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Particle and shear characteristics of granulated coal ash as geomaterial

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ABSTRACT: In this study, single particle crushing tests were carried out on various kinds of granulated coal ash to evaluate the crushing characteristic of each individual grain. Then, drained monotonic triaxial compression tests were carried out under different confining pressures on specimens prepared by granulation. The effects of the confining pressure on the shear characteristics, as well as its relation to shear strength, were examined taking into account the crushing strength. As a result, it became clear that contrary to that observed in natural sands, the particle crushing strength of granulated coal ash did not depend on the particle size. Moreover, the crushing strength affected the shear characteristics, i.e., as the crushing strength increased, the shear stiffness became higher and the shrinkage of the volumetric strain became smaller. Therefore, crushing strength can be a useful parameter in evaluating the shear characteristic of the granulated coal ash.

1 INTRODUCTION

In recent years, the challenge concerning the depletion of good geomaterials and the effective use of renewable resources have become a social responsibility. Therefore, the applicability of various by-product materials as geomaterial should be examined. Coal ashes are inevitably produced by burning coal. In Japan, based on the law to "promote usage of renewable resource" (resources recycling law) which was enforced in 1991, the coal ashes generated from thermal power plants are specified as by-product of electric industry and there is a duty to promote their effective usage. Moreover, in the fiscal year 1999, 7.6 million tons of coal ashes were generated, and this quantity tends to increase every year. At the present, about 80% of the coal ashes are used effectively and the majority is used as blended material in cement, such as in civil engineering field. Since a large quantity can be utilized at once in this field of application, it is expected that civil engineering usage can be an acceptable alternative for the predicted increase in coal ash utilization.

The works on the application of coal ashes to geotechnical engineering have been performed by many researchers, such as Horiuchi (1996) and Sawa et al. (2002). The authors have been studying the mechanical properties of granulated coal ash formed by milling process with small amount of cement added and whose particle size is almost equivalent to that of sand or fine gravel. The use of granulated coal ash has many advantages, such as the suppression of leaching of heavy metals and the possibility of outdoor curing. In addition, since granulated coal ashes are produced artificially, the particle strength can be grasped easily. Furthermore, another advantage is that it is possible to control the particle strength, something which cannot be carried out in natural sands. The present research was carried out in order to investigate the possibility of the positive utilization of such advantage.

In this study, single particle crushing tests were carried out on various kinds of granulated coal ash to evaluate the crushing characteristic of each individual grain. Then, drained monotonic triaxial compression tests were carried out under different confining pressures on specimens prepared by granulation. The effects of the confining pressure on the shear characteristics, as well as its relation to shear strength, were examined taking account into the crushing strength.

2 SAMPLE PROPERTIES

In this research, four kinds of sand-size granulated coal ashes were used. The compositions of coal ashes and cement additive differ in Type A and Type B. The composition of Type C was the same as that of Type A, but manufactured using different method. Finally, Type C and Type D were similar except for the kind of coal ash used. The composition, machine type and curing condition of granulated coal ashes are shown in Table 1. Table 2 shows the physical properties of the samples used. The specific gravities of the particles of granulated coal ashes are very low because of the presence of air vesicles in individual grains. In particular, the

Table 1. Composition, machine type and curing condition.

Sample	Composition (%) Coal ash	Cement	Addition	Type of machine	Curing condition
A	85	5	10	eirich	natural
B	80	10	10	mixer	dry
C	85	5	10	mortar	w=
D	85	5	10	mixer	40 ∼ 50%

Table 2. Physical properties of each granulated coal ash.

Sample	G_s	e_{max}	e_{min}	d_{50}(mm)
A	2.35	2.544	1,916	0.385
B	2.36	2.679	1968	0.467
C	2.41	2.222	1.522	0.561
D	2.28	2.280	1.512	0.368
P.I. Masado	2.62	0.967	0.491	0.546

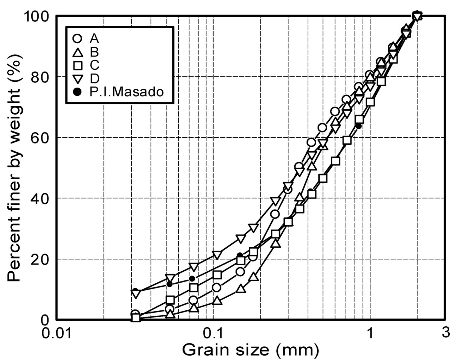

Figure 1. Grain size distribution curves.

maximum and minimum void ratios, which were determined using the methods specified in the Japanese Geotechnical Society Standards, were found to be very large for granulated coal ash. The particle size distribution curves depicted in Figure 1 show practically similar curves for granulated coal ashes and P.I. Masado. These materials contain about 10 ∼ 20% fines and are well-graded with high coefficient of uniformity.

3 SINGLE PARTICLE CRUSHING TEST

The test was carried out by placing a particle on the lower plate in the most stable direction and then moving the upper plate at a constant rate of displacement to crush the particle (Nakata et al., 2001). Since the plates are flat, the loads during test are applied at two points in the vertical direction. Force and displacement were measured during test. The load measuring capacity was 4.91×10^2 N with a resolution of 9.81×10^{-3} N. On the other hand, the displacement was measured by un-contacted type with

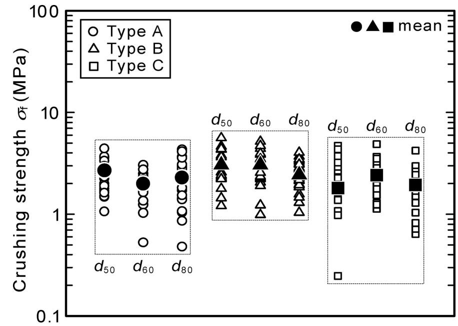

Figure 2. Crushing strength for each grain size of granulated coal ash.

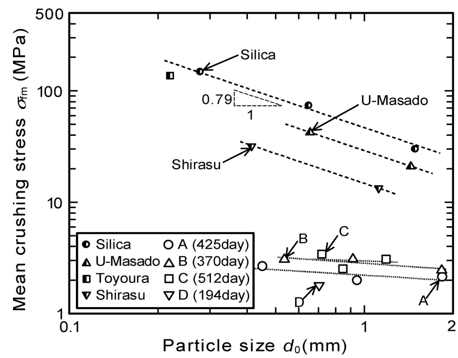

Figure 3. Effect of particle size on mean crushing strength.

measuring capacity of 2.00 mm with a resolution of 1.00×10^{-3} mm. Displacement rate of 0.1 mm/minute was applied. Single particle crushing test was carried out on d_{50}, d_{60}, d_{80} size particle of each granulated coal ash. Crushing strength σ_f is defined as in Eq. (1). The average value of each crushing strength σ_f in the same condition is defined as mean crushing strength σ_{fm} (Eq. (2)).

$$\sigma_f = F_f \big/ d_0^2 \tag{1}$$

$$\sigma_{fm} = \sum_{j=1}^{n} \sigma_f \Big/ n \tag{2}$$

where F_f is the maximum load, d_0 is the initial height of particle, n is total number of particles tested.

Figure 2 shows all the values of crushing strength for each grain size (d_{50}, d_{60}, d_{80}) of granulated coal ashes (Types A–C). The variation of crushing strength σ_f and the value of mean crushing strength σ_{fm} for each grain size of granulated coal ashes are similar. Figure 3 shows the mean crushing strength against particle size. The figure shows data for the granulated coal ashes (Types A–D) and, for comparison purposes, include data for natural sands. It is already known that for natural sands under the same conditions, a smaller particle has a higher crushing strength, and a

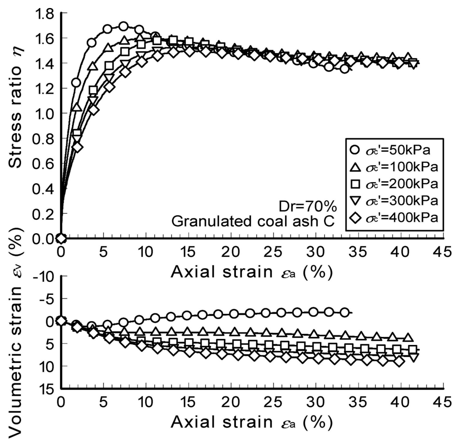

Figure 4. Stress ratio $\eta(=q/p')$ and volumetric strain ε_v plots against axial strain ε_a.

regression line drawn through this data on a log-log scale has a slope of −0.79 (Nakata et al., 1999). In the comparison among mean crushing strengths for granulated coal ashes, it was found that Type B with the most cement content has higher strengths than Type A and Type C. In granulated coal ashes, the grain size dependency of strength as observed in natural sands was not seen. This would be because the calcium silicate hydrate is present uniformly and the internal structure is homogeneous.

4 TRIAXIAL COMPRESSION TEST

Triaxial compression tests were carried out under consolidated and drained condition for granulated coal ashes. To prepare the test specimens, granulated coal ash was water-pluviated into a mould which was then gently tapped until a relative density of 50% and 70% were achieved. Specimens were isotropically consolidated to 50, 100, 200, 300, and 400 kPa. Subsequently, the specimen was sheared under a drained condition at an axial strain rate of 0.1%/min until the critical state. Because consecutive voids from the surface to the particle interior side are present, it is not easy to completely saturate granulated coal ash. The saturated specimens were made using de-aired granulated coal ashes. The de-aired granulated coal ashes were soaked in de-aired water and were placed in a vacuum tank for three or four days.

Figure 4 shows the stress ratio and volumetric strain plots against axial strain for granulated coal ashes. The granulated coal ash had a much greater range of peak stress ratio η_{peak} depending on the confining stress, with a marked decrease occurring in the peak stress ratio η_{peak} as σ'_c increased. It was dilative at 50 kPa and only became compressive at $\sigma'_c \geq 100$ kPa with large compressive strains occurring at $\sigma'_c = 400$ kPa.

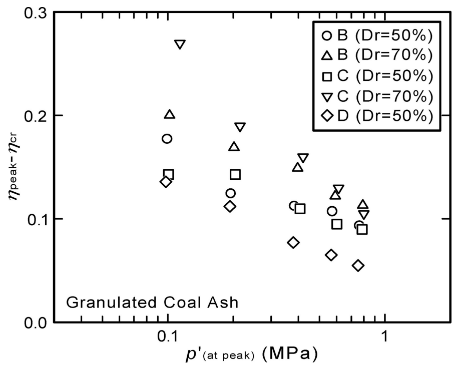

Figure 5. Relationship between η_{peak}-η_{cr} and effective mean principal stresses p' at peak stress ratio.

The residual stress ratio shows a constant value, and is not influenced by the confining pressure. It is thought that this behaviour is caused by the particle crushing and by the fact that particle strength is low. This result is consistent with the research results obtained previously on particle crushing of the sand.

Several experimental results have shown that the peak friction angle ϕ_p of sands increases with increasing relative density *Dr* and decreases with increasing confining stress *p* (e.g., Vesic and Clough (1968), Bolton (1986)). Using experimental results for several sands, Bolton (1986) showed that the combined effects of relative density and confining stress on the peak friction angle can be represented by a mathematical expression. Gutierrez (2003) revised this expression by using the peak stress ratio instead of the peak friction angle. The expression relating the peak stress ratio to the confining pressure is formulated as:

$$\eta_{peak} = \eta_{cr} + CDr\ln\left(p_{cr}'/p'\right) \quad (3)$$

where *C* is a material parameter, *Dr* is relative density, and, η_{cr} is stress ratio at the critical state. The critical state was defined as the state at which a soil mass is continuously deforming at constant volume, and constant effective stresses. The p'_{cr} was defined as the effective mean principal stress when the peak is equal to the stress ratio at the critical state.

The relationship between η_{peak}-η_{cr} and effective mean principal stresses p' at peak stress ratio is presented in Figure 5. As the effective mean principal stresses p' increases, η_{peak}-η_{res} approaches 0. It is thought that the drained shear strength demonstrated by the dilatancy of granulated coal ash decreases due to particle crushing associated with stress increase. The value when η_{peak}-η_{res} becomes 0 is p'_{cr}. The p'_{cr} was determined based on each individual experiment result. The findings are summarized in Table 3. From the table, the p'_{cr} does not depend on the relative density and indicates almost the same value. Figure 6 shows the relation between $(\eta_{peak}$-$\eta_{cr})/Dr$ and $p'_{cr}/p'_{(at\ peak)}$.

Table 3. p'_{cr} from each experiment results.

		Sample		
		B	C	D
p'_{cr}	$Dr = 50\%$	7.788	8.524	3.941
	$Dr = 70\%$	7.871	7.389	–

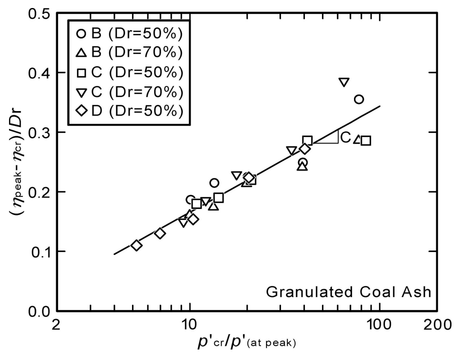

Figure 6. Relationship between η_{peak}-η_{cr}/Dr and $p'_{cr}/p'_{(atpeak)}$.

Although the data points are scattered, the relation can be represented by a straight line.

5 EVALUATION OF SHEAR STRENGTH OF GRANULATED COAL ASH BY PARTICLE STRENGTH

The relationship between p'_{cr} and σ_{fm} is presented in Figure 7. Although the data points are few, a unique relation seems to exist between the two parameters. The relation between $(\eta_{peak}$-$\eta_{res})/Dr$ and σ_{fm}/p' is shown by using this unique relation in Figure 8, which indicates a good correlation. From this relation, the following expression is obtained when solving for η_{peak}.

$$\eta_{peak} = \eta_{cr} + C' Dr \ln(\sigma_{fm} / p') \quad (4)$$

where C' is a material parameter. From Eq. (4), crushing strength can be a useful parameter in evaluating the shear characteristic of the granulated coal ash.

6 CONCLUSIONS

The effects of the confining pressure on the shear characteristics, as well as its relation to shear strength, were examined taking account into the crushing strength. As a result, it became clear that contrary to that observed in natural sands, the particle crushing strength of granulated coal ash did not depend on the particle size. Moreover, the crushing strength affected the shear characteristics, i.e., as the crushing strength increased, the shear stiffness became higher and the shrinkage of the volumetric strain became smaller. Therefore, crushing strength can be a useful parameter in evaluating the shear characteristic of the granulated coal ash.

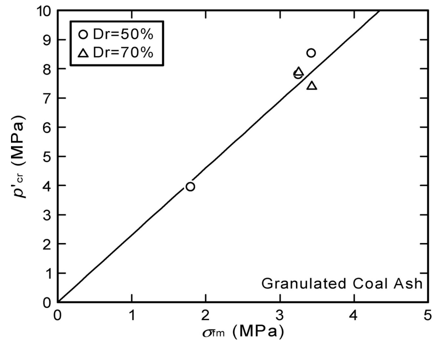

Figure 7. Relationship between p'_{cr} and σ_{fm}.

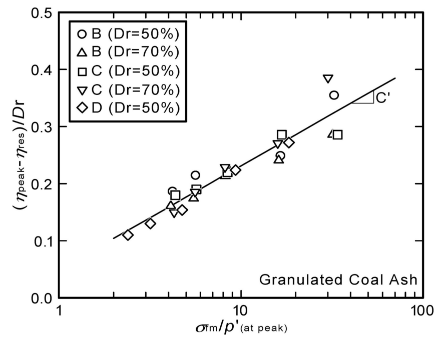

Figure 8. Relationship between $(\eta_{peak}$-$\eta_{cr})/Dr$ and $\sigma_{fm}/p'_{(at\ peak)}$.

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