Performance Assessment of Concrete with Partial Replacement of Portland Cement by Coal Ash

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ABSTRACT

In Brazil, only 6.4% of electricity comes from power plants and only 1.6% of this amount use coal as fuel. However, there are incentives for diversification of the Brazilian energy matrix, very dependent of rainfall seasons. Pecém Port Complex, located 50km from Fortaleza, has a 720 MW thermoelectric plant producing energy from coal. In a partnership with this thermoelectric, we sought to evaluate alternative uses of ash generated in the process. One of the alternatives tested was the partial replacement of Portland cement by coal ash in concretes with two w/c ratios (0.45 and 0.55). Physical and chemical characterization of the ash was done by XRD, XRF, SEM and laser particle size, as well as determining the pozzolanic activity index with cement. Portland cement was replaced by the ash in contents of 3%, 7% and 9%, by volume. Tests were done on concretes in its fresh state (consistency index, density and air content) and in hardened state (compressive strength, tensile strength by diametral compression and water absorption at 28 days of age). Results indicate that the use of ash in concrete presented satisfactory results in the fresh state and in the hardened state, with an improvement in compression strength for contents of 6% for w/c ratio of 0.45 and 9% for w/c ratio of 0.55 and increased tensile strength for the content of 6% of coal ash.

1. INTRODUCTION

In Brazil, the largest concentration of thermoelectric plants are in the South, particularly in the states of Santa Catarina and Rio Grande do Sul, but some other regions of the country have already shown interest in this type of power generation. However, the waste generated by the burning of coal has been a hindrance to the massive deployment of this model. In the process of power generation in thermoelectric plants, for every 100 tons of coal used, 42 tons of ash are produced[1]. For this reason, studies that attempt to take advantage of these wastes have been encouraged.

In the other side, the use of concrete for various applications has been growing and requires greater production of cement. The Brazilian cement industry ended the year of 2011 registering a domestic consumption of cement in the order of 64.5 million tonnes, 97% of its production capacity and has already projected an increase of consumption to 2012 of around 10.4%, ever recorded in the first months[2]. This also represents environment degradation by CO_2 increase in the atmosphere arising from the combustion of raw materials and by the large scale extraction of this raw material. Thus, the use of coal ash replacing cement in concrete production reduces environmental impact due to the reduction of raw materials extraction, giving a destination to a waste generated in thermoelectric plants, among other advantages.

Another relevant aspect is the use of coal ash in mortar and concrete can improve technical characteristics[3]. So, the aim of this study is evaluate the replacing of cement by coal ash in physical and mechanical properties of concrete in its fresh and hardened conditions.

2. MATERIALS AND METHODS

2.1 MATERIALS CHARACTERIZATION

The cement used in research was a Brazilian Composed with filler Portland cement (CP II F 32) manufactured by CSN, specific gravity of 3.1 kg/dm³ and Blaine of 3287 cm²/g. Coarse aggregate was granite crushed rock with maximum diameter of 25 mm and fineness modulus of 7.00. Fine aggregate was river natural sand with fineness modulus of 2.86. Physical aggregates characteristics are shown in Table 1. A water reducing additive with specific gravity of 1.2 g/cm ³ was also used.

Table 1 – Physical aggregates characteristics

Characteristic	Fine aggregate	Standard	Coarse aggregate	Standard
Maximum grain size	4,75 mm	NBR 248/03	25,00 mm	NBR 248/03
Finess modulus	2,86 mm	NBR 248/03	7,00 mm	NBR 248/03
Bulk density	-	NBR NM 45/03	1,43 g/cm³	NBR NM 45/03
Compacted bulk density	-	NBR NM 45/03	1,52 g/cm³	NBR NM 45/03
Specific gravity	2,58 g/cm³	NBR NM 52/03	2,64 g/cm³	NBR NM 53/03

The ash used was produced in a power plant in Portugal with the same technology and raw material of that in Brazil. It was packed in metal drums of 200 litres (Figure 1) and sent to Brazil. For the study, a sample was dried in an oven at 110°C until constancy of weight and sifted through 0.075 mm sieve (Figure 2).

Figure 1 – Natural coal ash

Figure 2 - 75μm sieved coal ash

To determine coal ash particle size distribution, a sample was subjected to tests on laser diffraction particle size analyzer equipment, brand Malvern, model Mastersizer 2000 MSS, according to Brazilian Standard NBR 8629 [4], which provides proceedings for particle size coal analysis. The results of laser granulometry are shown in Figure 3 and the physical characteristics are presented in Table 2.

Figure 3 – Particle size distribution of coal ash

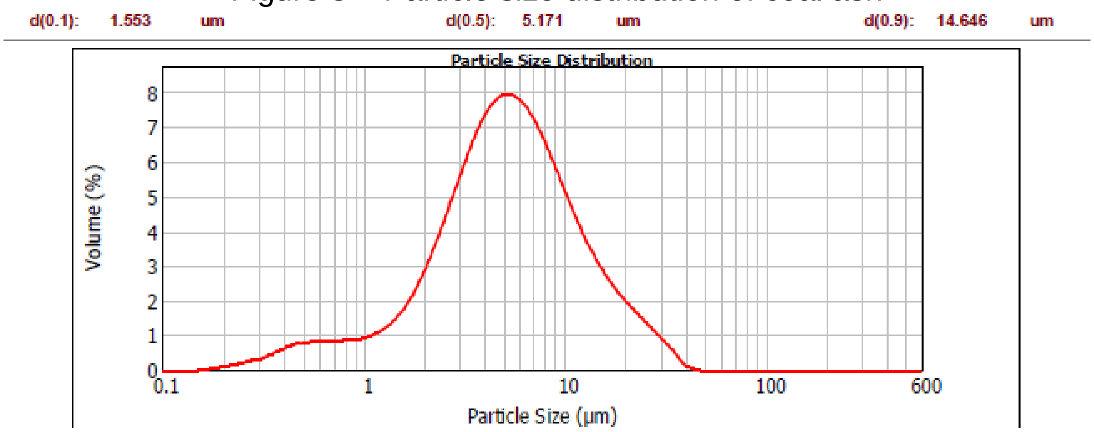


Table 2 – Physical coal ash characteristics

Characteristic	Value	Standard
Blaine (cm^2/g)	12080	NBR NM 76
Umidity (%)	0,93	NBR NM 24
Specific gravity (g/cm^3)	2,26	NBR NM 23

The coal ash, because it is a porous material, presented a specific gravity equal to 2.26 g/cm^3, less than the value of the CP II F-32 cement, that is equal to 3.10 g/cm^3.

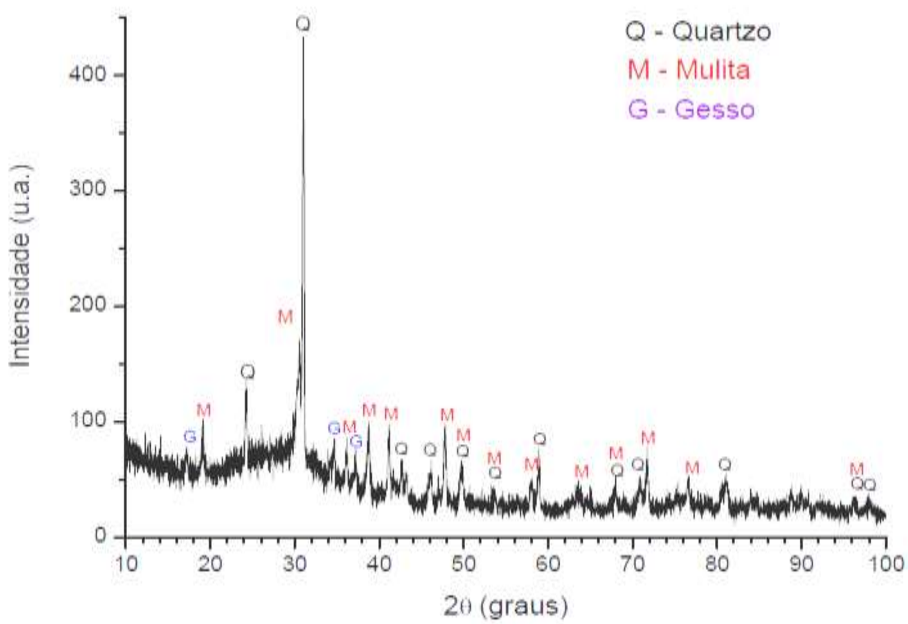
For chemical characterization, a sample of coal ash was tested in a fluorescence X-ray equipment, Model ZSXMini II, manufacturer Rigaku. Results are in Table 3 and can be noticed that the ash composition is largely made of silicon-aluminous-ferrous, being the sum of the amounts of SiO_2, Al_2O_3 and Fe_2O_3 equal to 75% of component oxides in their chemical composition.

Table 3 – Chemical coal ash components

Components	Loss of Ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	SO_3	TiO_2	MgO	P_2O_5	SrO
Content (%)	16.19	43.62	24.71	6.60	2.49	2.18	1.67	1.05	0.87	0.12	0.09
Components	Na_2O	V_2O_5	Co_3O_4	ZnO	CuO	ZrO_2	NiO	MnO	Cr_2O_3	Rb_2O	Eu_2O_3
Content (%)	0.07	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.003

Mineralogical characterization of the ash was carried out in an X-ray diffractometer PANalytical XPert Pro MPD brand equipped with a tube of Cobalt. The diffractogram shows a characteristic amorphous halo of pozzolanic materials and compounds identified as crystalline quartz, mullite and gypsum. The diffractogram and the identification of crystalline peaks can be seen in Figure 4.

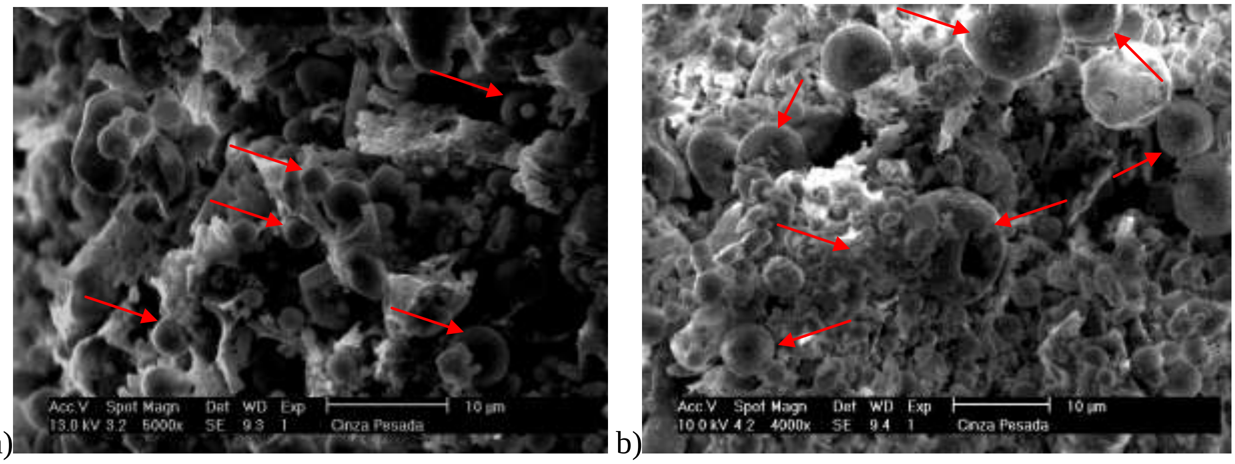
Figure 4 – Coal ash X-ray diffratogram



The microstructural analysis was obtained using the scanning electron microscope (SEM), model PHILIPS XL - 30. The images were generated by secondary electrons with a voltage of 10KV. The increase was 4000 and 5000 times. The particles of coal ash are almost entirely spherical, with a small amount with hollow spheres (cenospheres) (Figure 05).

Pozzolanic activity test with Portland cement was performed in accordance with Brazilian Standard NBR 5752 [5]. The result show 98.5% pozzolanic activity index that qualifies this coal ash as a pozzolan class C, according to NBR 12653 [6].

Figure 5 – SEM pictures of coal ash. a) 5000x; b) 4000x



2.2 CONCRETE PRODUCTION

Two reference concretes without coal ash were designed by ABCP method for water/cement ratio of 0.45 and 0.55. Six more concrete mixtures were produced replacing cement by coal ash in volume contents of 3%, 6% and 9%. All mixtures are presented in Table 4. The workability measured by slump test were set as 80mm ± 10mm.

Table 4 –Consumption of material per m³ of concrete

Mixture	Cement (Kg)	Coal Ash (kg)	Fine Aggregate (Kg)	Coarse Aggregate (Kg)	Water (Kg)	Aditive (g)
REF - 0.45	432,8	0,0	714,0	1025,6	194,7	458,3
T3 - 0.45	419,8	10,0	714,0	1025,6	193,4	444,9
T6 - 0.45	406,8	19,9	714,0	1025,6	192,0	690,5
T9 - 0.45	393,8	29,9	714,0	1025,6	190,6	185,8
REF - 0.55	354,5	0,0	779,9	1024,5	195,0	261,5
T3 - 0.55	343,9	7,8	779,9	1024,5	193,4	172,6
T6 - 0.55	333,2	15,5	779,9	1024,5	191,8	272,3
T9 - 0.55	322,6	23,3	779,9	1024,5	190,2	317,5

For each concrete mixture, tests in fresh conditions were performed: consistency index (slump test), according to NM 67 [7], specific gravity and air content according to NBR 9833 [8].Seven cylindrical specimens 10cm x 20cm (diameter x height) were casted for each concrete mix.

Were molded bodies seven-to-diameter cylindrical specimens of 10 x 20 cm, according to NBR 5738 [9] each concrete mix. After 24 hours of casting, all specimens were demolded and cured in water tank with lime until 28 days of age.

Compressive strength, tensile strength by diametral compression and water absorption by capillarity were performed in the specimens.

3. RESULTS

3.1 RESULTS IN FRESH CONDITIONS

Test results on fresh concrete are presented in Table 05.

Table 4 –Physical characteristics of fresh concrete

Mixtures	Content of SP (%)	Consistency index (mm)	Specific gravity (Kg/dm^3)	Air entrainment (%)
REF - 0.45	0,11	90	2,42	2,11
T3 - 0.45	0,11	90	2,42	2,54
T6 - 0.45	0,17	90	2,43	2,97
T9 - 0.45	0,05	90	2,43	2,97
REF - 0.55	0,07	70	2,39	1,70
T3 - 0.55	0,05	70	2,40	2,13
T6 - 0.55	0,08	90	2,41	2,55
T9 - 0.55	0,10	70	2,43	3,40

As can be seeing in Table 4, all concretes consistency was guaranteed in values between 80±10mm by the using of superplasticizer (SP). Can be noted that the consumption of SP in concretes of 0.55 water/cement (w/c) ratio was lower that 0.45 w/c ratio concretes. This behavior is coherent and expected once the volume of water in 0.55 w/c concretes is higher then in 0.45 w/c ratio concretes.

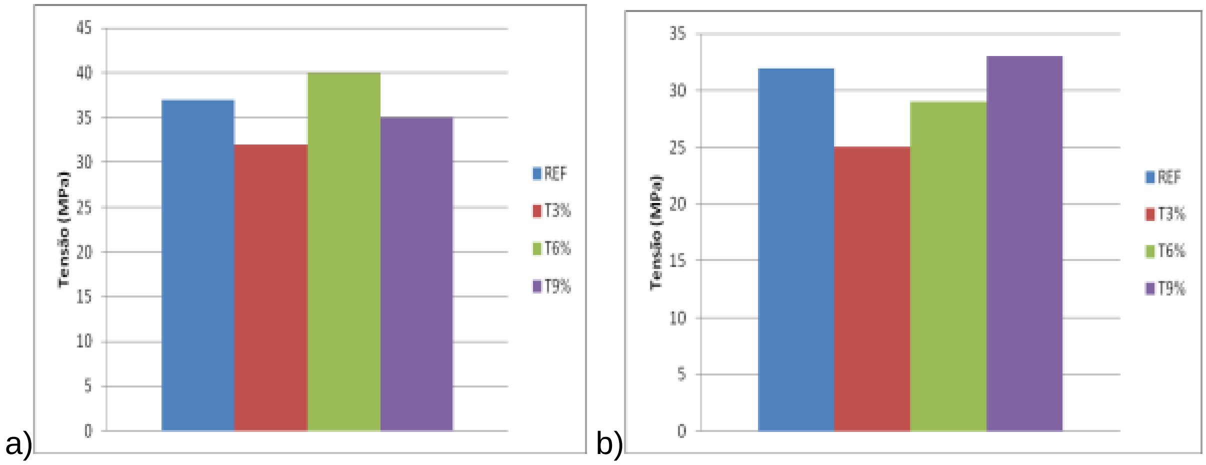
Despite used coal ash have a specific surface area of 12.080 cm^2/g, which is much greater used cement specific surface (3.287 cm^2/g), in general the use of coal ash in concretes almost does not modify the content of SP to reach the desirable workability. This behavior can be explained because the contents of coal ash in concrete were very small and due to the rolling effect propitiated by the ash, once it has spherical particles that facilitate the movement of the aggregates in concrete.

Regarding the specific density, the results showed that this property does not modify with the incorporation of coal ash in concretes. However, the air entrainment increases with the increase of coal ash content in concrete. Coal ash contents of 3%, 6% and 9% increases the incorporated air content in 20,4%, 40,8% and 40,8% for 0.45 w/c, respectively, and 25,3%, 50% and 100% for 0.55 w/c, respectively. This result is unexpected once it is known filler and pozzolanic ashes effects.

3.2 RESULTS IN HARD CONDITIONS

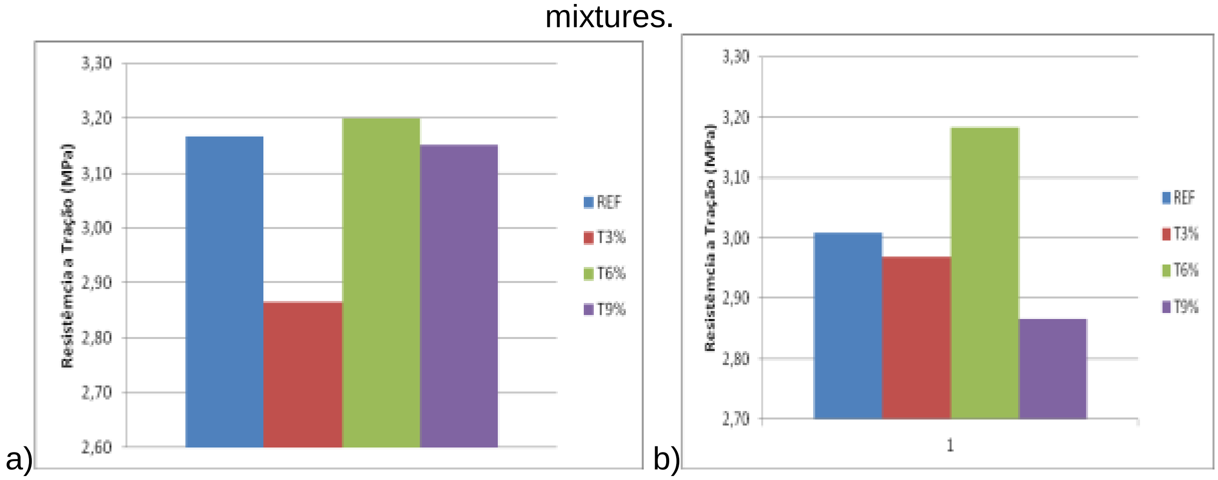
Figure 6-a and 6-b show compressive strength results for concretes with w/c ratios of 0.45 and 0.55, respectively. In Figure 6-a can be seen that compressive strength of 0.45 w/c ratio concrete decrease for 3% and 9% of coal ash and increase 8% for 6% of coal ash. In Figure 6-b, 0.55 w/c ratio concrete’s compressive strength decrease for coal ash content of 3% and 6% and increases 3% for 9% of coal ash. These results are coherent with air entrainment results once voids content in concrete increased.

Figure 6 – Compressive strength results. a) 0.45 w/c ratio mixtures; b) 0.55 w/c ratio mixtures.



Tensile strength results are showed at Figure 7-a and 7-b for 0.45 and 0.55 w/c ratio concretes, respectively. It is possible to notice that tensile strength behavior did not follow compressive strength behavior once, according to Figure 7-a, for 0.45 w/c ratio concrete, 3% of coal ash decreases highly tensile strength and 6% and 9% of coal ash almost did not change tensile strength value. For 0.55 w/c ratio concrete, according to Figure 7-b, 6% of coal ash increases highly tensile strength while 3% and 9% decreases it. We believe that this great decrease for 0.45 w/c ratio and great increase for 0.55 w/c ratio were produced by errors during the tests.

Figure 7 – Tensile strength results. a) 0.45 w/c ratio mixtures; b) For 0.55 w/c ratio mixtures.



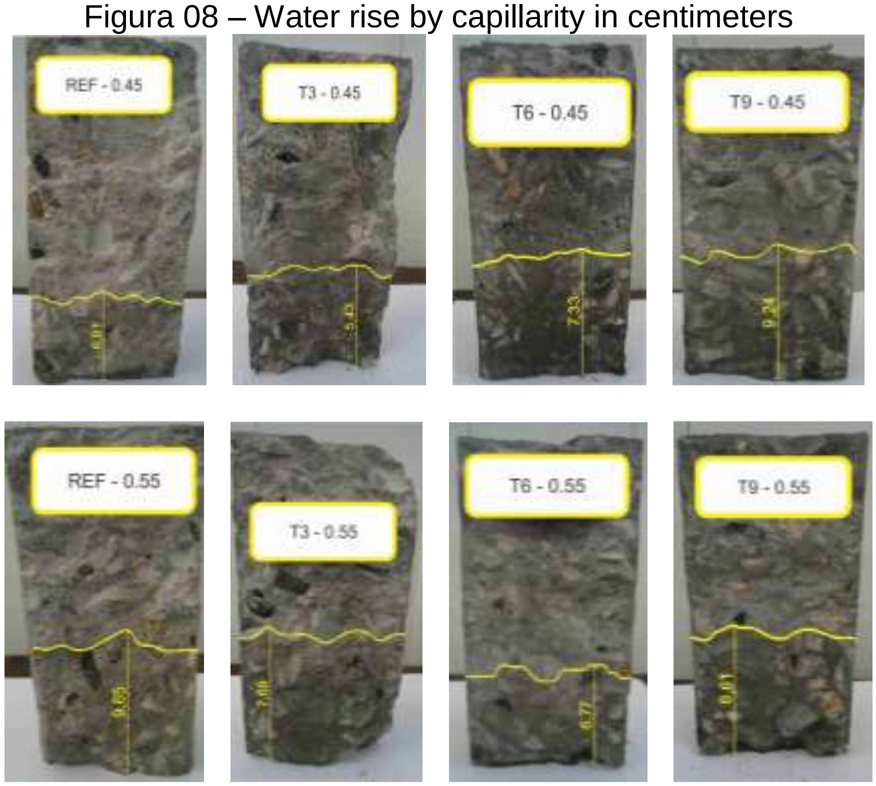
Water absorption by capillarity results are shown in Table 5. It can be observed that 0.45 w/c ratio concrete has a different behavior of 0.55 w/c ratio concrete when coal ash was inserted in concrete mixtures. For 0.45 w/c ratio concretes, the presence of coal ash in concrete mixtures increased water absorption reaching increases of 23%, 58% and 104% for 3%, 6% and 9% of coal ash, respectively, at 24 hours. However, for 0.55 w/c ratio concretes, 3%, 6% and 9% of coal ash in the mixtures decreases concrete's absorption in 37%, 30% and 21%, respectively, at 24 hours.

Table 5 – Concrete's water absorption by capillarity

Mixtures	Water absorption (%)					
	Time (h)					
	0	3	6	24	48	72
REF - 0.45	0,00	0,07	0,10	0,26	0,42	0,56
T3 - 0.45	0,00	0,08	0,14	0,32	0,44	0,51
T6 - 0.45	0,00	0,12	0,19	0,41	0,55	0,60
T9 - 0.45	0,00	0,18	0,35	0,53	0,86	1,04
REF - 0.55	0,00	0,26	0,36	0,63	0,82	0,95
T3 - 0.55	0,00	0,10	0,19	0,40	0,57	0,69
T6 - 0.55	0,00	0,21	0,25	0,44	0,63	0,73
T9 - 0.55	0,00	0,14	0,32	0,50	0,88	1,10

Results of water rise by capillarity for 0.45 and 0.55 w/c ratio concrete mixtures are shown in Figure 8. As can be seen, water rise by capillarity of 0.45 w/c ratio mixtures with coal ash were higher that reference concrete, with exception of mixture T3-0.45. However, all coal ash mixtures for 0.55 w/c ratio presented water rise by capillarity lower than reference concrete. These results are coherent with water absorption results.

Figura 08 – Water rise by capillarity in centimeters



The reduction in water absorption and in water rise probably occurs due to precipitation of silicates generated by chemical reactions of coal ash with calcium hydroxide in larger voids of hardened paste, such as capillary channels [2]. However, this behavior does not appear in 0.45 w/c ratio mixtures.

4. CONCLUSION

Coal ash tested is lighter and finer than cement and seems be a pozzolan. However, when tested in concrete mixtures replacing cement, results does not were well once air entrainment increased and compressive and tensile strength almost does not change. Best results were obtained for water absorption by capillarity and for water rise once for 0.55 w/c ratio concretes decreases up to 37% were observed. More tests should be done since results are not coherent with literature texts.

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