Feasibility of Coal Ash Utilization from Pecem Power Plant Landfill in Concrete

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ABSTRACT

The use of pulverized coal ash to produce energy generates by-products such as fly ash and bottom ash. Coal combustion residues are produced in great quantity and there are many issues related to it. Not only they pollute the environment and are potentially toxic substances, but also have relatively high disposal cost since they must be displaced in protected landfills. The coal ash produced by two power plants in Ceará, Brazil, called Pecém I and Pecém II, was the object of study in this research. A great amount of coal ash was produced during the power plants preliminary tests phase, which are heterogenous due to unstable burning processes in the furnaces. The purpose of this research is to study this waste by improving its quality through grinding until the particle is smaller than 0.15 mm, adding it into the concrete mixture and analyze its technical and environmental feasibility. Six concrete mixtures with different ash percentages and one control mixture were produced and investigated in this research. The w/ag ratio was 0.5 and kept constant in all mixtures, and coal ash replaced cement in volumes of 7.5% and 15%. Some properties of the used ashes have been determined such as unit weight, particle size distribution, x ray fluorescence, x ray diffraction, loss on ignition, leaching and solubility. The tests conducted in concrete were slump test, compressive strength, water absorption, void ratio, leaching and solubility tests. The results present that concrete mixtures have satisfactory compressive strength development and good environmental performance.

INTRODUCTION

Coal is one of the main energy sources in the world, being responsible for over 40% of the total electricity production[1]. The burning of coal to produce energy in coal-fired power plants generates by-products such as fly ash and bottom ash, which can cause environmental damages, since it is filled with toxic substances and can contaminate soil and water. Another problem related to coal combustion products is that these residues must be displaced in protected landfills, resulting in high disposal costs.

In the northeast of Brazil, two coal-fired power plants denominated Pecem I and Pecem II were installed in 2012 and 2013, respectively. They currently produce 1.085 MW of energy[2,3], which is equivalent to generate electricity to 7 million people[3]. During their preliminary tests phase, the burning temperature in the furnaces was still unstable, therefore producing heterogenous residues. Approximately 315.000 m³ of ash with very heterogeneous characteristics was produced and disposed of in landfills without previous separation. Aiming to reduce the environmental and economic impacts caused by coal combustion products, the power plants Pecem I and Pecem II firmed a partnership with Federal University of Ceara (UFC) researchers to develop short-term and long-term solutions to reuse this residue in secondary applications, since it is known that this residue possesses a great potential, especially in the concrete industry.

By combining the use of coal combustion residues and the production of concrete, it is possible to reduce the environmental impact caused by both the cement industry and the power plants, since there will be a decrease in extraction of raw material as well as the reuse of a by-product damaging the environment. Many research has been done on the subject, however, it is essential to analyze physically and chemically each ash produced, since each power plant generates a by-product with different characteristics that depend on many factors such as combustion temperature, coal origin, among others.

The biggest disadvantage of the ashes produced during the power plants tests phase is its high level of heterogeneity, therefore being necessary to carry out a set of laboratory experiments to study the main characteristics of this residue and understand how it behaves when mixed with other materials, such as concrete.

The emphasis of this article has been given to the analysis of the produced coal ash and verify its technical and environmental feasibility when added into the concrete mixture. This paper presents data on the performance of concrete using 7.5% and 15% in volume of ashes in substitution of cement on its fresh and hardened state.

MATERIALS AND EXPERIMENTAL METHOD

Materials

The concrete mixes were made using cement, fine and coarse aggregates, water, coal ash and admixture. The used cement was a Brazilian high early resistance Portland cement type (CP-V ARI), specific density of 3.0 g/cm³. The used coarse aggregate was crushed granite with maximum grain size of 25 mm, and fine aggregate was natural sand with maximum grain size of 4.8 mm. The power plants Pecem I and II provided the coal ash, which replaced in volume different fractions of cement. A concrete plasticizer Muraplast FK 110 NE was used to help maintain the water ratio constant and concrete workability. The aggregates used in the mixtures met the requirements of ABNT NBR 7211[4]. The following Table 1 shows the characterization of the used aggregates.

Table 1 – Characterization of the used aggregates in the concrete mixtures[5].

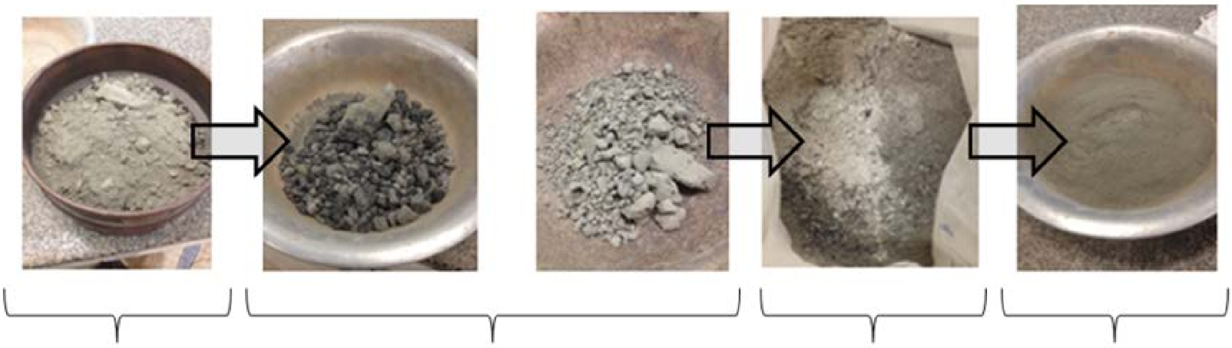
Characteristic	***Fine Aggregate***	***Standard***	***Coarse Aggregate***	***Standard***
Specific Gravity	2,55 g/cm³	NBR NM 52:09	2,64 g/cm³	NBR NM 53:09
Bulk Density	1,41 g/cm³	NBR NM 45:06	1,42 g/cm³	NBR NM45:06
Water Absorption	0,52%	NBR NM 39:01	0,85%	NBR NM 30:01
Maximum grain size	4,8 mm	NBR NM 248:03	25 mm	NBR NM 248:03
Finess Modulus	2,67	NBR NM 248:03	7,28	NBR NM 248:03

Collection of coal ash samples

The ashes produced by Pecem I and Pecem II that were object of study in this research were disposed of in a residue landfill and collected following a pre-defined sampling plan. In total, 21 samples were collected from approximately 0.5 m of the basin surface. An initial investigation was performed to identify the main characteristics of the ashes, and each sample was submitted to physical and chemical tests such as particle size distribution, particle density, x-ray fluorescence (XRF), leaching, solubility and pH test. The first results showed that elemental composition and other properties of the collected ashes were varying at each sampling location, hence it was concluded that this residue possesses heterogeneous characteristics.

Owing to the large quantity of sample materials required for concrete production and investigation, it was opted to use a simplified analysis method which is the composite sampling. The used methodology to do the composite sampling comprised in divide the basin area where the samples were collected in three different parts, and the samples of each part were mixed proportionally. Before the samples were mixed, they were subjected to a quality improvement process which consists on grinding the coal ash until the maximum particle size is 0.15 mm, therefore creating a finely divided coal ash powder, as shown in the following Figure 1. After this improvement process, the samples were mixed proportionally, generating 3 different composite samples, hereon called AC-1, AC-2 and AC-3. This procedure substantially reduced analytical costs, since it was possible to reduce a set of experiments to study the ash and the use of raw material to produce concrete.

Figure 1 – Ash Improvement process.



Characterization of the composite samples

In order to understand how ash can influence the properties of fresh and hardened concrete, tests were conducted to investigate physical and chemical properties of the composite samples AC-1, AC-2 and AC-3 such as specific mass, laser granulometry, x-ray fluorescence, X-ray diffraction, loss on ignition, leaching and solubility. The chemical analysis and physical properties of the samples are presented in Table 2.

The specific gravity of the ash samples was conducted in accordance with NBR NM 23[6]. The results show that ashes are lighter than the particles of the cement used, which has a specific gravity of 3.00 g/cm³. Because of this, the greater the volume of cement replaced by ash, the lighter the concrete will be.

For elemental composition, it was performed the XRF of samples AC-1, AC-2 and AC-3. The chemical composition of the samples is presented in Table 2. It is observed that the samples have similarities in their chemical composition and the materials consist of high amounts of calcium, silicon, iron and with lower percentages of aluminium, but still significant. It is important to highlight the high calcium content of the ashes, which is a result of the process adopted by the power plants to be in accordance with standards. Other elements such as S (sulfur), K (potassium), Ti (titanium), Sr (strontium), Cl (chlorine), Mg (magnesium), Mn (manganese), Ni (nickel), Rb (rubidium) and Zn (Zinc) were identified in the tests, but in less quantity, with summed up values ranging from 10% to 13%. Toxic metals such as Ti, Sr, Mn, Ni and Zn have been found and can cause concern regarding the environment and human health.

Table 2 also shows the results obtained for the loss on ignition test. It is possible to verify that the loss on ignition ranges from 9.7% to 12.5%. This test is generally an accepted method for estimating the amount of unburned coal in the material. According to NBR 12.653[7], which defines the parameters to determine if coal ash is a pozzolanic material, the maximum value for loss on ignition is 6%. Therefore, none of the samples can be classified as a pozzolanic material due to the high level of LOI.

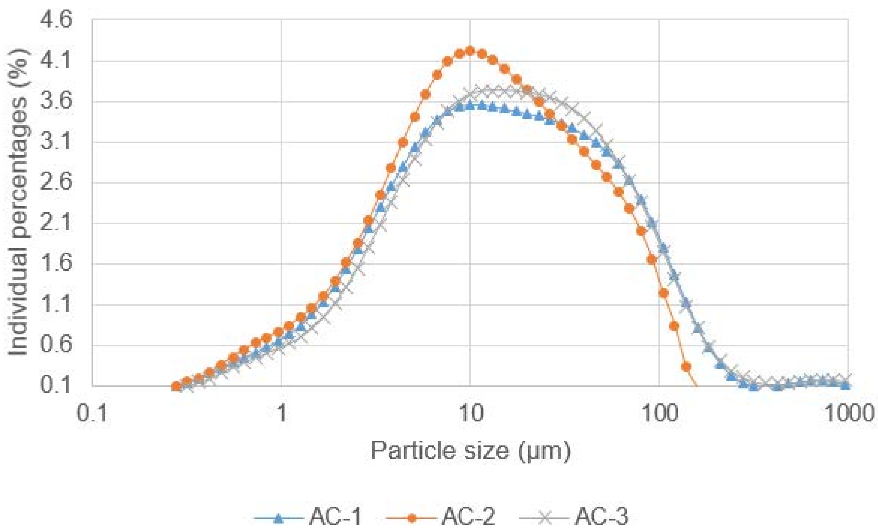
Table 2 – Physical and Chemical properties of the ash samples AC-1, AC-2 e AC-3.

		Samples		
		AC-1	AC-2	AC-3
Physical Tests				
Specific Gravity (g/cm³)		2.381	2.368	2.376
Chemical Analysis				
Ca (%)		25.59	36.30	26.36
Si (%)		30.41	24.94	30.20
Fe (%)		20.62	18.82	20.91
Al (%)		10.88	82.07	11.68
S (%)		4.43	5.47	3.93
K (%)		3.62	3.43	3.61
Ti (%)		2.01	2.06	2.16
Sr (%)		0.46	0.49	0.60
Cl (%)		0.21	0.15	-
Mg (%)		1.41	-	-
Mn (%)		0.22	-	0.22
Ni (%)		-	-	0.10
Rb (%)		-	-	0.11
Zn (%)		0.13	0.13	0.11
L.O.I (%)		11	12.47	9.73
Solubility (mg/L)	**Limit (mg/L)**			
Fluoride	**1.5**	3.91	7.05	3.16
Chloride	**250**	110.73	133.45	-
Bromide	**-**	-	-	17.85
Nitrate	**10**	8.52	31.76	34.89
Sulfate	**250**	-	1932.33	1706.44
Leaching (mg/L)	**Limit (mg/L)**			
Fluoride	**150**	0.86	371.22	0.49
Chloride	**-**	44.64	90.99	33.41
Bromide	**-**	-	-	-
Nitrate	**-**	-	16.68	-
Sulfate	**-**	-	1049.53	413.34

The results obtained in the solubility and leaching tests are also presented in Table 2. Several substances were detected in the leached extract as fluoride (F-), chloride (Cl-), bromide (Br^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}). Many of these elements can impact the environment due to their toxicity. However, some of these substances had concentrations below the limits specified in NBR 10.004[8]. It is of great importance to inform that the leaching and solubility analysis occurred only for anions, due to equipment limitations.

The ashes particle size distribution was determined through a laser diffraction technique, and the results are presented in Figure 1. The AC-1, AC-2 and AC-3 diagrams are very similar in terms of the size of the particles range and their individual percentages. However, AC-2 possesses a greater number of fine particles ranging from 5 μm to 20 μm, therefore being relatively thinner than the other samples.

Figure 1 – Comparative on the particle grain size curves of AC-1, AC-2 e AC-3.



The mineralogical composition of the ashes was also determined by conducting the x-ray diffraction test (XRD), which identifies the crystalline phases of a material. The results of the XRD tests are shown in Figures 2 to 4. After analyzing the diffractograms, it was possible to observe the predominance of the crystalline phases quartz (SiO_2) and calcite ($CaCO_3$), and considerable amounts of anhydrite ($CaSO_4$) and mullite ($Al_6Si_2O_{13}$) were also detected.

Figure 2 – AC-1 Diffractogram

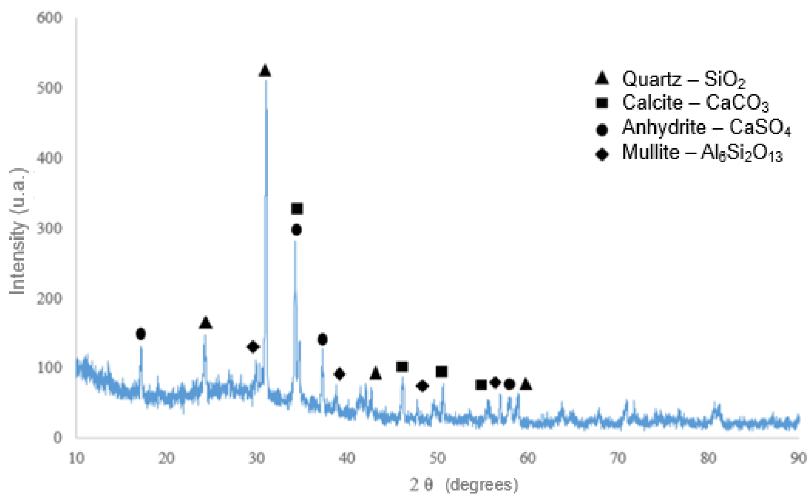


Figure 3 – AC-2 Diffractogram

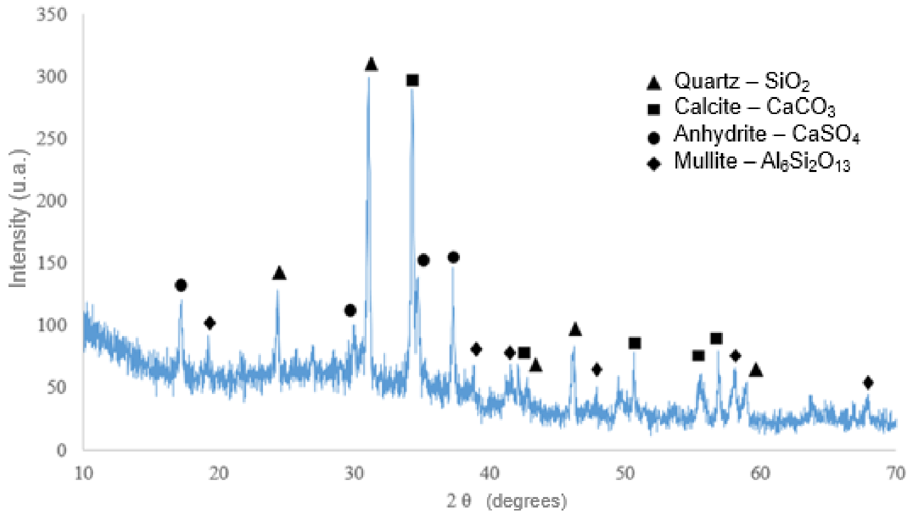
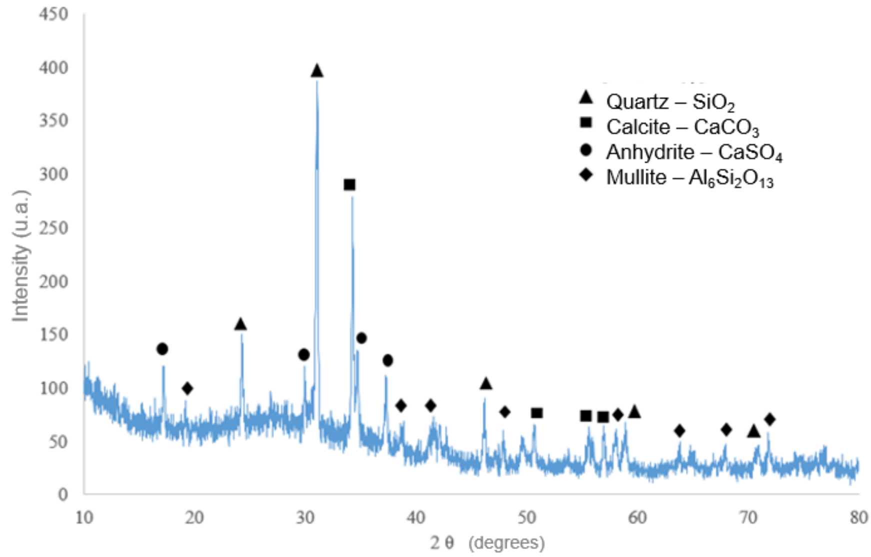


Figure 4 - AC-3 Diffractogram



CONCRETE PRODUCTION

In this study, it was investigated a conventional concrete mixture in which coal ash samples AC-1, AC-2 and AC-3 replaced Portland cement in volumetric proportions of 7.5% and 15%. In total, six concrete mixtures with coal ash and one control mixture were produced as per NBR12655[9]. The water/agglomerate ratio in volume remained 0.5 in all produced concrete specimens. All concrete specimens are cylindrical shaped and have dimensions of 100 mm in diameter, 200 mm in height. Specimens were cured in lime-saturated water until the experiments day. The cylinders were subject to compressive strength testing, water absorption, void ratio, leaching and solubility tests.

The material proportions for the all mixtures are shown in the Table 3.

Table 3 – Concrete mixtures proportions

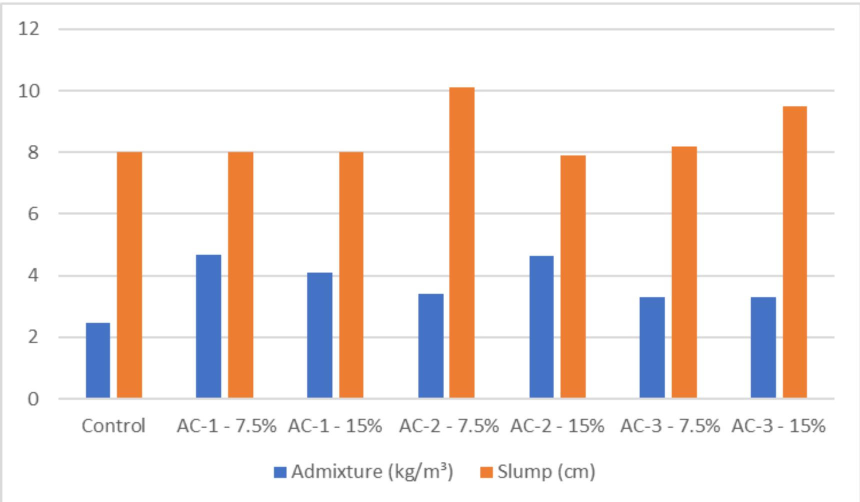
Mixture	Cement (kg/m³)	Coal Ash (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	Admixture (kg/m³)
Control	360,0	0,00	693,90	1077,12	180,0	2,48
AC-1 - 7,5%	333,0	21,43	693,90	1077,12	180,0	4,67
AC-1 - 15%	306,0	42,86	693,90	1077,12	180,0	4,11
AC-2 - 7,5%	333,0	21,31	693,90	1077,12	180,0	3,41
AC-2 - 15%	306,0	42,62	693,90	1077,12	180,0	4,65
AC-3 - 7,5%	333,0	21,38	693,90	1077,12	180,0	3,30
AC-3 - 15%	306,0	42,77	693,90	1077,12	180,0	3,30

RESULTS IN CONCRETE

Slump and admixture quantity

The admixture used in the concrete production was added until the concrete reached an adequate consistency and workability, with slump of 100 mm ± 10 mm, according NBR NM 67[10]. It can be seen in Figure 2 that the amount of additive used in the concrete mixtures with ash is 33.2% to 88.3% higher than the amount of additive used in the control concrete mixture. Therefore, it is possible to conclude that the amount of the additive increased considerably in the concretes with ash, probably due to the composition of the ash, which has high rates of unburned coal and irregular particles, increasing the total surface area and consuming more water to fill up the voids.

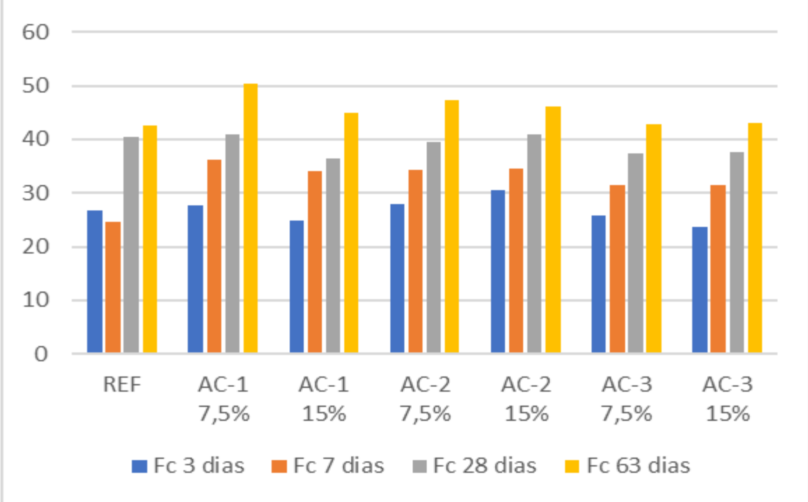
Figure 2 - Slump values and admixture quantity used for concrete production.



Compressive strength

The compressive strength is one of the most important properties when determining the concrete quality. The tests were carried out in accordance to NBR 5739[11] and the values were obtained at 3, 7, 28 and 63 days after wet curing. The results plotted on the graph below are the average values of two cylinders tested at each age and coal ash percentage. Since it was used a high early resistance cement type, all mixtures reached high compressive strengths in the first 7 days, with numbers higher than 30MPa, as presented in Figure 3. A statistical analysis was conducted and it was possible to conclude that the concrete mixtures with coal ash do not influence significantly the compressive strength of concrete.

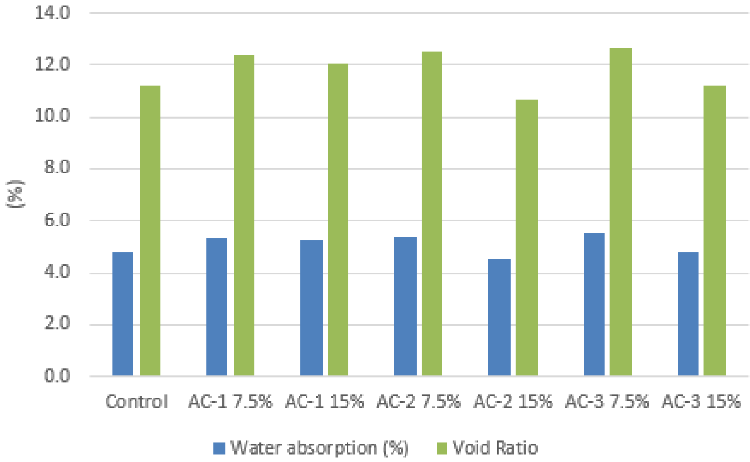
Figure 3 - Compressive strength results



Water absorption and void ratio

The concrete specimens with and without ash were submitted to water absorption and void ratio tests, according the procedures in NBR 9778[12]. The Figure 4 presents that there is a tendency to slightly decrease water absorption and void ratio when the content of ash in the concrete mixture increases from 7.5% to 15% of ash. This occurs because the quantity of fine particles is greater, and therefore leads to filling the voids. Figure 4 also shows that ash concretes have similar values in relation to the control mixture in terms of water absorption and void ratio, demonstrating that the addition of ash does not influence these properties in a considerable manner.

Figure 4 - Water absorption and void ratio results



Leaching and Solubility tests

The leaching and solubility tests evaluate the potential of the residue to release toxic substances to the environment. Tables 4 and 5 show the results obtained in the solubility and leaching tests of the concretes produced.

Table 4 – Solubility results

Mixture	Fluoride (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Nitrate (mg/L)	Sulfate (mg/L)
Control	**5.2**	39.3	-	-	14.8
AC-1 7.5%	**2.8**	7.6	-	-	19.2
AC-1 15%	0.7	9.0	24.9	-	-
AC-2 7.5%	**4.6**	42.4	-	-	12.4
AC-2 15%	**3.9**	66.6	-	31.5	14.6
AC-3 7.5%	**5.8**	32.9	-	21.6	14.4
AC-3 15%	**13.9**	27.3	-	-	12.8
Limit	1.5	250.0	-	10.0	250.0

Table 5 – Leaching results

Mixture	Fluoride (mg/L)	Chloride (mg/L)	Sulfate (mg/L)
REF	375.1	48.3	150.5
AC-1 7.5%	370.1	48.3	156.8
AC-1 15%	367.8	47.3	171.6
AC-2 7.5%	370.3	48.5	153.2
AC-2 15%	380.4	45.1	179.7
AC-3 7.5%	400.1	31.0	169.0
AC-3 15%	379.1	45.8	165.3
Limit	150.0	-	-

Several substances were detected, such as fluoride (F^-), chloride (Cl^-), bromide (Br^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}). Many of these elements in concrete can harm the environment due to their toxicity, however, in the solubility test only fluoride and nitrate presented amounts greater than the allowed by NBR 10004[8]. In the leaching test, it was detected high concentrations of fluoride in all mixtures. It was surprising to verify that high fluoride concentrations are presented in the control concrete mixture for both solubility and leaching tests, because it is not usually discussed how harm concrete can be for the environment in terms of releasing toxic substances during its lifespan. In addition, it was found that the sulfate content in the concretes with ash decreased substantially compared to the content found in the ash samples AC-1, AC-2 and AC-3. However, it should be noted that the amount of ash in the concrete is around 1% to 2% of the total volume. So, this decrease in sulfate concentration may be related to the low amount of ash in the concrete, and not to the fact that the cementitious compounds encapsulated these elements. But it is important to highlight that when coal ash particles are surrounded by concrete or mortar, the leaching velocity can have a considerable decrease when compared to unprotected coal ash disposal areas[13].

CONCLUSIONS

The tests results provided relevant information and the following conclusions can be considered.

1. The uncertainty in the properties of the produced ashes generated several questions about how it would be possible to use a low quality residue with heterogeneous properties. Due to this, the composite sampling methodology was adopted and provided important results for the study. The ash characterization showed that the composite samples AC-1, AC-2 and AC-3 have several similar physical and chemical characteristics after the grinding improvement process. This fact is relevant when it comes to the feasibility for future applications of coal ash, because it facilitates the reuse of these residues and it is possible to have a better control on the characteristics of the produced concretes.

2. Although grinding process can be costly, it is extremely necessary, since it improved residue quality, particle size distribution and increased the reactivity of the coal ash.

3. It was concluded that concretes mixed with 7.5% and 15% of coal ash as cement replacement do not significantly influence the final resistance of the concrete. Only the AC-1-7.5% concrete mixture presented a significant difference in resistance at 63 days. This small difference between the compressive strengths obtained shows that these ashes are a suitable and technically feasible material for use in concrete. To sum up, these ashes can be efficiently used as long as they are properly studied and designed.

4. Regarding water absorption and void ratio results, it was possible to notice a slight decrease when increasing the amount of ash from 7.5% to 15%, probably

due to the finess of the material that contributes to the particle packaging process. Statistically, coal ash did not influence this property of concrete either.

5. The most affected property with the use of ash in this study was the workability of fresh concrete. The amount of additive needed has increased greatly, and this is a fact that can make the concrete production more expensive. The explanation for this may be the large amount of unburned coal in the ash, as verified in the loss on ignition test, and the large amount of fine material, which in turn provides a larger amount of particles in the mixture with irregular surface and greater surface area, consequently increasing water demand.

Even though the used ashes are not classified as a pozzolanic material, they present a good performance and much potential to be explored, because its use in concrete as a substitute for cement has brought good results and can bring environmental benefits such as recycling of industrial waste, reducing the emission of greenhouse gases during cement production, preserving raw materials and saving energy, adding to this it can reduce displacement costs.

Thus, these ashes presented good performance when mixed in the concrete, being able to be used in the proportions studied without affecting significantly the mechanical properties of the concrete. However, it must be emphasized that these ashes must undergo the improvement process before they are used. Another point important to highlight is that the amount of additive has increased considerably. These two facts can make the concrete economically unfeasible, but they are essential for the reuse of this residue.

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