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Research Note

Influence of grain shape and gradation on the shear behavior of sand mixtures

A.F. Cabalar*

Department of Civil Engineering, University of Gaziantep, 27310, Gaziantep, Turkey.

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KEYWORDS

Triaxial compression;
Cyclic direct shear;
Grain shape;
Grains size;
Sand mixtures.

Abstract. This paper investigates triaxial and cyclic direct shear behaviour of different sand mixtures, considering variations of shape, size, and mixture content. In most studies, investigations of stress-strain properties of soils were carried out using clean sands. However, granular soils in the field may contain a considerable amount of grains in different physical characteristics (i.e., shape, size). Therefore, behaviour of the various sand mixtures in triaxial compression and cyclic direct shear testing apparatuses has received our attention in this study. Two different sizes (0.25 mm–0.5 mm and 1.0 mm–2.0 mm) of sands with distinct shapes (rounded and angular) were tested in triaxial and cyclic direct shear apparatuses. The mixtures of coarser and finer geomaterials were tested in various mix ratio values from 5% to 50% by weight. Based on the examinations during shearing of these materials, it was observed that behavior of the sand mixtures was closely related to the grain shape of host materials as well as fines content in both testing apparatuses, whilst size of the sands was not found to be significantly effective in the results.

1. Introduction

Most studies have investigated shear strength and stress-strain properties of soils using clean sands. However, such an assumption is not valid in the field due to the presence of soil grains with various shape and size characteristics. It is not easy to define the behaviour of soils composed of sand, silt, clay, etc. on either side of a component alone, as they have both properties of coarser and finer geomaterials. The properties of these soils, called intermediate soils, vary due to the density and mixture content. Difficulties arise in understanding their stress-strain behaviour, compression mechanism, and liquefaction potential [1-11]. For example, Vallejo and Mawby [12] reported that shear strength of the clay-sand mixtures was fully controlled by the sand below 25% of fines content. Salgado et al. [13] found that fines entirely control the soil behaviour in terms of dilatancy and shear strength when the fines content is more than 20%. Researches related to the influence of fines on liquefaction potential have been subjected to intensive research in soil mechanics [13-15]. Xenaki and Athanasopoulos [16] demonstrated that, for silt content from 0 to 44%, the liquefaction resistance of the sand with a constant global void ratio decreased, compared to that of the clean sand. However, this trend is reversed for values of fines content more than 44%, whereas the liquefaction resistance of the mixtures varied monotonically when the intergranular void ratios were kept constant and the values of fines content increased. Thevanayagam [17] observed that, at the same void ratio, liquefaction resistance of sand with silt decreased with an increase in fines content up to a threshold value. Beyond this value, interfines contacts become significant as

*. *Tel.: +90.342.3172417*
E-mail address: cabalar@gantep.edu.tr

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the intercoarse contacts diminish, and the liquefaction resistance starts to be fully controlled by interfine contents only. Efforts have also been made to develop correlations of the influence of fines on compressional characteristics of coarse-grained soils [1,18,19]. Monkul and Ozden [18] employed a series of oedometer tests on reconstituted kaolinite-sand mixtures, indicating that percentage of fines and stress conditions can influence the compression characteristics. Cabalar and Hasan [1] observed the behavior of various sand-clay mixtures to relate various sizes and shapes of sands with clay in different viscosity pore fluids to compressional behavior. They concluded that oedometer tests' results were significantly affected by the amount of clay and size/shape properties of the sand grains.

The fact is that grain size and shape characteristics have a significant effect on the engineering properties of soil matrix [20-28]. Terzaghi is one of the first researchers to make an investigation into understanding the shape characteristics using flat-grained particles [29]. Terzaghi [29] postulated that the compressibility of sand was governed by the grain size-shape, uniformity, volume of voids, and fines content. Based on the observations made by Gilboy [25], any system of analysis or classification of soil, which neglects the presence and effect of the shape, will be incomplete and erroneous. Numerous researches were carried out in this respect due to the importance of grain shape and its role in the behaviour of sands for practicing engineers and researchers in helping to estimate soil behaviour. Holubec and D'appolonia [30] demonstrated that the results of dynamic penetration tests in sands depend on grain shape. Cornforth [31] indicated how grain shape my affect the internal fiction angle (φ). Cedergren [32] showed that grain shape affected the permeability. Grain shape also plays a significant role in the liquefaction potential [33]. Wadell [34], Krumbein [35], Powers [36], Holubec and D'appolonia [30], Youd [37], and Cho et al. [38] introduced a detailed explanation of grain shape. Two independent properties were typically employed to describe shapes of a soil grain: (a) Roundness (R) and (b) Sphericity (S); the former is a measure of the extent to which the edges and corners of a grain have been rounded; the latter describes the overall shape of a grain. It is a measure of the extent to which a grain approaches a sphere in shape. Wadell [34] proposed a simplified sphericity (S) parameter, ($D_{\max-\text{insc}}/D_{\min-\text{circ}}$), where $D_{\max}$-$D_{\min}$ is the diameter of a maximum inscribed circle and $D_{\text{min-circ}}$ is the diameter of a minimum sphere circumscribing a sand grain. Wadell (1932) [34] defined roundness (R) as $D_{i-\text{ave}}/D_{\max-\text{insc}}$, where $D_{i-\text{ave}}$ is the average diameter of the corners of the grain. Figures 1-3 describe R, S and a chart for comparison between them to determine grain shape [35,36].

As it is a particulate material, behavior of soil is complicated and the interaction of individual grains and the material response is not very well understood. Numerous researchers have studied the relationship between the grain characteristics and overall behavior of soil. The present study adds to the recent researches by exploiting triaxial and cyclic direct shear tests on sand mixtures with various fines to quantify accurately

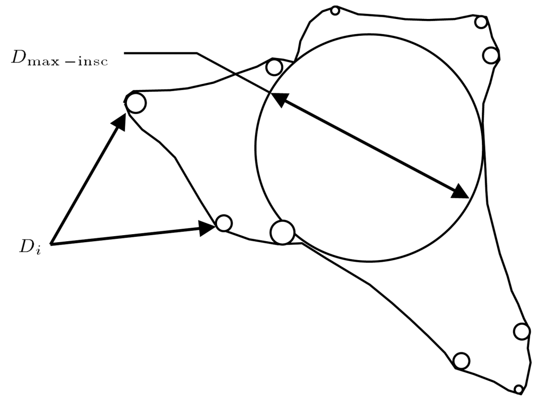

Figure 1. Graphical representation of roundness, R (redrawn from Muszynski and Vitton [24]).

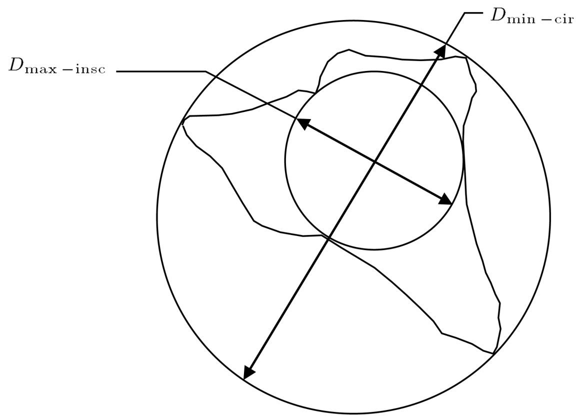

Figure 2. Graphical representation of sphericity, S (redrawn from Muszynski and Vitton [24]).

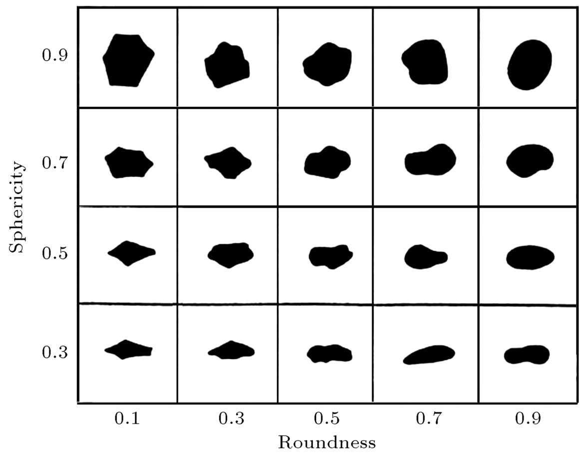

Figure 3. Comparison chart [28].

the grain shape and size of host and fine geomaterials, as well as the fines content. For this purpose, the results of an intensive series of triaxial and cyclic direct shear tests on various sand mixtures are presented.

2. Experimental study

This study reports the experiments carried out to determine the effects of various sizes and shapes of grains on the behaviour of sands tested under monotonic and dynamic loading. Twenty-four tests conducted during the investigation are presented.

2.1. Materials

The materials used in the tests described in this paper were 'Trakya' and 'crushed stone' sands obtained from Turkey. Trakya sand, which is commonly used in the experimental works, was supplied by Set/Italcementi Group, Turkey, confirming TS EN 196-1. It was obtained from the Thrace Region in North-west of Turkey. The crushed stone sand used in this investigation is widely consumed in civil engineering works, in particular earthworks, in Gaziantep, Turkey. Figure 4 shows their grain shape in Scanning Electron Microscope (SEM) pictures. As is seen, Trakya sand grains have a round shape, as the crushed stone sand grains have an angular shape. In fact, the shape of soil grains is accepted as a useful grain property in the case of coarse-grained soils where it is significant in influencing the engineering behavior of these soils. Two different gradations of both sands falling between 0.25 mm–0.5 mm and 1.0 mm–2.0 mm were artificially selected to provide uniform specimens for visual classification purposes. Hence, Figure 5 presents the grain size distribution of four different materials.

Today, it is a widely known fact that particle size and shape of soils grains, with a significant effect on physical properties of a soil matrix, depend on composition, grain formation, transportation, and depositional environments. Some of the properties affected by shape are density, porosity, permeability, compressibility, and shear strength [20,24-29,33-36]. Based on the information given in the study recently performed by Muszynski and Vitton [38], the authors have evaluated R using visual methods and S using manual/visual methods for a number of individual particle images of each of four sands using binary images generated by Scanning Electron Micrography (SEM) and scanner. Accordingly, R estimates for the crushed stone sand and Trakya sand were obtained as 0.19 and 0.35; S estimates were found as 0.56 and 0.65 relatively.

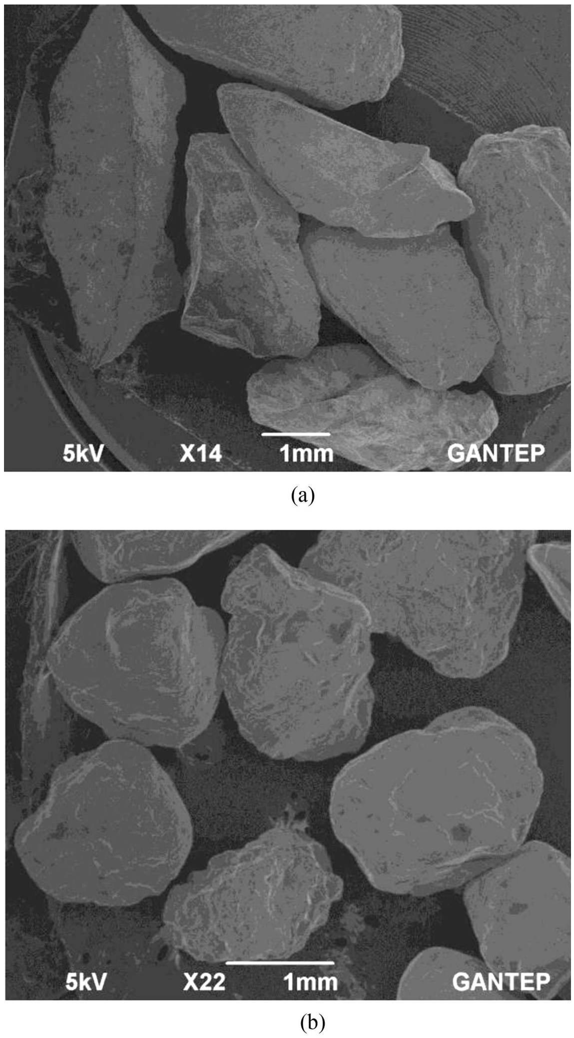

Figure 4. SEM pictures of (a) crushed stone sand, and (b) Trakya sand used during the experimental study.

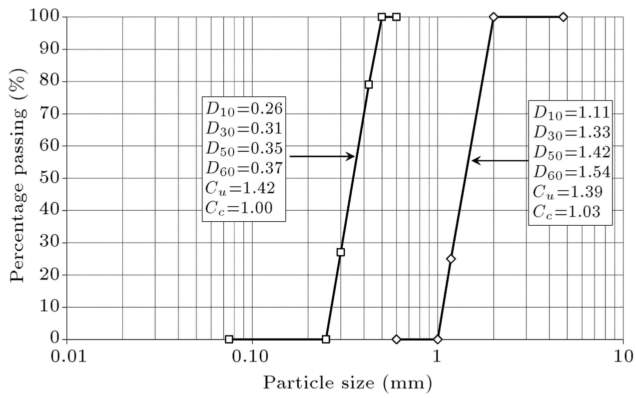

Figure 5. Particle size distributions for the sands used during the experimental study.

2.2. Test set-up

Triaxial tests were carried out in a fully automated triaxial loading apparatus, which is a product of Geocomp, thus confirming ASTM D2850- D4767. Cyclic direct shear tests were conducted using a setup, which is capable of performing the consolidation and shearing steps of a standard direct shear and residual shear test (fully automated), confirming ASTM D3080 (www.geocomp.com). These tests in the present study were selected to study shear strength determination and compare different types of testing conditions in static and dynamic applications.

2.3. Specimen preparation

The specimens in 'triaxial testing' apparatus were approximately 38 mm in diameter by 76 mm height. A membrane was attached to the pedestal using two o-rings, and a two-part split mould was then placed around the pedestal. The membrane was stretched inside the mould and fixed at the top. For the initial sand/water specimen, the required amount of sand was weighed, mixed with de-aired water, and then spooned, without vibration, into the mould. When the mould was completely filled, the membrane was stretched over the top platen and attached to o-rings. A small suction (of the order of 10–15 kPa) was applied to the specimen, before stripping the two-part split mould, installing the triaxial cell onto its base, and filling the cell with de-aired water. The suction employed for the specimen on the pedestal was then reduced, while the confining cell pressure gradually increased until the desired starting values of total and effective stress were achieved automatically by the system. This technique is very similar to the specimen preparation technique described by Cabalar and Clayton [9].

The specimens in 'cyclic direct shear test' apparatus were approximately 63.5 mm in diameter by 25.4 mm height. Similar to the technique followed for the specimens in triaxial tests and the initial sand/water specimen, the required amount of sand was weighed, mixed with de-aired water, and then spooned, without vibration, into the mould. When the mould was filled completely, the top platen was placed on it.

2.4. Test procedure

The specimens in 'triaxial tests' were isotropically consolidated to 100 kPa effective stresses, with a backpressure of 500 kPa and a cell pressure of 600 kPa, before being sheared 'CU'. A minimum B-value of 0.95 was obtained before being sheared. Similarly, all the specimens in 'cyclic direct shear tests' were loaded with 100 kPa vertical stresses. The behavior of the sand mixtures with various fines contents was investigated through Constant Normal Load (CNL) tests. The cyclic tests were strain-controlled tests with the displacement of ±3 mm and with the loading rate of 2 mm/min. The rate of loading was 0.075 mm/min during the triaxial tests (Table 1).

3. Results and discussion

The interaction among the sand grains depends on the relative density of soil matrix. The relative densities of all specimens are between 40.1 and 48.6%, obtained by predetermining the weight of dry soil and volume of the mould to be filled. From the study by Terzaghi and Peck [39], most specimens are described to be of medium dense, providing an insight into the behavior

Table 1. Test scheme employed during the experimental study.

Test type	Sand type	Gradation	Samples tested
Triaxial Test (TX)	Trakya Sand (TS)	1.0-2.0 mm (G1)	TS-G1 with 5% CSS-G2
			TS-G1 with 10% CSS-G2
			TS-G1 with 15% CSS-G2
			TS-G1 with 20% CSS-G2
			TS-G1 with 30% CSS-G2
			TS-G1 with 50% CSS-G2
Cyclic Direct Shear test (CDS)	Crushed Stone Sand (CSS)	0.25-0.50 mm (G2)	CSS-G1 with 5% TS-G2
			CSS-G1 with 10% TS-G2
			CSS-G1 with 15% TS-G2
			CSS-G1 with 20% TS-G2
			CSS-G1 with 30% TS-G2
			CSS-G1 with 50% TS-G2

of intermediate soils. The relative density of a soil is described as a ratio of the difference between maximum void ratio and existing state to the difference between its maximum and minimum void ratios. Specimens dilate or contract substantially during test in accordance with the relative density values [40]. Some of the engineering properties, including shear strength, permeability, and compressibility of a soil matrix, depend on the relative density. Therefore, the relative density values here in the experimental works were aimed to be kept at a constant range (ASTM D 4253-4254). The fact is that the significance of grain shape has been well documented as grain shape estimates are valuable for researchers and practicing engineers to interpret soil behaviour. However, there are limitations of image-based analysis systems for characterizing some types of sand size grains. Due to such limitations, it would be useful for the practice of soil mechanics to employ the existing visual approach. Muszynski and Vitto [38] proved that an engineer or technician can accurately characterize very angular sands, moderately rounded sands, and perfectly rounded sands using visual means. It is realized that this indication is also consistent with the observations made by Cho et al. [37]. From the binary images generated by SEM and scanner, R estimates for the sands used during the experimental study were determined as 0.19 for crushed sand and 0.35 for Trakya sand; S estimates were found to be 0.56 for crushed sand and 0.65 for Trakya sand.

The study describes systematically the engineering behavior of various sand mixtures tested under monotonic and cyclic loading, involving deviatoric stress, axial strain, pore water pressure, shear stress, and horizontal strain, observed during triaxial compression and cyclic direct shear tests. Actually, triaxial and cyclic direct shear tests have been widely used to observe the behavior of various soils; however, researches correlating engineering properties of sand mixtures with grain size and shape characteristics are relatively few. Therefore, the objectives of this study include the investigation of the impacts of grain size and shape characteristics on the behaviour of various sand mixtures and the understanding of the behaviour of the sands, which are widely used in earthworks projects in a certain part of Turkey. Variations of deviatoric stress and pore water pressure with axial strain for 1-2 mm clean crushed stone and Trakya sands are presented in Figure 6. As can be seen from the figure, the shearing process goes on until about 10% strain is reached for both. The tests stopped before 10% strain level in order to judge the behavior of the specimens over relatively small strain levels. Crushed stone sand exhibited a lower series of deviatoric stress values than the Trakya sand within the measured strain level. The pore water pressure values reached about 545 kPa and 530 kPa for crushed stone sand and Trakya sand, respectively. Figure 7 shows the effect of particle characteristics of both sands on stress path, where the Trakya sands exhibit dilatancy as the crushed stone sands show contraction behaviour.

The results of Trakya sand and the crushed stone sand show that the characteristics of the mixtures tested are ascribable to the presence of the finer grains in the samples' tested triaxial testing. As is seen in Figure 8, it was found that the presence of 0.5-0.25 mm Trakya sand (0%, 15%, 30%, and 50%) in the specimens tested had a marked effect on the deviatoric stress versus strain and pore water pressure versus strain

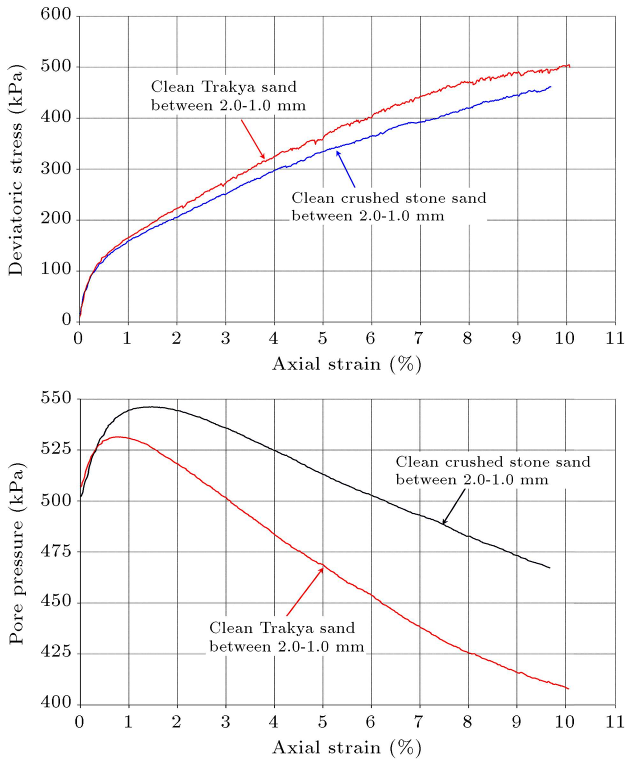

Figure 6. Triaxial results of clean crushed stone sand and Trakya sand (q, u, kPa).

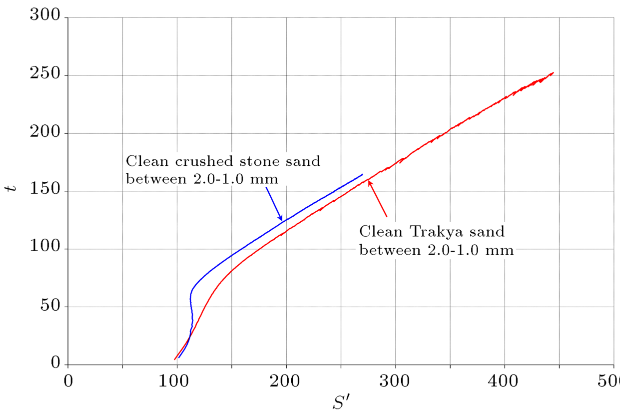

Figure 7. Stress path for clean sands.

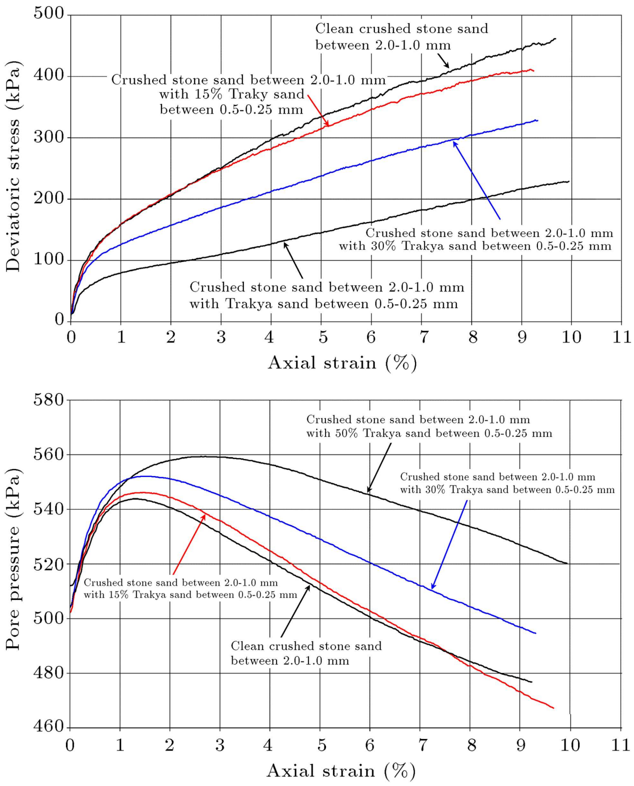

Figure 8. Effects of 0.5-0.25 mm Trakya sand on the 2.0-1.0 mm crushed stone sand.

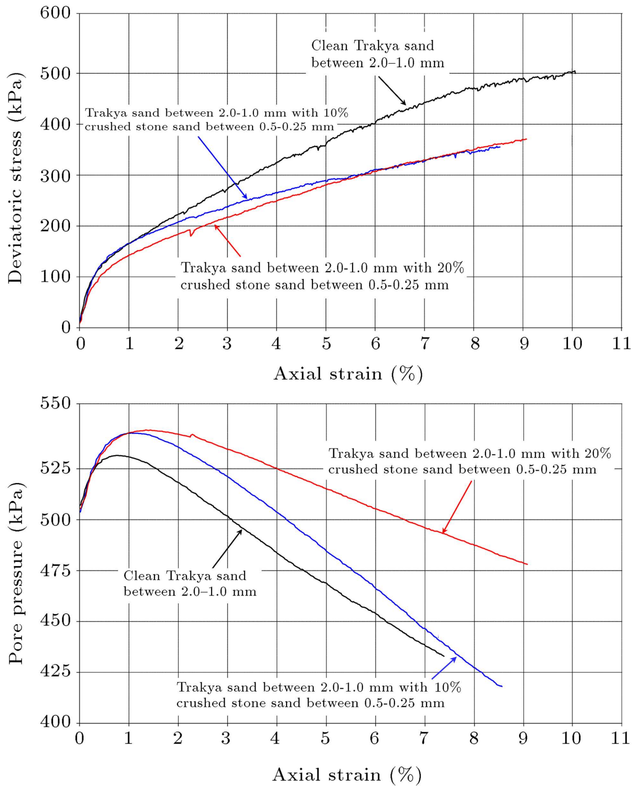

Figure 9. Effects of 0.5-0.25 mm crushed stone sand on the 2.0-1.0 mm Trakya sand.

relationships. The author postulated that finer grains occupy the voids between the coarse sand grains. Based on the amount of finer grains present, the crushed stone sand grains are in contact with each other and the behaviours of specimens tested are controlled by the crushed stone sand grains. When the contacts between the crushed stone sand grains are reduced by infilling finer grains, the behaviour of the specimens starts to change. It is the finer Trakya sand grains that mainly control the soil behaviour, as there are no or very few contact between the coarser crushed stone sand grains. Therefore, a remarkable decrease in deviatoric stress at the measured strain level can be observed when the amount of finer grain increases. Figure 8 also indicates the effects of 0.5-0.25 mm Trakya sand content on the pore water pressure versus strain behaviour of the mixture. The 1.0-2.0 mm clean crushed stone sand specimen behaves as might be expected; however, the addition of finer grains causes a delay in dilation, low undrained shear strength, and high level of pore water pressure generation during shear. A similar triaxial testing programme was directed mainly towards an investigation of 1.0–2.0 mm Trakya sand with 0.5–0.25 mm crushed stone sand at different proportions (0%, 10%, and 20%). The testing programme on these mixtures, under the same conditions, has resulted in the same mechanical principles obtained previously (Figure 9).

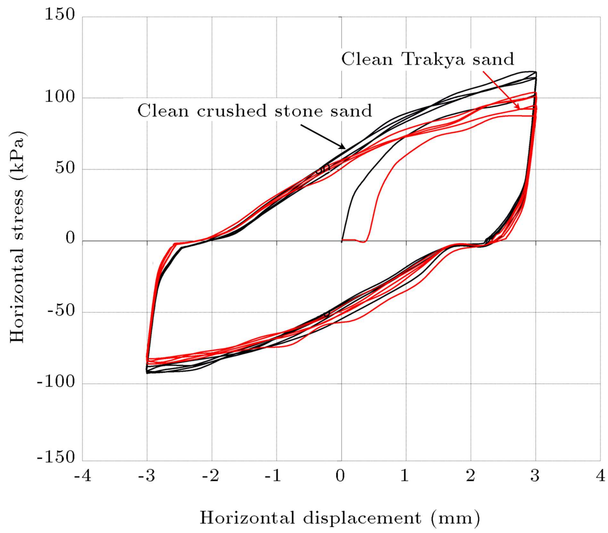

Figure 10. Cyclic direct shear tests on clean crushed stone sand and Trakya sand.

The cyclic direct shear testing results of clean crushed stone sand and Trakya sand are presented in Figure 10. This plot indicates the effects of shape on the cyclic shear behaviour of the sands. The crushed stone sand, which has an angular shape, has a higher shear stress than the Trakya sand, which has a round shape. It is seen that the sand grains with higher/lower

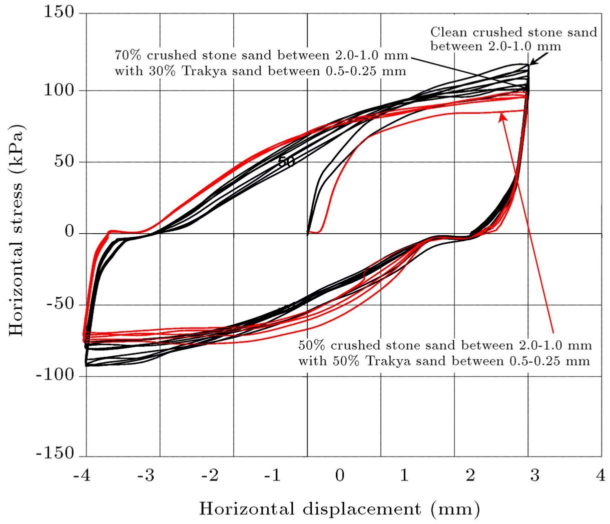

Figure 11. Effects of 0.5-0.25 mm Trakya sand on the 2.0-1.0 mm crushed stone sand.

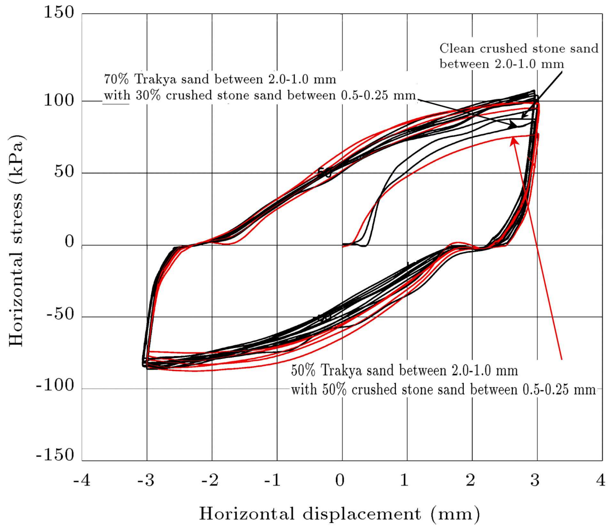

Figure 12. Effects of 0.5-0.25 mm crushed stone sand on the 2.0-1.0 mm Trakya sand.

R and S values exhibit higher modulus in the measured shear strain range. The interaction between coarser (2.0-1.0 mm) and finer (0.5-0.25 mm) grain matrices affects the overall stress-strain behavior. Figure 11 denotes the influences of 0.5-0.25 mm Trakya sand (30% and 50% by weight) on the 2.0-1.0 mm crushed stone sand. It is observed that shear modulus (slope of the loops) decreases with an increase in finer grains content for the measured strain range. Figure 12 shows the influences of 0.5-0.25 mm crushed stone sand (30% and 50% by weight) on the 2.0-1.0 mm Trakya sand. In assessing the cyclic direct shear testing results, stiffness and damping may be expressed mainly by both the differences in shape characteristics of host grains and amount of finer grains, regardless of the shape characteristics of finer grains.

4. Conclusions

Engineering behavior of various sand mixtures was examined using an extensive series of experiments in triaxial compression and cyclic direct shear testing apparatuses. The effects of mixture ratio and grain shape characteristics (R, S) on both the triaxial and direct shear behaviors were investigated by using two different sizes (0.25 mm–0.5 mm and 1.0 mm–2.0 mm) of sands with distinct shapes (round and angular) at a 100 kPa effective stress and 0.075 mm/min shearing rate in triaxial tests, 100 kPa vertical stress, and 2.0 mm/min shearing rate in cyclic direct shear tests. The tests reported in this paper indicate three new facets of various sand mixtures' behavior:

1. The shape of the finer grains does not have a significant impact on the behavior of specimens;
2. Specimens consisting of the host sand with higher roundness (R) and lower sphericity (S) lead to higher strength;
3. The quantity of finer grains has a major influence on the behavior specimens.

This suggests that, depending on the amount of finer grains and the shape of host sands, the microstructure of a mixture constitutes different ways of packing arrangements, leading to different stress-strain responses.

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Biography

Ali Firat Cabalar is a Professor of Geotechnical Engineering at the University of Gaziantep, Turkey. Professor Cabalar's current research interests include biotechnological applications in soil mechanics, road pavement subgrade design, environmental geotechnics, soil dynamics, and soil behavior at microscale including stick-slip phenomena.