% and dry unit weight of 16.7 kN/m3 were weighed and mixed thoroughly. The mixture of pure clay and water was kept in a closed medium during 24 hours for more homogenizing soils' water content. The split mold was assembled properly by tights and a thin layer of oil was applied to the inside of the split mold. The homogeneous soil sample was divided into three layers, the first layer was poured inside the mold and two spacers were put above the soil. The soil was compacted under static compaction energy with a low compaction rate using the unconfined compression test machine as shown in Fig. 5(a).

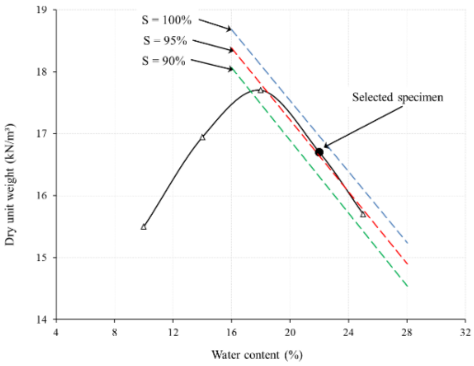


Fig. 4 Compaction curve for pure clay specimens (in order to select the water content and unit weight of the triaxial specimens of clay and sand column)

Compression of the sample was continued until the edge of the compaction piston attaches to the extension collar. The same processes were followed for the second layer using one spacer, the last layer was compacted without a spacer using the piston and extension collar only (see Fig. 4), The mold and clay specimen was kept under compaction loads for 30 minutes to eliminate any rebound response of clay specimens.

After completing the compaction process, the specimen was seated inside a drilling machine and a hole with 2 cm at the center of the specimen was constructed along the clay specimen. the diameter of the hole was then rechecked to ensure the diameter of the hole (see Figs. 5(b)-5(d)). Clay specimen was seated on the triaxial cell pedestal directly above the pours stone, the specimen was circumferenced by a membrane and split mold. The required amount of coarse material for constructing the sand column corresponding to a relative density of 53% was weighed and divided into three parts, The relative density of the sand was selected as 53% corresponding to a medium-dense state of the sand and can easily satisfied in the field works. The first part of the coarse material was poured inside the hole via a glass funnel and compacted using a small steel rod. The processes were repeated for the second and third layers of sand column until the desired amount of sand filled the hole (see Figs. 5(f)-5(h)). The porous stone and top platen covered the soil specimen and the membrane was stretched over it and fixed with an o ring. In order to fix the membrane to the specimen side a small vacuum of about 20 kPa was applied to the specimen. After that, the split mold was stripped and two linear variable differential transducers (LVDT) were fixed to the specimen side at the middle third of its height using brackets and glue as shown in Fig. 5(i). This device was used for local strain measurement during the triaxial test.

After that, the soil specimen was saturated by applying water from its bottom to the top, then the triaxial cell was filled with water after its chamber was installed, and the vacuum applied to the specimen was reduced by increasing the confining pressure. The back pressure and cell confining pressure were gradually increased until the desired values of effective confining pressure (for example, for 200 kPa effective confining pressure, the cell pressure was 500 kPa and the back pressure was 300 kPa). Soil specimen was kept under these pressures overnight for about 17 hours. After completing soil consolidation, the specimen was sheared using a conventional triaxial loading machine with a 5 kN submersible load cell, pore water pressure censorious, Two LVDTS, and an external linear displacement sensor (LDS). Specimens were tested at the drained condition (CD) according to ASTM D7181 standards under a strain rate of 0.025 mm/min, this rate was selected to give time for pore water to drain out the specimen

3. Results and discussions

A series of consolidated drained triaxial tests were performed to study the response of soft clay reinforced with a sand column. To investigate the effect of sand column materials shape on the performance of clay with the sand column in load-carrying capacity, three different grain shapes were selected. All triaxial specimens were saturated at a back pressure of 300 kPa. Then the specimens were isotopically consolidated under effective confining pressure at 50, 100, and 200 kPa. The results of triaxial tests on pure clay specimens without sand column were used as a benchmark (control) in order to compare the results that were obtained from the specimens with sand columns.

3.1 Stress-strain response of clay with the sand column

The variation of the deviatoric stress (q) and volumetric strain with the average local axial strain for pure clay specimens without sand column are presented in Fig. 6(a). It is clearly observed from the analysis of the figure that the deviatoric stresses increase sharply with the average local strain until the axial strain of about 1.0%, 1.3%, and 2.0% for effective confining pressures of 50, 100, and 200 kPa, respectively. Also, the figure exhibited increases in the deviatoric stresses when the effective confining pressure increases during the shearing of specimens until failure. The pure clay specimens (without sand column) triaxial shear responses were used as a benchmark to compare and assess the shear response of treated clay specimens with the sand column. Figs. 7-9(a) present the variation of deviatoric stress vs. average local axial strain of clay specimen with sand column (sand column with different grain shape) for effective confining pressures of 50, 100, and 200 kPa, respectively.

As proposed by Balaam *et al.* (1977) the stress-strain data of the clay specimens with sand columns have been analyzed as a single element assuming that the stress and strain were homogeneously distributed. In general, figures show a significant improvement in the drained deviatoric stress of specimens treated with the sand column. I can attribute this behavior to the high stiffness and strength of sand column material if it was compared with the stiffness of the soft clay. These results are in line with the results recorded by (Sivakumar *et al.* 2004, Najjar *et al*. 2010, 2013, Frikha *et al*. 2015). Also, from the analysis of these figures, it can be

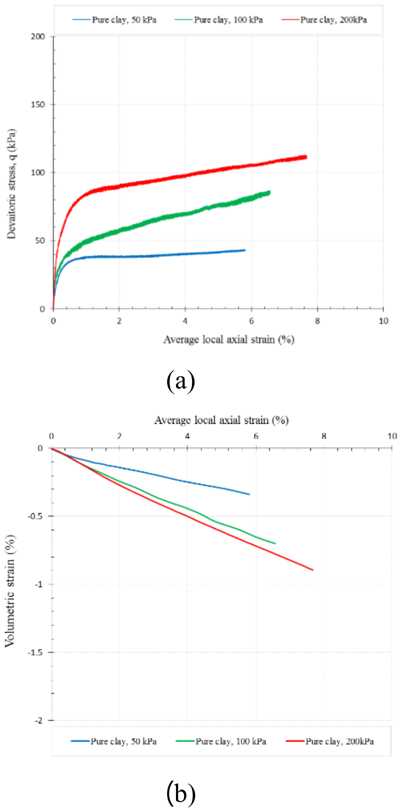
(a) (b) (c) (d)

(e) (f) (g) (h)

(i) (j) (k)

Fig. 5 Triaxial tests sand column specimen preparation processes

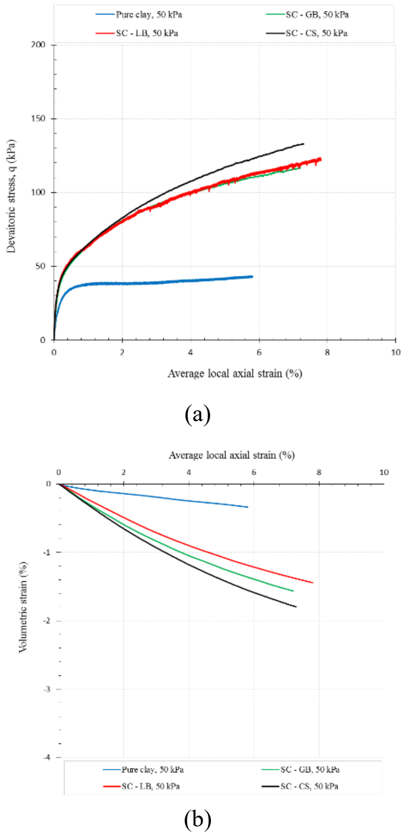
deduced the significant effects of the grain shape of sand column material on the stress-strain response of soft clay and sand column. The increases in the drained shear strength (deviatoric stress at 6% axial strain) were about 153%, 159%, and 187% for specimens treated with the sand column of GB, LB, and CS, respectively. These improvements for specimens tested under 50 kPa effective confining pressures. Note that these increases were estimated in comparison to the shear strength of the untreated soil. While, when the specimens were tested under 100 kPa effective confining pressures, The improvements in the drained shear strength were about 62%, 67%, and 114% for specimens treated with the sand column of GB, LB, and CS, respectively. In addition, the percentage increases in the deviatoric stresses were about 113%, 116%, and 153% for specimens reinforced with the sand column of GB, LB, and CS, respectively, when the specimens were tested under an effective confining pressure



(a)

(b)

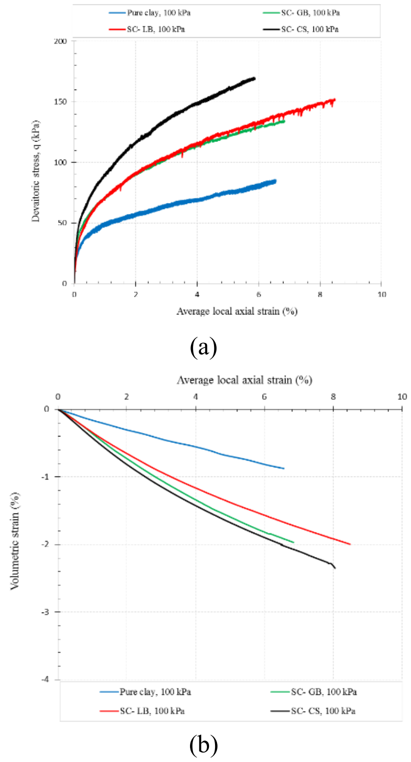
Fig. 6 Deviatoric stress and volumetric strain versus local axial strain for pure clay specimens



(a)

(b)

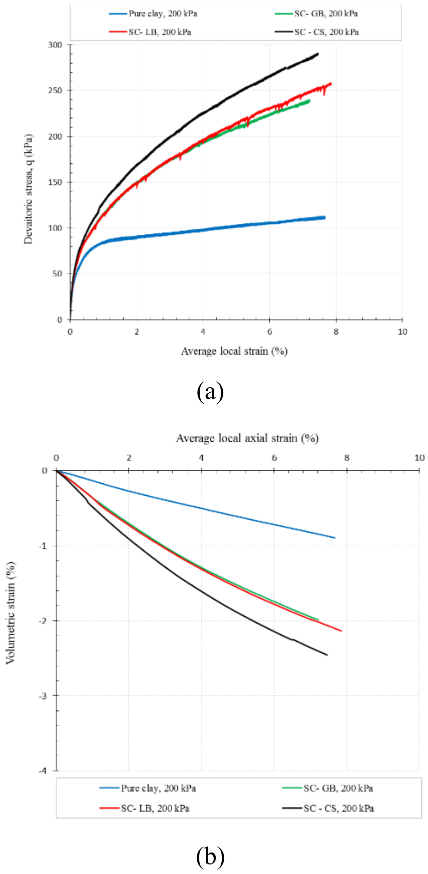
Fig. 7 Deviatoric stress and volumetric strain versus local axial strain for clay and sand column under 50 kPa effective confining pressure (Different sand grains shape)



(a)

(b)

Fig. 8 Deviatoric stress and volumetric strain versus local axial strain for clay and sand column under 100 kPa effective confining pressure (Different sand grains shape)



(a)

(b)

Fig. 9 Deviatoric stress and volumetric strain versus local axial strain for clay and sand column under 200 kPa effective confining pressure (Different sand grains shape)

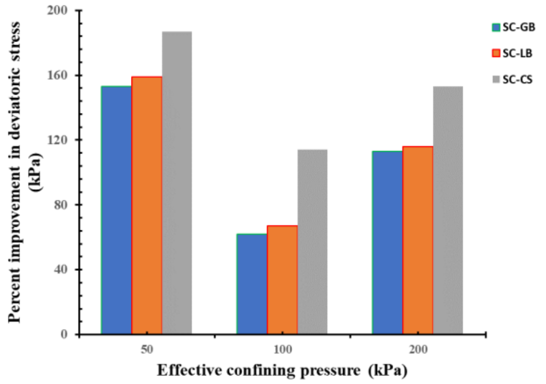
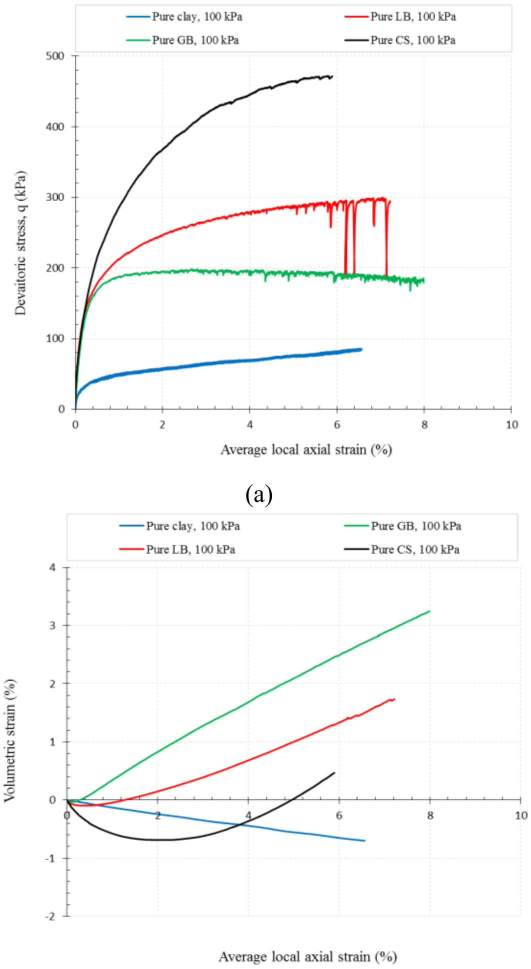


Fig. 10 Variation of the percent improvement in deviatoric stress vs. Effective confining pressure and shape of sand column material's grains



(a)

(b)

Fig. 11 Deviatoric stress and volumetric strain versus local axial strain for clay (control specimen) and materials used for sand column (Different sand grains shape) under 100 kPa effective confining pressure

of 200 kPa. Fig. 10 presents the percent improvements in the drained shear strength for all specimens that were tested under different effective confining pressures. The results and discussion above exhibit that the percent improvement in the drained shear strength for clay with the sand column of crushed sand material is significant and higher than their values in specimens with the sand column of the other two materials. The reason for this behavior may be due to the higher shear strength of crushed sand that resulted from sand grain interlocking in a higher degree (Guo and Su 2007). With the aim of evaluating the shear strength response of sand column materials alone, a series of consolidated drained triaxial tests were conducted on sand column materials alone under 100 kPa effective confining pressure. The results of these tests are presented in Fig. 11.

The figure shows that the deviatoric stress of the specimens increases with the angularity of the grains of the materials. In the same axial strain level, the deviatoric stress of crushed sand specimens is greater than the LB sand specimens, and its value for the last one is greater than the deviatoric stress of GB specimens (see Fig. 11(a)). These results are in line with results obtained by Guo and Su (2007). Also, Similar results were obtained by Siahaan *et al.* (2018), they recorded that larger peak deviatoric stresses are obtained for columns with angular sand grains, they attributed this behavior to the greater degree of grain interlocking which results in higher shear strength.

3.2 The volumetric strain of clay specimens with sand column

The variations of the volumetric strain versus the average local axial strain for pure clay specimens and treated clay specimens with sand columns are presented in Figs. 6-9(b). For pure clay specimens as presented in Fig. 6(b), the volumetric strains were contractive and similar in the specimens that were tested under different confining pressures. In addition, the contraction behaviors of the clay specimens increase as the confining pressure increases. The effect of the sand column inclusion on the volumetric strain during shear is significant and become higher as the effective confining pressure increase see Figs. 7-9(b). Also, it is clearly observed from the analysis of these figures that the volumetric strain (contraction behavior) in specimens with a sand column of crushed grains is higher than their values in specimens with a sand column of other materials on one hand; on the other hands, as the angularity of the grains of sand column materials decreases, the volumetric strain and contraction behavior decrease. The reason for this behavior can be obtained in Fig. 11(b). This figure presents the variation of volumetric strain with the average local axial strain for specimens of sand column material alone. It can clearly observe the contraction behavior of specimens with crushed sand and the dilation behavior of specimens with the other two materials. It can be concluded that the negative volumetric strain (contraction behavior) of the specimen increases as the angularity of the grains increases.

3.3 Stress path space of clay with the sand column

The stress path space for consolidated drained tests of pure clay specimens and clay with sand column are presented in Figs. 12-15. The stress paths were drawn

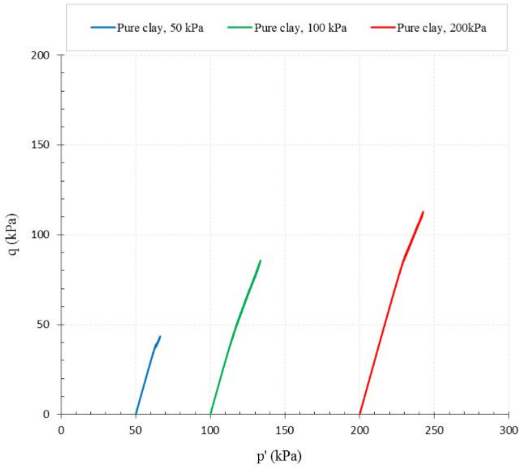


Fig. 12 Stress path space results for pure clay specimens

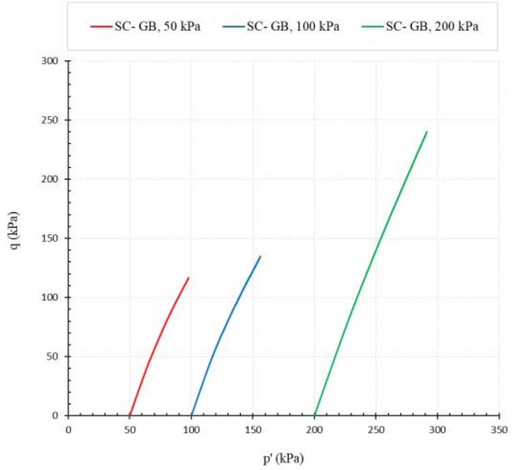


Fig. 13 Stress path space results for clay specimens with sand column (glass bead grains)

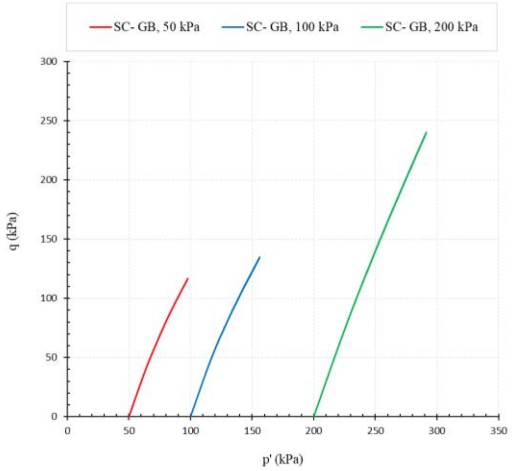


Fig. 14 Stress path space results for clay specimens with sand column (Leighton Buzzard sand)

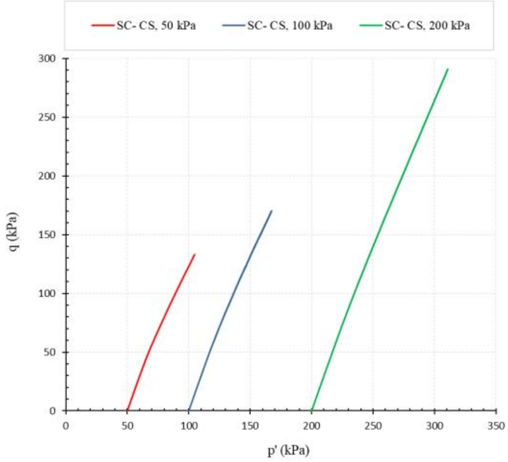


Fig. 15 Stress path space results for clay specimens with sand column (crushed sand)

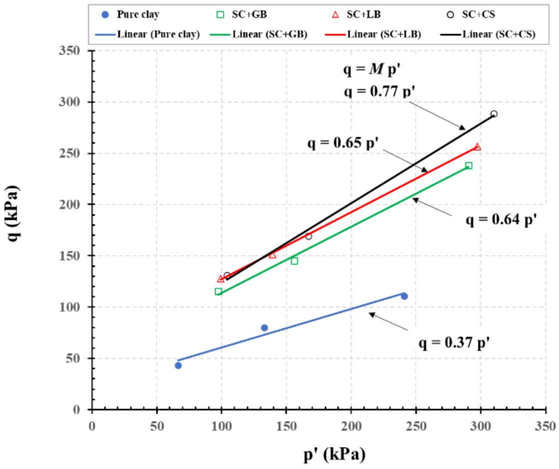


Fig. 16 End points of stress path space for pure clay and clay with the sand column with different grain shapes.

according to MIT school as the relation between the deviatoric stress (q) and mean effective stress (p´). In general, the specimens in all cases have a contraction behavior. The deviatoric stress and the contraction behavior of the specimens increase as the angularity of the sand column grains increases and as the effective confining increases. On the other hand, Fig. 16 presents the ultimate conditions that can be shown by the slope of the critical lines that connected the end point of stress paths for specimens under different effective confining pressures (M=q/p´). The analysis of this figure shows significant changes in the position and slope of the critical line as the sand column is included in clay specimens. The endpoint of the stress paths line of the specimen becomes higher with the inclusion of the sand column from one hand and become higher too as the angularity increase of the grains of sand column materials on the other hand. Also, it is noted that the slope of the critical lines increases (M value) with the inclusion of the sand column and as the angularity increases of the sand column material's grains. Fig. 17 shows the results of stress path analysis of pure clay specimen and sand column materials specimen alone. Specimens were tested in a consolidated drained state under 100 kPa effective confining pressure. The objective of this figure is to examine the stress path responses of the sand column

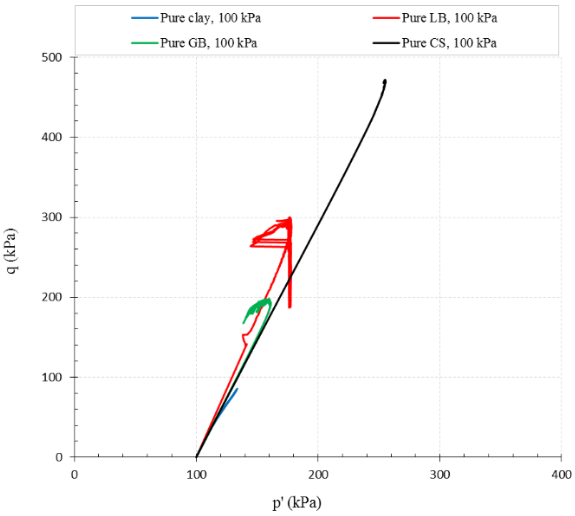


Fig. 17 Stress path space results for pure clay and specimens of materials used for the sand column with different grain shapes at 100 kPa effective confining pressure

materials alone, to illustrate the changes in the stress path of clay with the sand column of these materials. The endpoints of stress path lines rise and become more dilated as the angularity of the grains increases.

3.4 Stiffness of clay specimens with the sand column

The variations of the secant Young's modulus (Eu) with the average local axial strain for specimens of pure clay and clay with sand column were presented in Figs. 18-20. The stiffness of the specimen in this paper was quantified as the secant young's modulus (Secant modulus is the slope of a line drawn from the origin of the stress-strain diagram and intersecting the curve at the point of interest, $Eu=\Delta\sigma/\Delta\varepsilon$). In general, the stiffness of the clay triaxial that was tested in consolidated drained conditions increases significantly with the inclusion of sand columns. This behavior was noted in all types of sand column material. The reason for this behavior as the authors thought might be the higher values of the sand column material's stiffnesses if its compared with the stiffness of the pure clay specimens (see Fig. 21).

This response of the clay specimen with the sand column is in line with the results recorded by (Najjar *et al.* 2010, 2013, Siahaan *et al*. 2018). Furthermore, the effect of the sand column material's shape on the change in the stiffness of the specimens is clear and significant in all effective confining pressures. Figs. 18-20 show that the stiffness values of the specimens with sand column increase as the angularity of sand column materials grains. The improvement in the stiffness values with the angularity of the grains may be because of the higher strength and stiffness values of the sand with angular grains. The friction and interlocking in angular sand grains are higher than their values in sand grains with rounded and subrounded grain shapes'. This behavior was illustrated and proved in Fig. 21 which presents the stiffness values for sand column materials alone that were tested in consolidated drained conditions under 100kPa effective confining pressure.

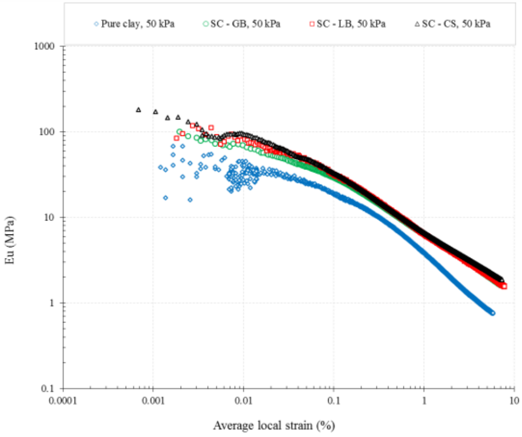


Fig. 18 Stiffness versus local axial strain of clay specimens with sand columns of different grain shapes tested under 50 kPa effective confining pressure

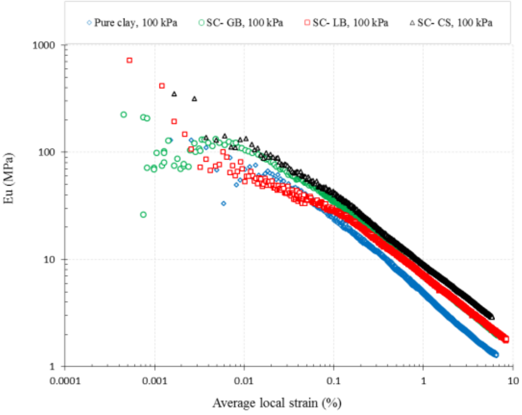


Fig. 19 Stiffness versus local axial strain of clay specimens with sand columns of different grain shapes tested under 100 kPa effective confining pressure

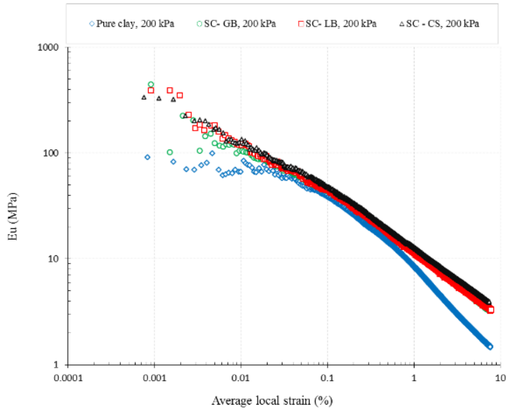


Fig. 20 Stiffness versus local axial strain of clay specimens with sand columns of different grain shapes tested under 200kPa effective confining pressure

3.5 Effect of the sand column on the relation of volumetric strain with q/p´

The changes in the variation of the volumetric strain versus q/p' (deviatoric stress/mean effective stress) for pure

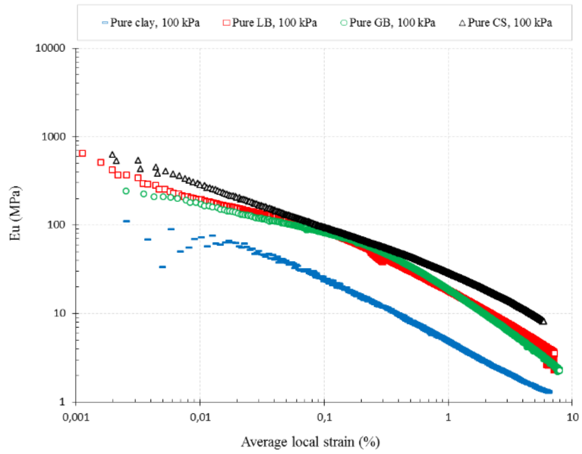
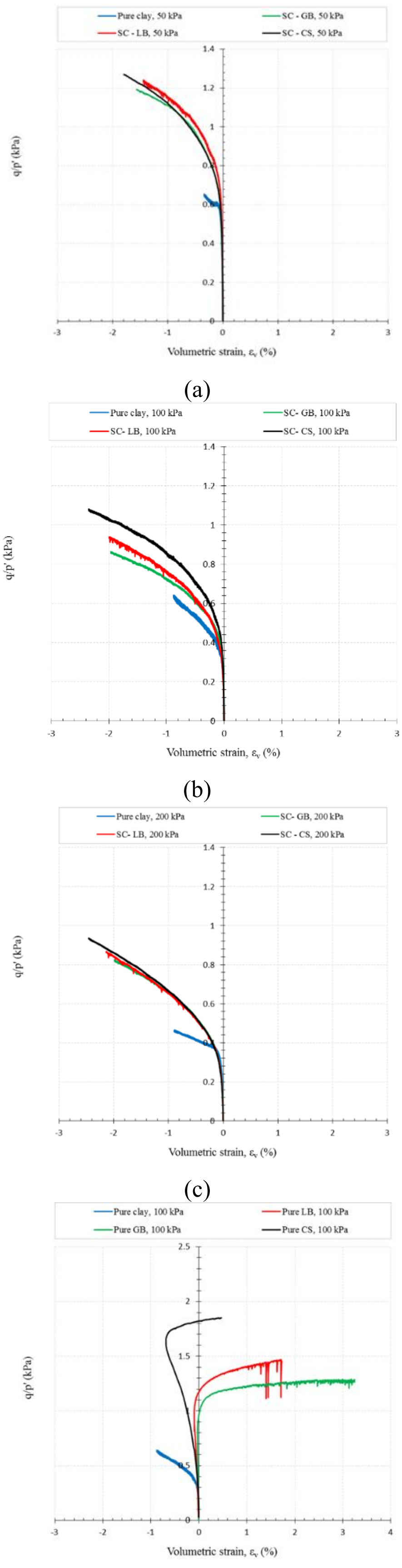


Fig. 21 Stiffness versus local axial of pure clay specimens and specimens for materials used for sand columns of different grain shapes under 100kPa effective confining pressure

clay specimens and clay specimens with sand column are presented in Fig. 22. In general, the analysis of these figures shows that as the specimens were tested under high effective confining pressure in consolidated drained conditions, the volumetric strain (contractive response) in the specimen starts at a low level of shearing. This response was noted in pure clay specimens and specimens with the sand column. This response may be due to the densification processes that occur in soil specimens when they were tested under high effective confining pressures. In this case, soil grains become close to each other as the specimens consolidated and sheared under high effective confining pressure. Also, as the sand column is included in clay specimens the volumetric strains (contractive response starts at high shearing or loading level. In addition, the contractive response of the specimen decreases as the angularity of the sand grains increase. The contractive response of sand grains is lower than the contractive response of clay grains (Fig. 22(d)). This figure presents the relation between the volumetric strain and q/p’ for pure clay specimens and sand column materials specimens alone. Therefore, the inclusion of sand column in clay specimens lead to making the specimens more dilative. On the other hand, the dilative response of crushed sand grains specimen starts at a high shearing level. This response made the specimen of clay with crushed shape sand column to contract at a high shearing level. this response as the authors thought depends on the sliding and interlocking of angular-shaped grains which is different from the sliding and interlocking amount of well-rounded and sub-rounded grains.

3.6 Shear strength parameters of clay specimens with sand column

The effective Mohr circles for consolidated-drained tests and the corresponding failure envelopes for pure clay specimens and clay specimens with sand column are illustrated in Fig. 23. The analysis of the results showed that



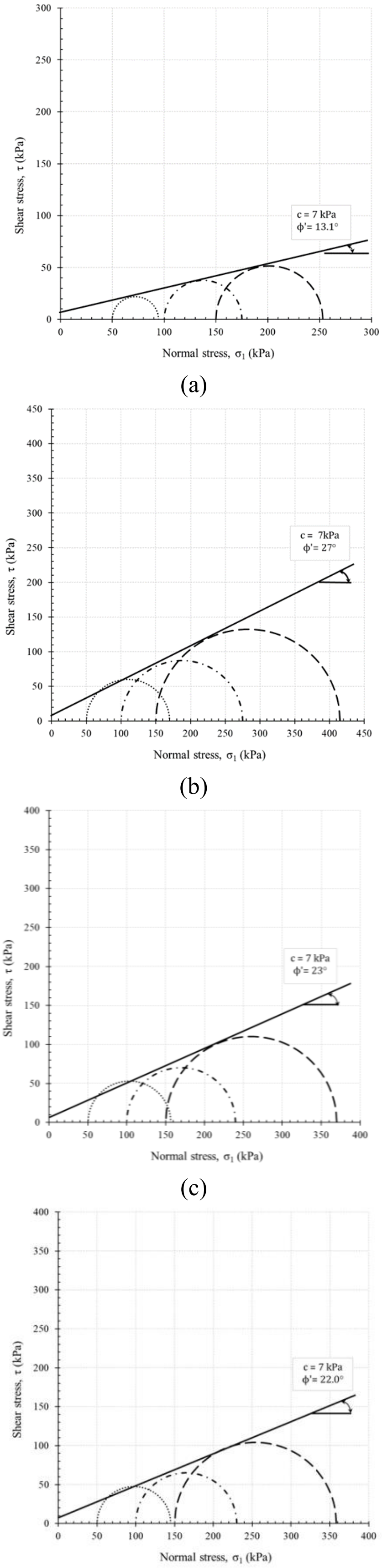
(a)

(b)

(c)

(d)

Fig. 22 Volumetric strain versus q/p′ for clay and sand column with different sand grains shape and different effective confining pressure



(a)

(b)

(c)

(d)

Fig. 23 Mohr's circle for clay specimens with the sand column, the materials of a sand column in different grain shapes

the effective shear strength parameters of pure clay specimens (control specimens) were c´=7 kPa and ϕ´=13.1(Fig. 23(a)). In general, the inclusion of sand column in clay specimens did not have a significant effect on the effective cohesion values on one hand, while sand column inclusion increased the effective angle of friction on the other hand. The results are in trend with the results that were obtained by (Najjar *et al.* 2013, Black *et al.* 2011, Siahaan *et al.* 2018). The effective angle of internal friction of coarse-grained material is higher than its value in fine-grained material like clay, due to the difference in the shear strength compounds (sliding, rolling, and interlocking) between them. Also, it was noted from the analysis of Fig. 23 that sand column with crushed grains resulted in high improvements in the effective angle of internal friction if compared with other types of sand grains (27° for specimen with the sand column of crushed sand; 23° and 22° for specimens with the sand column of Leighton Buzzard sand and glass bead grains, respectively. This response as the authors thought resulted from the shear strength response and compounds of the sand column material itself. The rolling and interlocking frictional strength of the crushed grain sand is higher than their values in sub-rounded and well-rounded grains (Cho *et al.* 2006, Guo and Su 2007). The installation of a sand column with crushed grain results in a higher shear strength from the specimen of clay with the sand column of other grain shapes.

4. Conclusions

Based on the analyses of the experimental results of a series of isotopically consolidated–drained triaxial tests on soft clay specimens and clay with sand column specimens, the following conclusion can be drawn on the influence of the effective confining pressure and grains shapes of sand column material on the mechanical properties of soft clay.

- In general, the presence of sand column within soft clay specimens improved the deviatoric stress, stiffness (secant modulus of elasticity), and shear strength parameters (effective angle of internal friction).
- The improving percents in the deviatoric stress increase as the angularity of the sand column material's grains. The percentage improvement in deviatoric stresses were 153%, 159%, and 187% for specimens with the sand column of GB, LB, and CS grains, respectively; for specimens that were tested under 50 kPa effective confining pressure. While in the case of specimens that were tested under 100 kPa effective confining pressure, the percentage improvement were 62%, 67%, and 114% for specimens with the sand column of GB, LB, and CS grains, respectively. Also, when the specimens that were tested under 200 kPa effective confining pressure, the percentage improvement in the deviatoric stresses were 113%, 116%, and 153% for sand column materials of GB, LB, and CS grains, respectively.
- The inclusion of sand column within soft clay specimens made its behavior more contractive and is dependent on the effective confining pressure. As the

angularity of sand column grains increase, the specimen become more contractive.

- The critical lines that were drawn through the end point of the stress path lines become at high level and slope (M) increases as the sand column was used for soft clay improvements, and as the angularity of the grains of sand column materials increased, this indicate that the dilative behavior of the specimen increased as the sand column was used and as the angularity of the sand grains increased.
- In general, the stiffnesses (secant modulus of elasticity) of soft clay specimens were improved significantly as sand columns were used. Also, sand columns with angular grains shapes produced higher improvement in soil specimens than other types of grains shapes.
- The effective cohesions of soft clay specimens were not significantly affected by the presence of sand columns. However, a clear improvement was noted in the effective angle of internal friction values when the sand column was used. Also, sand columns with crushed sand (angular shape) produce a higher improvement percentage in the effective angle of internal friction than other shapes of sand grains.

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