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Properties of the self-compacting concrete with fly ashes
Propriedades de concreto auto-adensável contendo cinzas volantes

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ABSTRACT

Self-compacting concrete is a high performance concrete with excellent rheological properties that can be spread in areas of difficult access. Self-compacting concrete requires a high consumption of cement production, which has a negative effect on the environmental aspect, since the production of cement releases significant amounts of CO_2. This study aims analysis the influence of the substitution (20 and 40% by weight) of Portland cement by fly ash on the self-compacting concrete properties in the fresh state (spreading, workability, passing ability - J-ring test, viscosity - V-funnel test) and hardened (compressive strength). The passing ability was proved more effective to the mixture with 20% of replacement. To the viscosity, control concrete had lower flow time in V-funnel. The compressive strength results at 28 days showed a reduction of 9.5% for concrete with 20% fly ash and 77.0% for concrete with 40% fly ash compared to the control concrete.

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1. Introduction

In Brazil, the gross production of coal in 2015 was 13 million tons. Of these, 6.7 million tons were destined energy production. The Brazilian southern states were responsible for 100% of the coal consumption (58.5% in Rio Grande do Sul, 40.0% in Santa Catarina and 1.5% in Paraná). The Jorge Lacerda thermoelectric complex, located in the Santa Catarina state, produced, in the months of 2018, on average, 344.5 MWh. On this process, 89031.07 tons of ash were generated, of which 54191.86 were commercialized and 34839.22 were sent to sedimentation basins (Department of Thermal Generation - Jorge Lacerda Thermoelectric Complex, 2019).

Waste from thermoelectric plants is formed by non-combustible components and not-burned particles of coal due to incomplete combustion. These residues are classified in light of fly ashes and heavy or bottom ashes (Kreuz *et al*., 2002). The high cost of storage and the concern with the proper disposal of this residue have been encouraging alternatives in waste management for several applications such as pozzolanic cement production, concrete, and mortar mixtures (Rohde and Machado, 2016).

The self-compacting concrete (SCC) is a high performance concrete with excellent rheological properties and high resistance to segregation. The SCC can be spread over long distances by only its own weight and can fill out complex shapes with congested steel in areas of difficult access, without the need for vibration (Metha and Monteiro, 2014). It has sufficient stability to be handled and released without segregation or exudation. As a result, the use of SCC can reduce the work time and the labor cost, in addition to improving the working environment by eliminating the vibration and noise during its production. For these reasons, SCC has been widely used in various types of works (Barbhuiya, 2011; Das and Chatterjee, 2012; Ashtiani *et al*., 2013; Zhao *et al*., 2015).

In order to provide high fluidity and to avoid segregation and exudation during transport and application of the SCC, its production demands a large amount of Portland cement (450-600 kg/m³), so its production cost is remarkably greater than a conventional vibrated concrete. In addition to the economic issue, excessive use of Portland cement also has a negative effect on the environmental aspect (Barbhuiya, 2011; Zhao *et al*., 2015).

Cement production releases significant amounts of CO_2 to the atmosphere; it is estimated that the industry already emits 5% of the CO_2 generated in the world (Escola Politécnica da USP, 2015). The emission of CO_2 varies from country to country and depends on the technology and raw materials used in the production. Brazil currently has an emission factor of about 610 kg CO_2/t cement, one of the lowest in the world. Almost 30% less than China, with emission factor of 848 kg CO_2/ton cement, one of the highest in the world (Escola Politécnica da USP, 2015).

An alternative to solve this problem is to replace part of the SCC cement by mineral additions. Fly ash is a mineral admixture type often used in the production of SCC (Dehwah, 2011; Dinakar, 2012; Ponikiewski and Gołaszewski, 2014; Faseyemi, 2015). It is a very fine residue derived from the burning of mineral coal in thermoelectric plants.

The use of mineral addition in the production of SCC, besides reducing the production cost of the SCC, can also generate environmental benefits (Pathak and Siddique, 2012).

In this study, the percentages of mineral additions to replace Portland cement were 20% and 40% (by weight). The following properties in fresh SCC were tested: spreading and workability (through spreading - *slumpflow test*), passing ability (J-Ring), setting and viscosity times (V-Funnel). The compressive strength was measured in the hardened state.

2. Materials and methods

2.1. Materials

2.1.1. Cement

In this study, we used the Portland Cement, CP II-Z-32 type (Votoran, 2014). The manufacturer, as per Tables 1 and 2, provided the physical properties and chemical composition of the cement.

Table 1 - Physical properties of the cement CP II-Z-32 (Votoran, 2014).

Fineness		**Setting time**	
Residue on sieve 75 µm (%)	Specific area (m²/kg)	Start (h)	End (h)
≤ 12.0	≥ 260	≥ 1	≤ 10
Compressive Strength (MPa)			
1 day	3 days	7 days	28 days
-	≥ 10	≥ 20	≥ 32

According to Kurtis (2012), the CH phase occupies 20-25% of the solid volume of the cement paste. The cement used CP-II-Z has 6 to 14% of pozzolana. If the replacement of 40% cement by fly ash is considered. And of the remaining 60% and cement, 14% is pozzolan. Even so, there would be a considerable amount (51.6%) of responsible cement to result in CH. There are already works on concrete with high levels of fly ash, reaching up to 70% of replacement.

Table 2 - Chemical composition of cement CP II-Z-32 (Votoran, 2014).

	Chemical composition (% weight)
	CP II - Z - 32
Al_2O_3	6.77
CaO	52.79
Fe_2O_3	3.15
MgO	4.15
SiO_2	22.41
SO_3	2.79
($K_2O + Na_2O$)	0.78
Loss on ignition	5.00

2.1.2. Mineral additions

Five types of self-compacting concrete were prepared, replacing cement with mineral admixture (20 to 40% by weight). With pozzolanic mineral addition, fly ash type, provided by the Thermoelectric plant 1 (FA1); one with fly ash provided by the Thermoelectric plant 2 (FA2) and the other one without mineral addition (control self-compacting concrete). Both the two Thermoelectric are located in the southern region of Brazil.

The typical fly ash contains between 60% and 90% of amorphous silica (Metha and Monteiro, 2014). A recent study (Gobbo, 2009), using XRD-Rietveld techniques, shows that Brazilian fly ash present amorphous content between 50% and 70%. These values are consistent with previous results reported by Kihara et al. apud (Effting, 2004) and obtained by optical microscopy and XRD.

Over 85% of most fly ashes comprise chemical compounds formed by the elements silica, aluminum, iron, calcium and magnesium. Table 3 shows the chemical composition of Brazilian fly ash FA1 and FA2, where we note the similarity of its characteristics and the calcium content of less than 5% (Effting, 2004).

Table 3 - Physical and chemical properties of the fly ash studied. FA1 by FRX test and FA2 supplied by the manufacturer.

(%)	Fe_2O_3	CaO	K_2O	SO_3	SiO	Al_2O_3	MgO	Na_2O	SrO	TiO_2	ZrO_2	Umidity	Loss on ignition
FA1	7.01	21.58	3.18	2.38	40.20	24.11	-	-	-	1.44	0.10	-	2.50
FA2	5.28	2.31	2.08	0.49	62.14	23.23	0.83	0.08	0.20	0.85	0.07	0.33	2.47

The fly ash particles are typically spherical, presenting themselves in small quantities as hollow spheres, which may be empty (cenospheres) or filled with other smaller spheres (plenospheres) (Figure 1). Their diameters range from less than 1 to more than 150 µm, most of them less than 45µm. The wide range of variation is mainly determined by the equipment used for burning (Effting, 2004).

The specific surface of the fly ash ranges from 300 to 700 m^2/kg (as measured by nitrogen adsorption technique), very similar to that of Portland cement (350-600 m^2/kg). The fly ash density ranges from 1900 to 2400 m^2/kg, while the ordinary Portland cement is around 3150 kg/m^3. Thus, the mass substitution results in a considerably greater volume of materials (Effting, 2004).

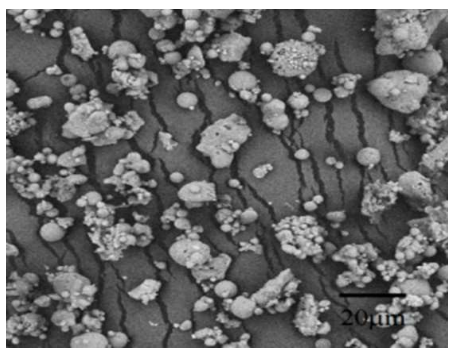

Figure 1 - Fly ash 1 morphology, showing dispersion size particles, 500X magnification.

To determine the pozzolanic activity in cement according to NBR 5752 (ABNT, 2012) three mortars were prepared, one mortar for each fly ash and a reference mortar only with cement. The mortar must have the consistency of 225±5 mm. Three cylindrical specimens (05 cm x 10 cm) were moulded in 4 layers, with 30 strokes per layer. After 24 hours, the specimens were demoulded and placed in a tank with water saturated with calcium hydroxide per 28 days. The activity index pozolanic is determined by Eq. 1

$$\frac{fcb}{fcA}.100\ (\%) \quad (1)$$

where:
f_{cb} = Average resistance, at 28 days, of the specimens with cement and material to be tested (mortar with fly ash).
f_{ca} = Average resistance, at 28 days, of the specimens with cement only (reference mortar).

2.1.3. Addmixture

The addmixture used was a modified polycarboxylate-based superplasticizer provided by the company Allchem.

2.1.4. Aggregates
Two types of medium and fine river sand were used as fine aggregate, and artificial gravel was used as coarse aggregate. Both materials are from the northern region of Santa Catarina, Brazil. The particle size (fineness modulus and maximum diameter) and the physical properties of the aggregate are shown in Table 4.

Table 4 - Characteristics of the aggregates used in the self-compacting concrete.

Properties	Aggregate		
	Coarse aggregate	Medium sand	Fine sand
Fineness modulus	6.38	2.08	1.67
Maximum diameter (mm)	19	2.36	1.18
Specific weight (g/cm³)	2.89	2.64	2.70

2.2. Mixture design of self-compacting concrete

In this study, we used five mixtures of self-compacting concrete, with a standard mixture (without mineral addition), two mixtures using fly ash FA1 replacing cement in different ratios (20% and 40% by weight) and two mixtures using fly ash FA2 in the same proportions. We used a fixed binder consumption of 520 kg/m³, a ratio water/cement of 0.48 and the total amount of aggregated mass was maintained at 1537 kg/m³. The proportions of the materials used for the standard mixture and to mixtures containing the fly ashes are detailed in Table 5.

The maximum amount of additive superplasticizer oriented by the manufacturer (1.5% on the mass of the cement) was used. The water/cement ratio was increased until obtaining a mixture that could be classified in relation to the properties of consistency and passing ability. The inclusion of fines in the mixture (increasing the amount of fly ash) could be a solution to reduce water/cement ratio. On the other hand, increased cement replacement would reduce compressive strength. Then the water/cement ratio was kept higher, with less fly ash, as long as there was no segregation.

Table 5 - Proportion of materials adopted in the study (for 1m³ concrete).

Materials (kg/m³)	Mixtures		
	Concrete of control	20% FA	40% FA
Cement	520	416	312
Fly ash	-	104	208
Medium sand	536	536	536
Fine sand	383	383	383
Coarse aggregate	618	618	618
Water	250	250	250
Superplasticizer	7.8	7.8	7.8
Water to cement ratio	0.48	0.48	0.48

2.3. Sample preparation and curing conditions

The mixing operation of the materials, namely cement, fly ash, aggregates and water was made in a common mixer with 120 liter capacity, as per NBR 12655 (ABNT, 2015b). After mixing these materials, superplasticizer additive was added and mixed for another 5 min, then a variety of tests were made to determine the properties of the concrete in fresh state. Then, five cylindrical specimens were finally cast for each trait with dimensions of 200 mm x 100 mm as per NBR 5738 (ABNT, 2016). Once demolded, they were placed in the tank with water saturated with calcium hydroxide at 23 °C and kept submerged until the disruptions ages of 14 and 28 days, as per NBR 5739 (ABNT, 2007). It is noteworthy that it was only possible to demold the specimen safely after seven days of age, due to the fact that the used additive delayed the initial setting time.

2.4. Procedures for the tests

2.4.1. Fresh properties of self-compacting concrete
2.4.1.1. Slumpflow test - spreading
This test is to determine the fluidity of the self-compacting concrete in free flow under the action of its

own weight, using Abrams cone, as can be seen in Figure 2. This test was performed as per NBR 15823-2 (ABNT, 2010b).

Figure 2 - Self-compacting concrete slump flow test, (a) Abrams's cone and (b) the spreading measure.

2.4.1.2. Workability

The self-compacting concrete workability is measured by varying the Flow Test value over time. To do so, we measured the Slump Flow value immediately after mixing, and it was remeasured 30 min after the first test.

2.4.1.3. Passing ability (J-Ring test)

Passing ability is the self-compacting concrete ability to flow within the mold, passing through the obstacles (16 steel bar with 10 mm in diameter), without flow or segregation obstruction. This test was performed as per NBR 15823-3 (ABNT, 2010c), as shown in Figure 3.

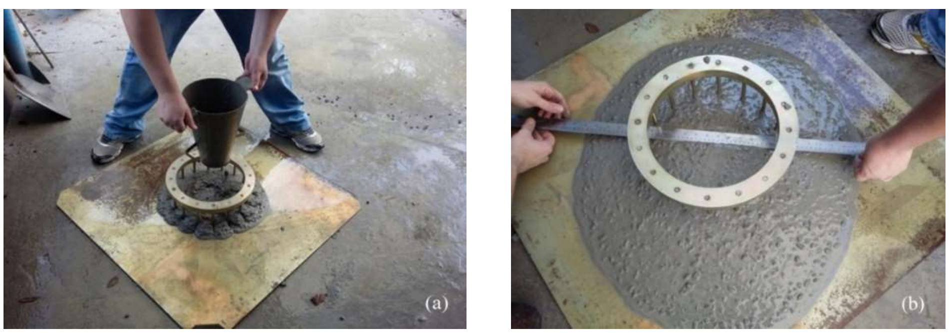

Figure 3 - Self-compacting concrete passing ability test, (a) beginning of flow through the J-ring J and (b) SCC resistance measurement to the lock.

2.4.1.4. Viscosity (V-funnel test)

The determination of the self-compacting concrete viscosity (Figure 4) is performed by measuring the flow time of a concrete weight through the funnel V. This test was performed as per NBR 15823-5 (ABNT, 2010d).

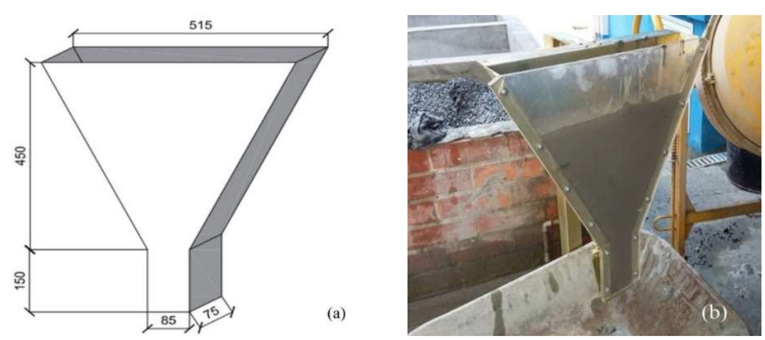

Figure 4 - Self-compacting concrete viscosity test, (a) V-funnel dimensions (mm) and (b) Self-compacting concrete draining through the V-funnel.

2.4.2. Properties in the hardened state

2.4.2.1. Compressive Strength

The determination of the compressive strength of the concrete cylindrical specimens was accomplished through machine press EMIC, PC 200 I model, with a nominal capacity of 200 tf, as per NBR 5739 (ABNT, 2007) for ages 14 and 28 days.

3. Results

3.1. Pozzolanic activity of fly ashes

The fly ash FA1 and FA2 had pozzolanic activity of 94.15%. and 87.56%, respectively (Figure 5).

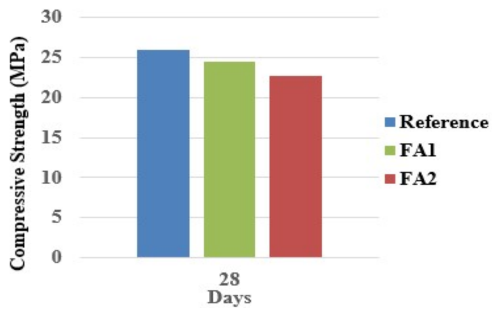

Figure 5 - Pozzolanic activity results.

According to NBR 12653 (ABNT, 2014) , the minimum acceptable value for a material to be pozzolanic is 90%. In this way only FA1 is considered pozzolanic material. It should be noted that in this work the ashes were not ground. They were used in the way they are supplied by thermoelectric plants to the cement industry. It is well known that if fly ash were ground it would be much more reactive. But grinding ash still had a cost.

3.2. Fresh properties of self-compacting concrete

3.2.1. Slumpflow test - spreading

The value to be considered in the slumpflow test is found as the arithmetic mean of two measurements perpendicular to the diameter, carried in millimeters, as per NBR 15823-2 (ABNT, 2010b).

Also according to this standard, the control self-compacting concrete whose spreading was 750 mm is classified as SF2, suitable for most standard applications, such as pillars and beams, while self-compacting concrete dosed with replacement of 20% and 40 % bulk cement by fly ash FA1 and FA2 are classified as SF1, indicated for unarmed groups or with low steel ratio, such as slabs or piles. This means that the addition of fly ash significantly reduced the specific spreading ability. As can be seen in Table 6, in a previous study (Siddique *et al.*, 2012) the fly ash also reduced the spread of self-compacting concrete when compared to concrete without fly ash.

Table 6 - Results of Slumpflow test – spreading.

Mixture (% weight)	Slumpflow (mm)	Observation:
Control	750	without mineral addition
20% FA1	670	Fly ash from thermoelectric plant 1 – FA1
40% FA1	565	Fly ash from thermoelectric plant 1 – FA1
20% FA2	615	Fly ash from thermoelectric plant 2 – FA2
40% FA2	625	Fly ash from thermoelectric plant 2 – FA2

3.2.2. Workability

As can be seen in Figure 6, the use of both fly ashes improved retention of workability compared to the concrete of control.

In the case of fly ash FA1 (Figure 6a), the more fly ash, the better the maintenance of workability over time.

For ash FA2 (Figure 6b), the workability of the concrete with 20% fly ash, instead, decreased

5.69%. For concrete with replacement of 40%, the reduction was 3.20%. As to the control self-compacting concrete (no mineral addition), the loss of workability after 30 minutes was 14%. This fact can be justified due to the reduction of the hydration heat that the ash provides to the mixture, causing the evaporative water loss to be lower, ensuring a longer workability.

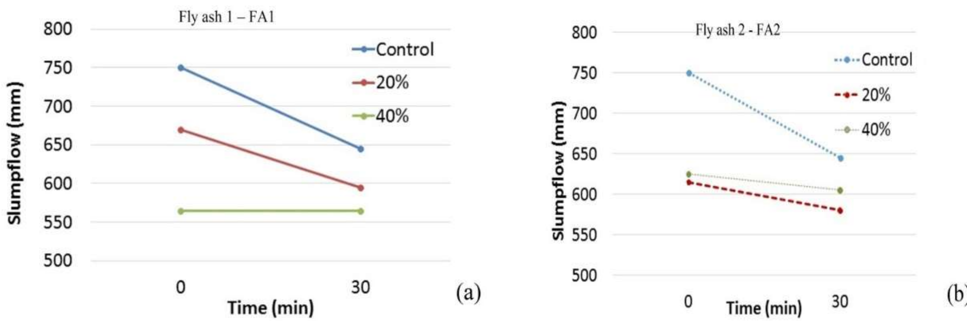

Figure 6 - Slumpflow variation over time, (a) fly ash from thermoelectric 1 and (b) fly ash from thermoelectric 2.

3.2.3. Passing ability (J-Ring test)

As per NBR15823-1 (ABNT, 2010a), the smaller the variation between the spreading amount (Slumpflow test) and the *J-Ring test* value, the better the passing ability of the self-compacting concrete. In this case, as can be seen in Table 7, the FA1 fly ash replacement for cement significantly improves the passing capacity of the concrete. This improvement is proportional to the amount of ash used. To the extent that in the case of substitution of 40% ash, the classification changed from PJ1, which is concrete suitable for steel with a spacing of 80-100 mm, to PJ2, which is concrete suitable for steel with spacing of 60-80 mm.

The self-compacting concrete with replacement of 20% of FA2 for cement achieved a significant improvement in the passing ability, but it failed to change the classification as per standard (PJ1). In general, the replacement of cement by ash improved the passing capacity.

Table 7 - Classification in J-Ring test, NBR 15823-1 (ABNT, 2010a).

	J-Ring				Observation:
Mixture	**Slumpflow (mm)**	**J-Ring (mm)**	**Variation (mm)**	**Classification**	
Control	750	680	70	PJ1	without mineral addition
20% FA1	670	625	45	PJ1	Fly ash from thermoelectric plant 1 – FA1
40% FA1	565	545	20	PJ2	Fly ash from thermoelectric plant 1 – FA1
20% FA2	615	590	25	PJ1	Fly ash from thermoelectric plant 2 – FA2
40% FA2	625	570	55	PJ1	Fly ash from thermoelectric plant 2 – FA2

3.2.4. Viscosity (V-Funnel test)

With respect to the viscosity, it was observed that the greater the amount of fly ash 1, the greater the time required to empty the funnel. However, the addition of the FA1 ash did not alter the classification as per NBR 15823-1 (ABNT, 2010a), as can be seen in Table 8, which remained as VF1, that is, a concrete suitable for structural elements with high density fittings.

Table 8 - Classification in V-Funnel test, NBR 15823-1 (ABNT, 2010a).

	V-Funnel		Observation:
Mixture	**Time (s)**	**Classification**	
Control	5.28"	VF1	without mineral addition
20% FA1	6.51"	VF1	Fly ash from thermoelectric plant 1 – FA1
40% FA1	8.57”	VF1	Fly ash from thermoelectric plant 1 – FA1
20% FA2	8.66"	VF1	Fly ash from thermoelectric plant 2 – FA2
40% FA2	6.85"	VF1	Fly ash from thermoelectric plant 2 – FA2

As to the replacement of cement for fly ash 2, in the ratio of 20%, it reduced the flow capacity of the concrete through the funnel, increasing its apparent plastic viscosity more significantly than that for concrete with 40% fly ash 2.

In general, the addition of fly ash increases the apparent viscosity of the plastic self-compacting concrete, reducing its flow capacity, but not to the point of changing its classification as to the use.

3.3. Properties of concrete self-compacting concrete in the hardened state

3.3.1. Compressive Strength

For self-compacting concrete dosed with replacement of 20% of the mass cement for fly ash FA1, the disruption after 14 days showed resistance very close to that of the control concrete, 26.32 and 26.09 respectively. However, this difference becomes more pronounced after 28 days, the control mixture reached 34.71 MPa compressive strength while the concrete mixtures with 20% FA1 reached 31.69 MPa. With 40% replacement, the compressive strength was 19.61 MPa.

It is noted from Table 9 that for the self-compacting concrete dosed with replacement of 20% and 40% of the mass cement by fly ash FA2, the compression strength decreased significantly. While the control mixture reached 14 days 26.32 MPa, the mixtures with 20% and 40% fly ash FA2 respectively achieved 13.62 MPa and 3.52 MPa. It was expected that within 28 days this difference would decrease as the ash increases the concrete strength in the final ages, which actually happened, but not significantly. Whereas after 28 days, the control mixture obtained 34.71 MPa and the other mixtures with 20% and 40% replacement reached 20.80 MPa and 14.22 MPa respectively.

Table 9 - Compressive strength of self-compacting concretes studied.

Mixture	**Compressive strength (MPa)**		**Observation:**
	14 days	**28 days**	
Control	26.32±0.23	34.71±0.91	without mineral addition
20% FA1	26.09±0.43	31.69±0.88	Fly ash from thermoelectric plant 1 – FA1
40% FA1	13.20±0.81	19.61±1.05	Fly ash from thermoelectric plant 1 – FA1
20% FA2	13.62±0.21	20.80±0.65	Fly ash from thermoelectric plant 2 – FA2
40% FA2	3.52±1.12	14.22±0.95	Fly ash from thermoelectric plant 2 – FA2

As per standard NBR 8953 (ABNT, 2015a), a concrete can be classified for structural purposes when its compressive characteristic strength (fck) is not less than 20 MPa. This causes both concrete with 20% FA1 showing compression strength of 31.69 MPa and concrete with 20% FA2 showing resistance equal to 20,80 MPa to be classified as C30 and C20 structural concrete respectively, whereas both exceeded 20 MPa after 28 days (considered the statistical control by total sampling).

These results showed that even reaching values lower than that of standard concrete, concretes with fly ash can be used in construction, respecting the calculation of values defined in the project. The waste management of fly ash for use in concrete production is a way to reduce the consumption of natural raw material, also reducing its final disposal in landfills.

4. Conclusion

Analyzing the results, it is observed that the replacement of cement CP II-Z by both fly ashes in the percentages of 20% for self-compacting concrete is a viable alternative.

The addition of fly ash significantly reduced the specific spreading ability.

For fly ash 1, the more fly ash, the better the maintenance of workability over time. Regarding the maintenance of the workability of the concrete self-compacting concrete with fly ash 2, which measured the spread after 30 minutes, the control mixture obtained a 14% reduction in workability, the mixture with 20% substitution achieved a reduction of 5.70% and the mixture with 40% replacement achieved reduction of 3.2%. Thus, it was concluded that the action of pozzolan, with its ability to decrease the hydration heat, thus reducing the water loss, minimized spreading reduction over time.

In passing ability, mixing with replacement of 20% fly ash 1 was the most effective. The smaller the variation between the amount of spreading (slumpflow test) and the value of J-Ring Test, the better the passing ability of the self-compacting concrete. The substitution of fly ash 1 for cement significantly improved the passing ability of the concrete. This improvement is proportional to the amount of fly ash

1 used. As to fly ash 2, the self-compacting concrete with 20% replacement obtained the best result for passing ability. In general, the replacement of cement by ash improved the passing capacity.

For viscosity, the control concrete had lower flow time in the V-funnel, consequently lower plastic viscosity. The mixture with 20% ash fly ash 1 obtained a reduction of 83% compared to the control and mixing with 40% replacement, 29.73%, which implies in the fly ash 1 efficiency as its proportion increases. This is another factor that can be explained due to decrease in water loss by reducing the hydration heat. As to the cement replacement for fly ash 2, in the ratio of 20%, it reduced the flow capacity of the concrete through the funnel, increasing its apparent plastic viscosity more significantly than that for concrete with 40% fly ash 2. In general, the addition of fly ash increases the apparent plastic viscosity of the self-compacting concrete, reducing its flow capacity, but not to the point of changing its classification according to the use.

For the compressive strength, concrete with fly ash 1 had the best performance, which was significantly superior to the performance concrete with fly ash 2. The control concrete reached 34.71 MPa compressive strength at 28 days, while concrete with 20% FA1 reached 31.69 and concrete with 40% FA1, 19.61 MPa. As to concretes with 20% and 40% FA2, they reached 20.80 MPa and 14.22 MPa respectively after 28 days.

In general, the replacement of up to 20% of the amount of self-compacting concrete cement for fly ash FA1 or FA2 is feasible because it meets the standard requirements, classifying these concrete as structural C30 and C20 respectively, as both exceeded 20 MPa after 28 days.

The cement used in this study, CP II-Z32, has up to 14% pozzolan in its composition. That is, the actual ash/binder ratio is probably greater than 20% and 40% and depends on the amount of ash that was added by the cement manufacturer, which probably impacted even more the compressive strength.

It is important to remember that despite the replacement of fly ash for cement being a great alternative, fly ash is a residue derived from an industrial process, so it does not undergo a quality control during or after its production. Thus, it is possible that different batches of the same product may show different characteristics. And this should be taken into account before the use of the cement replacement material.

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