COAL ASH SLURRY FOR EFFECTIVE UNDERWATER DISPOSAL

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ABSTRACT

In conventional underwater coal ash disposal, the major concern is to increase the disposal capacity by increasing the density. Underwater placement of coal ash slurry is thought to be one method to achieve this. The properties of the slurry and its density compared to the conventional disposal method, however, have not been studied. In this paper, the properties of a new high density slurry, the density of which is 96% of the maximum dry density, are shown from results obtained through laboratory tests. Since the density decrease during underwater placement is less than 4%, this slurry is expected to dispose of coal ash at 92% of the maximum dry density, even underwater. That corresponds to the same density as the field compaction, and 159% of the conventional disposal. The advantage of the new slurry method with regards to strength suggests new possibilities in the utilization of coal ash for stable fills.

Key words: density, laboratory tests, model test, particle breakage, rheology, slurry, underwater structure, wastes (IGC: K6/B12)

INTRODUCTION

In Japan, more than 4.6 million tons of coal ash are discharged annually from coal fired power plants, and it is estimated that this figure will increase up to 7-8 million tons by 1995. At present, 30-40% of the coal ash is used in construction materials, but the rest is disposed of on land and in the sea. Sea disposal of coal ash has increased in Japan, because of insufficient disposal land available near the power plants which produce it. A major concern now is how to increase the density of coal ash disposed underwater.

Conventional sea disposal can be classified into two types; wet and dry disposal. For wet disposal, coal ash is sluiced into the sea, i.e. coal ash is mixed with a large amount of sea water and is hydraulically transported through pipelines to the disposal site. Coal ash conditioned with water is transported by belt conveyors or dump trucks to the shore, and dumped into the sea. This is called dry disposal.

Despite the importance of disposal capacity, density data for coal ash disposed of underwater is limited to the following;

(1) According to the "Coal Ash Disposal Manual" (EPRI, 1979), dry density by wet disposal is 0.72 t/m^3 , compared with 1.12 t/m^3 by field compaction. The method and procedure by which these densities were obtained are, however, rather vague.

(2) A site investigation of wet disposal ground indi-

cates 1.20 t/m^3 average dry density, which is 83% of the maximum dry density (Cunningham et al., 1977). This density is higher than that of the data specified in the "Coal Ash Disposal Manual" (EPRI, 1979). The reasons for this higher density could be the following; (I) consolidation caused by downward water flow through the ash layer, (II) the maximum dry density data used being smaller than the average, and (III) the boring samples are not representative.

(3) Model wet disposal tests indicate dry density of $0.9-1.1 \text{ t/m}^3$ (Yasuhara et al., 1988) and 0.72 t/m^3 (Sugimoto et al., 1989), which are 70-85% and 62% of the maximum dry density respectively. Accumulation speeds of 2.4 m/day and 1.2 m/day were used in these experiments. The accumulation speeds used for the model tests are much higher than those of actual wet disposal, and this may cause the density of the sediments to be higher than the actual density.

Knowing the actual density is therefore crucial to the improvement of the efficiency of sea disposal. According to the information available, such as in the "Coal Ash Disposal Manual" (EPRI, 1979) and "Fly Ash Design Manual for Road and Site Applications" (EPRI, 1986), wet disposal coal ash ground is loose and has a low bearing capacity. This is due to the fact that coal ash has a self-hardening property, which is the result of chemical reactions between water and calcium compounds in the coal ash. Coal ash particles form a loose sediment on the seabed, and immediately increase in strength adequate to

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support the weight of subsequent layers of coal ash. This implies that field densification of disposed coal ash should be achieved as soon as possible. A method for accomplishing this, however, has not yet been found.

Fly ash, the fine spherical particles which make up 70% of coal ash, has been used as an additive for mortar and concrete to improve their fluidity. It is also used as the main component of slurries for construction materials such as grout (Littlejohn, 1978; Funston et al., 1984) or fill for a man-made island (Horiuchi et al., 1992). If the density of coal ash slurry is high enough, then underwater placement of the slurry provides a new effective disposal system to increase both the density and bearing capacity.

In order to confirm the advantages of this new disposal method, a series of laboratory tests has been conducted. At the beginning of this paper, the potential for wet disposal will be analyzed using results obtained from one set of sedimentation tests. Next, a new method of preparing high density coal ash slurry will be presented and finally the feasibility of slurry disposal will be discussed based on the test results.

EXPERIMENTS

Materials

(1) Coal Ash: more than 50 kinds of coal fly ash were used in this study. All the samples were collected from Japanese coal fired power plants and kept dry. Table 1 shows the chemical and physical properties of representative samples. Each chemical composition is shown as an oxide form of the element. Scanning Electron Micrographs are shown in Figs. 1, 2 and 3, where large irregular particles and particle aggregates are seen among spherical particles.

(2) Mixing and curing water: pH 8 artificial sea water and natural sea water were used for preparation and curing

of the samples. The difference in the water did not have an effect on slurry properties.

(3) Mortar plasticizer: a lignin sulfonic acid compound, amounting to 0.1% of the coal ash weight, was added to the mixing water to decrease the slurry viscosity.

Procedures

(1) Sedimentation tests

In order to obtain the density data for wet disposal, model sedimentation tests were carried out in polyacryl pipes (3 m in depth and 19 cm in diameter), as shown in Fig. 4. Four types of coal ashes were selected for the test; H and I for less self-hardening type, and A and G for self-hardening type. Each type was adjusted to water content of 140%, and was poured at a given rate of 1 l/min into each pipe filled with artificial sea water.

Although the total amount of coal ash sluiced in a pipe was 20 kg, daily amount for the sluicing was selected in four categories; i.e. 20 kg in one day, 4 kg per day over 5 days, 2 kg for 10 days and 1 kg for 20 days. The borders of each layer were marked with kaolin in order to determine the degree of consolidation. After 28 days from the last sluicing, samples were obtained from the pipes in order to determine the dry density.

(2) Slurry property tests

Coal ash slurries were prepared by two different techniques, single mixing and double mixing as shown in Fig. 5. The advantage of double mixing was discovered accidentally during the preliminary test stage. This testing was necessary in order to confirm the amount of water required for the flowable slurry; namely coal ash slurries prepared by the addition of water step-by-step and mixing showed less viscosity than the singly mixed slurries. In the standard double mixing procedure, the ratio of the initial water to the total water (initial water ratio) was fixed at 67%.

Table 1. Properties of coal ash

Coal Ash Name		A	B	C	D	E	F	G	H	I	All Coal Ashes		
											Min.	Max.	Av.
Specific Gravity		2.23	2.25	2.31	2.38	2.28	2.15	2.32	2.23	2.26	2.15	2.46	2.25
Mean Diameter (μm)		41.0	17.0	11.5	9.7	7.8	23.0	14.0	11.0	12.0	7.7	47	17.8
Max. Dry Density (g/cm^3)		1.37	1.36	1.47	1.42	1.25	1.24	1.16	1.07	1.10	1.04	1.47	1.25
Optimum Water Content (%)		20.3	21.0	17.2	20.5	24.0	24.8	32.4	36.2	34.1	17.2	36.2	25.9
Ignition Loss (%)		2.40	3.34	1.66	3.57	4.61	2.64	5.32	8.41	2.33	0.58	9.98	4.25
pH		—	12.8	12.7	12.6	12.7	12.8	12.4	11.9	12.1	3.2	13.0	12.1
Chemical Composition (%)	SiO ₂	53.0	53.5	51.0	50.3	56.6	61.0	58.8	49.1	64.6	41.1	65.0	54.4
	Al ₂ O ₃	27.8	23.7	25.0	28.0	26.2	25.7	19.7	27.9	24.8	19.7	35.9	25.3
	Fe ₂ O ₃	5.40	4.81	5.87	5.52	3.86	2.24	5.56	5.59	3.25	1.86	12.5	5.32
	CaO	7.60	7.28	9.12	6.12	3.40	3.82	6.01	3.18	1.62	0.48	9.12	4.96
	SO ₃	0.40	0.33	0.40	0.73	0.39	0.14	0.75	0.38	0.32	0.10	0.96	0.45

Fig. 1. Scanning electron micrograph
Fresh coal ash G

Fig. 2. Scanning electron micrograph
Fresh coal ash H

Fig. 3. Scanning electron micrograph
Fresh coal ash I

A Hobert type mixer was used to prepare the slurries at a rotary speed of 140 rpm and a planetary speed of 60 rpm.

The viscosity of the coal ash slurry was determined within 1 minute after the preparation, using (i) a 15 cm slump cone for plasters, and (ii) a PA flow cone (ASTM C939-87).

Samples for strength tests were prepared by pouring the slurry into plastic molds 5 cm in diameter and 10 cm in height. The samples in the molds were immersed and

Fig. 4. Model sedimentation test

Fig. 5. Procedure for slurry preparation and tests

cured in water at 20°C until the strength test was performed. Strength was determined by a laboratory vane test or an unconfined compression test, followed by dry density measurement.

RESULTS

Sedimentation Tests

In Fig. 6, the changes in thickness of each layer are plotted against time. It is clear, that most of the foregoing accumulated layers are consolidated due to the weight of the subsequent layers. The consolidation of each layer, however, was up to 2%, and ceased within 24

Fig. 6. Change in thickness of layers

Table 2. Results of sedimentation tests

Coal Ash	Average Dry Density ρ_d : (t/m ³)	Accumulation Speed (cm/day)	Maximum Dry Density $\rho_{d_{max}}$: (t/m ³)	Density Ratio $\rho_d/\rho_{d_{max}}$ (%)
A	0.838	106.4	1.37	61.2
G	0.720	119.0	1.16	62.1
H	0.679	103.0	1.07	63.5
H	0.652	22.0	1.07	60.9
H	0.612	11.6	1.07	57.2
H	0.606	6.0	1.07	56.6
I	0.724	96.0	1.10	65.8

Fig. 7. Density distribution of sedimentation samples

hours after the next lift. This means that small but sufficient strength to withstand consolidation develops within 48 hours after the sluicing, even in the case of the less self-hardening coal ash.

All the average densities, calculated from the total height, are listed in Table 2. The dry density distribution and the total height of the samples are shown in Fig. 7. Since the upper part of each sediment layer was very loose as typically seen in 20 kg $\times$ 1 layer (legend: * in Fig. 7), the effect of the accumulation speed (daily thickness of the sediment) on density may be vague as determined from the density distribution in Fig. 7. The total height data, however, indicates an obvious tendency; the dry density of the sediment increases with the increasing daily amount of coal ash sluiced. This means that the disposal speed is one of the greatest factors in determining the density.

The first layer in Fig. 6 does not show consolidation. Based on the results of the vane shear strength test after 90 days, the first layer shows two to three times higher strength than the others. It would be reasonable to speculate that this strength difference existed at the early stage of the test, and prevented the first layer's consolidation. This strength difference appears to result from a chemical reaction between the coal ash and the sea water; the coal ash sluicing increased the pH of the sea water, and changed the magnesium ions in the sea water to the hydroxide precipitation. This precipitation would cause coal ash particles to adhere and thereby increase the strength. All the magnesium ions, however, were changed into hydroxide during the first sluicing.

Properties of Slurries

(1) Viscosity and effect of mixing method

The viscosities of coal ash slurries are shown in Figs. 8 and 9, in which the slurry viscosity decreased with water

Fig. 8. Effect of mixing method on PA flow

content increasing and differed greatly from the coal ash type. In Fig. 8, the double-mixing slurries indicate less viscosity than the other two conventional slurries; the single-mixing slurries and the single-mixing slurries with mortar plasticizer added. Viscosity decrease of the cement paste due to plasticizer addition results from the dispersal of the cement particles. As seen in Fig. 8, the dou-

ble mixing has a greater effect on decrease of the viscosity than the addition of plasticizer. The mechanism of the double-mixing effect, therefore, can not be explained by coal ash particle dispersal. The slumps of the slurries are shown in Fig. 9, where the advantage of double mixing for coal ash is confirmed; the higher slump being obtained by the double mixing at the same water content. This means that with the double mixing, a higher density slurry can be produced than with the conventional methods.

Fig. 9. Effect of mixing method on slurry viscosity

The relationship between the slurry slump and the dry density of the hardened sample is shown in Fig. 10, where the dry densities of the slurries decrease with increasing slump. The results of the underwater placement tests (Horiuchi et al., 1992) indicate that the slope of the placed slurry mass is closely related to the slump, and the appropriate slope for the underwater placement, from 5° to 10°, can be attained by using slurries with 10–11 cm slump. The dry densities of the slurries at given slumps are listed with the data for the sedimentation tests in Table 3, where densities of 10–11 cm slump slurries are shown to be much larger than the average density of the sediments. Comparing the two mixing methods at the same slump, the double mixing gives a higher dry density than the single mixing. This advantage was confirmed experimentally for other types of coal ash used in this study.

The effect of initial water content on the slump of the double-mixing slurry is shown in Figs. 11 and 12. As seen in Fig. 11, the highest slump is obtained when the initial

Table 3. Dry density of slurries

Sample Coal Ash Density		Dry Density of Slurries						Average Dry Density of Sedimentation Test Samples 〔Accumulation Speed〕 96 ~ 119 cm/day
		Double Mixing Slurry			Single Mixing Slurry			
		Slump 9 cm	Slump 11 cm	Slump 13 cm	Slump 9 cm	Slump 11 cm	Slump 13 cm	
A	ρ_d ρ_d / ρ_{dmax}	— —	1.36 99.3	1.24 90.5	— —	— —	— —	0.838 61.2
B	ρ_d ρ_d / ρ_{dmax}	1.31 96.3	1.30 95.6	1.28 94.1	1.30 95.6	1.25 91.9	1.18 86.8	— —
C	ρ_d ρ_d / ρ_{dmax}	1.42 96.6	1.40 95.2	1.37 93.2	1.39 94.6	1.35 91.8	1.29 87.8	— —
D	ρ_d ρ_d / ρ_{dmax}	1.36 95.8	1.34 94.4	1.32 93.0	1.32 93.0	1.28 90.1	1.22 85.9	— —
E	ρ_d ρ_d / ρ_{dmax}	— —	1.10 88.0	1.05 84.0	— —	1.05 84.0	1.00 80.0	— —
F	ρ_d ρ_d / ρ_{dmax}	— —	1.22 98.4	1.17 94.4	— —	1.12 90.3	1.07 86.3	— —
G	ρ_d ρ_d / ρ_{dmax}	1.17 100.9	1.15 99.1	1.10 94.8	1.14 98.3	1.09 94.0	1.02 87.9	0.720 62.1
H	ρ_d ρ_d / ρ_{dmax}	1.02 95.3	1.00 93.5	0.98 91.6	0.99 92.5	0.98 91.6	0.96 89.7	0.679 63.5
I	ρ_d ρ_d / ρ_{dmax}	1.09 99.1	1.05 95.5	1.00 90.9	1.06 96.4	1.02 92.7	0.96 87.3	0.724 65.8

ρ_d : Dry Density (t/m³) ρ_d/ρ_{dmax} : Density Ratio (%)

Fig. 10. Effect of mixing method on dry density

Fig. 12. Effect of initial water content on slump peak of double-mixing slurry

Fig. 11. Effect of initial water content on slump of double-mixing slurry

Fig. 13. Strength development of double mixing slurries

water content is 40–45%. In Fig. 12, the slump peak is found to be at around an initial water content of 20% and is independent of the total water content. In both figures, the initial water content of the slump peak is noted to depend on the type of coal ash and corresponds to 116–126% of the optimum water content, at which a larger shear force may be exerted on the coal ash particles by the mixing process. A higher slump was also observed when the first mixing speed or first mixing time period was increased. These phenomena suggest that the double mixing effect may be caused by the mechanical change of coal ash particles which occurred during the first mixing.

(2) Strength development

The development of strength of the slurries is shown in Fig. 13, where coal ashes B and D indicate a long term strength development, similar to the compacted coal ashes (Gatti et al., 1982; Gray et al., 1972). In the cases of

coal ashes E, F, and H, the strength develops so slowly that an obvious increase can not be confirmed before two years curing. The same type of slow strength development was reported for the compaction sample (Sutherland et al., 1968), however, no discussion was made about the mechanism of strength development starting after two years. SEM observations on hardened coal ash slurries in Fig. 13 indicated the formation of chemical compounds on the particle surface, however, gave less quantitative information about the long term strength development.

Figure 14 shows the relationship between 28 day strength and density, in which unconfined compressive strength (q_u) can be approximately expressed with dry density (ρ_d) using the following equation; $q_u = A \cdot (\rho_d)^B$,

Fig. 14. Relationship between strength and density

where both A and B are constant. Using these relationships, the strength of the underwater sample can be estimated.

If an unconfined compressive strength of 200 kPa is required for actual land use, then the one year strengths of slurries E and F in Fig. 13 are not sufficient. Even though there remains the possibility of increasing their strength in the future, it may be difficult to attain sufficient strength for all types of coal ash. To enhance and accelerate strength development, the addition of cement or gypsum would be easy and effective (Horiuchi et al., 1985) with this slurry disposal system.

DISCUSSIONS

Mechanism of Double Mixing

The effect of double mixing is related to the initial mixing at a specific water content, as seen in Figs. 11 and 12.

Since some technical papers have reported the particle degradation of coal ash during the compaction process (Leonards et al., 1982; Sutherland et al., 1968), it would seem reasonable to conclude that some fractions in coal ash, such as large and irregular particles as shown in Figs. 1, 2 and 3, are broken into pieces by a shear force exerted during the mixing, and this change in size distribution may decrease voids in the slurry and increase its density.

To confirm the particle degradation, particle size distribution was measured using slurry samples without drying. The result is shown in Fig. 15, where the Hobert mixing, especially the double mixing, increases finer particles. The particle size change is not so large, however, it plays a role in decreasing the voids.

Because the initial mixing at approximately optimum water content changes voids, the procedure used in the compaction test, especially the mixing method, would affect its density. The effect of the mixing method was investigated through additional compaction tests (ASTM D698-91, Procedure A), in which the Hobert mixing time for coal ash/water mixtures was changed from 0 to 20 minutes. In Fig. 16, compaction curves obtained for coal ash G show that increasing the mixing time moves the curves upward. The same results were also obtained for coal ashes H and I. Since both the maximum dry density and the optimum water content are affected by the mixing method, the laboratory test results should be carefully considered when they are applied to field compaction.

Figure 16 also shows the importance of the initial mixing, at approximately optimum water content, on the slurry density. The highest density slurry can be obtained by initial mixing at 116–126% of the optimum water content. This difference in water content may refer to the different procedure followed; applying compaction energy or merely adding water.

Slurry Density

Since coal ash slurry should be placed underwater, the density of the slurry has to be evaluated at a given viscosity suitable for the placement. If the same specification applied in the Hakucho Ohashi project is chosen, the vis-

Fig. 15. Effect of mixing process on size distribution

Fig. 16. Effect of mixing time on compaction test results

cosity is with a slump of 11 cm (Kawasaki et al., 1992). In order to evaluate the slurry density, the density ratio (Rd: ratio of the dry density of the 11 cm slump slurry to the maximum dry density) is plotted against the mean diameter in Fig. 17. The mean diameter of the coal ash is an average 0.015 mm, so the average density ratio expected is 92% for single mixing and 96% for double mixing, respectively. The tendency in Fig. 17, in which Rd decreases with the decrease of the mean diameter, may be explained by the difficulty in breaking smaller particles.

Ground Density and Strength

The relationship between the average accumulation speed and average dry density is shown in Fig. 18 using the data shown in Table 2. At an accumulation speed of 100 cm/day, the density ratio ranges from 61% to 66%, and less self-hardening coal ashes H and I indicate higher values than the others. In the actual disposal, the accumulation speed would not exceed 10 cm/day, therefore the average dry density of the ground, coal ash H for example, can be estimated to be 58% of the maximum dry density. This density ratio, 58%, coincides with the information in the "Coal Ash Disposal Manual" (EPRI, 1979), if the field compacted density is 90% of the maximum dry density; i.e., $0.72/(1.07/0.90)=0.58$.

In the case of dry disposal, the density would be changed depending on the water depth; long sedimentation, deeper than 5 m, may disperse the humidified coal ash mass and will bring about a situation similar to wet disposal, whereas the shallower the depth, the closer the situation is to land disposal. The actual density of the dry disposal would be affected by the method, however it is expected that the average density would not be higher than 80% of the maximum dry density (Sugimoto et al., 1989).

Fig. 17. Density ratio of slurries (A~I: Coal ash name)

Fig. 18. Effect of accumulation speed on density

According to the results obtained in large-scale model tests (Horiuchi et al., 1992) and man-made island construction (Kawasaki et al., 1992), density decrease during placement would be less than 4%. Since the density ratio of the double-mixing slurry is 96%, the actual density ratio of the slurry disposal can be expected to be more than 92%. This density corresponds to 159% of the wet disposal and more than 115% of the dry disposal, and is even higher than field compaction made by 6 passes of a 10 to 12 ton rubber tired roller (EPRI, 1979).

As shown in Fig. 14, the strength is closely related to dry density. Since dry density of the wet disposed ground is 58% of the maximum dry density, the dry density of the wet disposed ground is far below the density range in

Fig. 19. Effect of calcium content on 28 day strength of double mixing slurry

this figure. If the relationship in Fig. 14 were sustainable at the lower density, the strength of wet disposed ground could be calculated to be 0 to 9 kPa at 28 days. To increase the strength of the wet disposal mass, a 5–10% cement addition during sluicing could be effective if segregation of the cement particles from the coal ash can be prevented even after deep sedimentation (Yasuhara et al., 1988).

In Fig. 19, the strength of an 11 cm slump slurry after 28 days is plotted against the calcium content. The relationship shows a rather large scattering, and an increase in the calcium content increases the strength. Advantages of the slurry disposal on static and dynamic properties are confirmed using a coal ash of 2.03% in calcium content (Yasuhara et al., 1991). It could be speculated that coal ash having more than 4% calcium content would develop unconfined compressive strength of 200 kPa or more, and is sufficient for land use.

CONCLUSION

In conventional underwater disposal of coal ash, increasing the mass density is a major concern, and a new disposal method, in which coal ash slurry is placed underwater, was thought to be the best solution. A series of laboratory tests were carried out to study the feasibility of this new method. Results obtained in the present study can be summarized as follows;

(1) Dry density of coal ash disposed by the conventional wet disposal increases with increasing accumulation speed. At an accumulation speed of 10 cm/day, the average dry density of the sediment can be estimated to be 58% of the maximum dry density.

(2) Dry density of slurry is decreased with decreasing viscosity. At a slump of 11 cm, which is suitable for

underwater placement, the dry density of the slurries are 84.0% to 99.3% of the maximum dry density.

(3) The slurries prepared by the double-mixing method, in which the initial mixing of coal ash with 2/3 of the total amount of water is followed by the second mixing with the remaining water, give higher density than the conventional single mixing; i.e., at a slump of 11 cm, average dry density of the double-mixing slurry is 96% of the maximum dry density and 4% higher than the single-mixing slurry.

Actual density of the slurry disposal using the double-mixing slurry can be predicted to be more than 92% of the maximum dry density. This 92% is the same as for field compaction, and corresponds to 159% of the conventional wet disposal method. This higher density leads to higher strength, and therefore may present new possibilities for the utilization of coal ash as stable fills for land reclamation in open water or other man-made island construction.

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