Geomechanics and Engineering, *Vol. 22, No. 2 (2020) 173-185*
DOI: https://doi.org/10.12989/gae.2020.22.2.173

Factors affecting particle breakage of calcareous soil retrieved from South China Sea

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(Received November 21, 2019, Revised June 9, 2020, Accepted June 17, 2020)

Abstract. Calcareous soil is originated from marine biogenic sediments and weathering of carbonate rocks. The formation history for calcareous sediment includes complex physical, biological and chemical processes. It is preferably selected as the major fill materials for hydraulic reclamation and artificial island construction. Calcareous sands possess inter pores and complex shape are liable to be damaged at normal working stress level due to its fragile nature. Thus, the engineering properties of calcareous soil are greatly affected by its high compressibility and crushability. A series of triaxial shear tests were performed on calcareous sands derived from South China Sea under different test conditions. The effects of confining pressure, particle size, grading, compactness, drainage condition, and water content on the total amount of particle breakage for calcareous soil were symmetrically investigated. The test results showed that the crushing extent of calcareous sand with full gradation was smaller than that a single particle group under the same test condition. Large grains are cushioned by surrounding small particles and such micro-structure reduces the probability of breakage for well-graded sands. The increasing tendency of particle crushing for calcareous sand with a rise in confining pressure and compactness is confirmed. It is also evident that a rise in water content enhances the amount of particle breakage for calcareous sand. However, varying tendency of particle breakage with grain size is still controversial and requires further examination.

Keywords: shear strength; particle breakage; water content; triaxial test; gradation

1. Introduction

Calcareous soil is widely distributed in coral reefs between N30° and S30°, where corals can survive. It is primarily composed of skeletal remains of marine organisms in ocean environments. Owing to their high void ratio and mineral components, calcareous soils tend to be crushed more easily under normal working stress compared with terrigeneous sands (Wang *et al.* (2017a)). There is now strong evidence to suggest that large deformations of granular media are accompanied by grain crushing (Lee and Farhoomand (1967), Billam (1971), Marsal (1973) , Miura and O-Hara (1979), Biarez and Hither (1994), Lade (1996), Yamamuro and Lade (1996), Coop *et al.* (2004), Xiao *et al.* (2017), Hyodo *et al.* (2017a), Hyodo *et al.* (2017b), Hyodo *et al.* (2017c), Wang *et al.* (2017b), Yoshimoto *et al.* (2017), Wu *et al.* (2018), Wu *et al.* (2020a), Wang *et al.* (2019), Wang *et al.* (2020), Ma *et al.* (2020)). Therefore, particle crushing can be attributed to the plastic compression of brittle granular media. Past investigations revealed that the particle crushing intensified with several factors including (1) confinement, (2) anisotropic consolidation, (3) abundance of intraparticle voids and plate-like shell fragments, (4) angularity of particles, and (5) particle size.

The particle crushing of calcareous soils has resulted in many engineering disasters, which has garnered considerable attention for the exploitation of marine mineral resources in tropical and ocean environments (Valent *et al.* (1982), Zhu *et al.* (2016)). As the main component of calcareous soil is calcium carbonate, its specific gravity is 2.82, which is larger than that of silica sand (approximately 2.65). Although the mechanical behavior of calcareous soil is consistent with the principal features of soil mechanics (Coop (1990)), it exhibits singular properties. The high internal friction angle of calcareous soil is easily affected by stress owing to its high compressibility and crushability, which greatly depends on the particle shape, grain size, stress level, and grading characteristics (Golightly and Hyde (1988), Wang *et al.* (2011), Lehane and Liu (2013), Shahnazari and Rezvani (2013), Yu (2017), Yu (2019), Nanda *et al.* (2018), Beemer *et al.* (2019), Ma *et al.* (2019). Moreover, those characteristics contribute to a specific creep behavior of calcareous soil (Wang and Wong (2010), Lade and Karimpour (2010), Wang *et al.* (2011), Lv *et al.* (2016), Ando *et al.* (2019), Arenaldi-Perisic *et al.* (2019).

In classical soil mechanics, soil particles are assumed to be incompressible and unbroken. Soil deformation is caused by the discharge of pore water and soil particle movement.

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ISSN: 2005-307X (Print), 2092-6219 (Online)

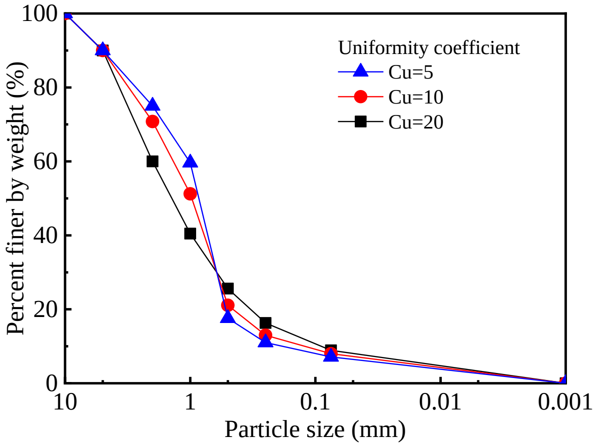

Fig. 1 Grading curves of three tested samples with different uniformity coefficients C_u

Table 1 Physical parameters of calcareous soils

Particle size (mm)	ρ_{dmin} (g/cm^3)	ρ_{dmax} (g/cm^3)	G_s	e_{min}	e_{max}
<0.075	1.11	1.45	2.73	0.88	1.46
0.075-0.25	1.08	1.30	2.73	1.10	1.53
0.25-0.5	0.93	1.18	2.73	1.32	1.94
0.5-1.0	0.86	1.17	2.73	1.33	2.17
1.0-2.0	0.83	1.20	2.73	1.28	2.29
2.0-5.0	0.8	1.33	2.73	1.06	2.41
5.0-10.0	0.8	1.32	2.73	1.07	2.41
C_u = 20	1.19	1.52	2.73	0.80	1.29
C_u = 10	1.19	1.57	2.73	0.74	1.30
C_u = 5	1.18	1.51	2.73	0.81	1.32

The classic soil strength theory is based on interparticle friction and slip. However, particle breakage occurs when soil particles are subjected to stress exceeding their own strength. In general, the shear strength of silica sand is higher than that of calcareous soil. The breakage of calcareous soil results in a continuous variation in soil gradation, causing additional compressibility (Mun and McCartney 2017) and foundation settlement (Meng *et al.* 2020). As calcareous soil exhibits the characteristics of high porosity (including internal pores), irregular particle shapes, and high brittleness. Therefore, the effect of particle crushing is critical for understanding the mechanical properties of calcareous soils.

Owing to the reasons above, mechanical properties of calcareous soils has been studied over recent decades. It has been revealed that particle breakage is regarded as the major reason for the excessive deformation of calcareous soils. Furthermore, it has been reported that particle breakage suppresses the dilatation behavior and reduces the peak strength of calcareous soils (Hanley *et al.* (2015), Wang *et al.* (2017a), Raisianzadeh *et al.* (2018), Karatza *et al.* (2019), Wang *et al.* (2019)). The amount of particle breakage is closely related to the plastic work. Liu and Wang (2002) conducted a consolidated drained triaxial drainage shear test and constant axial strain test on calcareous sand from Nansha Islands. Starting from the mechanism of particle breakage, the expression of breakage work for shear dilatation coupled with particle breakage was proposed. Moreover, the relationships among relative breakage B_r, axial strain ε_1, plastic work W_P, and breakage work W_B were analyzed. Plastic work owing to particle breakage W_B was proposed as the variant of function relation between particle breakage and the loading process. Furthermore, a relationship between the particle breakage index of calcareous sand and energy consumption was established. It is discovered that particle breakage caused acoustic emissions in calcareous sand (Zhang 2004). Acoustic emissions are elastic waves generated by energy release owing to particle breakage and reflects the degree of damage during shearing. Acoustic emission technology was employed to study particle breakage, which provided a new method for estimating the particle crushing of calcareous soil. Zhang (2004) studied the particle breakage of calcareous sand in compression and shearing processes and indicated that low single particle strengths contributed significantly to the particle crushing of calcareous sand.

Previous studies primarily concentrated on the effect of particle breakage on the mechanical behavior of calcareous soil. Studies focusing on the major factors governing the amount of particle breakage are rare. In this experimental investigation, the effects of several factors including particle size (Marachi *et al.* 1969, Verdugo and De la Hoz 2006, Frossard *et al.* 2012), grading, relative density, water content, confining pressure, and drainage condition on the total amount of particle breakage of calcareous soil were systemically investigated through a large number of triaxial shearing tests.

2. Sample preparation and testing procedures

The calcareous soil used in the triaxial tests was collected from Nansha Islands, China (Wang *et al.* 2011). The cylinder specimens for shearing were 61.8 mm in diameter and 120.0 mm in height. Prior to test, soil samples were dried and sieved. Coarse particles with grain diameter over 10.0 mm were removed. The maximum and minimum dry densities (Standard for Soil test method, GB/T 50123-1999), and specific gravity were measured for the tested calcareous sand. The physical parameters of the calcareous sand are listed in Table 1.

Hardin (1985) proposed the relative breakage B_r to quantify the degree of particle breakage. In this method, the area encircled by the particle distribution curve before the test and the vertical line d=0.074 mm was defined as the breakage potential B_p. The area encircled by the particle distribution curves before and after the test and the vertical line d=0.074 mm was termed the total breakage (B_t). The relative breakage B_r was defined as

$$B_r = B_t / B_p \tag{1}$$

To study the effect of particle size on particle crushing, the samples were categorized into seven particle groups according to their grain sizes and then tested (see Table 1). Three different grading curves of calcareous sand specimens were prepared, in which the uniformity

Table 2 Test conditions of calcareous soil

Test scheme	Factors	Water content ω (%)	Drainage condition	Effective confining pressure σ_3 (kPa)	Shear rate mm/min)	Termination axial strain (%)
1	Grain size	Saturated	CD	50, 100, 200, 400	0.60	20
2	Gradation	Saturated	CD		0.12	20
3	Relative density	Saturated	CD, CU		0.12	20
4	Water content	6, 12, 18, 24	CD		0.60	20

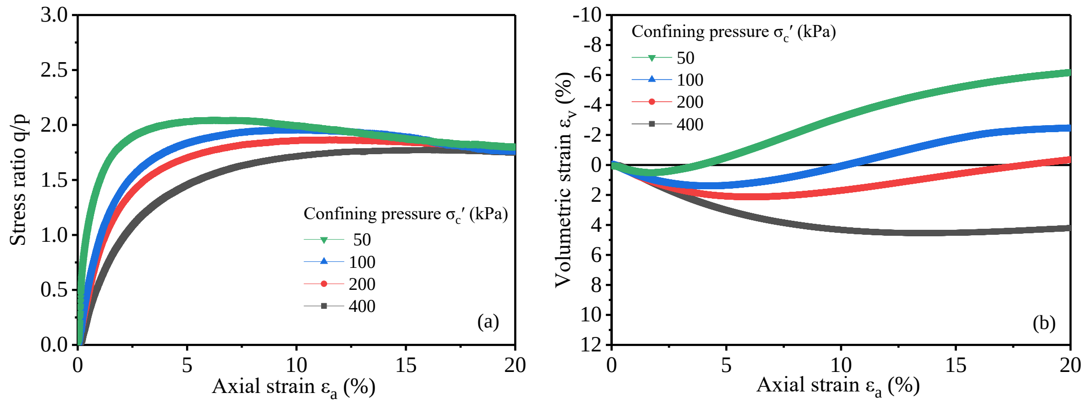

Fig. 2 Stress-strain curves of calcareous soil at different confining pressures (C_u=5, D_r=70%)

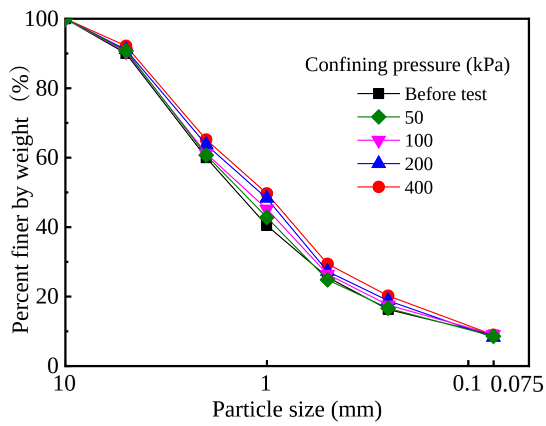

Fig. 3 Grading curves of calcareous soil before and after tests at different confining pressures

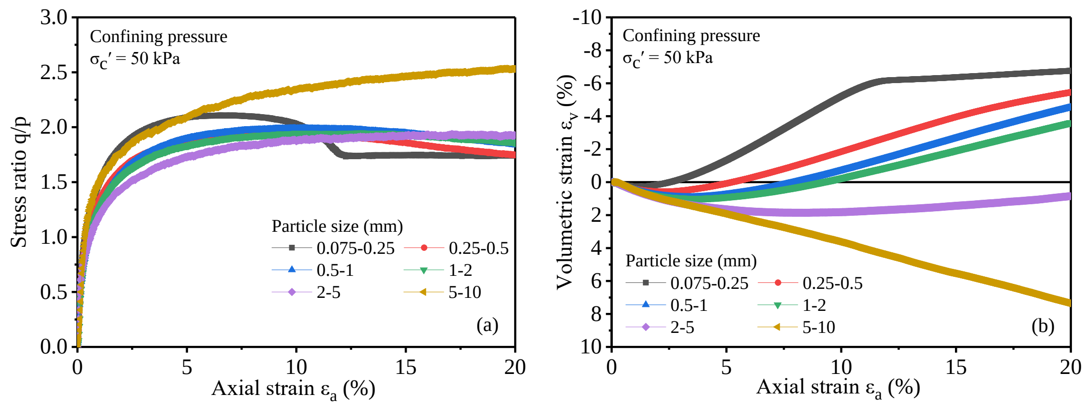

Fig. 4 Stress-strain curves of calcareous soil with different particle sizes at a confining pressure of 50 kPa (relative density D_r=60%)

coefficient C_u was set as 20, 10, and 5 with the same curvature coefficient C_c of 2 (Fig. 1). To examine the effect of soil density on shear response, triaxial shear tests were

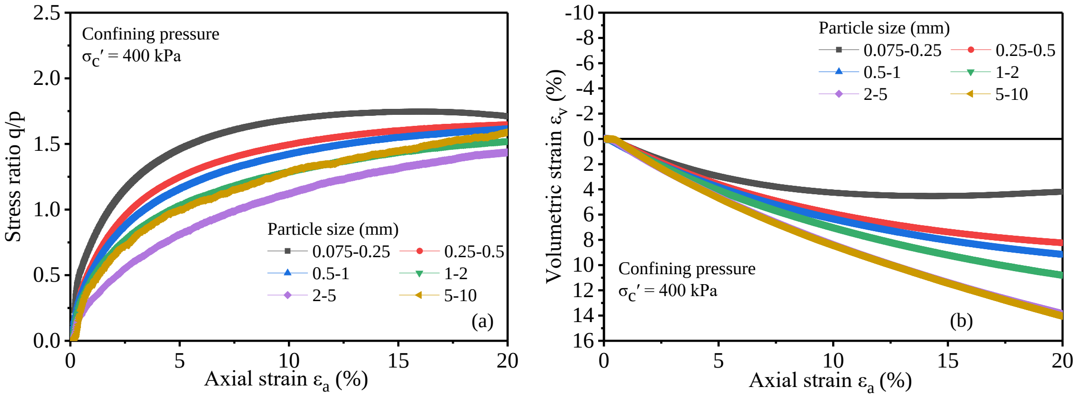

Fig. 5 Stress-strain curves of calcareous soil with different particle sizes at a confining pressure of 400 kPa (relative density D_r=60%)

conducted on sample with three relative densities of 70%, 85%, and 95%. To investigate the effect of drainage condition, consolidated drained (CD) and consolidated undrained (CU) triaxial shear tests were performed on soil samples with C_u =20. To analyze the effect of water content (Oldecop and Alonso 2003) on particle crushing, CD shear tests were conducted on samples with varying water contents of 6%, 12%, 18%, and 24% and C_u=20. Table 2 shows the specific experiment conditions and parameters. All tests were terminated at the axial strain of 20%. To quantify the amount of particle crushing, the soil samples were sieved to obtain the particle size distribution curves before and after testing.

Table 3 Percentage of soil mass of different grain sizes after testing

Particle sizes after triaxial test (mm)	Particle sizes before triaxial test (mm)					
	5-10	2-5	1-2	0.5-1	0.25-0.5	0.075-0.25
5-10	60.63%	-	-	-	-	-
2-5	26.82%	72.66%	-	-	-	-
1-2	2.52%	10.27%	61.40%	-	-	-
0.5-1	4.56%	11.07%	28.53%	82.26%	-	-
0.25-0.5	1.55%	2.20%	4.11%	9.54%	81.77%	-
0.075-0.25	2.62%	2.59%	4.08%	6.12%	15.94%	95.21%
<0.075	1.30%	1.21%	1.88%	2.09%	2.29%	4.79%

3. Results and discussions

3.1 Effect of confining pressure

Fig. 2 shows the stress-strain relationship of calcareous soil at various confining pressures. Sub-figure (a) denotes the stress ratio-axial strain curve, and sub-figure (b) expresses the volumetric strain-axial strain curve. The shear strength and deformation stress-dependence characteristics for calcareous soil are evident. The samples approximately attain the critical state when the axial strain is over 20% (Wu *et al.* (2013), Wu *et al.* (2014), Kajiyama *et al.* (2017a), Kajiyama *et al.* (2017b), Winter *et al.* (2017), Wu *et al.* (2019), Wu *et al.* (2020b)). Fig .3 shows the variation in the grain size distribution curves of the calcareous samples before and after shearing. An increase in the confining pressure resulted in a shift in the grading curve, thereby yielding a larger B_r. The breakage mode affects the evolution law of grain size distribution curve. Particle breakage mode of soil particle can be categorized into three categories: splitting, chipping, and grinding (Wang and Coop 2016). Splitting refers to breaking of the original particles into several fragments. Chipping means that a minor part is split away from the particle and the major part continues to sustain the substantial load. Grinding indicates that particles are ground into plenty of fine powders. The particle breakage mode of calcareous soil during shearing is dominated by splitting, meaning, most of the calcareous soil particles are broken into smaller fragments under stress.

3.2 Effect of gradation

Figs. 4 and 5 show the stress-strain relation of calcareous soil with different grain diameter sizes at confining pressures of 50 and 400 kPa, respectively. At a confining pressure of 50 kPa, the peak stress ratio of the samples decreased as grain diameter size range varied from 0.075-0.25 mm to 2-5 mm. It is noteworthy that the shear strength of calcareous soil with grain diameter 5-10 mm was the largest among all samples, as shown in Fig. 4 (a). This was likely due to the larger ratio of the grain diameter to the sample diameter. Additionally, the marked post-peak strain softening behavior of samples with grain diameter range 0.075-0.25 mm was due to strain localization (Khalid *et al.* 2003). Strain localization is regarded as the bifurcation phenomenon and granular materials undergoing nonhomogeneous deformation. Furthermore, it is related with the onset of sample failure. The marked post-peak strain softening behavior of samples with grain diameter 0.075-0.25 mm was due to the rapid development of a shear band accompanied by a strain softening behavior. The localization of deformation was closely related to the sand stability. At a confining pressure of 400 kPa, the decreasing tendency in shear strength of the calcareous soil as its grain diameter range varied from 0.075-0.25 mm to 2-5 mm was observed, as shown in Fig. 5(a).

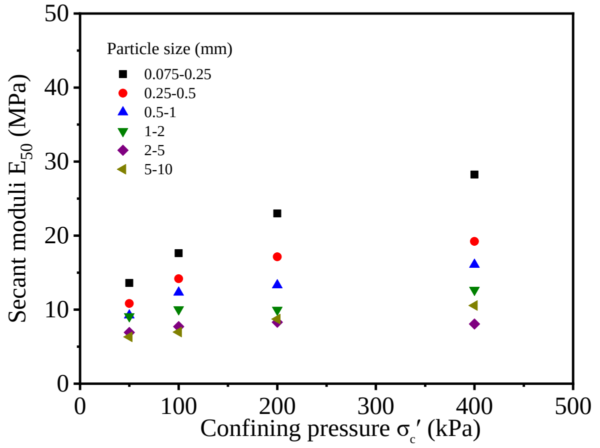

Fig. 6 Secant modulus and confining pressure of calcareous sand with different grain diameters

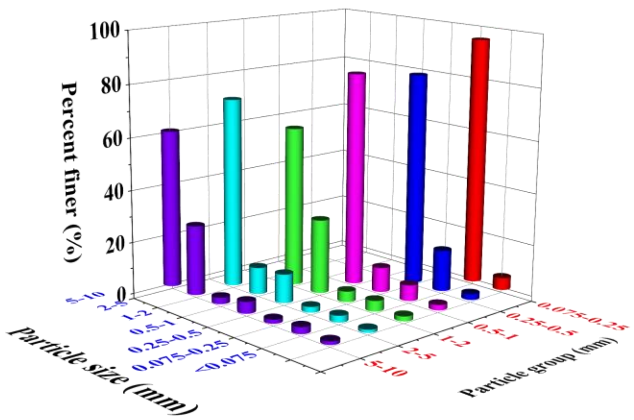

Fig. 7 Distribution of fine particle content in calcareous soil with different sizes after testing

Fig. 6 shows the secant moduli E_{50} of calcareous soil with different grain diameters at different confining pressures. Secant moduli E_{50} is an important parameter to quantify the stiffness properties of soil, which has been adopted in the Dunchan and Chang (1970) model. q_{50} is the half of the peak value from the deviatoric stress-axial strain curve, and ε_a is the required axial strain at q_{50}. The secant moduli $E_{50}=q_{50}/\varepsilon_a$ increases with the confining pressure for samples with a specific grain diameter owing to the higher densification at a larger consolidation pressure. An increase in the diameter reduced the secant moduli E_{50} of the calcareous soil sample.

Fig. 7 expresses the percent finer of particle size with different groups of grain size after shearing at a confining pressure of 400 kPa. Overall, the maximum content of smaller particles increased by 39.37% as a result of particle breakage. As shown in Fig. 7 and Table 3, the 2-5 mm particles increased by 26.82% after a triaxial shear test was performed on the specimen of the 5-10 mm particle group. Additionally, some smaller fine particles were generated simultaneously. As the calcareous soil particles were irregular (Fig. 8), the particles moved or roll over one another during shearing. In the triaxial shear or simple shear test, particle breakage suppressed the dilation behavior

Fig. 8 Calcareous sand grains with different shapes (a) flaky and (b) long columnar

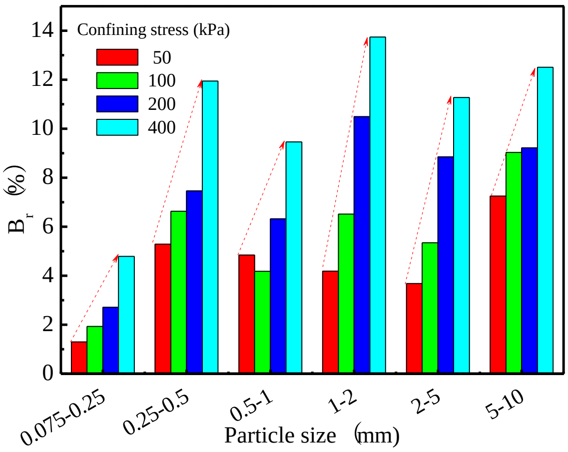

Fig. 9 Relationship between relative breakage B_r and particle size in CD triaxial test

under a given confining pressure. Owing to fewer inter-particle contact numbers in coarse particles than that in smaller particles, the inter-particle contacts of the coarse particles experienced a larger stress under the same level of outer stress. Once the contact stress on the grain was greater than the particle resistance strength, negligible particle breakage occurred. The particles probably moved into the voids by rolling or sliding. Therefore, the larger particles were more likely to be broken into smaller ones. Using a scanning electron microscope, McDowell *et al.* (1996) and McDowell *et al.* (2001) observed that grain fracture and inter-particle grinding were the main forms of particle

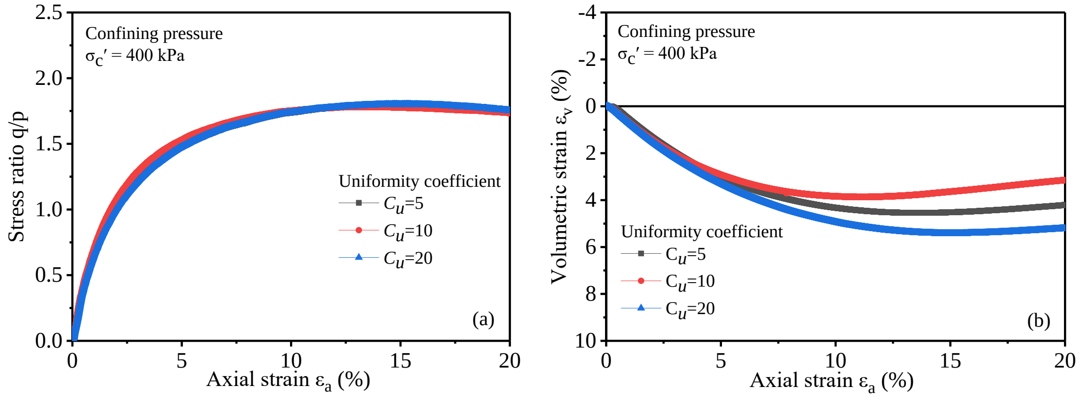

Fig. 10 Stress-strain curves of calcareous soil with different uniformity coefficients C_u in CD triaxial test (D_r=85%, 400 kPa)

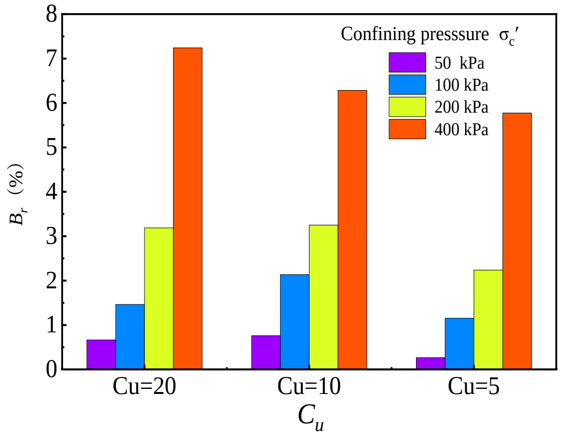

Fig. 11 Relationship between relative breakage B_r and uniform coefficient

Table 4 Percentage of each particle group after testing

Particle size D (mm)	Uniformity coefficient C_u		
	20	10	5
5-10	-2.01%	-1.78%	-1.82%
2-5	-3.83%	0.55%	-0.25%
1-2	-3.80%	-2.39%	-4.20%
0.5-1	5.98%	-4.37%	0.59%
0.25-0.5	-0.59%	2.92%	1.24%
0.075-0.25	4.50%	3.79%	3.30%
<0.075	-0.24%	1.29%	1.13%

Negative and positive numbers denote a decrease and increase in percentage, respectively

breakage caused by shearing, and only a small fraction of the particles were completely broken.

Furthermore, the crushing of calcareous grain size alerted the particle shape. The particle shape reversely affected the physical and mechanical properties of soil (Cho *et al.* (2006), Yang and Luo (2015), Xiao *et al.* (2019)). Linero *et al.* (2019) conducted a series of numerical analysis to investigate the effect of grading curves on the steady state shear strength and discovered that such effect was marginal. By contrast, the significant effects of grain size distribution considering both of grading and particle shape were numerically validated.

From the grain size distribution curves of calcareous soil before and after shearing, it was discovered that calcareous soils were crushed at a low confining pressure of 50 kPa (Figs. 3 and 9). The results indicated that the amount of theparticle breakage increased with the confining pressure (Figs. 3 and 9). An increase in the confining pressure increased the contact stress of the particles. Particle breakage occurred when the contact force was greater than the particle strength. Therefore, the particle breakage caused the soil to exhibit a less uniformly graded distribution and smaller particles, which resulted in more inter-particle contacts (Bishop (1966)) and reduced the particle contact forces. As the particle size decreased, the co-ordination number (number of contacts with neighbouring particle) increased and particle breakage weakened gradually.

Fig. 9 shows the relative breakage of calcareous soil with different particle sizes at different confining pressures in the CD triaxial test. The particle breakage amount of calcareous soil of particle group 0.075-0.25 mm was much smaller than that of larger particle groups. The particle breakage amount of calcareous soil increased when the grain size range varied from 0.075-0.25 mm to 1-2 mm. Zhang (2004) revealed that the particle strength of calcareous soil decreased with increasing particle size. Furthermore, it was demonstrated that the relative breakage increased significantly with an increase in the confining stress, as shown in Fig. 9 by the arrows. It is widely accepted that the larger the particle size, the more likely are the particles to be damaged under the same level of outer stress. The measured results indicated that the amount of particle breakage fluctuated as the grain size range increased from 1-2 mm to 5-10 mm. Therefore, the relationship between particle breakage and particle size is still controversial. The controversy on the effect of the grain diameter was recognized and further analyzed by Ovalle and Dano (2020). Ovalle and Dano (2020) examined the effects of particle size-strength correlation and particle size-shape correlation on the mechanical behavior of rockfill materials. The effect of grain diameter should be jointly considered with the effects of particle strength or particle shape. The variation in the relative breakage of granular

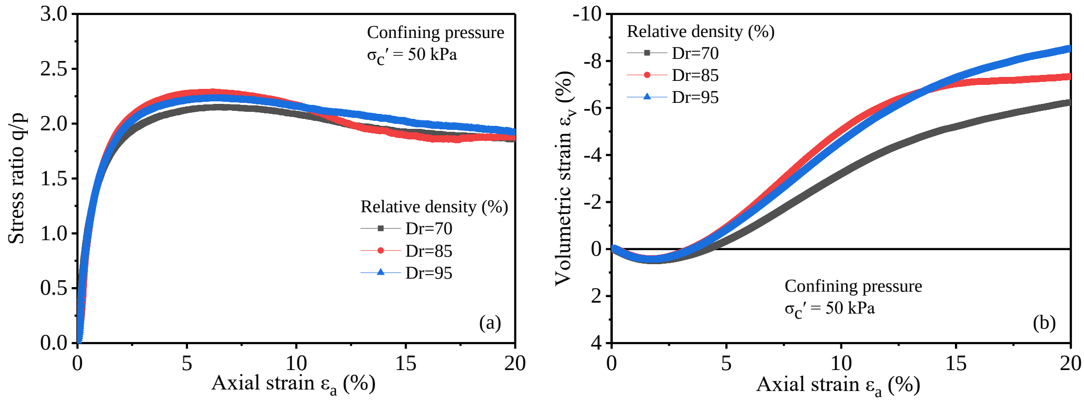

Fig. 12 Stress-strain curves of calcareous soil at different relative densities and a confining pressure of 50 kPa in CD test (uniformity coefficient C_u =20)

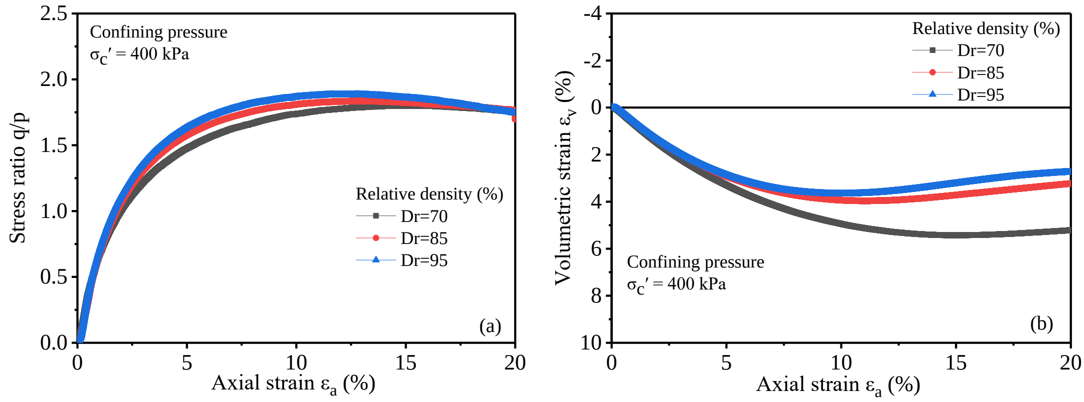

Fig. 13 Stress-strain curves of calcareous soil at different relative densities and a confining pressure of 400 kPa in CD test (uniformity coefficient C_u =20)

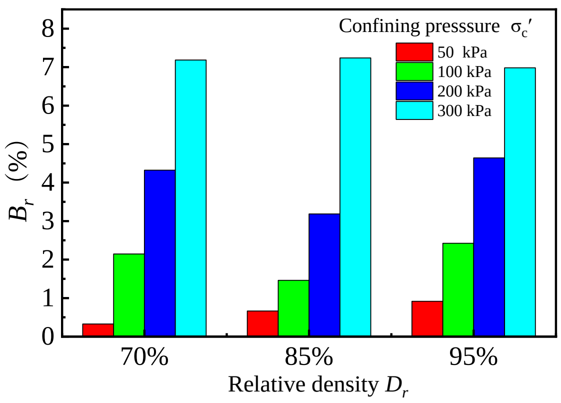

Fig. 14 Relationship between relative breakage B_r and relative density D_r in CD triaxial test

materials with the grain diameter is highly dependent on the predominant factor between the particle shape and particle strength.

3.3 Effect of uniform coefficient C_u

To study the effect of particle size distribution on the shear response and particle breakage amount, three samples with the same coefficient of curvature C_c=2 but different uniform coefficients C_u of 20, 10, and 5 were tested. Fig. 10 shows the corresponding stress-strain curves of calcareous soil with three levels of uniform coefficients C_u. Based on the measured results, the effect of uniform coefficient C_u on the shear and deformation characteristics is unclear. The stress ratio at the critical state is less dependent on the grading condition. Similar results have been reported in the previous studies (Cantor *et al.* 2018, Linero *et al.* 2019). Fig.11 shows the relationship between the B_r of calcareous soil with different uniform coefficients C_u in the CD test. The B_r of sample with C_u =20 differed slightly from that of C_u =10, and the relative breakage of the sample with C_u =10 at a confining pressure of 400 kPa was slightly lower than that of C_u=20. The relative breakage of the soil sample with C_u=5 was slightly lower than those of C_u=10 and C_u=20. Fig. 11 indicates that the relative breakage of calcareous sand with full gradation was much smaller than that of a single particle group. In the soil with a full distribution of particle size, coarse particles served as skeleton, and fine particles filled the voids among coarse grains (Voivret *et al.* 2007, Shire *et al.* 2016, Cantor *et al.* 2018). The increase in fine particles filled the large voids among the coarse particles, thereby increasing the compactness. When the coarse particles were enwrapped by fine ones, the contact force decreased. Therefore, the particle breakage of soil with full gradation was smaller than that of a single particle group.

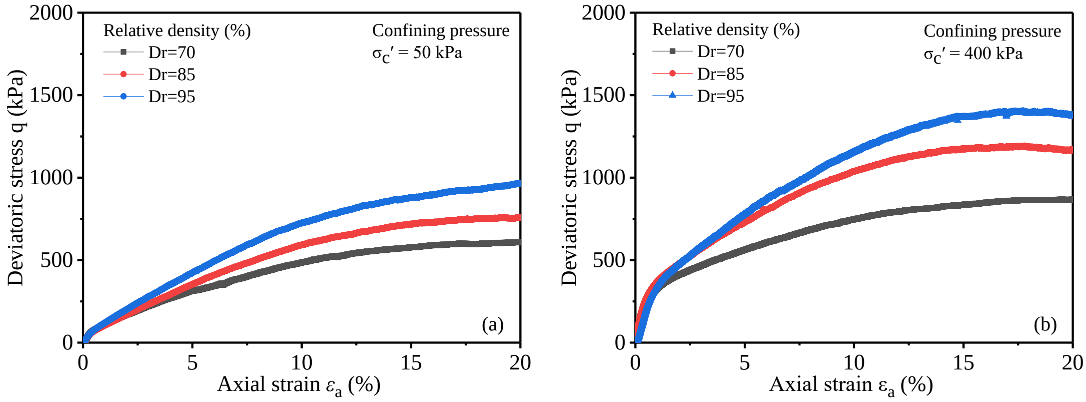

Fig. 15 Stress-strain curves of calcareous soil at different relative densities in CU triaxial test (uniformity coefficient C_u =20)

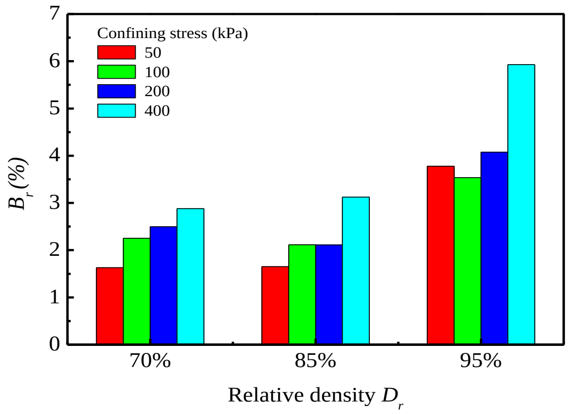

Fig. 16 Relationship between relative breakage B_r and relative density D_r in CU triaxial test

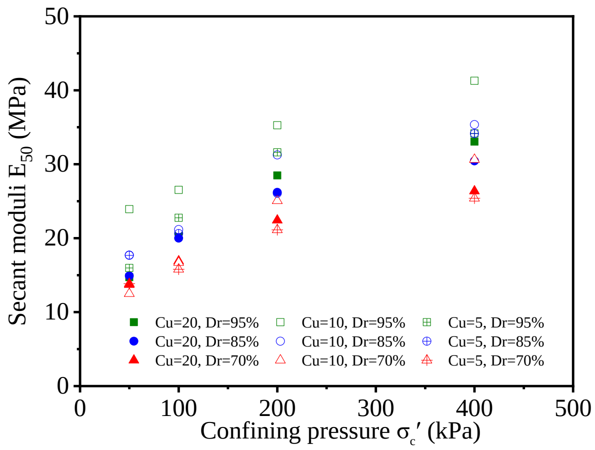

Fig. 17 Secant modulus and confining pressure for calcareous sand with different C_u

Table 4 shows the variations in particle size of soil samples with three gradation curves after the tests (using 400 kPa as an example). As shown in the table, most of the particles larger than 1.0 mm have a negative value, and most of the particles smaller than 1.0 mm have a positive value. Previous analysis has shown that the breakage of calcareous soil was dominated by local fragments, i.e., a larger soil particle broken into slightly smaller and even tiny particles. However, Table 4 shows that all coarse particles were broken into fine particles. Large calcareous soil particles were continuously broken into smaller particles. This phenomenon can be explained through the results reported by Marsal *et al.* (1967). It is typically considered that the positions of soil particles are adjusted and rearranged, while large particles are broken into small pieces. Therefore, the sample compactness increases, and the particles are re-stressed and broken.

3.4 Effect of density

Figs. 12 and 13 show the drained stress-strain relationship of calcareous soil with three levels of relative densities at different confining pressures. An increase in compactness increased the shear strength and prompted dilation tendency at two levels of the confining pressures. Fig. 15 shows the undrained stress-strain relationship of calcareous soil at confining pressures of 50 and 400 kPa. The density-dependence shear strength for calcareous soils is evident. Figs. 14 and 16 show the results of Br of calcareous soil with different relative densities in the CD and CU tests, respectively. It was discovered that the degree of particle breakage increased with the level of relative density. The particle breakage was sensitive to the confining pressure. In the CD test, the Br increased significantly with the confining stress, as shown in Fig. 14. Under the confining pressure of 50 kPa, the relative breakage in the CU test (Fig. 16) was 2-3.5 times higher than that in the CD test (Fig. 14). However, under high confining pressures, the relative breakage in the CU test was smaller than that in the CD test.

The effect of drainage condition on the particle breakage of calcareous soil was significantly affected by the effective mean stress. Although the initial confining pressures were identical for the CD and CU tests, the effective confining pressure in the CD test was always equal to the initial confining pressure. However, the effective mean stress changed according to the variation in excess pore pressure in the CU test. Fig. 16 shows that the total breakage amount of calcareous soil with a relative density of 95% is significantly higher than those of samples with relative densities of 70% and 85% under different confining pressures.

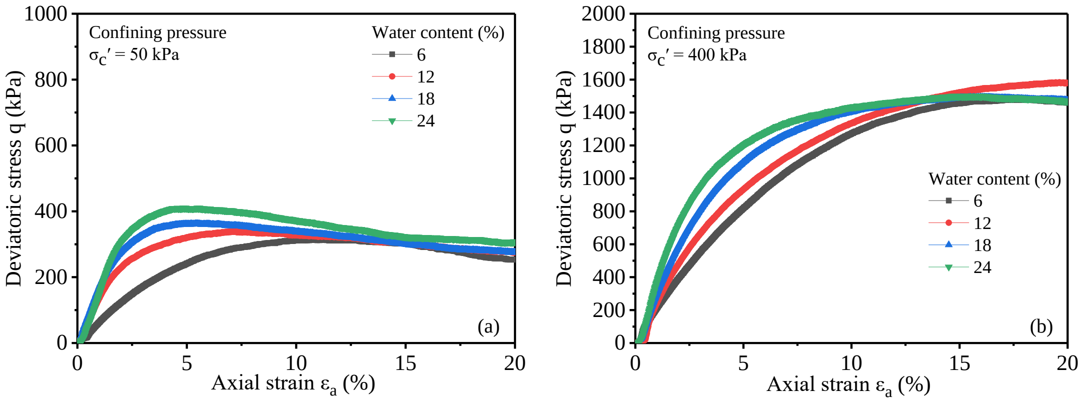

Fig. 18 Stress-strain curves of calcareous soil with different water contents in CU triaxial test (uniformity coefficient C_u =20, relative density D_r =85%)

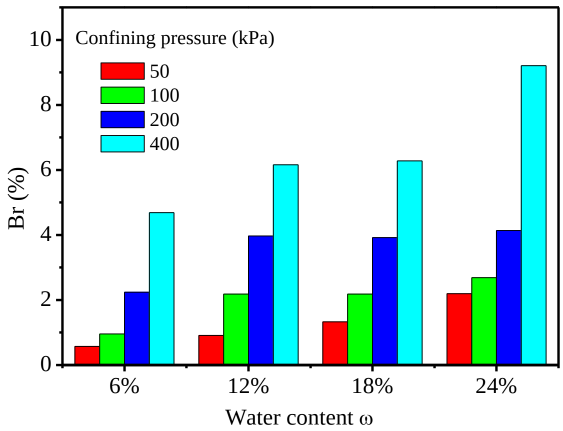

Fig. 19 Secant modulus and confining pressure for calcareous sand with different C_u

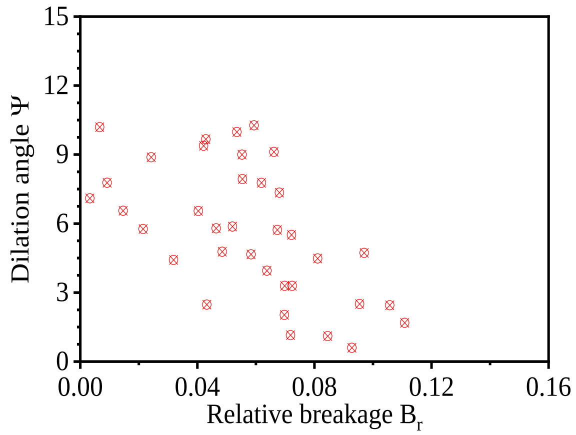

Fig. 21 Dilation angle and relative breakage for calcareous sand under various test conditions

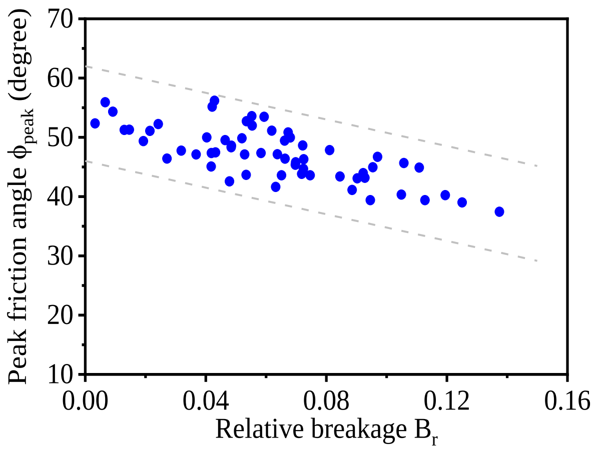

Fig. 20 Peak friction angle and relative breakage for calcareous soil under different test conditions

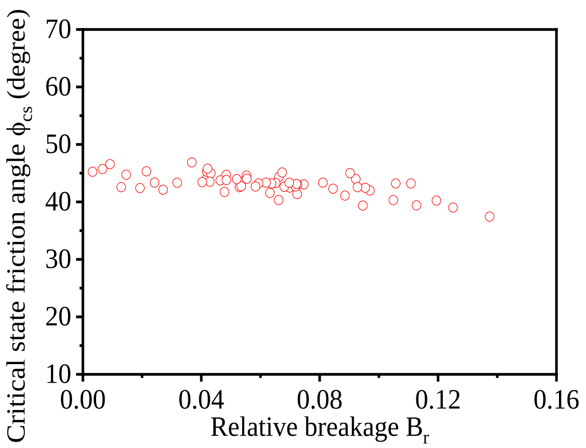

Fig. 22 Critical state friction angle and relative breakage for calcareous soil under various test conditions

The stiffness of crushable sand is susceptible to the pressure and compaction levels. Fig. 17 shows that the scant moduli E_{50} is plotted against the confining pressure for the calcareous soil at different confining pressures and densities. As shown, the secant moduli E_{50} increased linearly with the confining pressure. The results show that the secant moduli E_{50} of samples with uniform coefficient C_u=10 is higher than those of the other two samples. This may be because the secant moduli E_{50} is also affected by other parameters, such as the median diameter.

3.5 Effect of water content

The presence and content of water within calcareous sand pores and void space between grains alter the mechanical and physical properties. Fig. 18 presents the shear response of calcareous soil containing different water contents at two confining pressures. Unsaturated calcareous soil samples containing different water contents for shearing were formed. An increase in water content significantly enhances the shear strength of calcareous soil samples. Fig. 19 shows the plot of B_r against the water contents for calcareous soil samples. Under different confining pressures, B_r increased with the water content. It was discovered that water served as a lubricant in soil grains. Calcareous soils with high water content were more likely to roll and rearrange. During rolling and shearing, sand grains are easily ruptured and broken. Accordingly, an increase in water content will results in a larger amount of particle breakage.

3.6 Effect of B_r on the friction angle and dilation angle

Particle breakage reduces the shear strength resistance and suppress the dilation behavior. The effect of particle breakage on the friction and dilation angle are examined in the following section. Fig. 20 shows the relationship between the peak friction angle and Br for calcareous soil under different test conditions. The test results demonstrated that the range of peak friction angle for calcareous soil was between 40° to 60°. It was clear that the peak friction angle decreased linearly with the relative breakage. Hence, the effect of particle crushing on the peak shear strength or friction angle should be fully considered in field construction. Furthermore, the dilation angle decreased with the increase in relative density, although the data were slightly scattered (Fig.21). Fig. 22 shows the critical state friction angle against Br for calcareous soil under different test conditions. The triaxial test results for samples containing different water contents were excluded because the volume change of the sample was not measured. The test results indicated the critical state friction angle was less susceptible to a B_r within 0.12 in this study.

4. Plastic work and particle crushing

The triaxial test results obtained in this study demonstrated that both the stress and strain magnitudes significantly affected the amount of particle crushing. The energy input was necessary for grain cracks. The plastic work per unit volume W_p was discovered to be a suitable parameter to describe the evolution of B_r. Miura and O-Hara (1979) reported that surface increment was closely correlated with plastic work. Daouadji *et al.* (2001) and Yin *et al.* (2017) integrated the effect of particle breakage with the elastoplastic theory by altering the location of CS lines according to the evolution of a GSD computed using a function of plastic work W_p. Wu *et al.* (2020a) reported that the correlation between B_r and plastic work was dependent on the loading mode for silica sand at high pressures.

Fig. 23 shows the correlation between B_r and plastic work per unit volume of sample W_p. These two parameters exhibited a unique correlation, which was independent of the grain size, uniform coefficient, density, and drainage condition. The specific method to determine plastic work

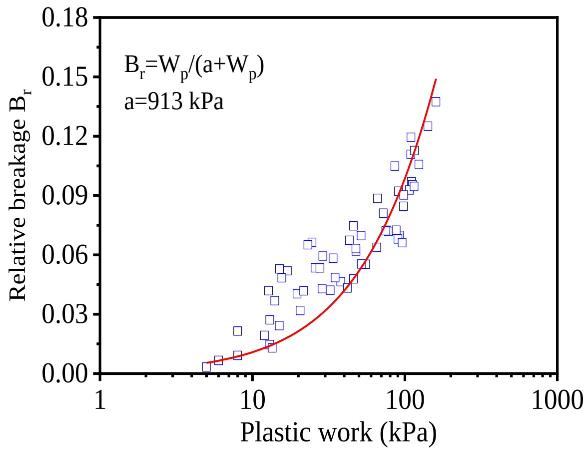

Fig. 23 Relative breakage and plastic work per unit volume for calcareous sand under different test conditions

per unit volume is available in (Miura and O-Hara (1979), Hyodo *et al.* (2017b)). The equation $B_r = W_p / (a + W_p)$ is expected to be adopted in the constitutive model to capture the evolution of particle breakage during shearing.

5. Conclusions

A series of triaxial shear tests was conducted to examine the effects of several parameters on the particle breakage characteristics of calcareous soil. These parameters, included confining pressure, relative density, drainage condition, particle size, water content, and grain size distribution. The tested samples were obtained from a coral reef in the South China Sea. The conclusions of this study are as follows:

(1) Increasing the confining pressure resulted in an increase in the particle breakage of calcareous soils. This phenomenon was observed in CD and CU triaxial shear tests. By contrast, the peak shear strength decreased with an increase in B_r. The variation in critical state friction angle was less susceptible to B_r at the stress level applied in this study.

(2) Water content significantly affected the particle breakage of calcareous soil. Under different confining pressures, the relative breakage increased with water content.

(3) The breakage of calcareous soil with full gradation was much smaller than that of a single particle group. The particle breakage of calcareous soil with a better grading distribution curve was much lower than that of a poorer grading distribution.

(4) As larger particles contained more defects and pores, the larger the particle size, the more likely were the particles to be damaged under the same outer stress. Moreover, the relative breakage of granular materials associated with the grain diameter is highly dependent on the predominant factor between the particle shape and particle strength. It appears that the relationship between particle breakage and particle size is still controversial and should be further studied.

(5) The degree of particle breakage increased with level of relative density owing to the higher stress applied on the denser samples.

(6) The relative breakage was well correlated with the plastic work per unit volume for calcareous soil regardless of density, uniform coefficient, grain diameter, and drainage condition.

Acknowledgments

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Science (No.XDA13010203), and the National Natural Science Foundation of China (Nos.41572297, 41877267, 41372318 & 51908153), Guangzhou City Technology and Science Program (201904010278).

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