THE EFFECTS OF BINARY AND TERNARY MIXTURES WITH FLY ASH AND LIMESTONE FILLER ON SHRINKAGE AND MECHANICAL PROPERTIES OF SELF-COMPACTING CONCRETE (SCC)

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ABSTRACT

The use of SCC may lead to a significant improvement of the environmental impact of the concrete industry due to the possibility of incorporating considerable quantities of sub products from other industries as partial replacement for cement. Furthermore, the use of mineral additions such as FA and/or LF reduces the cost of the material needed for the production of SCC and may improve its properties.

To this end, an experimental program was conducted to evaluate the effect of FA and LF in binary and ternary mixes of self-compacting concrete. Fresh properties of the SCC produced were tested for slump-flow diameter, V-funnel flow time and L-box height ratio. Besides these, the hardened properties of the SCC produced were tested for compressive strength and shrinkage.

The results indicate that the use of high volumes of FA and/or LF can improve shrinkage properties and can be used to obtain SCC with adequate strength.

Keywords: Self-compacting concrete; shrinkage; compressive strength; fly ash; limestone filler

INTRODUCTION

The need to reduce Portland cement consumption caused by the growing concerns with CO_2 emissions associated with its production process has led to a significant increase in the use of mineral additions to obtain blended cement and in the production of concrete itself. SCC, mainly due to its need to incorporate significant quantities of ultrafine materials (cement and mineral additions), offers great potential for the use of these sub products, such as FA and LF, as partial replacement of cement. Nevertheless, the use of significant quantities of mineral admixtures, with the consequent increase of the paste volume and decrease in the coarse aggregate, will alter the SCC's microstructure, leading to a change in shrinkage and mechanical properties.

Drying shrinkage, in the hardened state, can be defined as a volumetric variation caused by the water loss by evaporation. Initially, the water lost corresponds to the free water retained in the large capillary pores and does not cause significant shrinkage. However, when most of that water is lost, drying continues and an additional loss of the water retained in the smaller capillary pores can happen. With the consequent reduction of the pressure in the capillary pores, the tensile stresses in concrete increase and cracking may occur.

Given the fact that shrinkage is one of the main deterioration factors of concrete structures, including those of SCC, it is fundamental to discuss this subject. This paper intends to evaluate the physical properties, shrinkage and mechanical strength of SCC produced with binary and ternary mixes of FA and LF. For that purpose, a total of 11 self-compacting mixes were produced: 1 with cement only (C); 3 with C+FA in 30%, 60% and 70% replacement (f_{ad} by volume); 3 with C+LF in 30%, 60% and 70% replacement; and finally 4 mixes with C+FA+LF in combinations of 10-20%, 20-10%, 20-40% and 40-20% replacement.

EXPERIMENTAL PROGRAMME - MATERIALS AND MIX PROPORTIONS

The following materials were used: one type of cement complying with NP EN 197-1 (cement type I-42.5 R with specific gravity of 3.14; two mineral additions: fly ash (FA) complying with NP EN 450-1 and NP EN 450-2 with specific gravity of 2.30 and limestone filler (LF) complying with LNEC specification E 466 with specific gravity of 2.72; two limestone coarse aggregates complying with NP EN 12620, gravel 1 with specific gravity of 2.59, D_{max} of 11 mm and water absorption of 1.46% and gravel 2 with specific gravity of 2.64, D_{max} of 20 mm and water absorption of 0.78%; two siliceous sands complying with NP EN 12620, one coarse (0/4) with specific gravity of 2.55, fineness modulus of 3.70 and water absorption of 1.10% and one fine (0/1) with specific gravity of 2.58, fineness modulus of 2.03 and water absorption of 0.70%; a third-generation high-range/strong water-reducing admixture (S_p) complying with NP EN 934-1 and NP EN 934-2 (a modified polycarboxylic high-range water-reducing admixture in liquid form with a density of 1.07) and tap water complying with NP EN 1008.

With the goal of scoping all variants of contents used in the mixes and the corresponding analysis of the binary and ternary mixes of FA and LF, 11 SCC mixes were produced according to the NP EN 206-9. This data is shown in Tab. 1.

Table 1. Mix proportions and fresh properties of SCC

Mix proportions [kg/m³]	**SCC1 100C**	**SCC2 30LF**	**SCC2 60LF**	**SCC2 70LF**	**SCC3 30FA**	**SCC3 60FA**	**SCC3 70FA**	**SCC4 10FA20LF**	**SCC4 20FA10LF**	**SCC5 20FA40LF**	**SCC5 40FA20LF**
CEM I 42,5 R	707	512	297	222	503	290	218	506	506	297	293
Fly ash	---	---	---	---	158	318	373	53	106	109	215
Limestone filler	---	190	386	449	---	---	---	125	63	257	127
Superplasticizer	7	5	3	3	5	4	3	5	5	3	3
Water	189	175	168	170	183	180	178	180	180	168	175
Fine aggregate ($0.6Fa_{0/1}$+$0.4Fa_{0/4}$)	723	747	758	756	735	741	743	740	740	759	748
Corse aggregate ($0.6Ca_1$ +$0.4Ca_2$)	700	700	700	700	700	700	700	700	700	700	700
W/C	0.27	0.34	0.57	0.76	0.36	0.62	0,82	0.36	0.36	0.57	0.60
W/FM	0.27	0.25	0.25	0.25	0.28	0.30	0.30	0.26	0.27	0.25	0.28
Fresh properties											
Slump-Flow (SF) [mm]	770	710	710	680	680	670	660	780	740	690	650
V-funnel (t_v) [s]	9.3	10.3	9.1	9.9	7.3	8.4	8.6	9.3	10.8	9.1	10.0
L-box (PL) [-]	0.91	0.89	0.85	0.82	0.84	0.81	0.80	0.91	0.90	0.89	0.83

In order to evaluate only the change in the unitary substitution ratios of cement by mineral additions (f_{ad} by volume), the following conditions were taken into account: the volumetric ratio between mortar and coarse aggregates' content (V_m/V_g=2.625), as well as the absolute volumes of coarse aggregate (V_g=0.268 m^3/m^3) and mortar (V_m=0.702 m^3/m^3), were kept constant; the volumetric ratio between the total powder content, cement and mineral additions, and fine aggregates in the mix (V_p/V_s=0.80) was kept constant; the volumetric ratio between water and fine material content in the mix (V_w/V_p), as well as the percentile ratio in mass between the high-range water reducing admixture (S_p) and the fine material content (S_p/p%), varied depending on the need for water and S_p of each mix in order to obtain the self-compacity parameters according to the works of *Nepomuceno* and *Oliveira* [1] and *Silva et al.* [2].

EXPERIMENTAL PROGRAMME - TEST METHODS AND SAMPLE PREPARATION

The test procedure used in the determination of the compressive strength is described in NP EN 12390-3. This test was performed at 7, 28, 91 and 182 days. For that purpose, 150 mm cubic moulds were used, which were kept in a wet chamber (20 ± 2 ºC and RH ≥ 95%) after demoulding, at 24 hours. The specimens were tested immediately after being taken from the curing chamber. The test was performed in three moulds for each reference and test age with a 3000 kN hydraulic press and a loading rate of 0.6 ± 0.2 MPa/s (N/mm^2/s).

The determination of the total extension of shrinkage was performed according to the specification LNEC E 398, in prismatic moulds with 150x150x550 mm, tested during 182 days (daily until 14 days of age and weekly from 14 to the 182 days). The test started immediately after demoulding, at 24 hours, with the moulds being kept at a room temperature of 20 ± 2 ºC and a relative humidity of 50 ± 5 %.Immediately after demoulding, the gauge length was formed by gluing pins on the surface of the specimens. The length change was measured by means of a dial gauge extensometer with 200 mm gage length.

TESTS RESULTS AND DISCUSSION – PROPERTIES OF FRESH CONCRETE

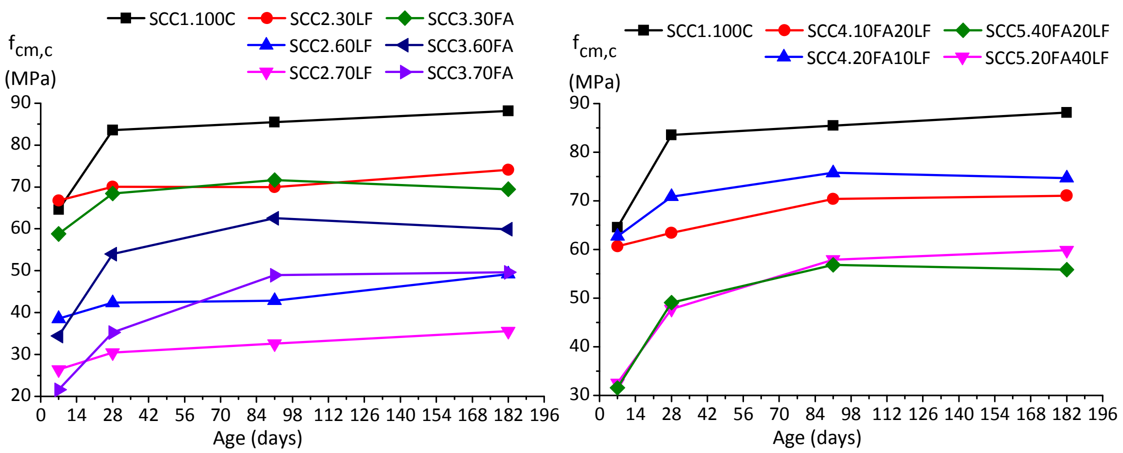
The studied properties of the SCC in the fresh state are listed in Tab 1. The results corresponding to the slump-flow are in the 600-800 mm range, indicating a good filing ability. The lowest values of the slump-flow were obtained for the ternary mix 40FA20LF. The results related to the V-funnel flow test are within the 7-11 seconds range and those of the L-box are all higher than 0.8, indicating a good passing ability. In general, it is possible to state that the values obtained for the properties in the fresh state of the SCC produced are within the recommendations of The European Guidelines for Self-Compacting Concrete [3].

TESTS RESULTS AND DISCUSSION - COMPRESSIVE STRENGTH

Fig. 1 shows the evolution of compressive strength values with age and with the additions substitutions ratio (f_{ad}) for all the SCC produced, in which it is possible to observe a more pronounced growth of the compressive strength in the early ages (7 days) for the binary mixes with LF. As for the binary mixes with FA, they show a more gradual evolution of the compressive strength which continuously grows beyond the early ages. The variations mentioned also happen for the ternary mixes, among which those with f_{ad} equal to 60% have a more gradual and continuous growth, compared to the more pronounced growth of those with f_{ad} equal to 30%. The mixes with 100% cement, as expected, show a distinct behaviour from the remaining mixes, growing sharply until 28 days and then stabilizing until the last test age (182 days).

The SCC1 mixes, corresponding to the SCC without additions, have the highest compressive strength, up to 90 MPa at 182 days. The SCC2 mixes (with LF) have, at 7 days, higher values than those found for the SCC3 mixes (with FA). Nevertheless, with age, the compressive strength of the SCC2 mixes tends to stabilize at 28 days, while that of the SCC3 mixes still shows some evolution at 91 days, ending up by stabilizing at 182 days at higher values than those of the SCC2 mixes. For the SCC3 mixes with f_{ad} of 60% and 70%, the final value of the compressive strength at 182 days increases significantly, especially the one with f_{ad} of 70%, when compared with the corresponding values of the SCC2 mixes.

Figure 1. Compressive strength for binary and ternary mixes at 7, 28, 91 and 182 days.



In both the binary and the ternary, one can find a decrease in the compressive strength with the increase of the additions substitution ratio, which is mainly due to the dilution effect related to the reduction in Portland cement content. In the particular case of the FA, it is even possible to observe a slower evolution of the compressive strength for higher f_{ad} levels mainly in the younger ages and stabilizing at 91 days. The values of compressive strength shown by the SCC3 mixes compared with the values for SCC1 are according to expectations. Considering the lower initial evolution of these SCC3 with FA (essentially due to the later effect of the FA pozzolanic behaviour, limiting the FA contribution to the compressive strength, at those initial ages, to the filer effect), it is expected that, at older ages and for f_{ad} levels lower than approximately 30%, the compressive strength evolves in a more significant way, being able to, in certain cases, reach values which are equal or even higher than the corresponding values in SCC with 100% of cement. This behaviour is mentioned by different authors for conventional concrete, stating that the optimal contents of FA substitution for C are lower than 20-30% [4] [5]. Accordingly, Cyr et al. [6] state that, from a certain content on (growing with the amount of cement), FA stops working as an addition, and works solely as a fine aggregate, which can be confirmed by the lower values of the compressive strength of SCC3.30FA compared to those of SCC1.100C.

TESTS RESULTS AND DISCUSSION - SHRINKAGE

In Fig.2 and 3, the curves for the shrinkage's total extension are shown, as well as the values referring to the EC2 equation. For an easier reading of the figures, the values for the shrinkage's total extension for CC, estimated according to the expression proposed in part 1-1 (General rules and rules for buildings) of the Eurocode 2 [7] and shown in the figures mentioned, only correspond to the minimum and maximum stresses obtained for the SCC produced referring to cylindrical moulds at 28 days and a calculated $f_{cm,cil}/f_{cm,c}$, of approximately 0.82.

Figure 2. Total shrinkage for binary mixes.

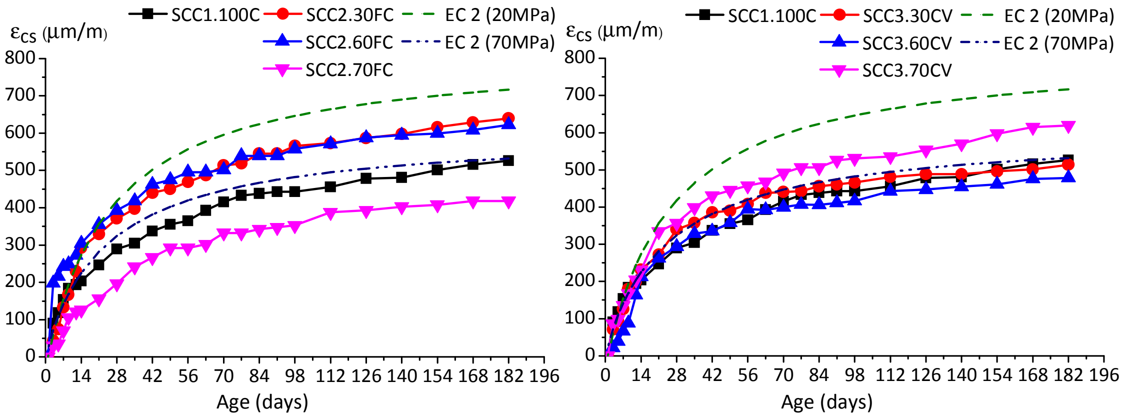
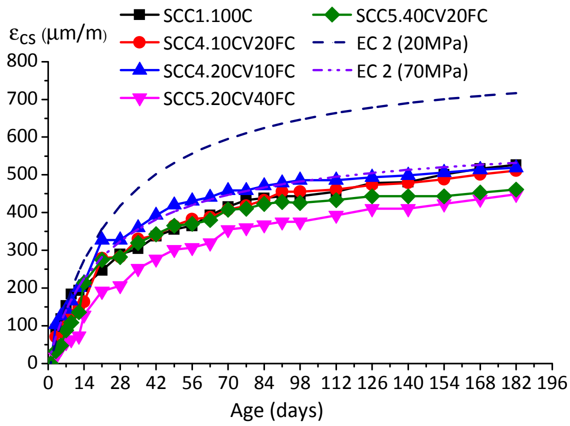


Figure 3. Total shrinkage for ternary mixes.



The figures show that the shrinkage's total extension is characterised by a higher initial evolution, reaching approximately 50% for the measured value (at 182 days) between 14 and 28 days, for the majority of the mixes. From 28 days, the shrinkage's total extension shows a more gradual evolution, reaching, at 91 days, between 80 and 90% of the final value measured at 182 days. The influence both of the LF and the FA on the shrinkage's total extension is not the same. In the case of the binary mixes with LF, the shrinkage increases slightly until f_{ad} of 30%, decreasing significantly for f_{ad} of 70%. For the binary mixes with FA, shrinkage decreases slightly until f_{ad} of 60% (minimum value) and reaches maximum values for f_{ad} of 70%. As for shrinkage's minimum values for binary mixes with LF, they are related to f_{ad} of 70% and the maximum to f_{ad} of 30%.

The decrease of the shrinkage for mixes with FA until f_{ad} of 60% can be explained by the fact the, with the increase in the FA volume, it is more likely that a lower hydration level is obtained, which will cause a higher volume of non hydrated material, leading the FA to work more as a micro aggregate favourable to the shrinkage decrease. As for the shrinkage increase observed for the mixes with FA and f_{ad} of 70%, it can be caused by the hydration reactions which are so slow that lead to a pore structure more open in the first days, increasing the drying and causing a higher shrinkage.

The ternary mixes follow a trend similar to that of the binary mixes with FA, namely a decrease in shrinkage with the increase of f_{ad}. Therefore, they have shrinkage values for mixes with f_{ad} of 30% which are higher than those of mixes with f_{ad} of 60%. These mixes (ternary) with a global f_{ad} of 60% show vary satisfactory values for shrinkage at 182 days, when compared to the values of the binary mixes, with differences of only ≈ 50 μm/m for the mixes SCC2.70LF and SCC3.60FA.

Fig. 2 and 3 allow concluding that, in general, the prediction model proposed by Eurocode 2 tends to underestimate the extension by shrinkage of the SCC studied. The exception are the binary mixes with LF (f_{ad} of 30%), which show values, at 182 days, around ≈115%, relatively to the prediction of the Eurocode 2 model for equivalent mechanical strength levels. The mixes SCC1.100C show values, at 182 days, which are slightly lower but very close to those determined by the Eurocode 2 method, corresponding to approximately 96% of that value. As for the SCC2.60LF, SCC3.30FA and SCC3.70FA mixes, they show values, at 182 days, close to 90% comparing to what is proposed by Eurocode 2. The remaining results are between 66% and 88% of the corresponding values determined by Eurocode 2. One should highlight the values for the total extension by shrinkage obtained by the mixes with LF and f_{ad} of 70%, which are of ≈58% regarding what is proposed by Eurocode 2 for equivalent mechanical strength levels.

CONCLUDING REMARKS

All the mixes produced reached the required workability thresholds to be classified as self-compacting. The SCC produced had adequate filling and passing ability as well as a good resistance to segregation.

In terms of compressive strength, even the mixes with f_{ad} of 70% reached 30 MPa at 28 days, in the case of the mixes with LF, and 35 MPa for the mixes with FA. The ternary mixes with a global f_{ad} of 60% have compressive strength of approximately 48 MPa at 28 days.

The use of FA and LF can improve shrinkage properties. The mixes with the most favourable results were SCC2.70LF, SCC3.60FA and the ternary mixes with global f_{ad} of 60%. In general the ternary mixes show interesting results. The mixes with greater shrinkage were the SCC2.30LF, SCC2.60LF and SCC3.70FA. It is reasonable to consider that the behaviour observed will probably be more conditioned by the influence of the additions used at the level of the paste hydration process and the microstructure refinement, than by the mechanical strength.

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