Properties of compression and single particle crushing for crushable soil

Les propriétés de compression et d'écrasement des particules pour un sol friable

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ABSTRACT: A series of mainly one-dimensional compression tests has been carried out to understand the compression properties of sands by examining particle crushing strengths and the distribution of the microscopic stresses for individual particles in the soil matrix. In a uniform material such as glass beads a large proportion of the particles do not carry any load or only a small load. As the shape of the grain becomes more angular and the surface roughness increases then the load distribution through the matrix becomes more uniform.

RÉSUMÉ: On a fait des essais a compression unidimensionnelle pour étudier les propriétés de la compression examinant la résistance du concassage et la distribution des contraintes microscopiques des particules individuelles dans le matrix du sol. Dans un matériau uniforme comme des sphères de verre une grande proportion des particules ne porte pas de la force ou porte seulement une force petite. Au fur et à mesure que la forme des particules devient plus anguleuse, la distribution des forces dans le matrix devient plus uniforme.

1 INTRODUCTION

Many soils consist of crushable materials such as volcanic ashes like Shirasu and Scoria, Masado a decomposed granite, and numerous calcareous sediments. It has been pointed out that crushable soils undergo breakage of particles under relatively low confining pressures (JGS, 1999) because of their particle characteristics such as irregular grain shape, fragility of the grain and its surface. It is important to know the mechanism of the breakage in detail in order to understand the mechanical behaviour of natural soils. Previous researchers in this field have been concerned to know the amount of particle breakage e.g. Marsal, (1967) defined a breakage factor. Particle crushing occurs when the force acting on a grain exceeds the crushing strength even if the breakage of the grain is in a soil matrix (which might be termed collective crushing). It is therefore necessary to know the crushing strength of the particle itself and the applied stress for the individual grain in the granular assembly. However there have been few studies to understand this from a micro-mechanical viewpoint. A series of mainly one-dimensional compression tests has been carried out to understand the compression properties of sands by examining particle crushing strengths and the distribution of the microscopic stresses for individual particles in the soil matrix.

2 ONE-DIMENSIONAL COMPRESSION

2.1 *Materials*

A list of materials used in this paper is shown in Table 1, which describes the physical properties and the single particle crushing test results for median sized particles (Nakata, et al., 1999). σ_f is a characteristic particle tensile strength for major particle splitting and is defined as $\sigma_f = F_f / d_0^2$. where d_0 is the distance between the platens at the start of the particle crushing test and F_f the load at failure. The subscript numbers show the probability of survival for the single particle crushing tests. That is $(\sigma_f)_{50}$ means 50% of particles split at or below this stress. $(\sigma_f)_{37}$ and m_f are Weibull statistical parameters (Weibull,1951, McDowell, et al., 1996, Nakata, et al., 1999) and indicate the characteristic crushing strength and the variability of the strength respectively. Volcanic ashes and decomposed granites have a higher coefficient of uniformity and hence well-graded grain distribution due to their process of production and sedimentation. These materials have a bigger void space than quartz materials such as Toyoura sand because of the irregularity and non-uniformity of the grain shapes and the assemblage of larger and smaller particles. On the other hand calcareous sediments have relatively smaller coefficients of uniformity. These materials are known as having a bigger void space. The reason is that the materials consist of skeletal remains of marine creatures which have complex particle shapes and internal voids. The effects of the particle shape on the magnitude of the maximum and minimum void ratios and the difference between them has been discussed by Yoshimura and Ogawa (1993). Crushable soils are known to have larger void spaces as a common characteristic leading to larger compressibility of these materials.

Table 1. Lists of physical properties and single particle crushing test results for material used.

Sample	e_{max}	e_{min}	D_{50}	U_c	$(\sigma_f)_{50}$	$(\sigma_f)_{37}$	m_f
Chiibishi	1.574	0.983	0.613	2.401	23.79	31.02	1.230
Quiou	1.431	0.915	1.114	2.299	13.39	16.77	1.013
$Shirasu_{-2.0}$	1.494	0.775	0.175	11.750	60.73	112.9	-
$Shirasu_{0.075-2.0}$	1.551	1.027	0.422	3.384	22.73	41.12	1.184
$Masado_{-2.0}$	0.958	0.582	0.509	22.40	33.80	35.18	2.046
$Masado_{1.4-1.7}$	1.216	0.847	1.550	1.102	19.08	24.18	1.230
G.B.	0.699	0.600	0.925	1.085	336.1	365.8	5.900
A.G.	1.145	0.746	0.925	1.085	53.10	62.10	2.100
Toyoura	0.977	0.609	0.202	1.334	117.6	147.4	2.170
$Silica_{0.15-2.0}$	0.936	0.588	0.736	2.197	63.89	72.87	2.172
$Silica_{1.4-1.7}$	0.881	0.632	1.550	1.102	25.64	30.96	3.038
$Silica_{0.6-0.71}$	0.968	0.659	0.655	1.088	63.89	72.87	2.172
$Silica_{0.25-0.3}$	1.088	0.666	0.275	1.095	87.32	110.9	1.822
$Silica_{-2.0}$	-	-	0.203	9.906	121.8	152.0	-
Aio	0.971	0.699	1.138	1.335	32.73	38.85	1.927

2.2 *One-dimensional compression*

The e - log σ_v curves for the dense sands subjected to one-dimensional compression are shown in Figure 1. The radius of curvature during yielding for the crushable materials is larger. The radius for the well-graded materials is also larger than that for uniformly graded materials. This trend for the curvature was also obtained for one-dimensional compression tests on volcanic coarse-grained soil sand (Miura & Yagi, 1997). The yield section of the compression curve has been shown to be the region encompassing the initiation of particle crushing. Therefore the difference of curvatures between well and uniformly graded materials could be due to the difference in the evolution process of the particle crushing under increasing stress.

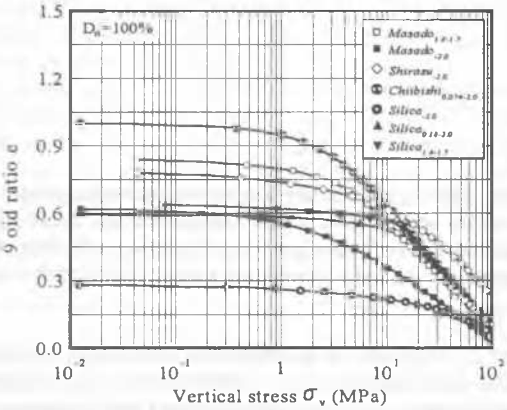

Figure 1. e - log σ_v curves for dense sands.

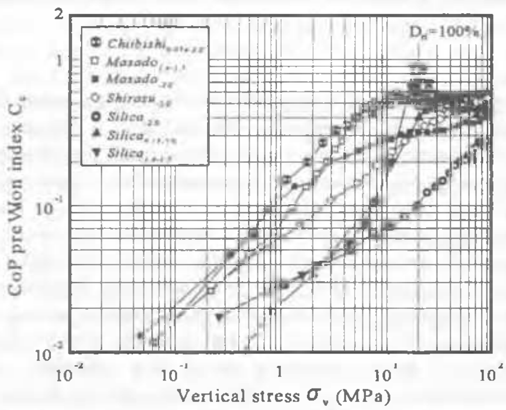

Figure 2. Variation of compression index as vertical stress increase.

The compressibility of the sand can be expressed by the variation of the compression index at each stress level (Yasufuku, et al., 1994). Figure 2 shows the variation of the compression index with increasing vertical stress using the same data as figure 1. The compression index is dependent on the stress level and increases with increasing stress. The rate of increase of the compression index with increasing stress seems to be strongly dependent upon the coefficient of uniformity. The compression index for crushable soils has a higher value up to 10MPa compared with that for silica sand. From the observations of coloured particles seeded in almost uniformly graded sand (Nakata et al., 2001) it has been found that major splitting of particles occurred mainly between the yield stress and the point at which the compression index C_c reached a maximum. It was observed that for this sand, after yielding, 50% of the particles had undergone major splitting. For well graded silica sand, there was a distinct difference in the crushing behaviour depending on the particle size. For the large seeded particles, a marked increase in the breaking of asperities and surface grinding occurred over the range between the stresses at yield and maximum compression index. For smaller particles on the other hand, the particle crushing in this region was characterised by a clear increase in the major particle splitting rather than the breaking of asperities. Damage for the smaller particles commenced at the earlier stage (before the yield region). The increase during yielding of the frequency of splitting of small particles was higher than that for the breakage of asperities on large particles but was slightly lower than that for the splitting of large particles inserted in the uniformly graded material. It is therefore considered that the higher compressibilities at lower stress levels, which is a common phenomenon of the crushable soils used , is governed by the damage to the smaller particles, the asperities and the surfaces.

A parameter has been defined which is a measure of the curvature of the e - log σ_v curve in the yield zone. The parameter R which indicates the increase in rate of the compression index with increasing stress is shown in fig.3 plotted against the coefficient of uniformity. R is defined as the ratio of the stress at the maximum compression index with that at C_c=0.1 i.e. $R = \ln\left|(\sigma_v)_{Cc=\max} / (\sigma_v)_{Cc=0.1}\right|$. As this parameter R increases, the curvature decreases and the radius of curvature increases, that is the material has an amorphous yield region. It can be seen in Fig. 3 that R generally increases with increasing coefficient of uniformity. In the results for U_c less than 3, the materials known as crushable soils and smaller grain sized materials have a greater R. If one considers that the more crushable soils have more irregular and non-uniform grain shapes, this parameter R should be dependent upon the particle shape. If it is true to assume that the asperities and jagged surfaces of larger particles have the same role as the smaller particles in relation to crushing, the effect on the parameter R should be substantially similar.

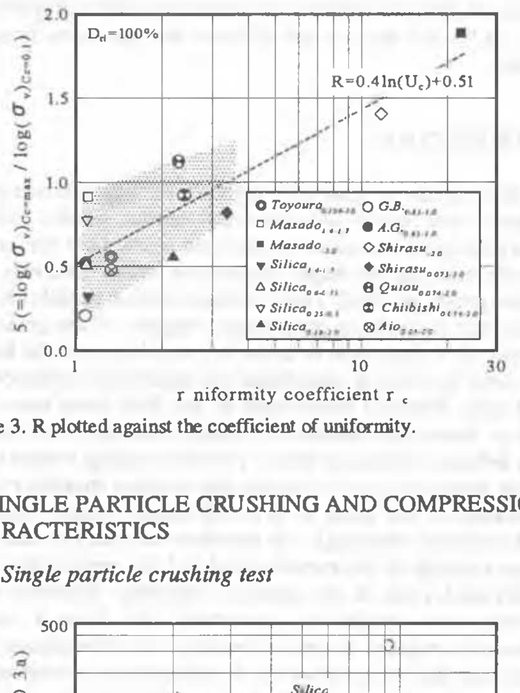

Figure 3. R plotted against the coefficient of uniformity.

3 SINGLE PARTICLE CRUSHING AND COMPRESSION CHARACTERISTICS

3.1 *Single particle crushing test*

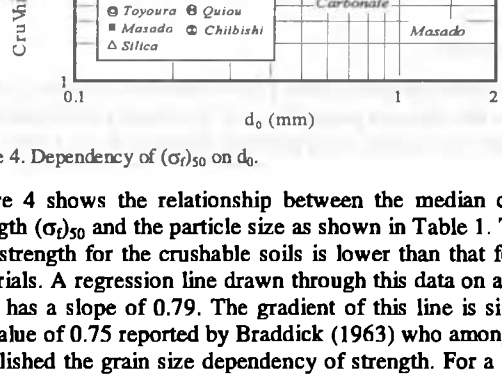

Figure 4. Dependency of $(\sigma_f)_{50}$ on d_0.

Figure 4 shows the relationship between the median crushing strength $(\sigma_f)_{50}$ and the particle size as shown in Table 1. The median strength for the crushable soils is lower than that for silica materials. A regression line drawn through this data on a log-log scale has a slope of 0.79. The gradient of this line is similar to the value of 0.75 reported by Braddick (1963) who among others established the grain size dependency of strength. For a slope of

0.79 the force when major splitting of particle occurs is less for smaller particles. This is true for any slope smaller than 2. The crushing strength for the crushable soils is more variable than that of silica because the individual particles of a crushable soil often consist of several minerals and even if they consist of a single mineral the degree of the weathering is different. In addition the asperities on a particle with irregular shape can break more easily. Therefore it is to be expected that any crushing phenomena for crushable soils would occur at relatively low stress levels. It is important to take into account the existence and strengths of smaller particles and asperities when discussing crushability and the resultant compressibility (McDowell and Bolton,1998).

3.2 *Single particle strength and macroscopic mechanical behaviour*

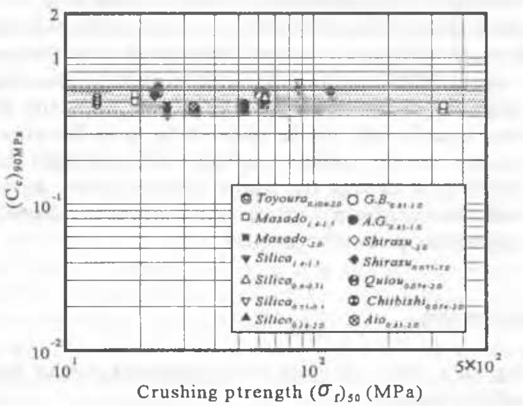

Figure 5. $(C_c)_{90MPa}$ related to $(\sigma_f)_{50}$.

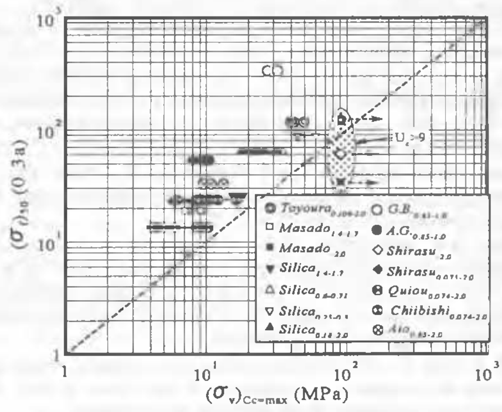

Figure 6. Relationship between $(\sigma_f)_{50}$ and $(\sigma_v)_{Cc=max}$.

Figure 5 shows the compression index at a vertical stress of 90MPa $(C_c)_{90MPa}$ related to the mean single particle crushing strength $(\sigma_f)_{50}$ for materials with various initial void ratios. The compression index at a vertical stress of 90MPa is virtually the same value of 0.5 irrespective of the kind of material, initial void ratio or single particle strength. This indicates that at high stress levels the compression properties depend on the geometric properties of both grain size and voids (McDowell, et al., 1996).

Figure 6 shows the relationship between the median crushing strength $(\sigma_f)_{50}$ and $(\sigma_v)_{Cc=max}$. From statistical microscopic observations for uniform particle sized sands, 50% of the particles have undergone major splitting when the compression index reaches a maximum (Nakata, et al., 2001). The differences for similar types of marks indicates the effect of the initial void ratio. The dashed line in the figure is where the median single particle strength would be equal to the $(\sigma_v)_{Cc=max}$. The value of $(\sigma_v)_{Cc=max}$ for the well graded crushable soils, if it had been reached, would be larger than that for $(\sigma_f)_{50}$. For the glass beads $(\sigma_v)_{Cc=max}$ is one tenth of $(\sigma_f)_{50}$. For the uncrushable and medium well graded crushable soils $(\sigma_v)_{Cc=max}$ is approximately half of $(\sigma_f)_{50}$.

3.3 *Discussion on stress distribution in granular material*

3.3.1 *One-dimensional compression*

Figure 7 shows the median single particle crushing strength $(\sigma_f)_{50}$ plotted against the average characteristic stress $(\sigma_{sp})_{Cc=max}$ applied to a particle embedded in a granular material when the macroscopic vertical stress reaches $(\sigma_v)_{Cc=max}$. The stress $(\sigma_{sp})_{Cc=max}$ is defined by the following equations assuming all particles have the same size and carry the same load in the matrix.

$$(\sigma_{sp})_{Ccmax} = \frac{F_{sp}}{\bar{d}_0^2} = (\sigma_v)_{Ccmax}\left(\sqrt[3]{\frac{(1+e)\pi}{6}}\right)^2 \quad (1)$$

For the purposes of clarity this figure only shows data for uniform particle sized materials with a coefficient of uniformity of about unity. In this figure it can be seen that there is a spread for marks of the same type. This difference is not only due to the initial void ratio affecting the force on a particle in a soil matrix but is also due to the fact that for a granular materials particle co-ordination numbers increase with increasing void ratio (e.g. Field, 1963). The increase of the co-ordination number would decrease the characteristic stress of a particle. The median single particle crushing strength $(\sigma_f)_{50}$ is larger than the average characteristic stress $(\sigma_{sp})_{Cc=max}$. If the assumptions above regarding particle size and loading were true then there would be hardly any major splitting of particles in the granular materials. Thus there must be a distribution of characteristic crushing stresses. This distribution is supported by the results of DEM analyses by Cundall and Strack (1979) and the bi-axial tests for photo-elastic material by Oda and Konishi (1974). In granular materials, there are two types of particle loading in the matrix. A proportion of particles will carry large forces while others will only carry small loads or even none at all.

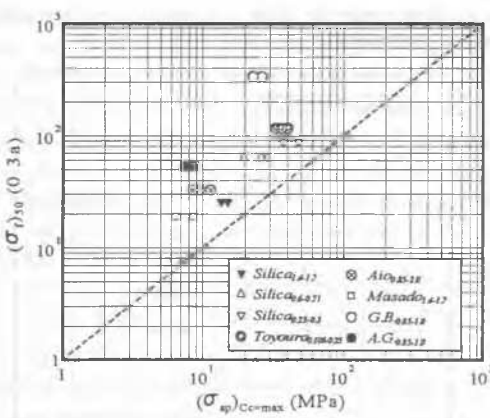

Figure 7. $(\sigma_f)_{50}$ plotted against $(\sigma_{sp})_{Cc=max}$.

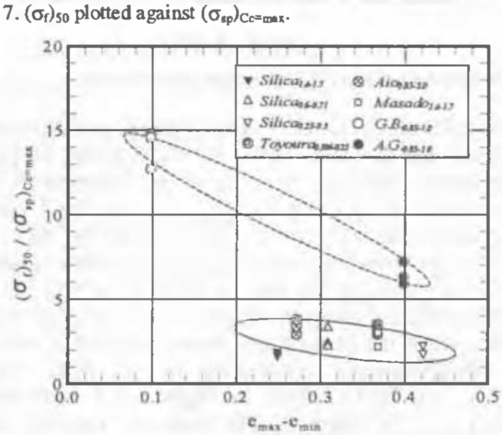

Figure 8. Ratio of $(\sigma_f)_{50}$ to $(\sigma_{sp})_{Cc=max}$ against e_{max}-e_{min}.

Figure 8 shows the ratio of $(\sigma_f)_{50}$ to $(\sigma_{sp})_{Cc=max}$ (the calculated matrix particle stress) against e_{max}-e_{min}. In this figure the ratio is

13-15 for glass ballotini, 6-7 for angular glass and 2-4 for other geomaterials. The ratio of $(\sigma_f)_{50}/(\sigma_{sp})_{Cc=max}$ is an indicator of the ratio of active to non-active particles. Thus in a uniform material such as the glass ballotini a large proportion of the particles are not carrying any load or only a small load. As the shape of the grain becomes more angular and the surface roughness increases then the load distribution through the matrix becomes more uniform.

3.3.2 *Constant stress ratio compression*

Figure 9 shows the results of stress ratio (q/p) constant and K_0 compression tests for uniform grain sized silica sand, $Silica_{1.4\text{-}1.7}$ using a high confining pressure triaxial compression apparatus. The stress level for the yield region decreases with increasing stress ratio. The radius of curvature in the yield region is also dependent on the stress ratio and decreases with increasing stress ratio. This tendency implies that the stress ratio on a granular material affects the evolution of particle crushing.

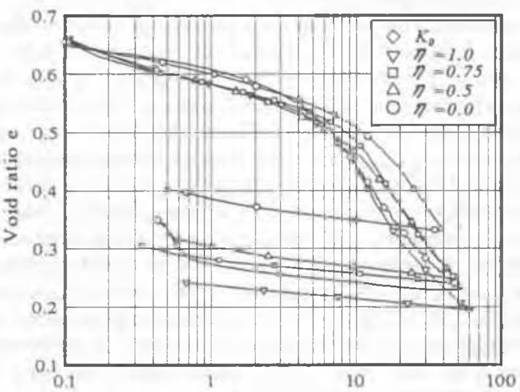

Figure 9. $e - \log p$ curves for $Silica_{1.4\text{-}1.7}$ subjected to stress ratio (q/p) constant and K_0 compression.

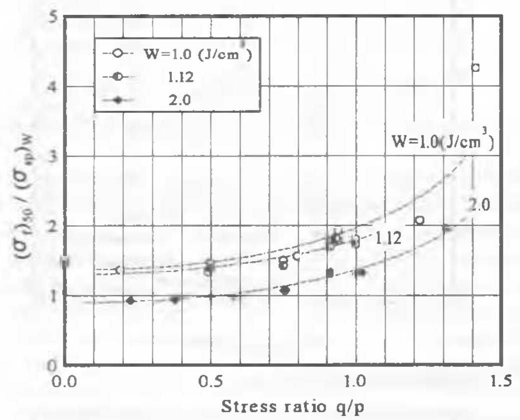

Figure 10. Ratio $(\sigma_f)_{50}/(\sigma_{sp})_W$ plotted against to stress ratio.

Miura & Yamanouchi (1977) have pointed out that where the plastic work has the same value, the same extent of particle crushing occurs. The ratio of $(\sigma_f)_{50}$ to the characteristic stress $(\sigma_{sp})_W$ obtained by replacing $(\sigma_v)_{Cc=max}$ in equation 1 with the stress $(\sigma_v)_W$ for total work of 1.0, 1.12, 2.0 J/cm^3 has been calculated. Figure 10 shows the ratio $(\sigma_f)_{50}/(\sigma_{sp})_W$ plotted against the stress ratio not only for the data in figure 9 but also the other conventional drained compression tests. It can be shown that the total work when the compression index becomes a maximum during one-dimensional compression is 1.12 J/cm^3. That is $(\sigma_f)_{50}/(\sigma_{sp})_W$ for W=1.12 J/cm^3 in figure 10 is equivalent to $(\sigma_f)_{50}/(\sigma_{sp})_{Cc=max}$ in figure 8. The value of $(\sigma_f)_{50}/(\sigma_{sp})_W$ for W=1.12 J/cm^3 has a constant value of 1.4 for stress ratios below 0.5; between 0.5 and 1.0 it grows slightly and over 1.0 there is a clear increase. Thus the stress ratio could be having an effect on the distribution of the characteristic stress on the particle.

4 CONCLUSIONS

(1) The compression index for crushable soils at stress levels less than 10MPa was higher than that of silica materials. Considering that the collective particle crushing under relatively low stress levels is governed by smaller particles and particle asperities, a crushable soil particle profile must contain these.

(2) The compression index at a vertical stress of 90MPa was virtually the same value of 0.5 irrespective of the kind of material, initial void ratio or single particle strength. This indicates that at high stress levels the compression properties depend on the geometric properties of both grain size and voids.

(3) On the basis of the evidence that 50% of the particles undergoing major splitting when the compression index C_c reaches a maximum, the ratio of the median single particle strengths to the characteristic tensile stress at C_c = maximum for particles embedded in the soil matrix was thought to be an indicator of the distribution of the stress induced on each particle. In a uniform material such as glass beads a large proportion of the particles do not carry any load or only a small load. As the shape of the grain becomes more angular and the surface roughness increases then the load distribution through the matrix becomes more uniform. It was also recognised that the non-uniform distribution was dependent upon the stress ratio.

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