Goumans/Senden/van der Sloot, Editors
Waste Materials in Construction: Putting Theory into Practice

Engineering Properties of the Coal Ashes stored in the "Valdeserrana" Lagoon. Andorra Power Plant (Spain).

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ABSTRACT: Andorra Coal-fired Power Plant produces annually over 1,000.000 tons of coal ashes (15% bottom ash - 85% fly ash) that are stored in the Valdeserrana Dam (a 18 Hm^3 lagoon).The chemical composition of the ashes placed in the lagoon is similar to that of dry ashes. However, the mineralogical analysis show a decrease of the vitreous components, which would account for a decrease of its pozzolanic properties. The ashes show no cementation while in the lagoon and behave very much like a natural soil. The gradation of the particles varies with the distance from the pouring point, being the coarser particles (bottom ash) closer to it. The coarser materials can be classified as a loose silty sand. The finer materials (fly ash) can be classified as weak silt with traces of sand. Both materials have high moisture content and high void ratios and are normally (or even under) consolidated. Still, they have low compressibility, good friction angles and high consolidation coefficients. Therefore these ashes can be efficiently improved by different methods like precharge or mixing with lime or cement if they are to be used as foundation soil.

1. INTRODUCTION

Andorra Coal-fired Power Plant (Teruel, Spain) produces annually over 1,000.000 tons of residual coal ashes. These ashes are composed approximately by 15% of bottom ash and 85% of fly ash. They are mixed together with water and conducted through a pipe to the Valdeserrana Dam where the sluice is poured and the ashes settle. The lagoon has a total capacity of 18 Hm^3 and about half of its total area (about 1/3 of its volume) is filled with ashes (see figure 1).

A research program is being carried out to investigate the potential uses of the ashes long time after its disposal in the lagoon. Its first part has assessed the chemical and geomechanical properties of the ashes, determining their aptitude as a foundation soil. The site investigation included field and laboratory testing. The paper presents their main results.

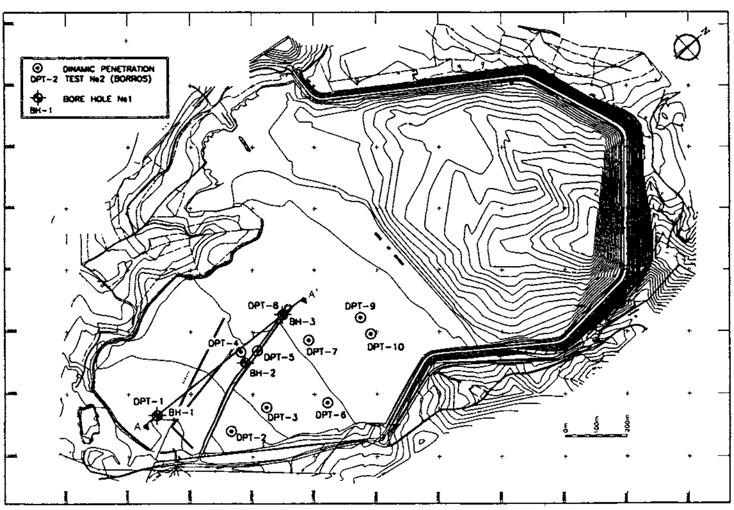

Figure 1.- (Courtesy ENDESA) Valdeserrana Dam. Site Plan.

2. EXPERIMENTAL PROGRAM

2.1. Bore Holes and Dynamic Penetration Tests

A total of 3 bore holes, reaching to a maximum depth of 21 meters, and 8 Dynamic Penetration Tests (DPT, Borros type) were carried out to investigate the general properties of the deposit.

The bore holes were placed along a small track that goes inside the lagoon, at different distances from the pouring point. The Dynamic Penetration Tests (DPT) were done with a very ligth machine that was able to circulate over the soft surface of ashes. A DPT was done beside each bore hole in order to correlate their results with the soil observed at the bore hole. The rest of the penetration tests (up to a total of 10) were placed at different points of the lagoon (see figure 1).

Figure 2 shows the main results of the field investigation. The ashes are placed directly over the natural soil and the deposit reaches a maximum thickness of 21 meters.

The investigation showed that the size of the ash particles of the deposit vary with the distance from the pouring point. Close to it (Bore Hole 1), where the water flows faster, the deposit contains mainly the coarser particles (mostly bottom ash). As the distance from the end of the pipe increases, the proportion of finer particles in the deposit increases, becoming a mixture of bottom and fly ash. At a far distance from the pouring point the deposit contains mostly fly ash (finer particles).

The underlying natural soil is formed by a Terciary sedimentary formation, composed by layers of very hard clay and cemented gravel. They can be considered as a rigid and impervious stratum.

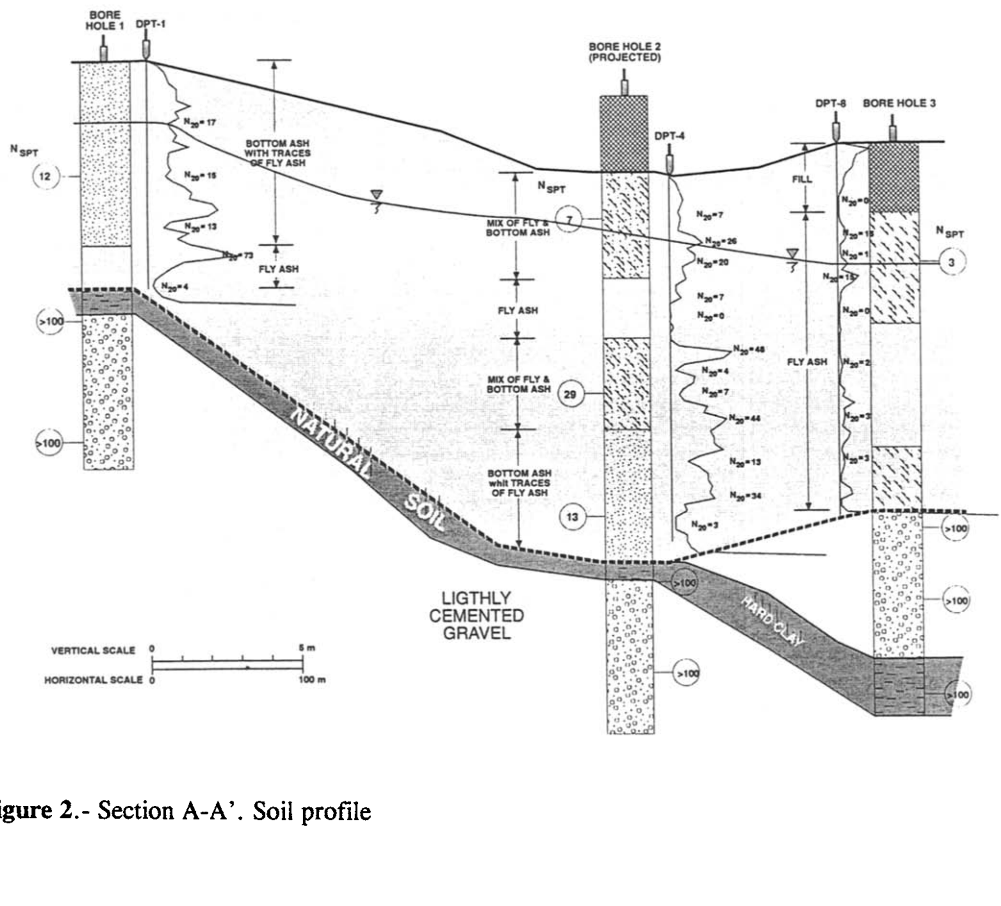

Figure 2.- Section A-A'. Soil profile

2.2. Chemical analyses

The chemical composition of ashes located at different depths and places (and therefore, of different ages) were determined. Table I shows the results of these analyses compared to the average composition of fly and bottom ashes before its disposal.

As can be seen in Table I both fly and bottom ashes have very similar chemical composition and they do not change much due to the disposal in the lagoon. Only a small descent of the calcium oxide (CaO) content can be observed.

Also, it can be seen that Andorra's ashes are of the silico-aluminous type (opposed to the sulpho-calcic type), with small CaO content, and almost no free calcium oxide, so they are not self-cementitious. Actually the ashes did not exhibit any cementation at the lagoon.

TABLE I .- Chemical composition of fly & bottom ashes before and after its disposal in the lagoon

Percent by weight	Andorra fly ash (average)	Bottom ash (freshly disposed)	Bottom & fly ash (old)	Bottom ash (old)	Andorra Bottom ash (average)
SiO_2	45,10	38.8	40.1	41,0	47,30
Al_2O_3	26,16	20.8	20,7	20,3	23,34
Fe_2O_3	16,46	29.4	30.2	27.7	19,26
CaO	7,51	6.11	4,2	5.81	7,01
MgO	1,28	0.97	0.87	0.90	1,20
SO_3	0,44	0.53	0,36	0.40	0,18
Na_2O	0,61	0.17	0,20	0.18	0,13
K_2O	1,38	1.01	1,42	1.15	1,07
Loss on ignition	2,57	0.90	0,53	1,13	-

Still, these ashes are pozzolanic *[1]*. The pozzolanic properties of a coal ash depend mainly on the vitreous components in its mineralogical structure. To investigate the pozzolanic potential of the ashes after its disposal, a mineralogical analysis was carried out on 3 samples of different ages from the lagoon and 1 sample of non-disposed fly ash. The results are shown in figure 3. They show that the ashes lose some vitreous components after its disposal, losing some of its pozzolanic properties. Still, simple tests show that the ashes still harden in the presence of calcium, keeping some -but not all- its pozzolanity.

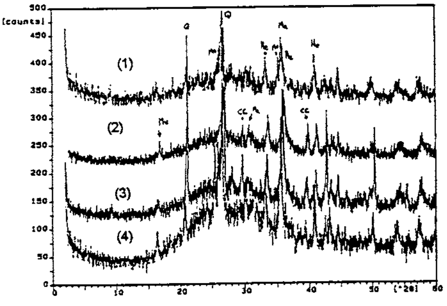

Figure 3.- Minerological analysis of Andorra's coal ashes

2.3. Index properties

The index properties of the different types of ashes were determined. The particle size distributions were obtained combining sieving and sedimentation procedures. Figure 4 shows the gradation curves. For the sake of comparison, the figure includes the typical ranges of fly and bottom ash *[2]*, *[3]*.

All the samples were "non plastic".

It can be seen in figure 4 that there are three different types of gradation curves. Each of them correspond to a type of ash deposit.

The deposits identified as "fly ashes" fit very well inside the typical range of fly ashes. They can be classified according to the Unified Soil Classificatin System (USCS) as silt with sand. Looking at the finer sizes in the curve, it can be seen that the percentage of clay (%finer 0,002 mm) varies from 11 to 18%.

The ashes identified as "mostly bottom ash" have a high content of fine particles (%finer than 0,08 mm betweeen 28 and 36), much higher than what is usual for bottom ashes. This is because they are not "pure" bottom ashes, they are "contaminated" with fly ash. According to the USCS they can be classified as a silty sand with some gravel.

The third type of gradation curves comes from a variable mixture of fly and bottom ashes. These curves are intermediate between the other two. Their USCS classification varies between "sandy silt" and "silty sand with traces of gravel".

The specific gravities of the ash particles (G_s) are very high, between 2.49 and 2.85, higher than what is usual in these materials. The high iron-oxide content and the neglectable carbon content in their composition may be the reason of these high G_s.

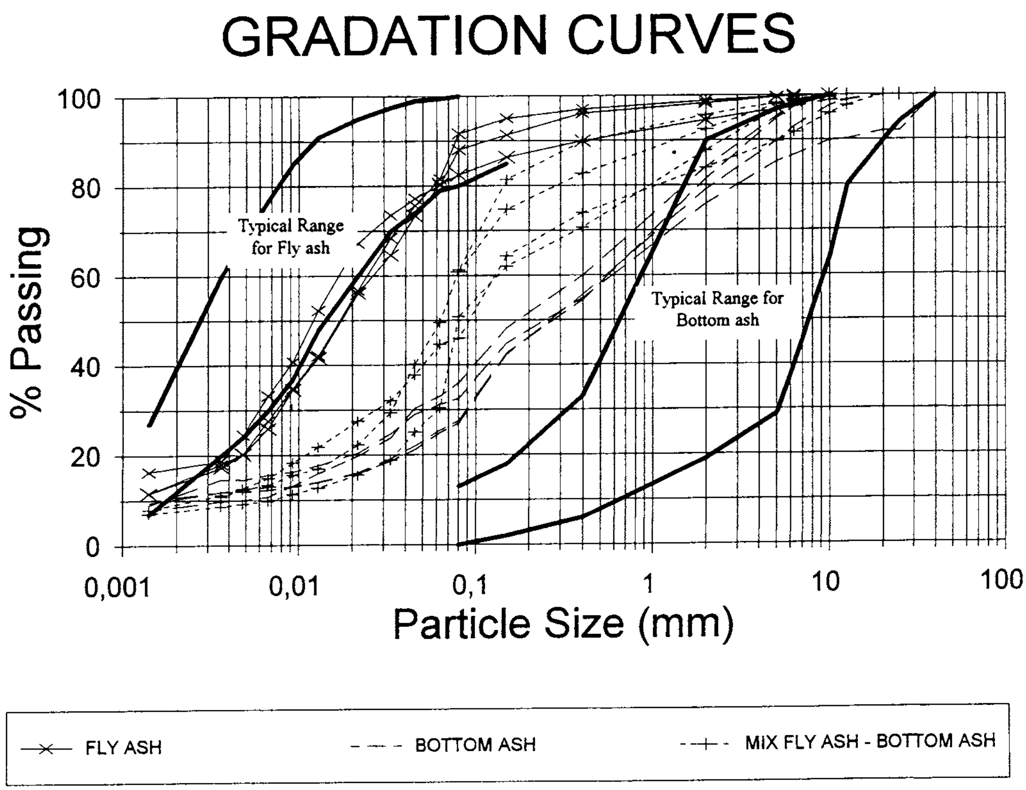

Figure 4.- Particle size distribution of Valdeserrana ashes.

2.4. *Density and porosity*

The ashes have been placed in the lagoon by hydraulic filling and they have not been consolidated or compacted. Therefore, they present high water contents and low densities.

Table II summarizes the properties of the 3 types of ashes identified. It can be seen that the ashes in the lagoon have high void ratios (from 0.64 to 1.07) and dry densities (γ_d) from 12.8 to 18.8 KN/m^3.

Even though these dry densities values seem high for a fly or a bottom ash (see *[2]*, *[3]*, *[4]*) they represent low relative densities (about 35%) for Andorra ashes due to their high specific gravity.

These values show that the state of the ashes in the lagoon is very loose.

2.5. *Shear strength*

The ashes stored at Valdeserrana Dam behave mostly as a frictional material. None of the ashes displayed any cementation. Only the fly ashes (finer particles), had a small undrained cohesion, similar to that of a non-plastic silt.

The friction angles were obtained by direct shear tests on undisturbed samples. The values obtained are high, typical in this materials (see *[3]*, *[4]*, *[5]*).

Table II.- Geotechnical properties of Valdeserrana coal ashes

Geotechnical Property	Mostly fly ash	Fly-bottom ash mixture	Mostly bottom ash
w_n (%) (natural water content)	32	19-38	26-29
e_0 (void ratio)	0.85	0.64-1.07	0.72
γ_d (KN/m3) (dry density)	14.2	12.8-18.4	15.8-17.7
N_{SPT}	0-3	7-29	12-13
N_{20} (Borros, average)	2.8	12	17
c_u (KPa)	15-25	-	-
φ' (°) (effective angle of shearing resistance)	32	33-35	39-50
C_c (compression index)	0.03	0.06-0.06	0.04
C_r (recompression index)	0.009	0.007-0.009	0.006
C_α (secondary compression index)	0.0017	0.0015-0.0038	0.0017-0.0025
C_c/C_α	0.06	0.025-0.07	0.028-0.04
k (cm/s) (permeability)	$1.0*10^{-6}$ - $5.0*10^{-6}$	$5.0*10^{-6}$	$6.0*10^{-6}$ - $1.2*10^{-5}$
c_v (cm^2/s) (coefficient of consolidation)	0.03-0.15	0.3	0.3-0.4

The friction angle of the fly ash is 32°, higher than what is usual for a natural soil of the same USCS classification. However, the undrained cohesion and the penetration tests performed in these ashes gave low resistances, what shows that the fly ash is normally or even under consolidated in the lagoon.

Bottom ash friction angles were higher, between 39 and 50°. Even though their relative density were low they showed values of φ' higher than what is usual for a natural soil of the same USCS classification. These values of the friction angle did not fit well with those obtained by empirical relations with dynamic penetration tests. The vesicular shape of the particles, different to the typical shapes of natural soils, may be the reason for this bad fitting.

The friction angles of the mixture of bottom and fly ash (33 to 35°) are between the angles of both materials. They are somewhat closer to the fly ash values, probably due to the high percentage of fine particles (50 to 61%), that become the ones governing the behavior.

In all cases, the ashes have higher friction angles than what be expected for natural soils of the same USCS classification and the same relative density.

2.6. Compressibility

The compressibility of the ashes has been estimated by one-dimensional consolidation tests. The values of the compression index (C_c) varied between 0,03 and 0,06, being very similar for all the ashes.

These indexes of compression show that the ashes have a compressibility similar to that of a medium dense sand. This would mean a very low compressibility (high stiffness) for a fine soil like fly ashes, and would be in the lower part of the usual range for fly ash *[2]*.

As for the bottom ash, it would mean that their compressibility is similar to that of a natural soil with the same USCS classification and the same relative density.

The recompression indexes (C_r) were between 1/3 and 1/6 of the virgin compression indexes (C_c), what shows that consolidation or compaction improves dramatically the stiffness of the deposits.

The ashes displayed very low secondary compression, almost neglectable for practical purposes.

2.7. Permeability, consolidation

The permeability of the deposits has been estimated by variable-head Lefranc tests performed inside the bore holes. The values of permeability fitted very well the values obtained by Hazen's empirical relation *[6]* :

$$k = 100(D_{10})^2$$

where k is the permeability in cm/s and D_{10} is the effective size of the soil in cm.

This good fitting is probably due to the spherical shape of the finer particles (fly ash). The permeability values ranged from 10^{-6} cm/s (fly ashes) to 10^{-5} cm/s (mostly bottom ashes), typical values for natural soils of the same USCS classification.

The coefficients of consolidation could not be obtained by the oedometer tests. The samples completed the primary consolidation very fast (less than 15 seconds) so it could not be observed. Therefore, the coefficients of consolidation were estimated using the permeability values and the volume coefficient of compressibility (m_v), related by :

$$c_v = \frac{k}{\gamma_w m_v}$$

The values obtained were very high, between 0.03 cm/s^2 (fly ash) and 0.4 cm^2/s (bottom ash). Therefore, consolidation of these deposits will take place very rapidly.

3. CONCLUSIONS

Andorra Coal-fired Power Plant produces annually over 1,000.000 tons of coal ashes. These ashes are composed approximately by 15% of bottom ash and 85% of fly ash. They are mixed together with water and conducted through a pipe to the Valdeserrana Dam (a 18 Hm^3 lagoon) where the ashes settle. The engineering properties of the ashes placed have been studied and are presented in the paper.

The chemical composition of the ashes placed in the lagoon is similar to that of dry ashes. However, the mineralogical analysis shows a decrease of the vitreous components, which would account for a decrease of its pozzolanic properties. Still, they keep some pozzolanity after its disposal. The ashes are not self-cementitious. They show no cementation while in the lagoon and behave very much like a natural soil.

The specific gravities of the soil solids are very high for a coal ash (average 2.8).

The gradation of the particles varies with the distance from the pouring point. The coarser particles (bottom ash) settle close to it while the finer particles (fly ash) settle at a higher distance. The coarser materials can be classified as a loose silty sand. The finer materials can be classified as weak silt with traces of sand. Both materials have high moisture content and high void ratios and are normally (or even under) consolidated. Still, they have low compressibility, good friction angles and high consolidation coefficients.

Therefore these ashes can be efficiently improved by different methods like precharge or mixing with lime or cement if they are to be used as foundation soil.

4. ACKNOWLEDGEMENTS

The authors want to express their gratitude to ENDESA for the funding of the study.

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