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AIR POLLUTION PREVENTION DURING FLY ASH DISPOSAL

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SYNOPSIS

The chemical and physical properties of five typical fly ashes are presented in this paper which also evaluates their compactibility based on the results of Proctor compaction test and relative density test. The variations of permeability, compressibility and shear strength parameters with density of fly ash are described. A wind tunnel was used to determine the erosion resistance to wind. It is found that the threshold wind velocity increased significantly with increasing density, water content, specific gravity, soluble matter and ferrous oxides contents. i) Infiltration of water into the fly ash due to irrigation and ii) water content decrease due to evaporation were investigated in order to find the optimum method of water sprinkling. By sprinkling water on the surface of fly ash under certain conditions, a thin shell, having high resistance to wind erosion, is found. Once the shell is broken, it will not be formed again by sprinkling water.

INTRODUCTION

The annual fly ash production from thermal power plants in China has been increasing steadily and is now more than 50 million tons a year. About 25% of the above mentioned amount is utilized in some way. The remaining material is usually disposed of as waste. The conventional way of disposing fly ash in China is to discharge ash in slurry form into ash lagoon, however, in recent years dry disposal has started to be used in some new power plants. Attention has been focused recently on air pollution prevention during fly ash disposal, and research was conducted in the laboratory and using field studies to find the optimum way of controlling density and water content of fly ash from the point of view of air pollution prevention. Meanwhile, the variation of engineering properties of fly ash with the corresponding changes in density as well as water content also needs to be investigated to estimate the stability and deformation of the disposed fly ash.

CHEMICAL COMPOSITIONS AND PHYSICAL PROPERTIES

Five samples were taken from different power plants in the north part of China representing typical fly ashes produced in this area as well as in some southern parts of China, because the power plants in both areas use the same kind of coal produced in the north part. These five samples are Datong fly ash from Shanxi Province, Gao-

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jing fly ash taken near the city of Beijing, Jiaozou fly ash from Henan Province, Shentou fly ash also from Shanxi Province, and Weihe fly ash from Shaanxi Province. Tables 1 and 2 show the chemical compositions of the fly ashes and of their extracted liquids. It can be seen from the tables that the Datong fly ash has higher Fe_2O_3, CaO and SiO_2 contents, but it has lower Al_2O_3 content in comparison with others. Among those five samples, the losses of ignition of Jiaozou and Weihe fly ashes are much higher than others. Geotechnical tests were conducted according to the procedures specified in the Chinese Standard Code of Soil Testing (1989). Most of them are similar to those of ASTM, except consistency limits and relative density tests. Fig. 1 shows the gradation curves of these five fly ashes. It can be seen in the figure that the Weihe contains the smallest grain sizes and the next one is Datong. The other three curves have nearly the same medium diameter d_{50}, among which Shentou's coefficient of uniformity is the largest. In regard to their specific gravities, they are not unusual and range from 2.11 to 2.45. Though fly ash is usually treated as a cohesionless material, the fall cone test is still used to determine its liquid and plastic limits. They are shown in Table 3. Their high consistency and low Plasticity Index reveal the porous nature of the particles. Nevertheless, the engineering properties of the fly ash sample could not be estimated based on their consistency limits alone.

Table 1 Chemical Properties of Fly Ash.

Name (1)	SiO_2 % (2)	Al_2O_3 % (3)	Fe_2O_3 % (4)	CaO % (5)	MgO % (6)	Na_2O % (7)	K_2O % (8)	SO_3 % (9)	Loss of ignition % (10)
Datong	51.5	22.1	15.4	4.3	0.7	0.3	1.7	1.0	4.6
Gaojing	48.7	36.5	7.0	3.2	0.9	0.3	0.9	0.5	4.3
Jiaozou	47.2	32.8	3.3	3.6	0.5	1.1	1.1	0.3	8.2
Shentou	45.3	46.8	3.6	2.8	0.5	0.3	0.4	0.5	1.2
Weihe	46.1	35.5	5.6	2.8	0.4	0.3	1.3	1.3	8.3

Table 2 Chemical Compositions of Extracted Liquid.

Name	Concentration, ppm						pH
	Ca^{++}	K^+	Na^+	SO_4^-	Mg^{++}	Soluble matter	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Datong	418.9	4.9	3.4	460	43.0	1272	12.4
Gaojing	216.4	2.5	4.5	150	2.0	974	11.5
Jiaozou	274.7	0.9	4.9	160	3.4	696	12.1
Shentou	172.7	0.5	0.5	410	9.8	561	10.4
Weihe	155.0	1.9	0.7	300	3.9	535	11.7

Table 3 Physical Properties Of Fly Ash.

Name	Grain compositions, %			Specific Gravity	Liquid Limit %	Plastic Limit %
	>0.05 mm	0.05-0.005 mm	<0.005 mm			
(1)		(2)		(3)	(4)	(5)
Datong	23	73	4	2.47	38	27
Gaojing	38	61	1	2.11	46	35
Jiaozou	36	62	2	2.21	34	25
Shentou	36	59	9	2.29	29	20
Weihe	6	82	12	2.18	59	47

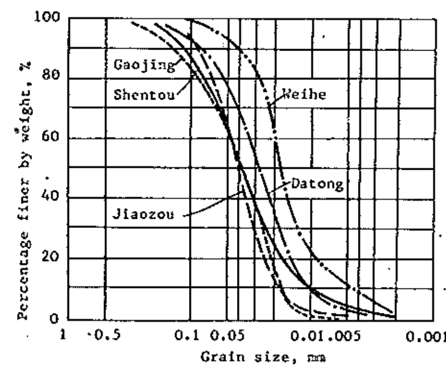

Fig. 1 Gradation Curves.

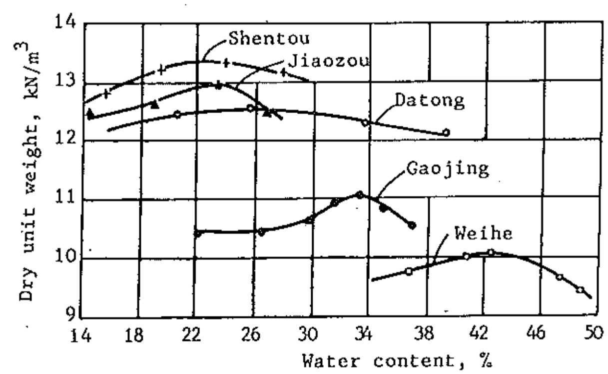

Fig. 2 Compaction Curves.

Table 4 Compactibility of Fly Ash.

Name	Relative density test		Compaction test	
	Maximum dry unit weight kN/m³	Minimum dry unit weight kN/m³	Maximum dry unit weight kN/m³	Water content %
(1)	(2)	(3)	(4)	(5)
Datong	12.8	6.8	12.4	26.0
Gaojing	12.0	7.4	10.9	33.2
Jiaozou	13.5	9.6	12.8	23.0
Shentou	13.4	7.9	13.0	22.0
Weihe	10.2	6.0	9.9	42.3

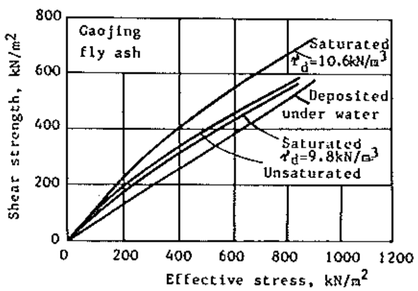

Fig. 3 Shear Strength Envelopes of Gaojing Fly Ash.

COMPACTIBILITY

The maximum and minimum dry unit weight of five fly ashes determined from the relative density test are an indication of its compactibility. They are shown in Table 4 together with the maximum dry unit weight determined in Proctor compaction curves as shown in Fig. 2. It has to be noted that the method used to determine the minimum dry unit weight was by pouring dry fly ash carefully through a funnel into a cylindrical metal container with a capacity of 0.25 litre. While the maximum dry unit weight was determined by hammer striking the dry fly ash through the wall of the same container as well as through a metal pad placed on the top of the sample. It can be seen from Table 4 that the maximum dry unit weight determined from the relative density test is generally larger than that determined from the compaction test. Furthermore the maximum dry unit weights of Shentou and Jiaozou fly ashes are greater than those of others, because of their relatively larger coefficients of uniformity. The field compaction test (Pu, Liu and Lee, 1989) on Gaojing fly ash reveals that the dry unit weight achieved by 6 passes of a 12 ton vibrating roller on 0.4 m lift at optimum water content is about 10.0 kN/m³, which is equivalent to relative density of about 0.80 or degree of compaction of 0.92. Based on the above mentioned test results and the data collected in the ash lagoon, specimens having relative density of 0.45, 0.65 and 0.80 were prepared for determining their engineering properties. A relative density of 0.45 is equivalent to the density of fly ash deposited under water; whilst relative density of 0.80 corresponds to well compacted density, and the relative density of 0.65 could be easily achieved by light compaction.

ENGINEERING PROPERTIES

Table 5 shows the values of coefficient of vertical permeability k of fly ashes determined in variable head permeameter on specimens having three different densities and corresponding moulding water contents. The values of k of these five fly ashes are in the same order of magnitude. They decrease with increase of density, however, the variation is small. Consolidation tests were conducted on similarly prepared specimens. Table 6 shows the coefficient of compressibility a_v of fly ashes both under unsaturated and inundated conditions. It can be readily seen from the table that the compressibility decrease with increasing density and decreasing water content. With regard to the strength characteristics, the consolidated drained triaxial test was used to determine the effective shear strength envelopes. Fig. 3 shows the variation of effective shear strength with density of Gaojing fly ash. The highest line denotes fly ash having a relative density of 0.80 in a saturated state, and the lowest line denotes fly ash having a relative density of 0.45 also in saturated state. The other two lines between them are the strength envelops of fly ash having a relative density of 0.65 in saturated and unsaturated states respectively. It can be seen from the figure that strength envelopes of fly ash having higher relative density are not linear. Therefore, their cohesion may not be zero, if the nonlinear envelop is approximated as a straight line. The approximate effective shear strength values of the five fly ashes shown in Table 7 increase slightly with increasing density and with decreasing water content.

THRESHOLD WIND VELOCITY

A wind tunnel was used to determined the relationship between density, water content and threshold wind velocity, the latter being the minimum wind velocity required to raise fly ash particles into the air as determined by visual observation. The water content denotes the average value within the surface layer having a thickness of 0.01 m. The specimen to be tested is placed at the bottom of a wind tunnel, which is 2 m long and has a square cross section with side length of 0.5 m. It is well known that the wind velocity varies with the distance above the ground surface. The threshold wind velocity in this paper is defined as the wind velocity at a height of 0.116 m above ground, which is approximately equal to half of the wind velocity at 10 m above the ground. The full lines in Fig. 4 denote the fly ash in loose state and the dashed lines denote the fly ash compacted to a density corresponding to 0.81 times the Proctor maximum dry unit weight. It can be seen from the figure that the threshold wind velocity increases substantially with the increasing density and water content. Among these five fly ashes, Datong fly ash has the highest resistance to wind and Weihe fly ash the lowest. The low threshold velocity of Weihe fly ash could be explained by its fine particles, but the high threshold velocity of Datong fly ash

Table 5 Permeability of Fly Ash.

Name	Specimen preparation			Coefficient of permeability
	Relative density	Water content %	Dry unit weight kN/m^3	m/sec
(1)	(2)	(3)	(4)	(5)
Datong	0.45	25.3	8.5	$2.2 \cdot 10^{6}$
	0.65	25.3	9.7	$1.8 \cdot 10^{6}$
	0.80	25.3	10.8	$0.5 \cdot 10^{6}$
Gaojing	0.45	24.8	8.9	$5.2 \cdot 10^{6}$
	0.65	24.8.	9.8	$1.2 \cdot 10^{6}$
	0.80	24.8	10.6	$0.9 \cdot 10^{6}$
Jiaozou	0.45	22.1	11.1	$1.7 \cdot 10^{6}$
	0.65	22.1	11.9	$0.6 \cdot 10^{6}$
	0.80	22.1	12.6	$0.5 \cdot 10^{4}$
Shentou	0.45	21.6	9.7	$1.1 \cdot 10^{6}$
	0.65	21.6	10.8	$0.3 \cdot 10^{6}$
	0.80	21.6	11.8	$0.1 \cdot 10^{6}$
Weihe	0.45	41.7	6.8	$4.7 \cdot 10^{6}$
	0.65	41.7	8.1	$4.1 \cdot 10^{6}$
	0.80	41.7	8.9	$0.8 \cdot 10^{6}$

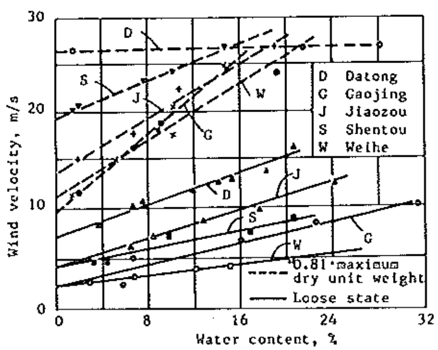

Fig. 4 Relation Between Threshold Velocity and Water Content at Two Different Densities.

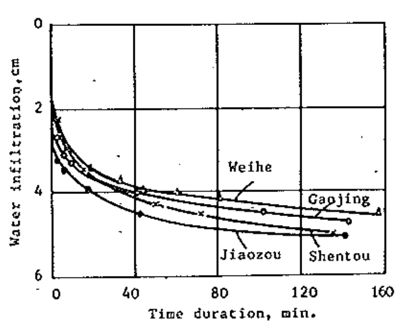

Fig. 5 Water Infiltration Against Time.

could not explained using the same reason, because the particle size of Datong fly ash is not the largest as shown in Fig. 1. Perhaps, the large value of specific gravity, ferrous oxides and soluble matter contents rather than particle size of Datong fly ash, shown in Tables 1, 2 and 3, plays an important role in wind resistance.

INFILTRATION AND EVAPORATION

Laboratory Tests

In the case of using water sprinkling to prevent air pollution, it is necessary to investigate the minimum time of sprinkling required to moisten the fly ash to a given depth. The decrease of water content in fly ash due to evaporation should also be investigated. Based on the results of these investigations, the optimum mode of sprinkling can be estimated. In the water infiltration test, fly ash is placed in a transparent cylinder having a height of 1 m and an internal diameter of 0.06 m. Then water, being equivalent ot depth of 0.07 m, is poured on the top of the specimen. The curves shown in Fig. 5 are the visual observation of water infiltration against time. It shows clearly that water can infiltrate to a depth in excess of 0.03 m within 20 minutes, and the infiltation is not directly proportional to the coefficient of permeability of fly ash. An evaporation test was conducted outside the laboratory. Fly ashes were compacted at close to their optimum water contents to densities equal to about 0.81 times their Proctor maximum dry unit weight. The decrease of average water content within a 0.01 m thick surface layer with time is shown in Fig. 6 along with the water evaporation curve determined in evaporating dish placed in the same place. It can be seen from the figure that the higher the initial water content, the quicker the evaporation in fly ash, irrespective of the permeability. Fig. 6 also shows that the water content decrease in fly ash is similar to that in an evaporating dish, but in much less degree. The ratio of water content decrease within 24 hours to original water content is another parameter for evaluating the evaporation characteristics of fly ash. The ratio varies with the original water content as shown by the lower curve in Fig. 7. It can be seen from the figure that the decrease of water content is small, when the original water content is lower than about 3% or higher than about 20%. These results indicate that the pore water may become continuous in Gaojing fly ash when the water content is higher than about 20%, therefore, it is considered possible that the supply of water from the lower part of fly ash is compensating for water loss in higher parts of the fly ash sample.

Field Tests

Field tests on Gaojing fly ash were carried out near the Gaojing power plant, Beijing. Field compaction testing reveals (Pu et al., 1989) that the compaction density increases from 9.6 to 10.3 kN/m^3, when placement water content rises from 16% to 30% under 6 passes of a 12 ton vibrating roller with a 0.3m lift. If the placement water content exceeds 33%, the fly ash will adhere to the surface of the roller thus prevent effective compaction. After the fly ash is compacted to the required density and placement water content, the ratio of water content decrease within 24 hours due to evaporation is as shown by the upper curve in Fig. 7. It is obvious that the shape of the curves either measured in laboratory or in field is very similar, though the

Table 6 Compressibility of Fly Ash.

Name	Specimen preparation			Coefficient of compressibility at 100-400 kPa	
	Relative density --	Water content %	Dry unit weight kN/m³	Unsaturated kPa⁻¹	Inundated kPa⁻¹
(1)	(2)	(3)	(4)	(5)	(6)
Datong	0.45	25.3	8.5		0.00082
	0.65	25.3	9.7	0.00019	0.00047
	0.80	25.3	10.8	0.00009	0.00013
Gaojing	0.45	24.8	8.9		0.00008
	0.65	24.8	9.8	0.00005	0.00005
	0.80	24.8	10.6	0.00005	
Jiaozou	0.45	22.1	11.1		0.00010
	0.65	22.1	11.9	0.00005	0.00005
	0.80	22.1	12.6	0.00004	0.00005
Shentou	0.45	21.6	9.7		0.00056
	0.65	21.6	10.8	0.00011	0.00044
	0.80	21.6	11.8	0.00006	0.00008
Weihe	0.45	41.7	6.8		0.00071
	0.65	41.7	8.1	0.00013	0.00029
	0.80	41.7	8.9	0.00010	0.00014

Table 7 Shear Strength Parameters of Fly Ash.

Name	Relative density	Effective shear strength parameters			
		Unsaturated		Inundated	
		Cohesion (kPa)	Angle of internal friction (Degrees)	Cohesion (kPa)	Angle of internal friction (Degrees)
(1)	-- (2)	(3)	(4)	(5)	(6)
Datong	0.45			0	32.0
	0.65	30	32.0		
	0.80	60	32.0		
Gaojing	0.45			0	33.0
	0.65	75	32.0	35	34.0
	0.80			55	39.5
Jiaozou	0.45			0	31.0
	0.65	60	31.0		
	0.80	50	34.5		
Shentou	0.45			0	31.0
	0.65	50	28.5		
	0.80	60	29.5		
Weihe	0.45			0	32.0
	0.65	40	31.5		
	0.80	60	33.0		

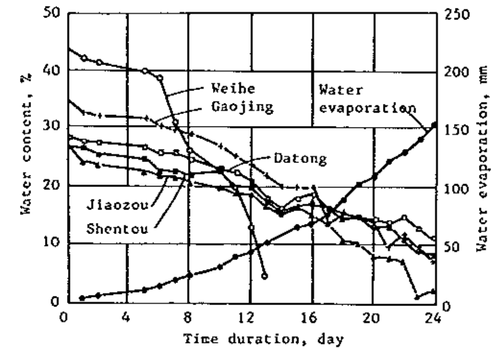

Fig. 6 Water Content Decrease due to Evaporation.

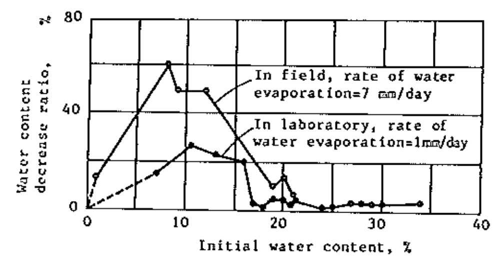

Fig. 7 Relation between Water Content Decrease Ratio and Initial Water Content of Gaojing Fly Ash.

intensities of evaporation are quite different. As soon as compaction is completed, water should be sprinkled on the surface. In this way, a thin shell having a thickness of 0.5 mm can be formed. The shell has high resistance to wind erosion, its threshold wind velocity will be about 18 m/s, even if its water content is decreasing to less than 2%. However, if the water content of fly ash is smaller than half of its optimum water content when the fly ash first received water sprinkling, the shell would not form. It was observed that the shell was easily broken by mechanical disturbance, and once it was broken, the shell would not form again as a result of water sprinkling. In the case of disturbed fly ash surface, the most effective way of preventing air pollution is sprinkling water constantly and keeping the fly ash in a moist condition.

CONCLUSIONS

Based on the test results from this study on five typical fly ashes, the following conclusions regarding to fundamental properties are reached.

1. The maximum dry unit weight corresponding to the minimum void ratio is generally larger than the Proctor maximum dry unit weight. In the case of Gaojing fly ash, a degree of compaction of 0.92 of Proctor maximum dry unit weight could be achieved by 6 passes of a 12 ton vibrating rolloer on 0.4 m lift on optimum water content, which is much smaller than that obtain in Proctor compaction test.

2. The coefficients of permeability of the tested fly ash are of a similar order of magnitude (10^{-6} m/s). Their variation with density is small.

3. The reduction of compressibility with the increasing density and with decreasing water content is obvious.

4. The effective friction angle increases slightly with increase of density, but the effective cohesion increases significantly.

5. The threshold wind velocity increases substantially with the increasing specific gravity, ferrous oxides and soluble matter contents, as well as the density and water content.

6. Irrigated water can infilter to 30 mm within 20 minutes. The rate of infiltration may not be directly proportional to the coefficient of permeability.

7. The rate of evaporation appears to be directly related to the initial water content.

8. When the water content of Gaojing fly ash exceeds 20%, the pore water becomes continuous, therefore, it is likely that water from the lower part of the fly ash will compensate for water loss due to evaporation.

9. Upon sprinkling water on the surface of fly ash, a thin shell, having high resistance to wind erosion, is found. However, once broken by mechanical action, it would not form again.

After knowing the above mentioned properties, some measures in fly ash disposal can be adopted for minimizing air pollution.

a. For a given fly ash, either increasing density or water content decreases air pollution.

b. Sprinkling water on the surface of fly ash for about 20 minutes is an effective way of moistening the surface of fly ash.

c. The water content of fly ash should be higher than half of its optimum water content when the fly ash first received water sprinkling.

d. Do not break the thin shell formed on the surface of fly ash after first receiving water sprinkling.

e. Increasing the density can significantly improve the wind resistance of fly ash, but the corresponding changes of permeability and strength is not very obvious.

f. The experience in specifying compaction of cohesive soils is not strictly valid for fly ash in the field.

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