Self-compacting mortar for mass concrete application with PAC technology

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Abstract. Preplaced-aggregate concrete (PAC) is defined in ACI 116R as "Concrete produced by placing coarse aggregate in a form and later injecting a portland cement-sand grout, usually with admixtures, to fill the voids.". As it is defined, there is a need of specific equipments and formworks to make a proper injection. Meanwhile, the development of self-compacting concrete (SCC) technology allowed achieving cementitious mixes that flow and compact by their own weight. The Portuguese Electric utility (EDP-Gestão da Produção de Energia SA) started a research for developing a new technology for mass concrete applications. The basic concept of this technology is the same as the PAC defined by ACI, however the mortar, instead of being injected, is just poured into the preplaced aggregate skeleton. The innovation consists in using a very fluid mortar with controlled bleeding which may fill the aggregate voids only by gravity. The results presented in this paper indicate that this new technology is promising for mass concrete applications.

Introduction

Self-compacting concrete (SCC) technology has allowed the development of specific concrete for new different applications. These include self-leveling, underwater, or architectural concrete. This paper presents the results of a study on a new technique that takes advantage of the material's flowing and self-compacting ability: preplaced aggregate concrete (PAC) without injection.

Preplaced aggregate concrete is defined in ACI 116R [1] as "Concrete produced by placing coarse aggregate in a form and later injecting a portland cement-sand grout, usually with admixtures, to fill the voids". As defined, it is necessary to use special equipment to carry out an adequate injection, and is also required to strengthen the formwork due to the pressure applied during the mortar injection.

From the advances on SCC rheology, the Portuguese Electric utility (EDP-Gestão da Produção de Energia SA) launched a study for the development of a new technology for mass concrete applications. The basic concept of this technology is similar to that defined in ACI 116R, with the difference that, instead of being injected, the mortar is simply poured in the skeleton of coarse aggregates. The filling of the gaps between aggregates is made only by the self-weight of the mortar. The innovation is the use of a very fluid mortar, with controlled bleeding.

The objective of this study is to design a mortar mixture in order to apply this new PAC technology in a cofferdam's section of a hydroelectric power plant under construction.

Being a technology whose information is still scarce, it has, by its characteristics, the potential to be cost-effective in mass concrete structures [2, 3], such as gravity dams.

This paper presents the results of the mix design development, for a self-compacting mortar, and of the application on a prototype which simulates real concreting conditions.

Materials

The materials used in the study were those intended to be applied in the construction of the above referred cofferdam. In the production of mortars, it was used a cement CEM II-B/L 32.5 N (according to European standard EN 197-1 [4]), a siliceous fly ash and a granitic crushed sand. The development of the mortar, to apply in the prototype, has included the evaluation of four polycarboxylic based superplasticizers (SP), identified here as V, S, X and A, from three different suppliers. The superplasticizers X and A belong to the same supplier.

The limestone filler content of the cement was 24.9%. The physical properties of the cement and the fly ash are presented in Table I. It should be noted that the fly ash presented a pozzolanic-activity index at 28 days of 84% (according to EN 450-1 [5]).

Table I – Cement and fly ash physical properties

Material	Density (kg/m^3)	Blaine fineness (kg/m^2)
Cement	3020	397
Fly ash	2280	415

It is presented in Table II the particle size distribution of the sand, expressed in terms of percentage of the material passing through the respective sieve opening.

Table II – Percentage of the sand passing through the sieve (opening in mm)

Opening	6.3	4	2	1	0.5	0.25	0.125	0.063
% sand	100	99.8	91.5	64.2	42.7	28.0	16.8	8.2

Table III presents the results for other characteristics of the sand. The dry particles density and water absorption were determined according to the procedure described in EN 1097-6 [6] and the bulk density by the EN 1097-3 [7]. The flow coefficient of the sand is determined in accordance with the procedure in EN 933-6 [8].

Table III – Other characteristics of the crushed sand

Characteristic	Result
Dry particles density, kg/m^3	2620
Water absorption, %	0.52
Bulk density, kg/m^3	1410
Flow coefficient (12 mm opening), s	37.7

Experimental procedure

Fresh mortars were characterized by the V-funnel and spread tests. In the V-funnel test the time that the mortar takes to flow through the lower opening is determined. This funnel was developed for tests on SCC mortars, allowing a good indication of the mortar's viscosity [9].

For the spread test, a truncated cone was used: base and top diameters of 100 mm and 70 mm, respectively; height of 60 mm. After filling the cone, without compaction, it was then lifted vertically without interfering with the flow. There were measured two perpendicular diameters, determining the result by the average of these two.

Development of the mortar to apply in the prototype

This chapter presents the most relevant steps to the decision on the choice of the mortar to be used in the prototype execution.

In the absence of experience in this technology, the initial mixture proportioning was established based in the existing knowledge concerning injection of mortars. The parameters chosen were the following: sand/binder=1, by weight; binder composition - 35% cement and 65% fly ash, by weight; water/powder (w/p) of 0.40; and use of superplasticizer on its saturation dosage.

In terms of performance, it was pointed out initially to make a very fluid mortar, with a spreading higher than 300 mm.

However, it was decided to increase the sand/binder ratio to 1.2, due to economic and temperature advantages.

It was found during the tests that, if the percentage of fly ash in the binder was 65%, the risk of segregation was significant, as shown in Fig. 1. In this figure two mortars, with different contents of fly ash, are compared: in the mortar with 65% fly ash the segregation is evident (a), one can see the separation of the constituents; and on the other one (b), with a lower fly ash content - 50%, there are no visible signs of segregation. These mortars were produced with a w/p higher than initially intended, about 0.45, and the superplasticizer (admixture V) content of 0.78% (a) and 0.85% (b). The measured spreadings were 346 mm and 318 mm, and the funnel flow-times were 3.1 s and 3.5 s, respectively. Based on these results, it was decided to limit the percentage of fly ash in the binder to 60%.

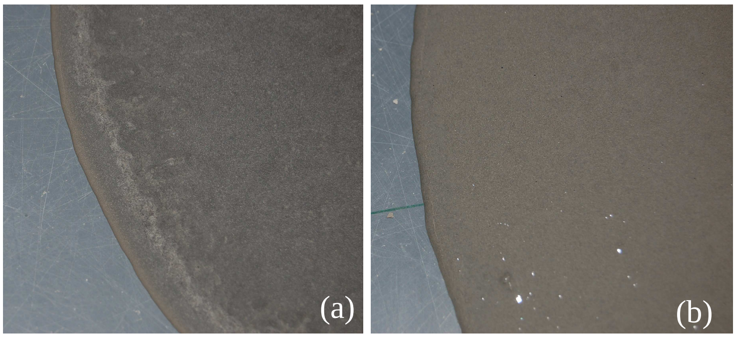

Figure 1 – Different segregation signs on mortars with two fly ash contents on binder - 65% (a) e 50% (b)

Although the superplasticizers are described as the same type, their mode of action is different, leading to different behaviors of mortars. Fig. 2 shows the appearance of the top surface on mortars, with identical compositions, but different SP. It was found that the superplasticizer V (Fig. 2 a) produced a lot of air, which led to the formation of a foam layer on the surface. This phenomenon would jeopardize the bond between mortar and the preplaced coarse aggregates. This factor led to the rejection of this superplasticizer.

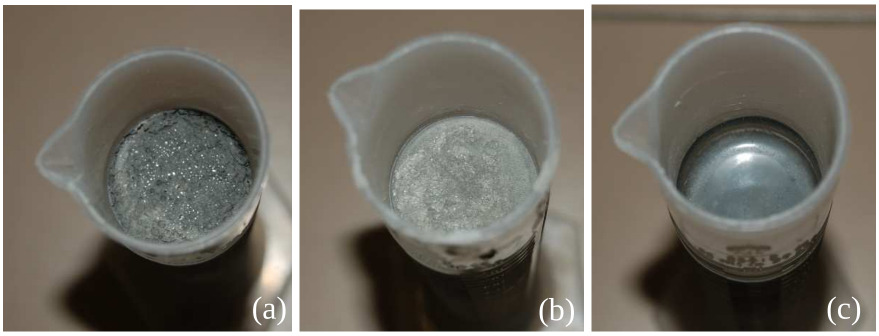

Figure 2 – Top surface of mortars with different SP: V (a), G (b) e X (c)

Before the execution of the prototype, there were molded two blocks, where were used the coarse aggregate fractions intended to be applied on site. These aggregates came from granite rock facies identical to that of the crush sand. The mortar for these blocks was produced in two mixtures of 27 liters. The mould of the block was a cylinder of about 57 cm in diameter and 40 cm high, which was previously filled with three coarse aggregate fractions: 19/38 mm, 38/75 mm and 75/150 mm. The volume occupied by the coarse aggregate was approximately 60% of the block (Fig. 3).

Figure 3 – Filling the cylindrical block

In the first block, the mortar was composed of 60% fly ash, of the total binder mass, a sand/binder ratio of 1.22 and a w/p of 0.45. A viscosity-modifying admixture (VMA) was used to increase the resistance to segregation. The contents of SP (admixture G) and VMA were 1.99% and 0.11%, respectively, by weight of binder. This mortar had a spread of 321 mm and a flow-time of 2.7 s. For the second block, the mortar was produced with other superplasticizer (admixture A) and a different VMA. The effectiveness of superplasticizer allowed reducing its content to 1.69% and the w/p to 0.43, leading to a mortar with a spread of 323 mm and a flow-time of 4.3 s. The higher viscosity observed on the mortar of the second block may be due to the higher solid content.

In addition to the execution of the blocks, two transparent tubes were filled with mortar to form columns of 2 m high, in order to obtain the effect of pressure, which was not simulated with the short blocks. This dimension of 2 m was chosen since it corresponds to the height planned for each concrete section of the cofferdam.

After 24 hours, some voids, with crack shape (Fig. 4 a), appeared visible in the column made with superplasticizer G. These voids were spaced about 50 cm along the column.

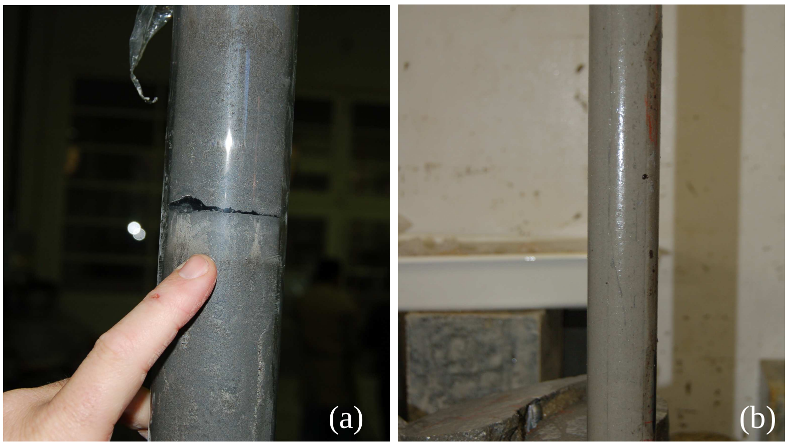

Figure 4 – Voids formation in the column (a) and mortar with no segregation (b)

The voids might have been formed due to the segregation of the mortar. The ascending movement of less dense components, such as water and air, which has accumulated at different heights, forming the voids observed. When reaching a certain accumulated volume, the segregated component can not rise anymore due to the cohesion of the surrounding mortar. The regular spacing of the large voids may be related with the need of a minimum volume for the rise to be interrupted, which is only possible if there is a minimum thickness of mortar for this to occur. Consider the analogy with air bubbles in a liquid, which rise more quickly when they are smaller, and conversely the greater the resistance to its rise when they take up more volume.

In the column of mortar, with the A superplasticizer (Fig. 4 b) there were no voids as mentioned above, which show greater resistance to segregation. This increased resistance to segregation can also be inferred by the greater homogeneity of the surface. On the surface of the other mortar (Fig. 4 a) one can see an irregular texture formed by the upward movement of the liquid phase, leaving signs of the percolation track.

The mortar selected for the prototype execution was the one that presented the highest resistance to segregation. Only small adjustments were needed in the admixtures dosage, given the greater difficulty of filling a larger block. The mixture proportion of the mortar applied in the prototype is presented in Table IV.

Table IV – Mortar mixture proportion applied in the prototype (kg/m^3)

Material	Sand	Cement	Fly ash	Water	SP A	VMA
Content	895.5	297.1	445.6	308.8	12.18	2.97

This mortar has the following parameters:
sand/binder = 1.2;
40% cement and 60% fly ash;
w/p = 0.42;
paste content = 65%, in volume;
SP content = 1.64%;
VMA = 0.40 %.

Execution of the prototype

The prototype mould had a cubic shape with inner edges of 1.97 m, with two faces (East and South) transparent, in order to view the filling (Fig. 5 a). Inside the mold a total of 11940 kg of coarse aggregates were placed: 5492 kg of 75/150 mm, 3821 kg of 38/75 mm, and 2627 kg of 19/38 mm. These fractions were weighed after washing, to clean the aggregates surface from fines particles.

The filling of the prototype with mortar was carried using 15 mixes, of about 227 liters each. However, only a small part of the 15th mix was used, resulting on a total volume of applied mortar of approximately 3120 liters. The pouring of mortar was carried out always in the same location and ran for about 4 hours (Fig. 5 b). The average spread of the applied mortar was 331 mm with a funnel flow-time of 3.3 s.

 (a)  (b)

Figure 5 – Prototype before filling (a) and location of the mortar pouring (b)

Given the quantities of coarse aggregate previously placed, whose saturated surface dried density was 2640 kg/m^3, the mixture proportion of the concrete in the prototype is as presented in Table V. The theoretical density of the indicated composition is 2363 kg/m^3.

Table V – Final mixture proportion of the prototype's concrete

Component	Mass (kg/m^3)	Volume (m^3/m^3)
Coarse aggregate 75/150	718.3	0.272
Coarse aggregate 38/75	499.7	0.189
Coarse aggregate 19/38	343.6	0.130
Sand	365.8	0.137
Cement	121.3	0.042
Fly ash	182.0	0.081
Water	126.1	0.126
SP	4.975	0.005
VMA	1.213	0.001

After the withdrawal of the formwork, one could check the quality of the concrete surface which can be considered good, as shown in Fig. 6. However, in areas closer to the pouring location, the upper parts of the northeast corner (Fig. 6 a), there is a high density of voids on the surface. While in the opposite faces (Fig. 6 b) this anomaly is almost nonexistent.

This phenomenon was attributed to the greater difficulty of mortar to fill areas that were subjected previously to percolation. As the placement of the mortar in the prototype ran for about 4 hours, the mortar poured earlier loses its flowability. The pouring was made from the top of the mould, so, when the gaps between coarse aggregates in this location are being filled, they are already partially occupied with early placed mortar. This leads to a decrease of the opening, blocking the flow.

The negative consequence of these defects is important mainly if they show continuity in the structure of concrete, which may be evaluated by permeability tests on cores. However, if possible, it is convenient to eliminate this problem.


(a)

(b)

Figure 6 – Surface appearance of North face (a) and West face (b)

It was then carried out in situ testing in hardened concrete and laboratory tests on samples taken from the prototype. The in situ tests were air permeability by the Torrent method, GWT water permeability and ultrasonic pulse velocity. The laboratory tests were done on cores taken from the prototype to determine the water absorption, water permeability, compressive and tensile strength, elastic modulus and ultrasound.

Due to page limit, this paper presents only the results of compressive strength and water permeability obtained in the laboratory, but more complete information is presented in a private report [10].

The compressive strength was determined at 90 days in 9 cores: 3 from North face, 3 of the eastern side, and 3 of the South face. The average results, transposed to 150 mm standard cubes, are presented in Table VI. This table also includes the average apparent density of the concrete.

Table VI – Compressive strength and density at 90 days

Face	South	East	North
Strength (MPa)	25.5	27.0	25.2
Density (kg/m^3)	2423	2383	2417

The differences on the average values of compressive strength are small, which suggest that there is no influence from the core extraction location. The variation on the density values is also small and is not correlated with strength, indicating that the differences should be attributed mainly to randomness.

The values of binder efficiency on strength can be considered satisfactory given the type of fine aggregate used.

The water permeability was determined in 9 cores, also taken from three faces of the prototype, at 90 days. The result of this test is a permeability coefficient (*K*), using the Darcy law (Eqn. 1)

$$K = \frac{QL}{AH} \tag{1}$$

where *Q* is the water flow rate, *L* is the height of the sample, *H* is the water pressure (water column of 150 m), and *A* is the cross sectional area of flow. The average results presented in Table VII were obtained assuming a constant flow of water through the concrete during 48 hours.

Table VII – Average water permeability coefficients (m/s)

Face	South	East	North
Result	2.27×10^{-11}	5.48×10^{-12}	1.17×10^{-11}

Coefficients of water permeability of concrete usually lie in values between 10^{-12} m/s and 10^{-13} m/s, at 90 days, for cement contents of 200 kg/m^3 to 400 kg/m^3. The dosage of cement in the prototype was much less than 200 kg/m^3 (Table V), but with the hydration of the fly ash one can use this value for comparison purposes. Thus, the obtained water permeability coefficients can be considered slightly higher than the ones for a conventional mass concrete used for dam construction, but still of the same order of magnitude. According to the Concrete Society Technical Report Nº31 [11], the tested concrete can be classified as having an average permeability.

This higher permeability could be attributed to the lower quality of the interface between mortar and coarse aggregates as a result of the tendency of the mortar to bleed. The air and the liquid tend to be trapped below the large aggregates, given the size of these particles, reducing the compactness of this zone. This phenomenon was expected, but, his effect on large scale highly depends on connectivity between porous zones. The results obtained on cores may be considered conservative due to the reduced sample size, when compared with the coarse aggregate dimensions, which indicates a promising behavior of this material in large structures.

Regarding the properties not presented in this paper, the elastic modulus and splitting tensile strength, the PAC presents a good or even better performance than conventional mass concrete (CMC). However, for other additional features also evaluated, tensile strength and water absorption, which are not usually controlled on site for CMC, PAC results were lower than comparable ones on CMC, for equivalent compressive strength, but in the same order of magnitude.

Conclusions

The selection of the type and content of the mortar components, specially the superplasticizer, must take into account the segregation resistance and flowability. Segregation on mortars, in particular it's bleeding, is a major factor of concern on this PAC technology.

The execution of a cubic prototype with a volume of 8 m^3, using an optimized mortar, showed that is possible to apply this new technology in large scale, namely in the construction of gravity structures, having been also useful to identify issues potentially relevant to its implementation in real conditions.

The experiment pointed out a number of aspects that need special attention in the implementation of PAC technology in real conditions:

- During the pouring, wetting with mortar areas that are not intended as pouring locations should be avoided.
- The work plan to be adopted should focus on reducing the filling time to avoid premature mortar hardening.
- Filling the same location with mortars produced at different times should be avoided. The filling up is more difficult if the gaps already contain some mortar with decreased fluidity.

Regarding the results on hardened concrete, for the properties usually controlled on site in dam construction, the PAC presented a good or even better performance than CMC. Properties related to transport mechanisms, e.g. water permeability, PAC presented lower performance, which can be related to the quality of the coarse aggregate –mortar bond, which depends on mortar's bleeding.

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