Crushability of Granular Materials at High Stress Levels

Concassage des matériaux granulaires à niveau de contrainte élevée

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ABSTRACT
The crushability of artificial and natural granular materials has been analyzed using one-dimensional strain-controlled compression tests and standard oedometer tests at high stress levels to study the effect on the breakage of a number of parameters such as: grain mineralogy, grain size, uniformity coefficient, strain rate and loading time. Measuring the breakage factor at different stages of compression, it was demonstrated that the crushing started before reaching the point of maximum curvature (yield point) in the compressibility curve. Beyond yielding the crushing increased abruptly. Among the natural materials analyzed, the lowest yield stress value occurs in the carbonate sand, and the highest in the silica sand. We found that the breakage increases with increasing size of the grains. Coarse uniform samples showed higher breakage than uniform fine samples and well-graded samples. The breakage increased with decreasing strain rate or increasing load application time. For natural soils it is difficult to study separately the influence of isolated parameters on the breakage. The study of homogeneous artificial materials facilitated this analysis.

RÉSUMÉ
Le concassage des matériaux granulaires artificielles et naturelles a été analysé d'abord à l'aide d'un type d'essai oedométrique unidimensionnel standard, suivi par le même type d'essai mais à déformation contrôlée. On a exécuté ces essais à des niveaux de contrainte élevés afin d'étudier efficacement les effets sur le concassage d'un certain nombre de paramètres: la minéralogie, le granulométrie, le coefficient d'uniformité, le taux de déformation et le temps de chargement. Avec Mesurant le degré de concassage à différentes étapes de la compression, il a été démontré que le concassage commence en effet déjà avant le point de courbure maximum (point de fluage) dans la courbe de compression. Au-delà de la contrainte de fluage, le concassage augmente brusquement. Parmi les matériaux analysés, le niveau inférieure de la contrainte de concassage on retrouve dans le sable de carbonate, hors que la valeur la plus élevée s'est reproduit dans le sable de silice. Nous avons confirmé que le concassage augmente avec la taille des grains. Le concassage s'est augmenté aussi avec la diminution de la vitesse de déformation ou avec l'avancement du temps de chargement. Pour les sols naturels, il est difficile d'étudier séparément l'influence de ces paramètres de façon isolée sur le concassage. L'étude des matériaux artificiels homogènes devrait faciliter cette analyse.

Keywords: granular material, crushability, high stress levels, compression

1 INTRODUCTION

It is well known that particle fracture plays a major role in the behavior of crushable soils. In many geotechnical engineering applications, such as penetrometer testing, pile driving and end bearing resistance, high earth or rockfill dams, granular soils may experience stresses high enough to break particles of even the strongest soil minerals (Bolton et al. 2008). Foundation problems associated with calcareous soils, particularly as experienced by the offshore constructions, have led to significant research focused on understanding the behavior of calcareous soils and how they differ from soils of siliceous origin.

Geotechnical engineering problems are usually analyzed using soil parameters which have been measured in situ or in the laboratory, and then applied in calculations as though they were always constant. However, engineering properties of granular materials, such as stress strain and strength behavior, volume change and pore-pressure developments, and variation in permeability depend on the integrity of the particles and on the amount of particle crushing (Lade et al. 1996). Therefore, it is important to identify and quantify the crushability of granular materials used for geotechnical applications.

To attempt to quantify the amount of particle breakage, different particle breakage factors have been proposed in literature. In this paper we will refer to the total breakage factor, Bt, defined by Hardin (1985) as the area between the original grain size distribution and the grain size distribution after crushing.

To identify the initiation of marked particle breakage of an aggregate, a suitable definition of yield would appear to be the point of maximum curvature on a plot of void ratio against the logarithm of stress (McDowell & Humphreys 2002).

This paper examines the yielding of granular materials subjected to one-dimensional compression, measuring the breakage factor at different stages. Strain controlled one-dimensional tests and oedometer tests have been performed in order to study the effect on the breakage of a number of parameters such as: grain mineralogy, grain size, uniformity coefficient, strain rate and loading time. Highly crushable and homogeneous artificial granular materials have been compressed to simulate the crushability of natural sands at high stress levels.

2 MATERIALS

Experiments were performed on artificial granular materials such as pasta of different sizes and on various natural materials including carbonate sand, glauconite sand and silica sand. The physical parameters of the materials analyzed have been determined (as shown in Table 1) following ASTM standard

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methods. Figure 1 shows the grain size distribution of the materials analyzed.

The pasta was chosen because it is highly crushable, homogeneous and available in different sizes. The natural sands were chosen in order to represent a wide range of crushability, mineralogy and grain size distributions. Due to heterogeneity of the carbonate sand, every specimen was reconstituted to reproduce the same starting grain size distribution.

3 METHODS

Specimens were dried at 105 °C, loosely poured with a funnel in oedometer confining rings and then vibrated to achieve an initial relative density of 50%. No water was added to saturate the samples.

To reach the elevated stress levels, testing was performed in a strain controlled manner. Strain controlled one-dimensional tests have been performed at high stress levels in order to determine the crushing onset (yielding) in the compression curve that defines the initiation of marked particle crushing. The total breakage factor (Bt) of the samples was measured at the end of strain-controlled tests by comparing the grain size distribution before and after testing. We studied the effect on Bt of a number of parameters such as: grain mineralogy, grain size, uniformity coefficient, strain rate and loading time.

A first series of strain controlled tests were performed to study the impact of the soil mineralogy on the crushability of the natural sands analyzed. The tests were carried out on the carbonate sand, the glauconite specimen and the silica sand at a rate of strain of 1.2%/min with a maximum vertical stress of 30 MPa.

A second series of tests were performed to examine the effect of the grain size on the breakage of the artificial pasta of different sizes. The tests were carried out on single grains and on agglomerates at a rate of strain of 1.2%/min with a maximum vertical stress of 1 MPa.

The tensile strength of the single particles was measured by compression between two flat platens until failure occurred. The tensile stress is calculated dividing the applied Force by the square of the distance between the platens (Jaeger 1967).

Table 1. Physical parameters of the materials analyzed

Material	Gs	ρ_{dmin} [g/cm^3]	ρ_{dmax} [g/cm^3]	$CaCO_3$ [%]	Uniformity coefficient
Small pasta	1.46	0.52	0.56	-	1
Medium pasta	1.32	0.36	0.38	-	1
Large pasta	1.32	0.34	0.35	-	1
Carbonate sand	2.73	1.43	1.64	85.6	2.63
Glauconite sand	2.60	1.30	1.45	0.9	1.56
Silica sand (Mol)	2.62	1.40	1.60	1.3	1.60

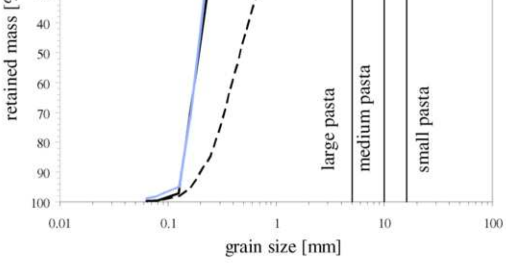

Figure 1. Grain size distribution of the materials analyzed

The total breakage factor was measured at different stages during strain-controlled tests to assess the initiation of marked particle crushing on the small pasta and on the carbonate sand.

For the third series of tests, the well graded carbonate sands were passed through a series of ASTM sieves. From the resulting fraction, uniform coarse and well-graded simulated carbonate sand samples were produced to study the impact of the uniformity coefficient on the breakage. For natural materials it is difficult to study the influence of isolated parameters such as the uniformity coefficient. For this reason, mixtures of different percentages of pasta were also analyzed to study in a controlled manner the impact of the uniformity coefficient on the breakage.

A forth series of tests was performed to study the influence of the strain rate on the crushability. The tests were executed on the pasta, the carbonate sand and the glauconite at strain rates of 0.4 %/min, 0.8 %/min 1.2 %/min, 2 %/min and 4 %/min..

Finally, standard oedometer tests have also been performed to study the time effect of a constant load by comparing the breakage of a long term oedometer test on the carbonate sand and a strain controlled test at various vertical stresses.

4 RESULTS AND DISCUSSION

4.1 *Effect of grain mineralogy on the breakage*

The natural materials studied have different characteristics: the Mol sand is fine, rounded and quartz-rich, while the carbonate sand is coarser, angular and contains 85.6% $CaCO_3$. Figure 2 shows that among the natural materials, the highest yield stress occurs in the silica sand and the lowest in the carbonate sand. Therefore, the carbonate sand is the most crushable, because a low yield stress is indicative of high compressibility due to particle crushing, as confirmed by the breakage factors measured at the end of the strain controlled test also shown in Figure 2. This behavior is mainly due to the grain mineralogy of the particles. The Mohs hardness of quartz is indeed 7, of glauconite is 2 and of calcite is 3.

Among the parameters that influence the breakage, not only the mineralogy, but also the shape of the particles play an important role. In fact, carbonate sands are more crushable than glauconite because they have angular particles with eccentric loading producing shear and tension stresses higher than on the rounded particles of glauconite sand.

Besides the mentioned parameters, the size of the grain and the uniformity coefficient also play a significant role. These parameters are studied in more detail with the help of artificial pasta and reconstituted carbonate sand samples as shown further on in sections 4.2 and 4.3.

4.2 *Effect of grain size*

Figure 3 shows that the compression curves of the pasta at relatively low stress levels (up to 1 MPa) resemble those of natural sands at high stress levels (30 MPa, Figure 2).

Moreover, Figure 3 proves that the breakage of an assembly of uniform particles increases with increasing size of the grains. A possible reason of this behavior is that the strength of the single particle decreases with increasing grain size (as shown in Figure 4). On the other hand, the breakage of an array of particles depends not only on the size of the particle, but also on the coordination number, that is the number of contacts with neighboring particles. Agglomerate of larger particles show less interparticle contacts per unit cross-sectional area compared to fine particles. The average interparticle stress level varies inversely with the number of contacts and is higher for agglomerates of larger particles.

As mentioned above, the total breakage factor (Bt) was measured at different stages during a strain-controlled test on the small pasta and on the carbonate sand. The Bt values obtained showed that crushing of the grains started before the yield stress and increased dramatically beyond this point (as shown in Figure 5). Figure 5 also illustrates that the uniform coarse pasta shows an abrupt increase of Bt respect to the well graded natural sand. A possible explanation of this behavior is given in section 4.3.

4.3 *Effect of the uniformity coefficient on the breakage*

Besides the artificial and natural materials mentioned above, mixtures of the pasta particles in various percentages and reconstituted uniform and well-graded carbonate sand samples were produced to study the impact of the uniformity coefficient on the breakage.

In this regard Figure 6 shows the grain size distribution of three uniform simulated sands and a reconstituted well-graded sand. The breakage factor of the well-graded sand was lower than that of the coarse uniformly-graded specimens and fell between those of the fine and the medium uniformly-graded samples as shown in Figure 7.

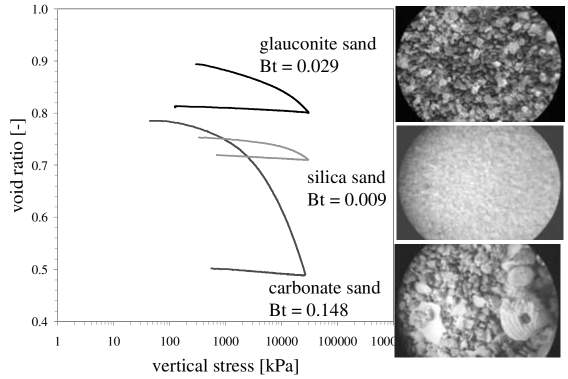

Figure 2. Impact of soil mineralogy on the breakage

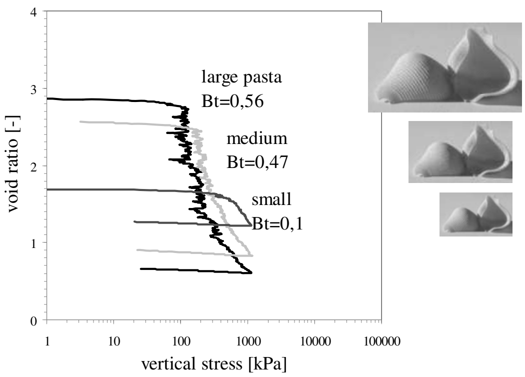

Figure 3. Impact of the grain size on the breakage

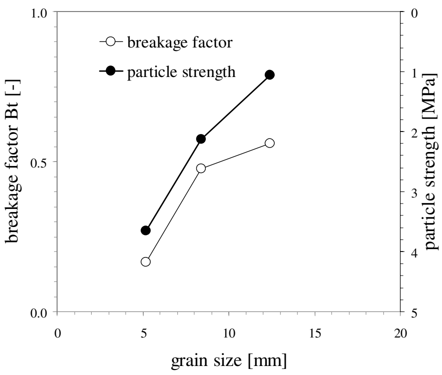

Figure 4. Particle tensile strength and Bt for various grain sizes

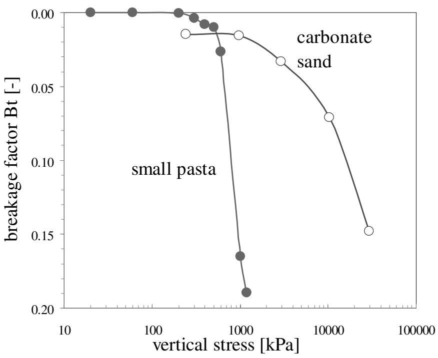

Figure 5. Breakage factor at different stages

The reason of this behavior is that both well-graded and fine uniform samples show more interparticle contacts per unit cross-sectional area than the coarser uniform sand with lower average stresses and consequently less extensive crushing.

The presence of fine particles helps to fill the spaces between the coarser particles leading to more contacts between the grains and hence increasing their resistance to crushing when stressed. Moreover, the three uniform sands can be different in mineralogy, shape and composition causing different yielding stresses and loss of porosity. As we have seen in section 4.2, with an increase in grain size the crushability of the pasta increases. Also for the uniform natural sands the Bt increases with the size of the grain (as shown in Figure 7).

This behavior is due not only to the particle strength and the interparticle stresses considerations highlighted in section 4.2, but also because larger particles of natural materials have more likely defects such as cracks, impurities, imperfections. Smaller natural particles are mostly originated from larger particles as a result of weathering and breaking through these defects. As this process continues, fewer defects and consequently fewer failures can be expected in the resulting fine particles.

It is clear here that for natural materials it is difficult to study separately the influence on the breakage of isolated parameters such as the uniformity coefficient. In order to separate the uniformity coefficient from the other parameters, mixtures of homogeneous pasta have also been studied. In this regard, Figure 8 shows that the breakage of mixtures of well graded pasta are in between those of the uniform samples. This result resembles the behavior of mixtures of carbonate sands

Moreover, the uniform coarser soil showed a sharper yield compared to the yield region of the well-graded sand. A possible explanation for this behavior is that the uniformly-graded coarse particles break around a same yield stress because there is a uniform distribution of particle strength. This phenomenon is attenuated by the presence of various grain sizes in the sample. These considerations explain the abrupt increase of the breakage of the uniform pasta when it reaches a yielding state as mention in section 4.2 and shown in Figure 5.

4.4 *Effect of strain rate and loading time on the breakage*

Figure 9 proves that Bt increases with decreasing strain rate for the pasta and for the glauconite, while the carbonate sand shows similar breakage values for the two strain rates analyzed. De Souza (1958) also noted more extensive particle crushing in tests during which stress was applied more slowly.

To clarify these results, standard oedometer tests have also been performed to study the time effect of a constant load by comparing the breakage of a long term oedometer test (lasted 720 hours per loading step) with a strain controlled test (lasted 1 hour) at different vertical stresses. Figure 10 shows that the breakage of the carbonate sand increases with loading time. The increase of the breakage of angular particles with time can be caused by crack growth in time under a sustained load as it occurs for ceramics.

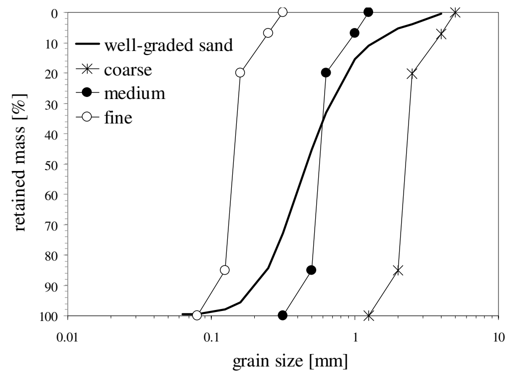

Figure 6. Grain size distribution of reconstituted uniform and well-graded carbonate sand samples

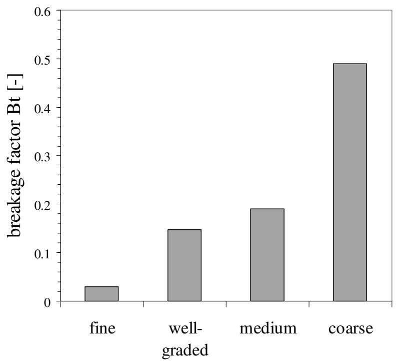

Figure 7. Breakage factor of fine, medium and coarse uniformly-graded and well-graded carbonate sands

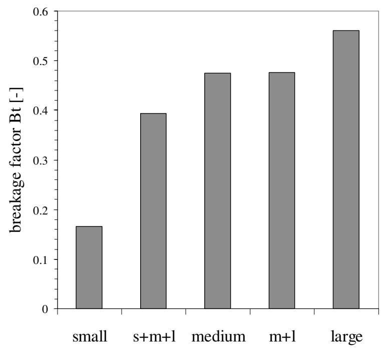

Figure 8. Bt for uniformly-graded and well-graded pasta samples (s+m+l=33%small+33%medium+33%large; m+l=50%medium+50%large)

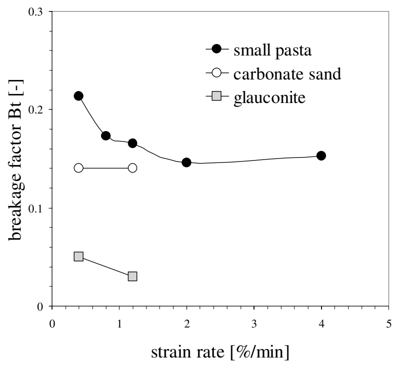

Figure 9. Decrease of the breakage with increasing strain rate

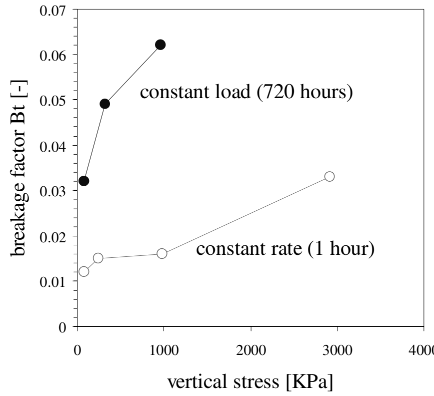

Figure 10. Increase of the breakage of the carbonate sand with loading time

5 CONCLUSIONS

Test results demonstrate that the crushing started before the point of maximum curvature (yield point) in the void ratio versus logarithm of vertical effective stress curve. The yield point defines the initiation of marked particle crushing.

The stress at the yield point varies depending on material characteristics. Among the natural sands, the lowest yield stress value occurs in the carbonate sand and the highest in the silica sand. We found that the breakage increases with increasing size of the grains. Coarse uniform samples showed higher breakage than uniform fine samples and well-graded samples. The breakage increased with decreasing strain rate or increasing load application time.

For natural soils it is difficult to study separately the influence on the breakage of the isolated parameters listed above. The study of homogeneous artificial materials facilitated this analysis.

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