Eco-efficient self-compacting concrete with reduced Portland cement content and high volume of fly ash and metakaolin

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Abstract. The eco-efficient, self-compacting concrete (SCC) production, containing low levels of cement in its formulation, shall contribute for the constructions' sustainability due to the decrease in Portland cement use, to the use of industrial residue, for beyond the minimization of the energy needed for its placement and compaction. In this context, the present paper intends to assess the viability of SCC production with low cement levels by determining the fresh and hardened properties of concrete containing high levels of fly ash (FA) and also metakaolin (MK). Hence, 6 different concrete formulations were produced and tested: two reference concretes made with 300 and 500 kg/m^3 of cement; the others were produced in order to evaluate the effects of high replacement levels of cement. Cement replacement by FA of 60% and by 50% of FA plus 20% of MK were tested and the addition of hydrated lime in these two types of concrete were also studied. To evaluate the self-compacting ability slump flow test, T_{500}, J-ring, V-funnel and L-box were performed. In the hardened state the compressive strength at 3, 7, 14, 21, 28 and 90 days of age was determined. The results showed that it is possible to produce low cement content SCC by replacing high levels of cement by mineral additions, meeting the rheological requirements for self-compacting, with moderate resistances from 25 to 30 MPa after 28 days.

Introduction

The self-compacting concrete must meet well defined characteristics, like cohesion, passing and filling ability, without the use of vibration even in densely reinforced structures. Thus the manufacture of high fluidity and stability concrete is mandatory, being necessary to make compatible the amounts of superplasticizer and fine particles (cement and mineral additions) in order to meet the demands for this kind of concrete [1].

The ideal design for a self-compacting concrete (SCC) is a commitment between two conflicting objectives. On one hand, SCC has to be as fluid as possible to ensure that it will fill the formwork under its own weight, but on the other hand, it has to be a stable mix to avoid segregation of solids during its flow [2-3]. The first is ensured by the use of superplasticizer and/or viscosity modification chemical admixtures, while the last is obtained by the selection of an appropriate amount of powder adding, in other words, cement and replacement materials, usually mineral additions, and by an adequate balance between solids and liquids in the mix [4]. Several methods of dosage for self-compacting concrete are proposed to comply with those characteristics. The most common methods are Okamura and Ouchi [1] and EFNARC [5], recently, other methods have been suggested [6-7].

The self-compacting capacity is ruled simultaneously by the deformability and segregation resistance. Deformability depends, essentially, on a minimally needed shear yield stress to surpass so that the concrete flows and on moderate viscosity, which avoids contact between aggregates, avoiding blocking, characterized by plastic viscosity. Resistance to segregation that represents the mix' stability depends on the moderate plastic viscosity. Such features describe the rheological behavior of fresh concrete that correspond, in a first approach, to Bingham's plastic model [8]. However, rheometers that directly measure shear yield stress and plastic viscosity are of hard access and usually impracticable for concrete testing in the field, so indirect measures are commonly used for these properties.

The concrete production plays an important role in constructions' sustainability since over 10 billion tons of concrete are produced every year, being the cement industry responsible by the emission of around 7% of the carbon dioxide total emissions to the atmosphere [9].

The study of eco-efficient or sustainable concrete has raised growing interest among the main recent publications about concrete, so that P. C. Aïtcin wonders whether it will be possible to eliminate Portland cement from concrete production and answers: "because not"; with the caveat that this will not happen any time soon, but it is possible [10].

Thus, the eco-efficient self-compacting concrete production that use low levels of cement in its formulation, are important allies for constructions' sustainability due to the reduction of the use of Portland cement, the use of industrial and agro-industrial residue, noise reduction, besides the minimization of energy use for placement and compaction.

Materials and methods

Materials

The concrete mixtures were produced with Portland cement CEM I 42.5R (C), fly ash (FA) class B according to the EN 450-1 [11] and F according to ASTM C618 [12], metakaolin (Mk), hydrated lime (HL), sand and gravel with maximum dimensions of 4 mm and 16 mm respectively, water and a polycarboxylate-based superplasticizer. Table 1 and Figure 1 present the chemical composition of the referred powder materials.

Table 1: Chemical composition of cement (C), fly ash (FA), metakaolin (MK) and hydrated lime (HL)

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	$Ca(OH)_2$	LOI
C (%)	19.92	4.36	3.51	62.92	1.83	2.86	-	-	-	3.12
FA (%)	48.61	23.79	7.91	3.06	2.07	0.40	0.78	3.78	-	2.64
MK (%)	47.00	37.10	1.30	0.10	0.15	-	0.20	2.00	-	12.75
HL (%)	0.33	0.45	0.08	-	0.84	-	-	-	97.75	-

LOI – loss on ignition

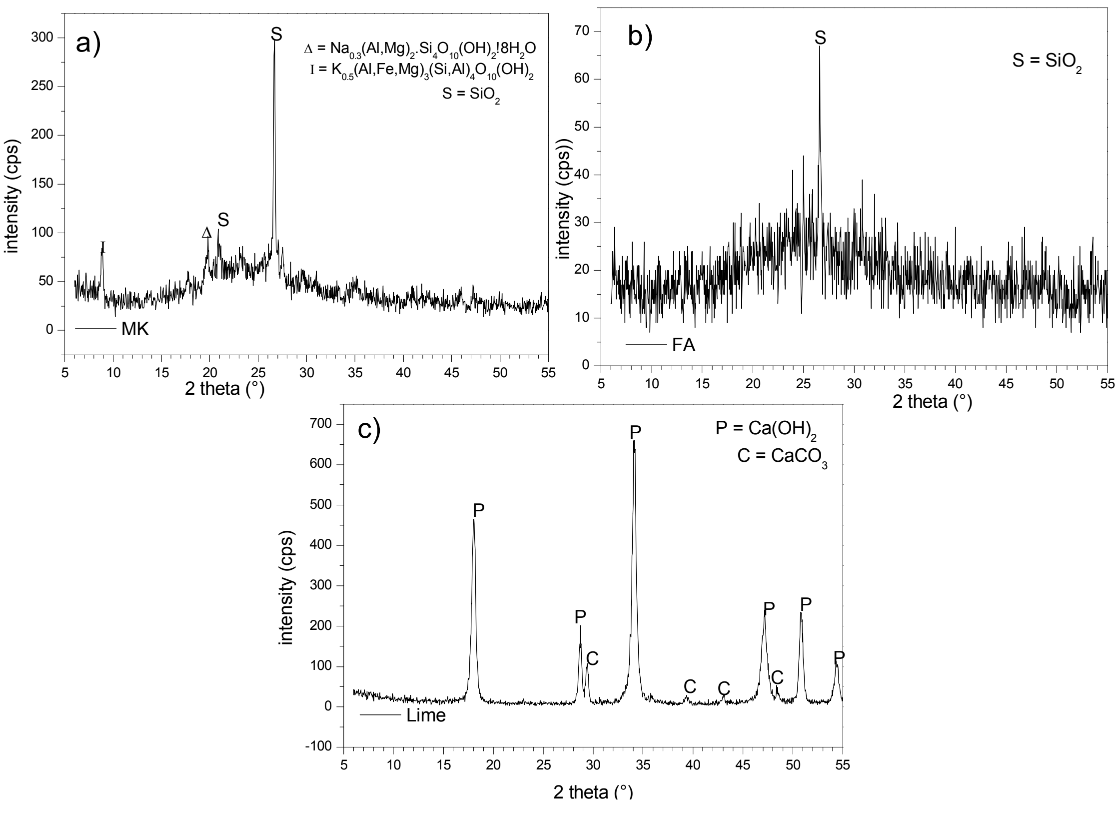

Fig 1. DRX: a) fly ash b) metakaolin c) hydrated lime

Figure 2 shows the morphology of FA where one can verify the solid silica sphere particles in different sizes, as well as the presence of plerospheres, which are typical of FA produced through coal combustion [13]. The mostly spherical grains and with diameters lower than the cement particles used tend to make it easier for the self-compacting concrete to move [14], as well as the SCC water retaining capacity with this material, reflected in its lower bleeding.

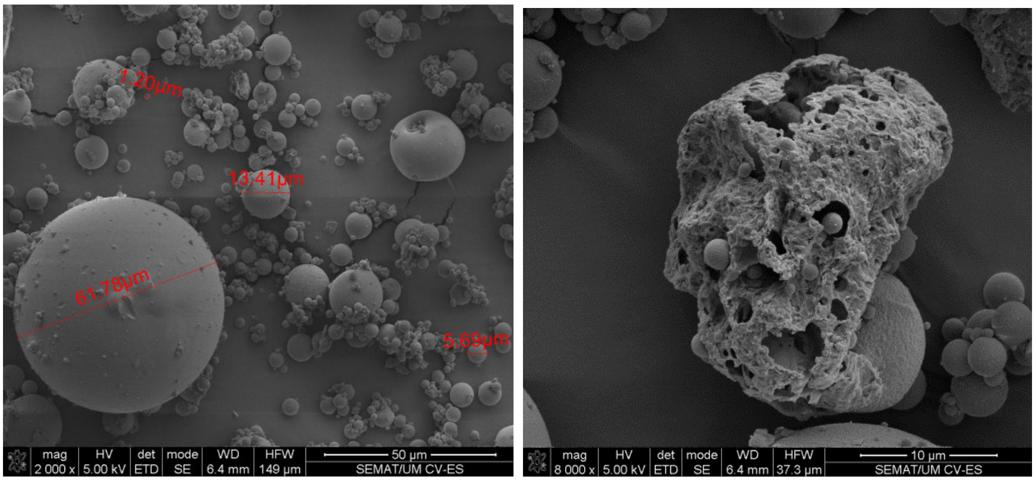

Fig. 2. SEM of fly ash

Six concrete compositions were produced, as shown in Table 2. The definition of such concrete types came from concrete with high levels of fly ash previously studied by Camões [3] which went through some adequacies in their compositions in order to meet the self-compacting concrete criteria.

Table 2: Concrete compositions

	B500	B300	FA	FA-HL	FA-MK	FA-MK-HL
C (kg/m³)	500	300	200	200	150	150
MK (kg/m³)	-	-	-	-	100	100
FA (kg/m³)	-	-	300	300	250	250
HL (kg/m³)	-	-	-	25	-	25
Sand (kg/m^3)	870	1053	870	870	870	870
Gravel (kg/m^3)	880	867	880	880	880	880
Water (kg/m^3)	200	180	170	170	170	170
superplasticizer (kg/m³)	13.0	7.8	9.0	9.6	9.6	12.3
Fines (C+FA+Mk+L)	500	300	500	525	500	525
Mortar content (M%)	60.9%	60.9%	60.9%	61.3%	60.9%	61.3%

The dry mortar content of the mix (M%), eq. 1, was the only adjusted parameter in order to try to reach self-compactability. For Camões' work [3] this level was approximately 53% and in self-compacting concrete (SCC) such level must vary from 60% to 65%. In this work the mortar content was been updated and the one used was 61% for concrete adequacy.

$$M\ \% = \frac{(L+S)}{(L+S+G)} \qquad (1)$$

Where:

L= fine particles (cement and mineral admixtures); S= sand; G= gravel, referring to the single concrete in mass.

The plain cement concrete with 300 kg/m^3 of binder (B300) was produced just for comparison of the mechanical properties of this common concrete with the other types of concrete with high mineral addition content. Therefore there is no pretension that such formulation will suit the self-compacting criteria.

Methods

Fresh concrete

The different concrete types were produced in vertical-axis concrete mixers. After being mixed the different concretes were tested for self-compacting ability. In order to classify concrete as self-compacting the fluidity, viscosity, passing ability and resistance to segregation requirements must be met. In the present paper were performed slump flow (flow and T500), J-ring, V-funnel and three bar L-box tests, figure 3, following the guidelines of EFNARC [5].

Fig. 3. Tests in fresh concrete

Hardened concrete

After molding the specimens were kept inside the molds for two days, afterward they were taken out of the molds and placed in cure by water immersion at a temperature of approximately 20 ± 2°C. Three specimens of each composition after 3, 7, 14, 28 and 90 days of cure were used for compressive strength determination.

Results and discussions

EFNARC parameters

Table 3 shows the dosage parameters of self-compacting concrete with reduced cement content (SCC-RCC) and concretes used as references (B500 and B300), calculated from concrete types described in Table 1, comparing with the parameters specified in EFNARC [5].

Table 3: concrete dosage parameters

	Fine (kg/m^3)	Paste (l/m^3)	Water (l/m^3)	Gravel (kg/m^3)	Sand (% in weight of total aggregates)	Water/fines ratio (l/m^3)
B500	500	360.26	200	880	49.7	1.25
B300	500	276.15	180	867	54.8	1.87
FA	500	358.07	170	880	49.7	0.90
FA-HL	525	369.23	170	880	49.7	0.85
FA-MK	500	359.84	170	880	49.7	0.90
FA-MK-HL	525	371.00	170	880	49.7	0.85
EFNARC	**380-600**	**300-380**	**150-200**	**750-1000**	**48-55**	**0.85-1,1**

The definition of SCC-RCC concrete came from the adequacy of a sort of concrete mixtures already studied in previous researches [3], intending to reach only the mortar level (60 to 65%), and the fines level (>500 kg/m^3). After the calculations to find if the new concretes, it was verified that with the adjustments in mortar level for 61% the concrete found met all of the dosage parameters specified by EFNARC and highlighted in Table 2.

According to Cuenca *et al* [15] there are no fixed deadlines or an exact method to determine the self-compacting concrete composition, although there are several dosage criteria that might serve as a basis such as EFNARC.

Therefore, the mortar and fines level parameters might be enough to define self-compacting concrete when associated to any other dosage method, since the objective of dosage methods is to ensure that the concrete meets the workability, resistance and durability criteria. As for SCC the workability criteria becomes the self-compacting properties, which are function of the water/fines material ratio and superplasticizer admixture that must promote adequate fluidity and viscosity.

Fresh concrete properties

The fluidity, filling capacity, viscosity and passing ability properties of self-compacting concrete with reduced cement content (SCC-RCC) were determined by the slump-flow, T500, V-funnel and L-box and are shown in Table 4. Table 5 shows the concrete types ratings according to EFNARC specifications [5].

Table 4: Fresh concrete properties

	Slump-flow		J-ring		V-test	L-box
Mix Id	T500 (s)	Slump-flow (mm)	T500 (s)	Slump-flow (mm)	Time (s)	H2/H1
B500	1.67	625	obstructed		4.6	0.75
B300	4.20	500	obstructed		*	*
FA	1.85	700	2.23	700	4.8	0.86
FA-HL	2.11	700	2.77	700	12.0	1.00
FA-MK	3.15	670	3.43	615	13.9	0.92
FA-MK-HL	2.63	700	3.89	695	12.8	0.89

* Not Performed

Table 4: Fresh concrete properties - classification according to EFNARC.

	B500	B300	FA	FA-HL	FA-MK	FA-MK-HL
Fluidity class	SF1	*	SF2	SF2	SF2	SF2
Viscosity class	VS1/VF1	*	VS1/VF1	VS2/VF2	VS2/VF2	VS2/VF2
Passing ability	PA1	*	PA2	PA2	PA2	PA2

Fluidity and viscosity

The parameters that define concrete fluidity and viscosity can be calculated by Γ_c and R_c, eq. 2 and eq. 3. These parameters should be representative of the concrete deformability and viscosity, respectively [1], were calculated for the studied SCC-RCC and are shown in Figure 4.

$$\Gamma_c = \frac{(Sfl_1 * Sfl_2 - Sfl_0^2)}{Sfl_0^2} \quad (2)$$

$$R_c = \frac{10}{t} \quad (3)$$

Where: Sfl_1 and Sfl_2 = slump flow measures (mm) and t = V-funnel draining time.

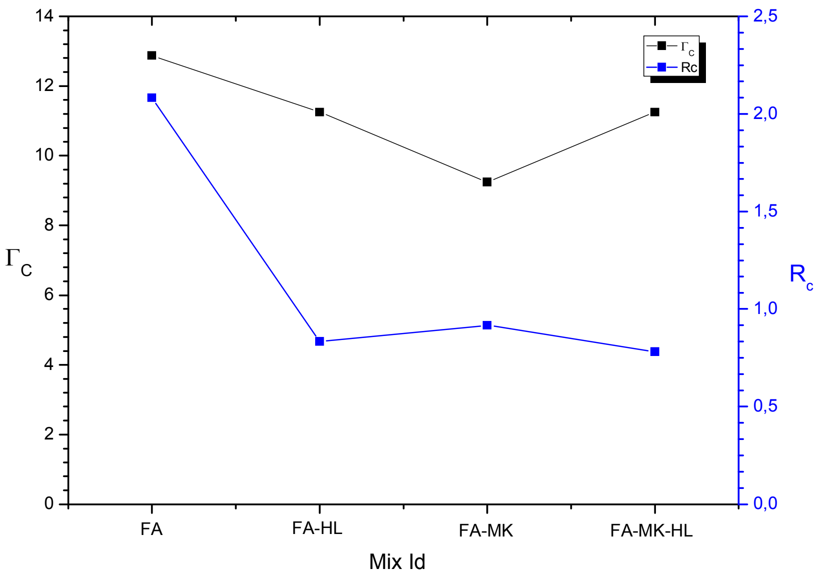

Fig. 4. Deformability (Γ_c) and viscosity (R_c) parameters

The FA-HL, FA-MK and FA-MK-HL concrete types are rated according to EFNARC as VS2/VF2 for viscosity, however one could see in Figure 4 that the types FA-HL and FA-MK-HL show equal viscosity according to the R_c parameter, while the FA and FA-MK types showed different viscosities, which demonstrates that the R_c parameter is more sensitive to viscosity changes.

Viscosity is a parameter influenced by the dosage of superplasticizer admixture and by the fines content in the mix, which shows the importance of determining synergy between cement + mineral addition + superplasticizer and the water/fines material ratio.

The definition of adequate superplasticizer level for each concrete mix depend on the cement-admixture compatibility. In many works about SCC this level is determined experimentally, having reported values from 0,6 to 4% about the cement mass [2, 4, 16].

As for fluidity parameter (Γ_c), which denotes the deformability of fluid state concrete, it is noticeable that FA-MK mix was less deformable. In other words, FA-MK show higher cohesion, a fact validated by visual evaluation. All the concrete types showed the same fluidity classification (SF2), according to EFNARC, even though FA-MK was more cohesive, which indicates that the Γ_c parameter proposed by Okamura and Ouchi [1] is more precise for determining deformability and therefore advisable for concrete evaluation with similar classifications according to EFNARC.

None of the SCC-RCC has shown segregation before or after the workability tests or during the mix stop. Only the FA concrete showed slight exudation on the borders of the concrete after the slump flow test. It is known that concrete types with high volumes of fly ash usually presents high cohesion [17]. However, one must take into account that the use of excessive superplasticizer may cause bleeding.

Viscosity can be indirectly determined by V-funnel and T500. Results obtained permits to classify the produced mixtures as VS1 or VS2 determined by T500 and VF1 or VF2 by V-funnel. The time value obtained does not measure SCC viscosity, but it is related to this property and describes the flow rate, as well as the R_c parameter.

One could verify that the concrete types FA-HL, FA-MK and FA-MK-HL are classified as VS2/VF2, once they present T500 > 2 sec and V-funnel between 9 and 25 sec, while FA is classified as VS1/VF1. According to EFNARC, self-compacting concrete VS1/VF1 has good filling capacity, even in densely reinforced structures. However this concrete is more susceptible to exudation and segregation, which was verified in FA concrete.

The FA and FA-HL concrete types are in the same fluidity class measured in slump-flow (SF2). However, they show different viscosity, VF1 and VF2 respectively, that can be justified by the inclusion of hydrated lime (HL). The incorporation of HL increases the fines content of the mix and therefore makes the mix more viscous, and thus more stable, avoiding the exudation commented previously in concrete FA.

The FA-MK and FA-MK-HL concrete types are under the same fluidity class (VS2) and viscosity (VS2/VF2). This fluidity class shows higher resistance to segregation, however there might be negative effects in the superficial finish and great sensibility related to the application type.

Passing ability

The passing ability was determined by three bar L-box and J-ring tests, describing the capacity of the fresh mix to flow through confined spaces and tight openings such as heavily reinforced areas, without segregation or uniformity loss and without causing blockage.

All of the SCC-RCC types of concrete were classified in L-box tests as PA2, according to EFNARC [5], which indicates that the blockage ratio is superior to 0,8, as indicated in Figure 5.

The spreading result in the J-ring tests also indicates passing ability, according to NBR 15823-3 [18] and ASTM C1621 [19], when compared to the slump-flow results. When the spreading difference between these two tests is lower than 25 mm it indicates lack of blockage (PJ1), as in concrete types FA-HL, FA-MK and FA-MK-HL. When the difference is between 25 and 50 mm it indicates minimum visible blockage (PJ2), as in concrete FA that obtained such classification due to a light observed bleeding.

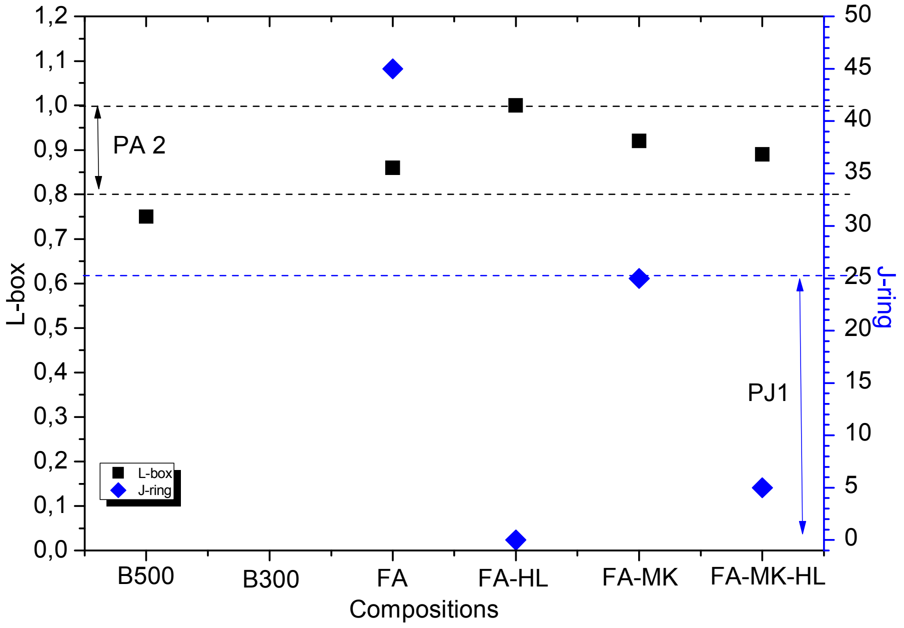

Fig. 5. Passing ability classification

Segregation and low passing ability, acting independently or in combination, may cause concrete blockage. Such facts were not verified in the analyzed SCC's, except for a slight bleeding detected on concrete FA that led to a lower blockage ratio (0.85) when compared to the other SCC's under analysis. Problems related to segregation or passing ability were also verified for concrete B300 which showed high fluidity (VS1) but revealed tendency to segregation after testing and lower blockage ratio, which characterizes self-compacting incapacity.

Therefore, the influence of a parameter over another was verified, thus reflecting over the self-compacting capacity which is ruled simultaneously by the deformability and resistance to segregation parameters, which can be categorized by viscosity.

Properties hardened concrete

Compressive strength

The compressive strength variation with curing age at 20±2ºC is shown in Figure 6. Observing the evolution of compressive strength over time, one could see that the types FA, FA-MK, FA-HL and FA-MK-HL showed compression strength at 28 days of 27.8, 32.6, 40.9 and 40.0 MPa, respectively. This determined compressive strength values may confirm the real applicability of such studied concrete types, namely in constructions where demanded concrete compressive strengths are of class C25 to C40, even with a low cement consumption, varying from 200 to 150 kgm^3.

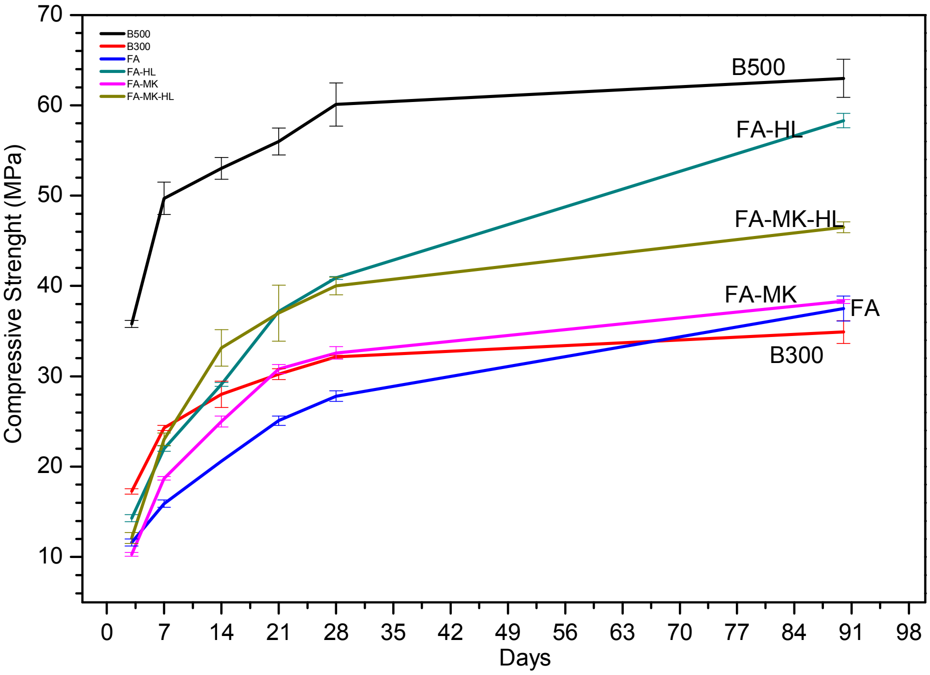

Fig. 6. Evolution of compressive strength with age

One could notice the importance of SCC for construction sustainability since it is possible to reach compressive strength above 30 MPa at 28 days using concrete with a significantly reduction, from 60 to 70%, of cement consumption when compared to SCC reference concrete B500 (500 kg/m^3). Even superior compressive strength than conventional concrete with cement consumption of 300 kg/m^3 (B300) can be achieved even with cement content reductions from 33.3% to 50.0% when compared to B300 cement consumption. Adding that to the benefits of self-compacting concrete such as higher productivity, lower noise level in constructions, reduction of problems associated to vibration, besides the expected durability gain by the use of mineral additions.

With the fresh and hardened state results determined we could characterize SCC-RCC's analyzed in the present study as high performance concrete, since according to Mehta [17] high performance concrete may be classified as those that has been tailored to meet specific engineering needs, such as high workability, very high early compressive strength, high toughness, and high durability to exposure conditions.

The compressive strength of FA-HL and FA-MK-HL concretes overcome B300's at low ages, from 9 to 12 days, respectively. This aspect may indicate high reactivity of FA and MK with lime, which is directly related to the amorphicity of FA and MK displayed in Figure 1. FA-HL concrete shows compressive strength of 58 MPa at 91 days close to the reference concrete's resistance, B500, which was of 63 MPa. Thus, it indicates the possibility to produce enhanced or even high compressive strength concrete with low cement levels when more advanced ages are taken into consideration.

One could verify that all the types of concrete containing hydrates lime presented higher compressive strength than the ones produced without it, confirming the great influence of adding lime to SCC-RCC's. This effect is more noticeably starting from 14 days when most of the cement lime hydration has already been formed and probably consumed by the mineral addition [20].

The compressive strength gain from 28 to 90 days was considerably lower in concretes made with metakaolin, FA-MK and FA-MK-HL. While those showed a strength gain around 15%, FA and FA-HL concretes displayed increases of 26 and 30% respectively. Such facts are related to the lower cement and higher water/cement ratio used in concrete made with metakaolin, and to the low level of free lime available for the reactions with mineral additions used, as determined by Anjos et al [20] in cement pastes with high levels of FA, MK and hydrated lime.

Conclusion

The mortar and fines content dosage criteria are enough to adequate previous concretes to accomplish SCC criteria.

The parameters Γ_c and R_c suggested by Okamura and Ouchi [1] were more effective in determining the fluidity and viscosity parameters than the EFNARC classifications [5], since compositions that showed different viscosity or fluidity by the parameters Γ_c and R_c, obtained the same EFNARC classification.

The passing ability is better assessed by the J-ring test than by L-box test, since the last did not detect the low ability of FA concrete, since it has classified it at the same rate as other concrete types. However using J-ring test results such concrete was clustered in a different class than the others.

The SCC-RCC's showed compressive strength at 28 days that varied between 25 and 40 MPa and at 91 days between 35 and 58 MPa, showing the possibility to produce enhanced or even high compressive strength concrete with reduced cement levels when more advanced ages are taken into account.

Based on the obtained results one can observe that it is possible to develop self-compacting concrete with low cement content showing adequate properties, thus contributing for the sustainability of the construction industry, by minimizing released energy and compaction, and mostly due to the drastic reduction of cement consumption for levels from around 150 to 200 kg/m^3.

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