Effect of the Quasi Rate of Loading in Particle Crushing and Engineering Properties of Black Tough Sand

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By

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In this study, the effect of the quasi rate of loading in the crushing of black tough sand will be studied experimentally. The experimental works will be conducted at different normal stresses, different relative densities, and different rates of loading using the direct shear tests. All test specimens were prepared with uniformly graded sand, passing sieve #4, and retained sieve #8.

The results of direct shear tests were used to investigate the factors influencing the amount of particle breakage and consequently the friction angle. After shearing of each specimen, sieve analysis was performed in order to determine the percentage of particle breakage. Results showed that the rate of loading in direct shear plays a significant role in the amount of crushing and in internal friction angles. The amount of crushing as well as shear strength was increased with the increased rate of loading. Moreover, microstructural analysis used scanning electron microscopy (SEM) analysis shown that the crushing from granular have primarily resulted from disintegration, grinding and abrasion of particles.

KEYWORDS: direct shear tests, particle crushing, relative density, rate of loading.

1. Introduction

Granular crushing is one of the major themes attracted the attention of a wide spectrum of scientists and engineers (Xiao et al. 2020). The crushing of granular materials encounters in driven piles, rock fill dams, railways, and landslides (Altuhafi et al., 2018, Kermani et al., 2018, Sevi and Ge, 2012 and Okada et al., 2004).

The granular materials composed a major part of the dams, foundations, base of highways pavements, highway embankments, retaining walls backfilled and rock fills, experience crushing as a result of variants loads either static or dynamic. Because of the persistence of the crushing, the initial engineering properties in which a structure designed was based upon it will alter during its engineering lifespan. These changes in engineering properties due to crushing could affect the stability of the structure and jeopardize its safety. Thus, there is a need to understand the evolution of crushing in granular materials. The evolution of crushing in granular materials will be very valuable to the geotechnical engineering community for the better design of civil engineering structures.

Past research has established that grain crushing is influenced by many factors. These factors are ranged from soil grain characteristics such as soil particle strength (Varadarajan et al. 2006) angularity and morphology (Karatza et al., 2019; Xiao et al., 2019), or soil matrix properties such as gradation (Honkanadavar and Sharma, 2014), porosity (Hyodo et al., 2016), and moisture content (Alonso et al., 2016), and anisotropy (Hattamleh et al. 2010, Hattamleh et al. 2013) and external factors such as induced stress (Hattamleh et al. 2010), loading duration (Fu et al., 2019), and loading rate (Huang et al., 2017 and; Parab et al., 2017).

The aforementioned researches were conducted on different types of granular material, specifically of silica, carbonate, and gypsum sands (Yu, 2017, Xiao et al., 2017, Yamamuro et al., 1996). The other searched granular materials include but not limited to ballast, rock fill, coal, and snow, among others

(Indraratna et al., 2020, Strahler et al., 2018, Zhang et al., 2017, Barracclough et al., 2016, and Xiao et al. 2020)

Particle breakage quantification also was subject to extensive research and different methods were suggested according to the parameters assessed. Different particle crushing index used in literature based on either global variation of grading, particular variation in grading sizes, a fine content portion, or grain area evolution through the test (Xiao et al. 2020). The most commonly used approaches are based on the change of the grain size distribution before and after crushing occurs e.g.(Hardin, 1985; Einav 2007). Other methods that sparingly used focus on the change in percentage passing for particular particle size (Miura et al., 2003) or an increase in the specific surface area of the particles (Miura and O-Hara, 1979, Ganju et al. 2019). Figure 1, after Xiao et al. 2020, summarized the different evaluation methods used to evaluate the grading indices. For instance, Einav (2007) postulates that the grain size distribution will start from an initial grading and ultimately reaches a final grading due to shearing and compression. The relative breakage index, Br_E , is defined as an area ratio

$$Br_E = \frac{Bt}{Bp} \quad (1)$$

Where Bt and Bp are shown in Figure 1b.

In this figure, (Figure 1), Bp , the ‘breakage potential’, is defined by integrating the entire area confined between the initial and final grain size distribution whilst Bt is the area between the current (at given compression stress), and the initial one, when there is no applied shear or compression stresses.

Cerato and Lutenegger 2006 conducted direct shear tests in five different sands with different properties. They used three square shear boxes of differing sizes (60 mm, 101.6 mm, and 304.8 mm), each at three relative densities (dense, medium, and loose). It was found that the friction angle ϕ can be dependent on specimen size and that the impact of specimen size is also a function of the sand type and relative density. The tests show that for well-graded, angular sands, ϕ decreases as box size

increases and that the impact of box size is dependent on relative density. Ovalle and Hicher (2019) studied the role of particle breakage in primary and secondary compression of wet and dry sand. The test results of one-dimensional compression tests on dry and saturated crushable sand show that flooding dry samples at constant stress promotes particle breakage and triggers collapse from the characteristic compression curve of the dry material to the compression curve of the initially saturated material. The link between the one-dimensional compressibility index and the amount of particle breakage does not depend on the stress level and the wetting condition. Saturated crushable sand is more compressible compared to dry sand, due to the increment of particle breakage with the material humidity. For a given stress path, when flooding dry crushable sand under constant stress, the creep index increases up to the same value obtained by a sample saturated from the beginning of loading.

The motivation of this work is the fact that the strength and stress characteristics of sands as determined from conventional testing such as direct shear tests are a function of their initial density and applied rate of loading. The initial density of the sand specimens is a function of the degree of compaction, with altering the densities the initial stiffness, peak strength, and volume dilation are varied and it depends on the rate of loading. However, the effect of the rate of loading in the quasi range is not well comprehended and this type of sand is not being subject to such research (Parab et al., 2017, Xiao et al. 2020).

The main objectives of the proposed research are to conduct laboratory investigations on the quasi rates affect sand shear strength and the consequent evolution of crushing in granular materials. The laboratory investigation will involve tests involve comprehensive direct shear tests. The tests will include specimens in the whole range of relative densities (very loose ($Dr=20\%$), loose ($Dr=40\%$), medium ($Dr=60\%$) and dense ($Dr=80\%$), four normal stresses (136 kPa, 245 kPa, 463kPa, and 899 kPa) and different quasi shearing rate (0.5 mm/minutes, 1.0mm/ minutes, and 2.0 mm/ minutes). The evolution of crushing in these tests will be evaluated by comparing the grain size distribution curves

before and after the shearing applied. The pertaining engineering properties will be evaluated thereafter.

2. Experimental Works

2.1 Materials

Black tough sand was selected for this study. The Black tuff obtained from Al-Hala area (Al Tafila) in southern Jordan. The main properties of the investigated sandy materials such as specific gravity, G_s , maximum density, ρ_{max} , and minimum density, ρ_{min} , and the corresponding standards, were these tests conducted according to, are given in Table 1. The grain sizes for the sand passed 2.36 mm (sieve#8) and retained on 4.75 mm (sieve #4). The uniformity coefficient and the coefficient of curvatures are equal to one for all types of sand because the specimens are single size. Therefore, these sands are classified as poorly graded sand, SP, according to the Unified Soil Classification System (USCS; ASTM 2487-17). Sand chemical composition, as obtained using standard X-ray fluorescence spectroscopy according to ASTM E1621 – 13, is presented in Table 2. It composed mainly of SiO_2 (40.00%-43.00%), with a considerable amount of Fe_2O_3 (12.75%-13.00%), Al_2O_3 (10.67%-12.64%) and CaO (9.35%-11.28%) oxides. Comprehensive characterizations of the used sand sources were given by (Al Dwairi et al. 2014, Khoury (2018), and Ibrahim et al. 2016). Scanning electron microscope supplied with energy-dispersive X-ray spectroscopy (SEM/EDX) image of the tested black tough is shown in Figure 2. The surface roughness as well as the present of phillipsite occurs as prismatic crystals, rosettes of radiating and spherulitic crystal are clearly shown in the image.

2.2 Test Setup

The device used for performing the experiments was a direct shear box produced by CONTROLS GROUP/ Italy. The maximum horizontal and vertical force is 5 kN with three analogue

channels, one for load cell and two for displacement transducers. Two linear variable differential transformers (LVDTs) are used to measure the horizontal and vertical displacements. The shear box was designed to accommodate a soil sample with a horizontal surface area of 6.00 cm by 6.00 cm and a height of 3.00 cm.

Direct shear tests were conducted according to ASTM D6528-17 (2017) on the four different relative densities identified as a loose, medium, and very dense sand on dry samples under four vertical stress conditions as follows (136 kPa, 245 kPa, 463 kPa, and 899 kPa) at three different rates of loading (0.50 mm/minute, 1.00 mm/minute and 2.00 mm/minute). Table 3 summarizes all tests performed, including relative densities, applied vertical stresses, and applied shearing rates in direct shear tests as well as sieves analyses for each test.

The data from direct shear tests were analyzed to examine the stress-strain response to the Mohr-Coulomb envelope and hence the shear strength parameters. Sieve analysis was performed on the sample taken to determine the extent of the percentage of particle breakage.

3. Experimental Results

Direct shear tests conducted on the prepared specimens as outlined in Table 3. Figure 3 illustrates the relationship between horizontal displacement vs. shear stress at the different relative density and normally applied stresses for black tuff sand at a shearing rate of 2.00mm/minutes. From the figure above, As the shear displacement increased, the shear stress increased arrived at the peak value, then when the shear displacement increased, the shear stress decreased arrived to a critical state. It can be noted the normal stress was small, the movement of sand particles was relatively easy and the relative displacement could quickly reach a stable state while the normal stress was large, the interaction between particles of sand was large and the displacement was relatively difficult, so a larger shear displacement was needed to realize a more stable state. On the other hand, the vertical displacement vs. horizontal

displacement for the same applied pressure and shearing rate at given relative densities were shown in Figure 4. As expected as applied pressure increased the amount of contraction is increased in all densities. However, the extent of contraction was a substantial decrease with increasing the relative densities, and in the medium range of applied stresses (245 kPa and 463 kPa) the contraction switch to dilation with progressing of shearing.

Mohr-Coulomb failure envelopes were obtained by plotting the attained shear stresses with vertical applied stresses under a different combination of test variables are presented in Figure 5. The presented envelopes are the those of the black tuff (BT) sand at low, medium and dense state ($D_r=20\%$, 40% , 60% , and 80%) at a different rate of loading (0.50mm/minute, 1.0mm/minute, and 2.00mm/minute). It can be observed that the failure envelopes are generally nonlinear for the range of applied vertical stresses used. This is attributable to the dilation of the sand especially at the low-stress levels. However, the increasing of vertical stress leads to more crushing of particles as well shown later, and therefore, the voids between sand particles were filled by smaller granules that will let the sand to become more densified.

The grain size distribution obtained from sieve analysis for Black Tough sand before and after subjected to shearing stresses at different normal stresses at different relative densities at a shearing rate of 1.0mm/minutes is shown in Figure 6.

4. Analysis and Discussion

4.1 Effect of Shearing Rate in Internal Friction Angle

The mobilized friction angles of the tested Black Tough sand were assessed to evaluate the effect of applying shearing rates. The mobilized peak friction angle and the mobilized residual friction angle which define respectively as:

$$\phi_p = \tan^{-1} \frac{\tau_{peak}}{\sigma} \quad (2)$$

$$\phi_r = \tan^{-1} \frac{\tau_{residual}}{\sigma} \quad (3)$$

where τ_{peak} : the peak shearing stresses, $\tau_{residual}$, and σ =the applying normal stresses.

The peak and mobilized residual friction angles of the tested sands for various applied normal stresses, various relative densities, and rate of loading are determined and presented in Figure 7 as a function normal stress. It is clearly shown from both figures that both peak and residual angles are substantially decreased with applied vertical stresses regardless of the relative densities of sand specimen and/or the applying shear rate. More or less, the effect of applying pressure and rates of shearing diminish in residual friction angle, especially for higher relative density. This outcome may explain why the downward motion of critical states line in the compression plane occur (Liu et al., 2014; Li et al., 2015; Liu and Gao, 2017; Xiao and Liu, 2017).

Furthermore, the effect of applying the shearing rate in both peak and residual friction angles (Equations 4 & 5) deduced as the gradient of failure envelope as:

$$\phi_p = \tan^{-1} \frac{\Delta\tau_{peak}}{\Delta\sigma} \quad (4)$$

$$\phi_r = \tan^{-1} \frac{\Delta\tau_{residual}}{\Delta\sigma} \quad (5)$$

is shown in Figure 8. It is obvious from this figure that increasing the shearing rate increased both friction angles regardless of the relative density. However, the amount of increasing seemed to be asymptote with a further increase in the shearing rate.

4.2 Analysis of Particle Breakage during shearing for black tuff sand

The amounts of particle crushing (breakage) reported here are based on what so-called *global grading indices* (Xiao et al. 2020). The particle breakage, Br_E (Einav (2007), calculated from grain size distribution parameters before and after shearing. The gradation curve shifts from the large to the smaller sieve sizes. The grain size distribution for the black tuff sand specimen after direct shear tests under different normal stresses and different relative densities at a different rate of loading were already

shown in Figure 6. After that, the percent of breakage, Br_E was calculated and presented for each rate of loading as a function of applying vertical stress in Figure 9A, 8B, and 8C for the rate of loading 0.50 mm/minutes, 1.00 mm/minutes, and 2.00 mm/minutes respectively.

It can be noted that the amount of crushing increased with the magnitude of the applied vertical stress and high relative density. Additionally, the particle breakage increases with an increased rate of loading. The results of sieve analysis tests showed the amount of crushing, Br_E , at low-stress level (136kPa) is slightly at ranges of (0.00-3.00) % while at moderate stress level (245kPa and 463kPa), the amount of crushing is increasing to (0.53-7.00) %. While at the high stress level (899kPa), the amount of crushing is significantly increasing to the range of (10.00-12.00) %. The amount of crushing was increased with relative density increased.

Lastly, a microstructural analysis, that used scanning electron microscopy (SEM) supplied with energy-dispersive X-ray spectroscopy (SEM/EDX), of samples taken from the shearing zone of tested specimens were conducted at different scales and magnifications to inspect what happened to the BT granules after shearing. Figure 10 shows that the granules of original sizes which confined between 2.36 mm and 4.75 mm were experience disintegration and cleavage as shown in the SEM image of 1.00 mm and 500 μ m scale and a magnification of 18 and 35 times, respectively, (Figure 10 A & B), abrasion and grinding as shown in the SEM image of 100 μ m scale and a magnification of 110 times (Figure 10 C) and scratching as shown in the SEM image of 10 μ m scale and a magnification of 2200 times(Figure 10 D).

5. Conclusions

The effect of the quasi rate of loading in the crushability sands and mechanical engineering properties of black tough sand was studied experimentally. This study utilized the direct shear test to conduct this task. Based on the results of the tests the following conclusion may be drawn:

1. The Mohr-Coulomb failure envelopes of this sand, in the range of normal stresses applied in this study, were nonlinear, specifically for peak shear strength.
2. For loose and medium state specimens, the shear stress increases uniformly with no peak. Whilst for dense specimens, the shear stress-shear displacement is shown to increase to peak then decreased to residual shear strength.
3. The rate of loading in the direct shear test plays a crucial role at shear strength, where the shear strength increases with increasing the rate of loading.
4. The peak friction angle is found to decrease with increasing of void ratio and normal stresses applied, while the opposites in the case of relative density as it well known.
5. The crushing of sand depends on normal stress and relative density which it was found that the amount of crushing increases with increasing normal stress and relative density, while the rate of loading increase the amount of crushing.
6. The crushed granules were derived from disintegration, abrasion and grinding processes.

Disclosure statement

The authors state that there is no potential conflict of interest will occur by publishing this research.

Data Availability Statement

All data, models, and code generated or used during the study appear in this research.

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Tables list

Table 1: Main properties of black tuff (BT) sand.

Table 2. Sands chemical composition of the black tuff (BT) sand.

Table 3. Tests Summary: relative densities, applied vertical stresses and applied shearing rates used in tests for the sand in a direct shear test.

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Figure 2: SEM image of tested sand particles

Figure 3: Shear stress and shear displacement at various relative density at rate of loading 2.0 mm/minutes for black tuff sand (a) $\sigma_n=136$ kPa (B) $\sigma_n=245$ kPa (C) $\sigma_n=463$ kPa and (D) $\sigma_n=899$ kPa

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Figure 10: SEM images at different scales.

Figures

Figure 1

Global grading indices as summarized by Xiao et al. 2020: (a) B_r proposed by Hardin (1985); (b) B_{rE} proposed by Einav (2007); (c) IG proposed by Muir Wood and Maeda (2008); (d) BBI proposed by Indraratna et al. (2005).

Figure 2

SEM image of tested sand particles

—●— $D_r=20\%$ —●— $D_r=60$ —●— $D_r=80$ —●— $D_r=40\%$

—●— $D_r=20\%$ —●— $D_r=40\%$ —●— $D_r=60\%$ —●— $D_r=80\%$

—●— $D_r=20\%$ —●— $D_r=40\%$ —●— $D_r=60\%$ —●— $D_r=80\%$

—●— $D_r=20\%$ —●— $D_r=40\%$ —●— $D_r=60\%$ —●— $D_r=80\%$

Figure 3

Shear stress and shear displacement at various relative density at rate of loading 2.0 mm/minutes for black tuff sand (a) $n=136$ kPa (B) $n=245$ kPa (C) $n=463$ kPa and (D) $n=899$ kPa

(A)

(B)

(C)

(D)

Figure 4

Vertical vs. Horizontal Displacement for Black tough at shearing rate of 2.0 mm/minute (A) Dr=20% (B) Dr=40% (C) Dr=60% and (D) Dr=80%.

Figure 5

Mohr Coulomb failure envelope for black tuff sand of sharing loading rate of (A) 0.50 mm/minutes (B) 1.0 mm/minutes and (C) 2.0 mm/minutes

Figure 6

Grain size distribution for Black Tough sand before and after subjected to shearing stresses at different normal stresses at different relative densities at shearing rate of 1.0mm/minutes.

Figure 7

Mobilized Friction Angle for Black Tough at different shearing Rate

Figure 8

Effect of shearing rate on mobilized peak friction angle taken from Failure Criterion Envelope for the black tuff (BT)

Figure 9

Evolution of Percentage particle crushing of Black Tough in direct shear at different normal stresses and different relative density at different shearing Rate.

Figure 10

SEM images at different scales.