12 Mar 1991, 10:30 am - 12:00 pm

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Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 1.10

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SYNOPSIS: The great part of fly ash produced by thermal power plants is either sluiced or filled in disposal areas in China. The dynamic properties of fly ash are important for solving geotechnical problems relating to fly ash mass under dynamic loadings. The high temperature during combustion makes fly ash nonplastic but pozzolanic. The nonplasticity causes the dynamic properties of sluiced and just compacted fly ash to be similar to ones of silts. The pozzolanic action causes obvious aging effect for compacted fly ash, by which an aging time of 180 days may increase maximum shear modulus by 75% to 400% and cyclic strength by 100% to 500%. All of these results are reported and discussed in the paper in detail. Based on the results four correlative equations are presented which could be used to preliminarily evaluate the dynamic properties of fly ashes.

INTRODUCTION

The production of fly ash has steadily increased in line with the increase in coal-fired generating capacity. It amounts to 50 million tons per year in China now and only one-fifth of which has been utilized. The major portion of this waste product is being either sluiced into lagoons or hauled in a slightly moistened condition to fill disposal areas for creating usable land. Through investigation of the dynamic properties of fly ash is important for solving geotechnical problems relating to the response and stability of fly ash mass under the action of dynamic loadings, including earthquakes.

Although fly ash is a tailings material it is somewhat different from mine tailings. Fig. 1 shows the grain size distribution of fly ash in comparison with tailings sand and slime after Garga and Mckay (1984). The grains of fly ash are mainly spherical with a part of hollow ones which causes the lower grain density and the higher void ratio for fly ash compared with natural soil or mine tailings. The properties of fly ash are dependent on various factors including the type of coal, the degree of pulverization, the type of combustion, as well as the type of collection and disposal equipment. The most essential factor which causes the characters of fly ash is that it has subjected to high temperature during combustion. Thus, fly ash is of nonplasticity due to lack of clay mineral although its fines content is quite high. But meanwhile fly ash has pozzolanic action. These characters are bound to be reflected in the dynamic properties. In this paper the results about shear modulus, damping and cyclic triaxial strength of saturated fly ash, obtained in the Institute of Water Conservancy and Hydroelectric Power Research(IWHR), are reviewed, as well as the results from literatures. And the aging effects on the dynamic properties of compacted fly ash are reported. Some correlative equations and conclusions in these topics are presented.

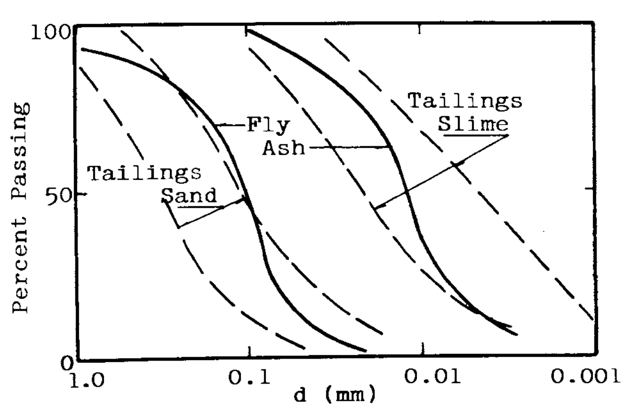

Fig. 1 Grain Size Distribution of Fly Ash

SHEAR MODULUS AND DAMPING OF FLY ASH

The shear modulus and damping of fly ashes are determined by resonant column tests. As it was pointed by Yu and Richart (1984) the maximum shear modulus of soils, G_o, should be related to $\sigma'_o=(\sigma'_a+\sigma'_p)/2$ rather than to $(\sigma'_a+\sigma'_p+\sigma'_s)/3$ for two-dimensional problems, in which σ'_a= the principal stress along the direction of shear wave propagation; σ'_p= the principal stress in the direction of the soil grain vibration or of the applied dynamic shearing stress; and σ'_s= the third principal stress, all of which are effective stress. The relationship between them could be written as

$$G_o = C P_a^{1-n} \sigma_o'^{\,n} = C P_a^{1-n} \left(\frac{\sigma'_a+\sigma'_p}{2}\right)^n \qquad (1)$$

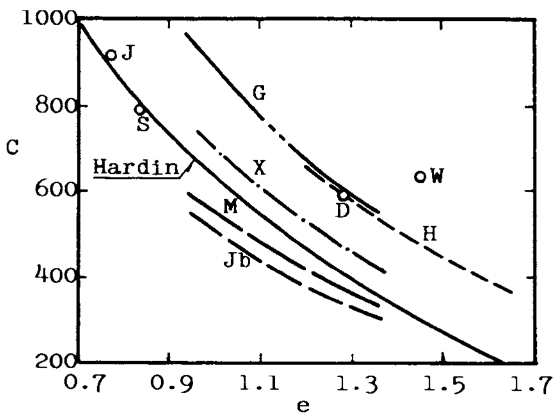

Fig. 2 Parameter C vs. Void Ratio e

in which P_a= the atmospheric pressure and could be taken as 98.1 kPa or 1 kgf/cm^2. Eq. 1 is also suitable for fly ash. The value of exponent n varies around 0.5 and could be taken as 0.5 on the average for fly ash as usually used for soils. The parameter C in Eq. 1 in relation to void ratio e is shown in Fig. 2 in comparison with Hardin [Hardin and Drnevich (1972)] equation for angular grained sands. In Fig. 2 the results of three fly ash samples are after Zhen, Gu and Wu (1985). Fig. 2 shows that the trend of variations in the parameter C of fly ashes with void ratio is quite similar to Hardin equation. Although the values of C for some ashes are 40% larger than Hardin equation, especially for the samples directly from ash silo, for most of the ash samples from lagoon the values of C are around Hardin equation. Usually relative density concept is precluded to use for soils with fines (fraction smaller than 0.074 mm) content greater than 12%. However, it is still used for fly ash because of its nonplasticity although its fines content ranges from 20% to 90%. The parameters C in Eq. 1 related to relative density D_r are plotted in Fig. 3, which are much lower than the values given by Seed and Idriss (1970) for sand at same relative density. The fact that the maximum shear modulus of cohesionless soils depends on void ratio rather than on relative density is also confirmed for fly ash by comparing Fig. 2 with Fig. 3.

The attenuation curves of shear modulus ratio and damping ratio curves of six ash samples under the same confining pressure of σ'_0=392 kPa are shown in Fig. 4 and Fig. 5 respectively. It seems these two curves are not largely affected by fly ash type either from lagoon or from silo. Under a definite pressure the effects of dry density and degree of saturarion on the two curves for each ash sample are smaller than the effect of fly ash type shown in Fig. 4 and Fig. 5. Only the effect of confining pressure σ'_0 is obvious. Fig. 6 shows a representative result of a fly ash sample under σ'_0= 49 kPa and 392 kPa as compared with the curves given by Seed and Idriss (1970) for sands. By introducing the reference shear strain γ_r defined as τ_{max}/G_o by Hardin and Drnevich (1972) the results under various pressures could be normalized quite well in a G/G_o vs. γ/γ_r and a D vs. γ/γ_r curves, respectively, as shown in Fig. 7. As Yu (1988) discussed, it would be more convenient to use the two normalized curves than to use two families of curves for evaluating the response of soil deposits or fill dams, suggested by Seed et al. (1986), as well as for evaluating the response of fly ash masses. In Fig. 7 also plotted are the curves given by Hardin and

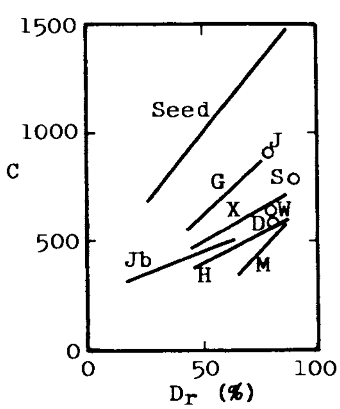

Fig. 3 Parameter C vs. Relative Density D_r

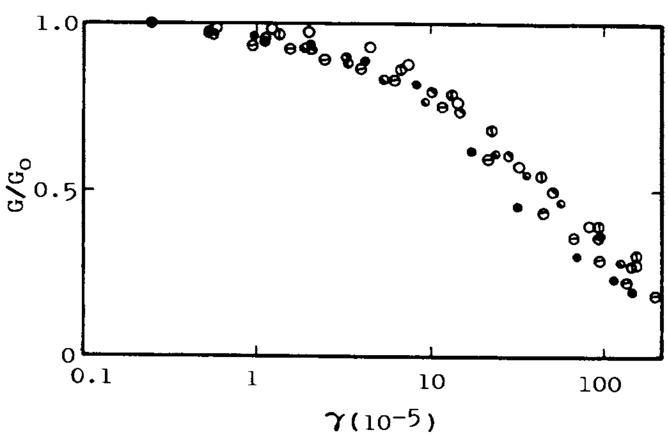

Fig. 4 Attenuation Curves of Shear Modulus Ratio of Fly Ashes

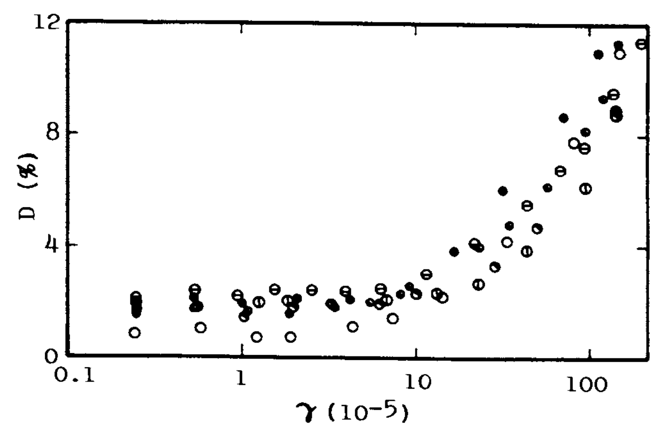

Fig. 5 Damping Curves of Fly Ashes

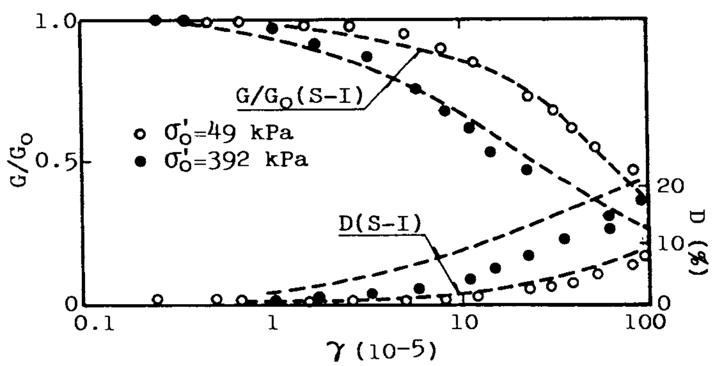

Fig. 6 Effect of Confining Pressure

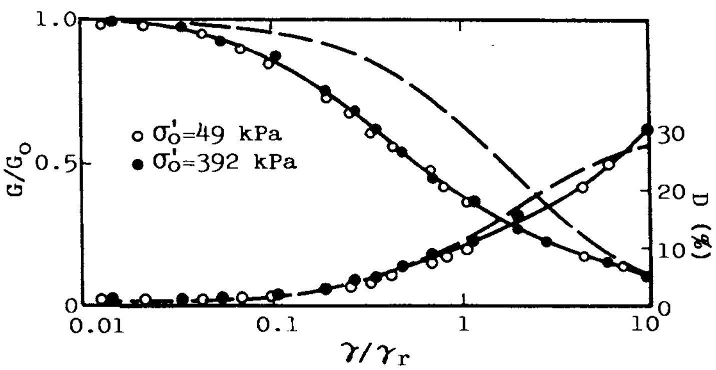

Fig. 7 Normalization for Effect of Confining Pressure

Drnevich (1972) for clean sand with dotted line for reference.

CYCLIC TRIAXIAL STRENGTH OF FLY ASH

Wang and He (1985) and Wang, Qin and He (1987) made a through investigation on the liquefaction and strength of six slucied fly ashes and found that saturated loose fly ash is vulnerable to liquefy under either static or dynamic loading. The cyclic triaxial strength ratio is defined as $R_d = \Delta\sigma_1/2\sigma'_0$, in which $\Delta\sigma_1$ is the amplitude of cyclic stress and $\sigma'_0 = (\sigma'_{1o}+\sigma'_{3o})/2$ is the average principal stress. The value of R_d is determined for the cyclic double amplitude of vertical strain, or the single amplitude strain in either extension or compression, to be equal to 5%. Under consolidation stress ratio $K_c = \sigma'_{1o}/\sigma'_{3o} = 1.0$ the cyclic strength ratio R_d of 19 fly ashes, two-third of which are obtained in IWHR, are presented in Fig. 8 in relation to mean diameter of grain, d_{50}. The values of R_d in the figure have been normalized to relative density D_r= 50% and cyclic number N= 30 cycles. Also plotted in Fig. 8 are the results of tailings sands and slimes after Garga and Mckay (1984), the conditions for which are as same as ones for the fly ashes except the tailings slimes corresponding to hydraulically-placed condition have not been normalized to D_r= 50%. Fig. 8 shows that

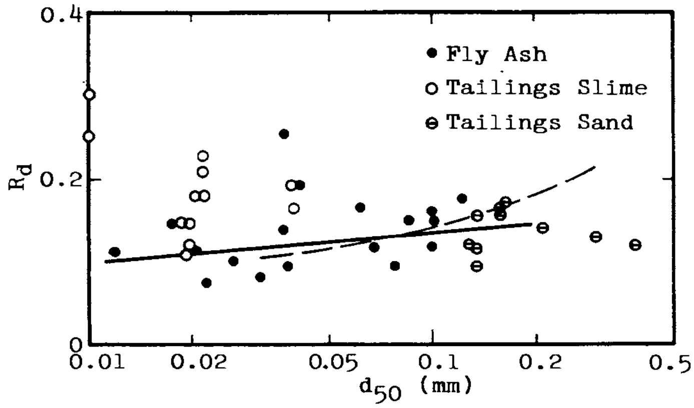

Fig. 8 Cyclic Strength Ratio vs. Mean Diameter of Grain

fly ashes exhibit a notably narrow range of cyclic strength behavior when normalized to D_r= 50% except one sample directly from silo. And the range for fly ash links up with the range for tailings sand. The dotted line in Fig. 8 was presented by Jiang and Wang (1986) for the silt taken from the lower reaches of Yellow River. It is also close to the range for fly ash. All the results show that the nonplasticity of fly ash makes its lower cyclic strength. The cyclic strength of some tailings slimes is higher than fly ash because of their plasticity. The correlative equation between cyclic strength ratio R_d and mean diameter of grain, d_{50}, for fly ash determined by the results in Fig. 8 is

$$R_d = 0.172 + 0.037 \times \log(d_{50}) \qquad (2)$$

Eq. 2 could be used to preliminary evaluate the cyclic strength of sluiced fly ash under stress condition of K_c= 1.0.

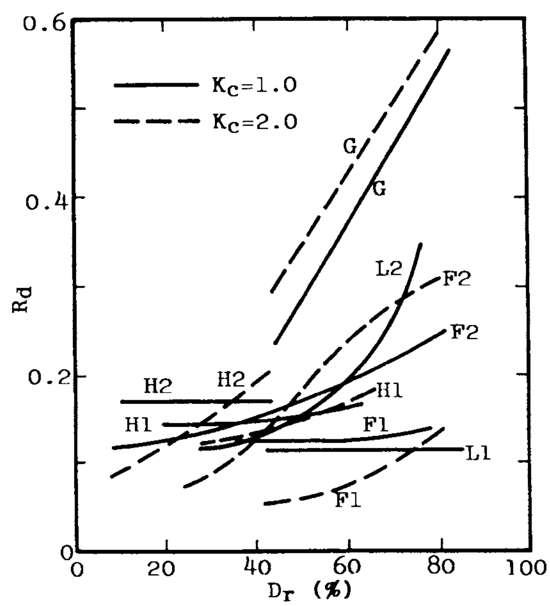

Fig. 9 Cyclic Strength Ratio vs. Relative Density

However, there are some characters about the cyclic strength of fly ash. Fig. 9 shows the values of R_d in relation to relative density D_r for fly ashes. It is intresting to note that for some samples from lagoon the effect of D_r on R_d is not significant. The ash sample G exhibits much higher value of R_d because it is taken from silo. Moreover for the sluiced fly ashes the R_d values for consolidation stress ratio K_c= 2.0 may be smaller than ones for K_c= 1.0 when the relative density is low. Nevertheless the effect of confining pressure on cyclic strength for fly ash is not as obvious as for tailings sand because the fines content of the former is much higher than the latter. Similar characters have been observed in the cyclic test results of loose silts.

AGING EFFECT ON DYNAMIC PROPERTIES

What has been discussed on the foregoing paragraphs are the dynamic properties of fly ash specimens sluiced or just compacted, i.e. without considering the aging effect. The aging effect is quite an event for compacted fly ash because of pozzolanic action.

Five fly ashes were taken for investigating the aging effect. The fundamental properties of the ashes are listed in Table 1. The specimens were compacted under the optimum water content to a relative density of 80% or 90% , then aged under room temperature and 100% relative humidity. The tests were carried out after 1 to 180 days aging time from the specimen preparation. Before testing the specimens were saturated by vacuum and applied a back pressure of 98 kPa.

The maximum shear modulus G_o increases with increasing of aging time T in three types as shown in Fig. 10. The first type as what ash W exhibits is that G_o is directly proportional to logarithm of aging time, log T. The other two types both resemble two straight lines on G_o vs. log T relation. The inclination of the second line is much higher than one of the first line. The turning point is at 7 days for ashes G and D, but at 28 days for ashes S and J, respectively. For ash J following the swelling of specimens the value of G_o at 28 days aging time is even smaller than the value at 1 day. But after then it increases substantially with increasing aging time. A similar variation of unconfined compression strength with aging time was

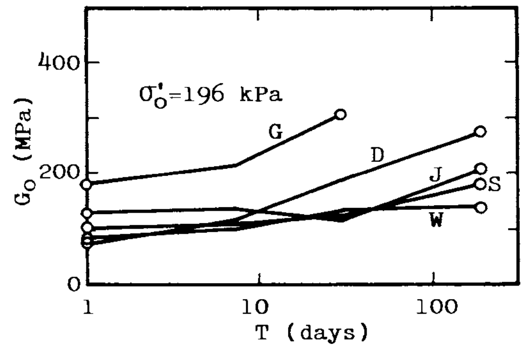

Fig. 10 Aging Effect on Maximum Shear Modulus

reported by Vasquez and Alonso (1981) and it was attributed to the action of anhydrite. The relations between the two parameters C and n in Eq. 1 and the aging time are plotted in Fig. 11. With increasing aging time the values of C increase obviously, but the values of n seem to decrease. All the results in Fig. 10 and Fig. 11 show that the pozzolanic action would sustained for quite a long time. The aging time of 180 days may increase maximum shear modulus by 75% to 400% over the value of 1 day. Zhen, Gu and Wu (1985) infered that fly ash would most likely be an effective isolation material in ground since the shear modulus of fly ash is only about 30% to 60% of the value of sand at same relative density. However, when the aging effect on shear modulus is taken into account for fly ash its effectiveness as an isolation material is doubtful.

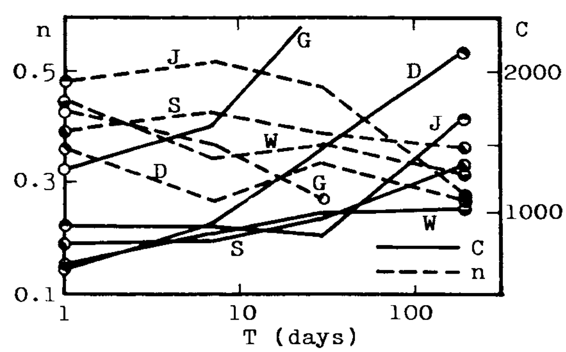

Fig. 11 Aging Effect on Parameters C and n

TABLE 1 Fundamental Properties of Five Fly Ashes

Sample	G_s	d_{50} (mm)	C_u	e_{max}	e_{min}	$(\gamma_d)_{max}$ (kN/m^3)	w_{op} (%)	D_r (%)	γ_d (kN/m^3)
G	2.11	0.037	2.76	1.81	0.73	10.89	33.2	80	10.59
S	2.29	0.0375	4.85	1.83	0.67	13.05	22.0	90	12.56
J	2.21	0.041	2.66	1.25	0.60	12.75	23.0	80	12.56
D	2.47	0.0265	3.24	2.60	0.91	12.36	26.0	80	10.79
W	2.18	0.0175	4.71	2.59	1.09	9.91	42.3	80	8.93

The aging effects on the shear modulus ratio G/G_o and the damping ratio D at shear strain amplitude of $\gamma = 3x10^{-4}$ are shown in Fig. 12. It seems from the figure that the ratios G/G_o increase and the dampings D decrease as the aging time increases, in other words the attenuation curve of shear modulus becomes steeper and the damping curve becomes flatter with the increase of aging time. But the variation of the two curves is not significant.

The cyclic strength increases with increasing aging time as shown in Fig. 13, in which the cyclic strength ratio R_d is determined by 2.5% axial strain under cyclic number of 30 cycles. The aging time of 180 days may increase R_d value by 100% to 500% over the value of 1 day. There are three types in the relation of the ratio R_d vs. the logarithm of aging time, $\log T$, as same as the three types discussed above for the relation between maximum shear modulus and aging time. Comparing Fig. 13 with Fig. 10 shows that the increasing type of R_d or G_o with aging time is identical for each ash sample. It exposes the existence of the relationship between G_o or the parameter C in Eq. 1 and R_d as plotted in Fig.14.

The aging effect for fly ash is mainly attributed to the pozzolanic action of free lime content and could be related to calcium cations or total

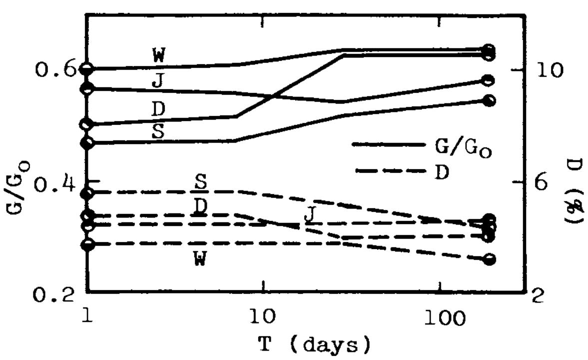

Fig. 12 Aging Effect on Shear Modulus Ratio and Damping Ratio

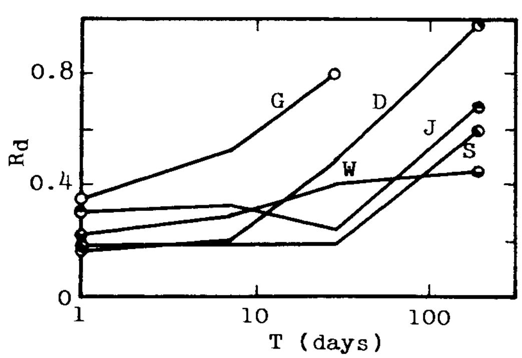

Fig. 13 Aging Effect on Cyclic Strength Ratio

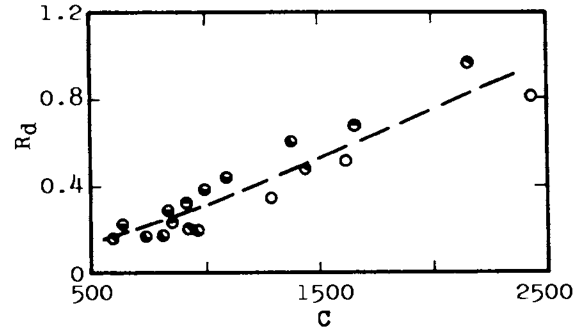

Fig. 14 Cyclic Strength Ratio R_d vs. Parameter C

dissolved solids in fly ash leachate. The values at an aging time of 180 days are selected to reflect the aging effect because the values at 28 days aging time may be influenced by swelling effect. The aging effect, which is expressed by the ratio of the parameter C at 180 days to 1 day aging time, C_{180}/C_1, in relation to the concentrations in fly ash leachate is plotted in Fig. 15. The figure shows that when the calcium cation concentration is greater than 300 ppm or the total dissolved solids is greater than 800 ppm, the aging effect increases rapidly with the increase of the two concentrations.

Both maximum shear modulus and cyclic triaxial strength of compacted fly ash with an aging time of 180 days solely depend on the calcium cation concentration in fly ash leachate as shown in Fig. 16. The following correlative equations are obtained as

$$(R_d)_{180} = 0.234 + 0.00174\, Ca^{++}(ppm) \quad (3)$$

$$(C)_{180} = 620 + 3.71\, Ca^{++}(ppm) \quad (4)$$

$$(n)_{180} = 0.384 - 0.00028\, Ca^{++}(ppm) \quad (5)$$

in which Ca^{++} is the calcium cations concentration in ppm. Eqs. 3 to 5 could be used to evaluate the dynamic properties of compacted fly ash

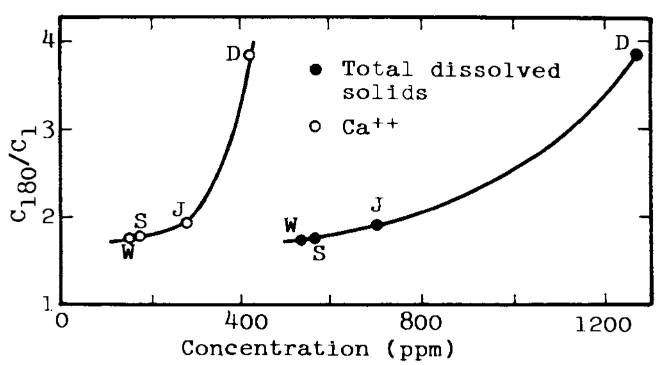

Fig. 15 Aging Effect vs. Calcium Cations and Total Dissolved Solids

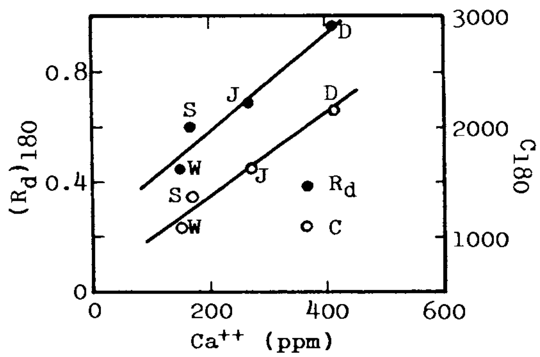

Fig. 16 $(R_d)_{180}$ and $(C)_{180}$ vs. Calcium Cation Concentration

with an aging time of 180 days and the maximum error is about 10%.

CONCLUSIONS

The test results and the review of previous investigations lead to the following conclusions relating to the dynamic properties of saturated coal fly ash.

1. The high temperature during combustion makes fly ash nonplastic but pozzolanic. These two characters greatly contribute to the dynamic properties of fly ash.

2. The cyclic strength of sluiced and just compacted fly ash is low due to its nonplasticity in spite of its high content of fines except some ashes directly from silo. The cyclic strength ratios normalized to relative density of 50% are correlated with mean diameter of grain for sluiced fly ash as Eq. 1, which are very close to the values of natural silts.

3. The maximum shear modulus of sluiced fly ash may be preliminarily evaluated by Hardin equation in relation to void ratio. But the maximum error may be up to 40%.

4. Aging effect is quite an event for compacted fly ash due to pozzolanic action. It is a sustained process and its major portion may occur after 7 or 28 days aging time. An aging time of 180 days can increase maximum shear modulus by 75% to 400% and cyclic strength ratio by 100% to 500% over the values of 1 day respectively.

5. The magnitude of aging effect for compacted fly ash depends on total dissolved solids, especially calcium cation concentration in fly ash leachate. The dynamic properties for an aging time of 180 days solely depend on calcium cation concentration as correlated in Eqs. 3 to 5, although for a shorter aging time they may be influenced by many other factors.

6. The effect of some factors, such as: type of fly ash, density, degree of saturation and aging time, on the attenuation curve of shear modulus ratio and the damping curve of fly ash are not significant except the pressure effect. However, the pressure effect could be normalized by introducing the reference shear strain.

ACKNOWLEDGMENT

This investigation was supported by the Earthquake Engineering Department, Institute of Water Conservancy and Hydroelectric Power Research (IWHR). The support is gratefully acknowledged. Dr. Wen-Shao Wang, Senior Research Engineer of IWHR, kindly permited the writers to quote his study results on fly ash. Senior Research Engineer of IWHR, Ms. Meng-Xin Qiu provided the chemical analysis results of the fly ash leachates. The writers wish to thank them for their support and advice relating to this paper.

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