# DURABILITY AND STRENGTH PROPERTIES OF CONCRETE CONTAINING COAL BOTTOM ASH

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ABSTRACT: In Europe coal bottom ash production represents approximately one tenth of coal combustion by-products. About 44% of coal bottom ash is used in the construction sector, but its application as addition in concrete is very low.

This study evaluates the influence of replacing cement by bottom ashes or fly ashes, from the same Portuguese coal power station, on the properties of fresh and hardened concrete, namely on workability, compressive strength, accelerated carbonation, chloride diffusion, absorption and capillary porosity.

The results revealed that concrete incorporating coal bottom ash have a performance analogous to that of concrete with coal fly ash, although it is necessary to increase the dosage of admixture to control the loss of workability that is generally observed with bottom ash. Coal bottom ash can than be envisaged as a promising addition type II for concrete.

## 1 INTRODUCTION

Fly ash and bottom ash are generated as combustion products during coal burning in power plants. According to the European Coal Production Products Association, the production of coal combustion products in 2007 in Europe (EU 15) was about 61 million tonnes. About on half of the produced fly ash and bottom ash is used in the construction industry but within different applications as depicted in Fig. 1.1. Fly ash is mainly used as concrete addition and cement raw material while bottom ash is used in the production of non-aerated concrete blocks and in road construction.

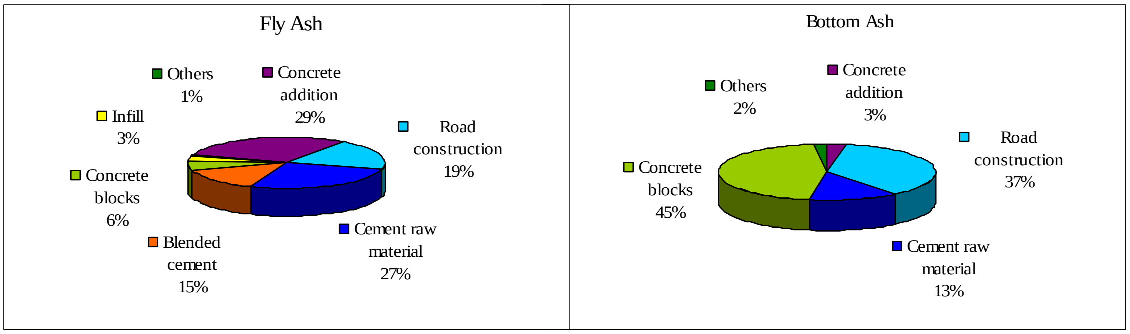

**Fig. 1.1** Use of fly ash and bottom ash in the construction industry in Europe [ECO07]

There is an extensive literature concerning the use of fly ash as concrete addition [Meh89, Nai94, Mal94, McC99]. However there are relatively few studies regarding the use of bottom ash as cement substitute in cementitious construction materials. Study of cement mortars with coal bottom ash as cement substitute evidenced the benefit of this residue on compressive strength, which is associated to a pozzolanic effect [Kur08].

Cheriaf et al. studied the pozzolanic properties of coal bottom ash by chemical and mechanical procedures and positive results were achieved in both cases. This research also highlighted that bottom ash reactivity could be enhanced by grinding: the bottom ash ground for 6h lead to an increase of 27% on the strength activity index, evaluated according to the European standard for fly ash in concrete [Che99].

Also Jaturapitakkul [Jat03] evaluated the replacement of cement by bottom ash in mortar and concrete and verified the importance of bottom ash grinding on the properties of the final product. Mortars containing 20 to 30% of bottom ash showed less compressive strength than a reference mortar at all ages but those with ground bottom ash revealed improvement on compressive strength after 60 days. In concretes with 20% of cement replacement by ground bottom ash and binder content of 260 and 440 kg/m$^3$ the increase on compressive strength occurred after 60 days and 14 days respectively, showing that the ground bottom ash can be used as a pozzolanic material.

This communication presents the results of a study aimed at evaluate the feasibility of the use of ground coal bottom ash in concrete as addition type II. This research includes the chemical and physical characterization of bottom ash required by the Portuguese standard on the use of pozzolans in concrete, NP 4220 [IPQ93], and assess the relative performance of concrete made with bottom ash in relation to a control concrete made with fly ash.

## 2 EXPERIMENTAL PROGRAM

### 2.1 Ashes preparation and characterization

Fly ash (FA) and bottom ash (BA) from the same Portuguese coal power plant were used in this study. Bottom ash, removed through a dry handling system beneath the boiler, was ground before assessing its feasibility as concrete addition. Fineness of both ashes was characterized through the residue on 45 µm sieve and Blaine specific surface.

The chemical composition of FA and BA was evaluated by X-ray fluorescence spectrometry. The ashes were also analysed in terms of their compliance with the Portuguese standard NP 4220 – Pozzolans for concrete [IPQ93].

Leaching tests on FA and BA were carried out according to European standard EN 12457-4 [CEN02] and the content of cadmium, lead, copper, chromium, nickel and zinc in the leachate were determined and compared with the limits of the Council Decision 2003/33/EC for the deposition of waste in landfills [Cou03].

### 2.2 Concrete mix design

All concrete mixes were prepared using cement CEM II/A-L 42.5 R, complying with EN 197 – 1 [CEN07], having a fineness (Blaine) of 387 m$^2$/kg and contents of $C_3A$ and alkalis of 9.2% and 0.7%, respectively. Crushed limestone was used as coarse aggregate and natural siliceous sand as fine aggregate. As water-reducing admixtures, wra, a plasticiser and two superplasticisers were used. Fly ash, FA, and bottom ash, BA, were used as concrete additions.

Mixtures were designed for the following binder contents, 300, 350 and 400 kg/m$^3$. For each binder dosage the workability was kept constant and the proportions of ash used were 25% and 33%. In the case of bottom ash addition two scenarios were considered: one where the water/binder, w/b, was kept equal to that of the control concrete by adjusting the percentage of admixture denominated by BA (w/b), and another in which the admixture content was the same as that of the control concrete named BA (wra).

### 2.3 Experimental procedures

The tests on fresh and hardened concrete, at the specified ages, were performed in accordance with the following documents:

- Compressive strength (cubes of 150 mm) - EN 12390-3 [CEN01].
- Accelerated carbonation (cores taken from cubes of 150 mm), 28d - Specification LNEC E 391:1993: $CO_2$ = 5.0 ±0.1%, RH = 65 ±5% and T = 23 ±3 ºC [LNE93a].
- Chloride diffusion (cylinders 100 x 200 mm) - Specification LNEC E 463:2004 (Equivalent to the standard NT Build 492:1999) [LNE04].
- Permeability to oxygen (cylinders 150 x 50 mm), 28d - Specification LNEC E 392: 1993 (Cembureau method) [LNE93b].
- Capillary absorption (cylinder 150 x 50 mm), 28d - Specification LNEC E 393: 1993 (Based on RILEM Recommendation CPC 11.2) [LNE93c].
- Porosity (cylinder 150 x 50 mm), 28d - Specification LNEC E 394: 1993 (Based on RILEM Recommendation CPC 11.1) [LNE93d].

Until the age of test the specimens were stored in a climate chamber with a relative humidity above 90% and temperature around 20±2 ºC.

## 3 RESULTS AND DISCUSSION

### 3.1 Ashes characterization

**Table 3.1** presents the results of fineness evaluation of the ground bottom ash and the fly ash by determination of the residue on 45 µm sieve and Blaine specific surface.

**Table 3.1** Ash fineness for fly ash, FA, and bottom ash, BA

| Procedure | BA | FA |
|---|---|---|
| Residue on 45 µm sieve (%) | 4.0 | 17.3 |
| Blaine specific surface (cm$^2$/g) | 3480 | 3500 |

The results regarding chemical composition of ashes and compliance with Portuguese standard NP 4220 are exhibited on **Table 3.2** and **Table 3.3** respectively.

Regarding chemical composition, silica and alumina represent 75% of bottom ash and about 82% of fly ash. The levels of iron oxide, calcium oxide and magnesium oxide in the bottom ash are nearly double that of fly ash.

**Table 3.2** Chemical analysis of fly ash, FA, and bottom ash, BA

| Parameter | BA | FA |
|---|---|---|
| % LOI at 600º C | 2.94 | 4.44 |
| % LOI at 975º C | 3.05 | 4.84 |
| % $SiO_2$ | 52.02 | 54.24 |
| % $Al_2O_3$ | 23.23 | 27.50 |
| % $Fe_2O_3$ | 9.11 | 4.46 |
| % $K_2O$ | 1.14 | 1.01 |
| % $Na_2O$ | 0.49 | 0.41 |
| % CaO | 6.00 | 3.57 |
| % MgO | 2.17 | 1.19 |
| % $SO_3$ | 0.65 | 0.75 |
| % Reactive CaO | 5.81 | 3.06 |
| % $TiO_2$ | 1.23 | 1.39 |
| % $P_2O_5$ | 0.71 | 0.92 |
| % Free CaO | 6.0 | 0.00 |
| % $Cl^-$ | 0.00 | 0.00 |
| % Reactive $SiO_2$ | 34.37 | 36.23 |
| % R.I. (KOH) | 28.50 | 25.92 |

**Table 3.3** Requirements of Portuguese standard NP 4220 for pozzolans for concrete

| Properties | BA | FA | Requirement |
|---|---|---|---|
| Loss on ignition (%) [950 ± 25ºC] | 3.05 | 4.84 | ≤ 12.0 |
| Chlorides (%) | 0.00 | 0.00 | ≤ 0.10 |
| Sulphur trioxide (%) | 0.65 | 0.75 | ≤ 3.0 |
| Silicon oxide + aluminium oxide + iron oxide | 85.4 | 86.2 | ≥70.0 |
| Magnesium oxide (%) | 2.17 | 1.19 | ≤ 3.0 |
| Fineness (%) | 4.0 | 17.3 | ≤ 40.0 |
| Density ($g/cm^3$) | 2.62 | 2.34 | Declared value ± 0.15 |
| Strength activity index at 28d, 38ºC (%) | 109.0 | – | ≥ 85.0 |
| Strength activity index at 28d, 20ºC (%) | 84.4 | 83.5 | ≥ 75.0 |

Ground bottom ashes, similarly to fly ashes, comply with the requirement of NP 4220 and also meet the requirement concerning strength activity index at 28 d and 20ºC of the European standard for fly ash for concrete [CEN05].

The contents of cadmium, lead, copper, chromium, nickel and zinc in the leachate from the ashes and the limits set out in Council Decision 2003/33/EC of the European Council regarding waste disposal in landfills for inert waste are presented in **Table 3.4**. Despite the differences in the contents of some heavy metals analysed in the leachate it can be concluded that bottom ash and fly ash meet the requirements of the Council Decision for waste disposal in landfill for inert waste.

**Table 3.4** Heavy metals content in leachate from fly ash, FA, and bottom ash, BA, and limit values for waste disposal at landfills for inert waste

| Parameter | BA | FA | Council Decision 2003/33/EC |
|---|---|---|---|
| Cadmium, Cd (mg/kg) | < 0,62x10$^{-3}$ | < 0,62x10$^{-3}$ | 0,04 |
| Lead, Pb (mg/kg) | < 4,10x10$^{-3}$ | < 4,10x10$^{-3}$ | 0,5 |
| Copper, Cu (mg/kg) | 1,97x10$^{-3}$ | 1,21x10$^{-3}$ | 2 |
| Chromium, Cr (mg/kg) | 24,7x10$^{-3}$ | 122,4x10$^{-3}$ | 0,5 |
| Nickel, Ni (mg/kg) | 29,7x10$^{-3}$ | < 22,4x10$^{-3}$ | 0,4 |
| Zinc, Zn (mg/kg) | 48,0x10$^{-3}$ | 71,9x10$^{-3}$ | 4 |

## 3.2 Tests on concrete

Data regarding water/binder ratio, percentage of admixture, slump, and compressive strength at 7, 28, 180 and 365 days for the different compositions of concrete are shown in **Table 3.5**.

**Table 3.5** Concrete compressive strength of reference concrete, FA, and of concrete containing ground bottom ash fixing water/binder ratio, BA (w/b) or fixing admixture content, BA (wra)

| Ash | Binder content (kg/m$^3$ concrete) &ash proportion | w/b ratio | wra (%) | Slump (mm) | Compressive strength (MPa) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | 7 days | 28 days | 180 days | 365 days |
| FA | 300(25%) | 0.550 | 0.50 | 150 | 29.3 | 38.8 | 50.0 | 53.7 |
| | 300 (33%) | 0.550 | 0.50 | 150 | 25.5 | 35.2 | 49.2 | 54.7 |
| | 350 (25%) | 0.434 | 1.00 | 160 | 40.0 | 50.7 | 67.9 | 72.8 |
| | 350 (33%) | 0.431 | 1.00 | 170 | 36.9 | 48.9 | 66.5 | 69.9 |
| | 400 (25%) | 0.375 | 1.00 | 230 | 47.7 | 57.5 | 78.4 | 82.9 |
| | 400 (33%) | 0.373 | 1.00 | 240 | 45.6 | 59.0 | 77.2 | 85.8 |
| BA (w/b) | 300 (25%) | 0.550 | 0.65 | 140 | 30.8 | 39.8 | 51.7 | 55.2 |
| | 300 (33%) | 0.550 | 0.75 | 150 | 26.4 | 36.3 | 48.1 | 52.5 |
| | 350 (25%) | 0.434 | 1.20 | 170 | 41.9 | 50.8 | 66.0 | 67.8 |
| | 350 (33%) | 0.431 | 1.20 | 160 | 37.8 | 49.7 | 63.6 | 68.7 |
| | 400 (25%) | 0.375 | 1.10 | 230 | 48.8 | 57.8 | 75.2 | 83.7 |
| | 400 (33%) | 0.373 | 1.10 | 240 | 45.7 | 57.5 | 74.6 | 81.6 |
| BA (wra) | 300 (25%) | 0.566 | 0.50 | 150 | 26.7 | 35.5 | 44.9 | 49.6 |
| | 300 (33%) | 0.567 | 0.50 | 140 | 23.9 | 32.1 | 43.3 | 47.9 |
| | 350 (25%) | 0.441 | 0.99 | 160 | 40.2 | 50.3 | 63.5 | 68.9 |
| | 350 (33%) | 0.443 | 1.00 | 170 | 34.7 | 45.3 | 60.1 | 64.6 |
| | 400 (25%) | 0.383 | 1.00 | 230 | 47.3 | 54.7 | 73.1 | 77.7 |
| | 400 (33%) | 0.383 | 1.00 | 230 | 42.1 | 55.6 | 72.4 | 75.3 |

The bottom ash leads to lower slump and it is necessary to increase the percentage of admixture or of mixing water to achieve a consistency similar to that obtained with the fly ash, especially in concretes with lower binder content. In this case the maximum difference on w/b was 0.017.

It must be emphasized that in the mix designs the same mass quantities of bottom ash and fly ash were used and owing to the higher density of the first it results in a slight increase of cement per cubic meter of concrete and a small reduction in the volumetric proportion of ash.

The results of compressive strength are summarized in Fig. 3.1 by making the average of the different binder contents and the two percentages of ash, in order to compare the performance of concrete with bottom ash in relation to concrete with fly ash at different ages. As shown, the difference in strengths of concretes with these ashes is virtually zero when w/b ratio is kept constant, although it can be noticed that fly ash concrete evidence a trend, for the medium to long term, of compressive strengths slightly higher maybe owing to the lower volume of bottom ash in concrete.

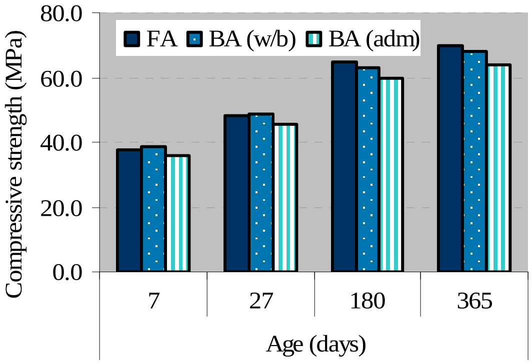

**Fig. 3.1** Compressive strength of FA and BA concretes

**Table 3.6** presents the results for the resistance to accelerated carbonation, chloride diffusion, oxygen permeability, capillary absorption and porosity, averaging the results of the different ash proportions, 25% and 33%, and in the case of bottom ash the two scenarios: equal w/b ratio and equal dosage of admixture.

A comparison of the average results of the chloride diffusion coefficient and accelerated carbonation resistance of the two ashes can be seen in Fig. 3.2. Fly ash and bottom ash have the same performance when w/b ratio is constant.

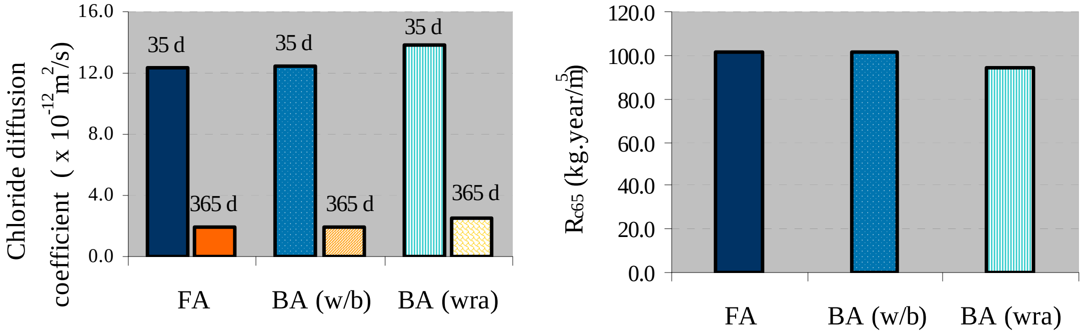

**Fig. 3.2** Chloride diffusion coefficient and accelerated carbonation resistance of FA and BA concretes

**Table 3.6** Durability related properties of FA and averaged BA concretes, for the different binder contents

| Ash | Properties | Binder content (kg/m3 concrete) | | |
|---|---|---|---|---|
| | | 300 | 350 | 400 |
| FA | Compressive strength 28 d (MPa) | 37 | 50 | 58 |
| | Accelerated carbonation resistance $R_{c65}$ (kg.year/m$^5$) | 39 | 92 | 175 |
| | Chloride diffusion coefficient$^-$ 35d (x10$^{-12}$ m$^2$/s) | 16.0 | 10.5 | 10.4 |
| | Chloride diffusion coefficient$^-$ 365d (x10$^{-12}$ m$^2$/s) | 2.9 | 1.8 | 1.1 |
| | Oxygen permeability coefficient, K (m$^2$) | 6.5E-17 | 2.1E-17 | 2.3E-17 |
| | Sorption coefficient (kg m$^{-2}$ h$^{-0.5}$) | 0.41 | 0.27 | 0.18 |
| | Porosity (%) | 13 | 12 | 9 |
| BA | Compressive strength 28 d (MPa)) | 36 | 49 | 56 |
| | Accelerated carbonation resistance $R_{c65}$ (kg.year/m$^5$) | 38 | 84 | 171 |
| | Chloride diffusion coefficient$^-$ 35d (x10$^{-12}$ m$^2$/s) | 17.3 | 12.3 | 9.8 |
| | Chloride diffusion coefficient$^-$ 365d (x10$^{-12}$ m$^2$/s) | 2.8 | 2.6 | 1.3 |
| | Oxygen permeability coefficient, K (m$^2$) | 4.5E-17 | 2.0E-17 | 1.5E-17 |
| | Sorption coefficient (kg m$^{-2}$ h$^{-0.5}$) | 0.39 | 0.25 | 0.17 |
| | Porosity (%) | 13 | 11 | 9 |

For the average results of oxygen permeability, the data follow the same tendency of the previous properties (Fig. 3.3), considering that the best performance of the bottom ash is not significant, although their higher fineness may have contributed to the lowest coefficient of permeability.

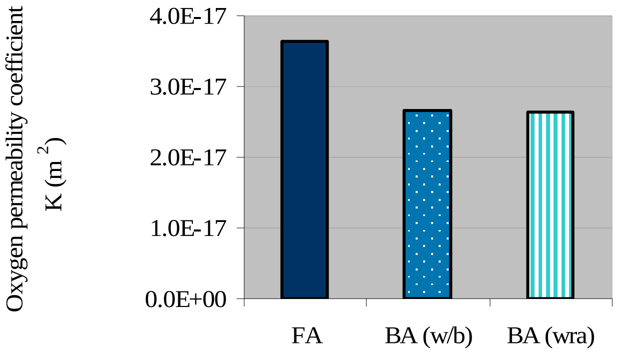

**Fig. 3.3** Oxygen permeability of FA and BA concretes

Finally, with regard to average values of capillary absorption and porosity Fig. 3.4 shows that the bottom ash showed slightly lower values, particularly for the same w/b ratio, but within the same order of magnitude.

It has to be underlined that the better performance on concrete with bottom ash with respect to oxygen permeability, water absorption and porosity may be due to the fact that cement content on those concretes was slightly higher and the ashes are finer.

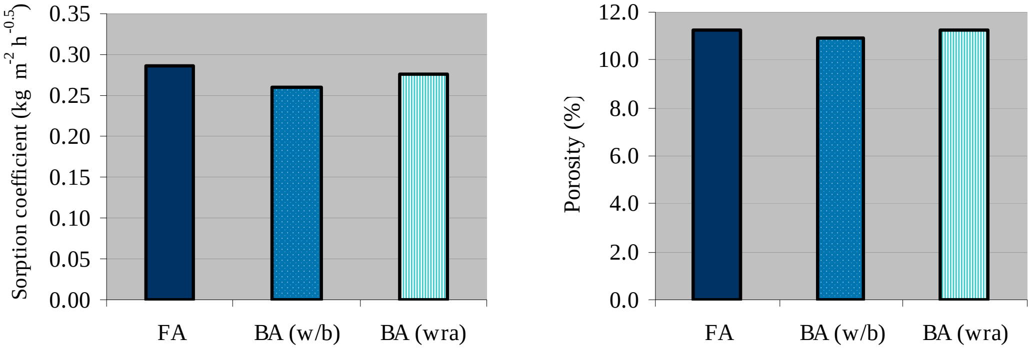

**Fig. 3.4** Capillary absorption and porosity of FA and BA concretes

## 4 CONCLUSIONS

The presented paper showed that the ground bottom ash meets the requirements of Portuguese standard NP 4220 and might be used as a concrete type II addition.

Moreover, the leaching tests showed that the contents of cadmium, lead, copper, chromium, nickel and zinc released from bottom ash meet the same limits for deposition on landfill as fly ash.

Tests on concrete showed that the ground bottom ash reduces the workability, and it is therefore necessary to increase the admixture content to ensure the same slump and keep the w/b ratio, particularly for lower binder contents.

If the w/b ratio is maintained, concretes made with bottom ash exhibit performance similar to that of concretes with fly ash, both in terms of compressive strength and resistance to environmental actions.

## ACKNOWLEDGMENT

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## REFERENCES

[CEN01] Comité Européen de Normalisation. CEN. EN 12390-3:2001. Testing Hardened Concrete – Part 3: Compressive Strength of Test Specimens.

[CEN02] Comité Européen de Normalisation. CEN. EN 12457 - 4: 2002. Characterization of Waste – Leaching – Compliance Test for Leaching of Granular Waste Materials and Sludges. One Stage Batch Test at a Liquid to Solid Ratio of 10 l/kg for Materials with Particle Size Below 10 mm (Without or With Size Reduction).

[CEN05] Comité Européen de Normalisation. CEN. EN 450 – 1 :2005. Fly Ash for Concrete Part 1: Definition. Specifications and Conformity Criteria.

[CEN07] Comité Européen de Normalisation. CEN. EN 197 – 1 :2000/A1:2004/A3:2007. Cement – Part 1: Composition. Specifications and Conformity Criteria for Common Cements.

[Che99] Cheriaf. M.. Cavalcante Rocha. J. et al., Pozzolanic Properties of Pulverized Coal Combustion Bottom Ash. Cement and Concrete Research, Vol., p.1387-1391, **ISSN 0008-8846.**

[Cou03] Council Decision 2003/33/EC Establishing Criteria and Procedures for the Acceptance of Waste at Landfills Pursuant to article 16 of and Annex II to Directive 1999/31/EC. Official Journal of the European Union L 11. 16 January 2003, p. 27-49.

[ECO07] European Coal Combustion Products Association. ECOBA. Production and Utilisation of CCPs in 2007 in Europe. Available online. accessed on 14 Feb 2010: http://www.ecoba.com/evjm.media/statistics/ECOBA_Stat_2007_EU15.pdf.

[IPQ93] Instituto Português da Qualidade. IPQ. NP 4220:1993. Pozolanas para betão. Definições. Especificações e Verificação da Conformidade.

[Jat03] Jaturapitakkul C.. Cheerarot R., Development of Bottom Ash as Pozzolanic Material. Journal of Materials in Civil Engineering, Vol. 15, p.48-53, 2003, **ISSN 0899-1561**.

[Kur08] Kurama H., Kaya M., Usage of Coal Combustion Bottom Ash in Concrete Mixture. Construction and Building Materials, Vol.22, p 1922-1928, 2008, **ISSN 0950-0618**.

[LNE93a] Specification LNEC E391: 1993. Concrete. Determination of Accelerated Carbonation Resistance.

[LNE93b] Specification LNEC E392: 1993. Hardened Concrete. Determination of thePermeability to Oxygen.

[LNE93c] Specification LNEC E393: 1993. Concrete. Determination of the Absorption of Water by Capillarity.

[LNE93d] Specification LNEC E394: 1993. Concrete. Determination of the Absorption of Water by Immersion.

[LNE04] Specification LNEC E463: 2004. Concrete. Determination of Chloride Diffusion Coefficient by Non-Steady State Migration Test.

[Mal94] Malhotra V.M., Ramezanianpour A.A., Fly Ash in Concrete. 2nd Edition, CANMET, MSL Report 94–45, 370 p., 1994.

[McC99] McCarthy M.J., Dhar R.K., Towards Maximizing the Use of Fly Ash as a Binder. Fuel, Vol.78, p.121–32, 1999, **ISSN 0016-2361**.

[Meh89] Mehta. P.K., Pozzolanic and Cementitious By-products in Concrete—Another Look. in: Proceedings of the 3rd International Conference on the Use of Fly Ash. Silica Fume. Slag. and Natural Pozzolans in Concrete. ACI SP-114. Trondheim. p. 1-43. 1989.

[Nai94] Naik T. R., Ramme B. W. et al. Use of High Volumes of Class C and Class F Fly Ash in Concrete. Cement Concrete & Aggregates. Vol. 16. p. 12–20. 1994.**ISSN 0149 – 6123**.