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Use of calcareous fly ash in SCC

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Abstract

The robustness of self-compacting concrete (SCC) mixtures is usually sensitive to alterations in the mixture constituents, which is also the case when using high volumes of calcareous fly ash as binder. In the present report, calcareous fly ash was used as 30% and 50% by mass of the total binder without changing the water to binder ratio. The expected loss of workability due to the increased water demand of calcareous fly ash was compensated by adjusting the dosages of the admixtures (superplasticizer and viscosity modifying agent). Slump flow, L-Box and segregation resistance tests were carried out on the fresh mixtures, showing that robust SCC can be produced with the addition of high volumes of calcareous fly ash. Mechanical characteristics of the test mixtures were also measured, showing adequate strength development, comparable to that of the reference concrete, while shrinkage deformations were reduced when higher volumes of calcareous fly ash were used..

Keywords: Calcareous fly ash, self-compacting concrete

1 Introduction

Self-Compacting Concrete (SCC) is a special concrete that shows adequate flow, passing ability and segregation resistance without the need for compaction. It requires specific design in terms of its constituents and a well known practice for optimizing SCC is the use of mineral admixtures such as fly ash, which often replaces around 35% of cement clinker (Hwang & Khayat 2008). This alternative is cost-effective, provided that fly ash is a locally available low-cost by-product, it contributes to the reduction of emissions and enhances consistency at low water-cementitious materials ratio (w/cm) (Vikan et al 2010).

In many areas such as Greece the available fly ash emanates from the burning of lignite, is of high calcium content and may be characterized as ASTM class C or as calcareous fly ash according to EN 197. It could be said that although these fly ashes constitute more than half of the total fly ash production in Europe, their exploitation is much less compared to that of siliceous type fly ashes, according to the ECOBA statistics (EUROCOAL 2011). This is attributed to problems related to their homogenization, their free lime and sulfate contents, as well as to the excess of calcium aluminate compounds when high-calcium fly ashes are used in combination with cement in concrete production. However, their abundancy as well as the potential for upgrading their quality provides a strong motive for their beneficial utilization in concrete production, since they contribute to early strength development more than siliceous fly ashes, due to their self-cementing hydraulic character (Papayianni 1992, Papayianni et al 2009). Moreover, the huge amount of fly ash output (around 11 million tons per year) allows for the selection of fly ash under prescribed limits.

While fresh concrete slump or expansion is usually adequate to assess the consistency of ordinary concrete, the robustness of SCC mixtures needs to be determined in terms of fluidity, passing ability and segregation resistance. Regarding the sensitivity of fresh SCC properties to changes in the constituent materials, several methodologies are proposed in the literature (Su et al 2001, Khayat 1999). Based on relevant guidelines and regulations, some limits concerning the constituents of SCC are suggested, as well as methods of assessing fresh SCC mixtures (EFNARC 2002, Nunes et al 2006). Literature on the use of calcareous fly ash in SCC is very limited. This lack of interest could be attributed to the particular behavior of calcareous fly ash in concrete mixtures. For example, calcareous fly ashes often increase water demand which seems to be a negative effect for SCC proportioning. However, as research has proven, there are ways to overcome such problems and have technical advantages from calcareous fly ash incorporation into the cementitious material of SCC (Papayianni & Anastasiou 2011).

In this paper, two different batches of calcareous fly ash (HCFA), having different contents of free lime, sulfur and silica, were used for 30% and 50% wt. of the total binder in SCC mixtures. Basic properties of fresh and hardened SCC were measured in order to determine if the addition of high volume of calcareous fly ash in the cementitious material may render a SCC of sufficient quality. A series of laboratory mixtures was prepared and tested for their fresh and hardened properties. The robustness of the fresh SCC mixtures was measured by recording flowability, slump-flow viscosity, passing ability and segregation resistance, while the characteristics of the hardened SCC test mixtures were assessed by measuring compressive and flexural strength, elastic moduli and early shrinkage deformations.

2 Experimental Part

2.1 Materials Selection and Concrete Mix Design

The binders used in the test mixtures were ordinary Portland cement type CEM I 42.5 N and two types of unprocessed calcareous fly ash (HCFA-1 from the Ayios Dimitrios Power Plant and HCFA-2 originating from the Ptolemaida Power Plant). Limestone filler was used in order to increase the content of fines, based on the recommendations found in the literature (Okamura 1997, Lemieux et al 2010, EFNARC 2002). Some characteristics of the fines used in the test mixtures are shown in Table 1.

Table 1. Characteristics of binders used for flowable concrete mixtures

Consituents (%)	CEM I42.5	HCFA-1	HCFA-2
SiO_2	20.3	29.4	48.4
Al_2O_3	2.40	6.69	14.0
Fe_2O_3	8.11	5.26	8.06
CaO	66.8	41.7	23.1
CaO_{free}	-	10.6	2.52
MgO	3.91	7.30	2.47
SO_3	2.55	3.85	4.01
Na_2O	0.57	0.38	1.16
K_2O	1.08	0.80	1.06
Insoluble residue (%)	0.80	9.93	-
Loss on ignition (%)	1.91	8.46	1.74
App. specific gravity (Mg/m^3)	3.14	2.45	2.34
Fineness (%), R_{45}	1.5	19	< 38

Following trial mixtures and based on previous experience, the amount of cement replacement with HCFA was decided to be 30% and 50%, while the total binder content was 400 kg/m^3. In order to improve fresh concrete fluidity and robustness, 160 kg/m^3 of limestone filler was also added, reaching a total of 560 kg/m3 of fines (< 125 μm). The aggregate used in all mixtures was crushed limestone with a maximum size of 16 mm and the aggregate gradation curve was optimized by combining three aggregate fractions (0-4 mm, 4-8 mm, 8-16 mm) in order to achieve the best packing factor of the aggregate mix as shown in Fig.1. The water to binder ratio was selected equal to 0.50 and a polycarboxylate-based superplasticizer (PC) was used at a percentage of 1÷2% wt. of cement + fly ash and a viscosity modifying agent (VMA) at a percentage of 0.25% wt. of the total cementitious content passing the 125 μm sieve. Table 2 shows the proportioning of the test mixtures.

Fig. 1. Granulometry of aggregate mix used in all SCC mixtures

Table 2. Proportioning of SCC mixtures

Material	Reference (CEM I42.5N)	30% HCFA1	50% HCFA1	30% HCFA2	50% HCFA2
CEM I 42.5N (kg/m^3)	400	280	200	280	200
HCFA (kg/m^3)	-	120	200	120	200
Limestone filler (kg/m^3)	160	160	160	160	160
w/cementitious ratio	0.45	0.49	0.51	0.50	0.50
Superplasticizer (% wt. of cementitious)	1.12	1.35	2.00	1.60	2.00
VMA (% wt. of material <45μm)	0.25	0.25	0.25	0.25	0.25
Sand 0-4 mm (kg/m^3)	978	978	978	978	978
Coarse sand 4-8 (kg/m^3)	326	326	326	326	326
Crushed limestone 8-16 mm (kg/m^3)	326	326	326	326	326

2.2 Fresh concrete properties

The slump-flow test was used to assess fresh SCC flowability, while T_{500}, which is the time required for the fresh concrete to reach a diameter of 500 mm during the slump-flow test and serves as an indication of viscosity, was also recorded in the same test. Passing ability was measured using the L-box test and segregation was measured by the segregation resistance sieve test which calculates the percentage of the fresh mixture passing from a No.4 sieve after being left to consolidate. The results of the fresh concrete testing are shown in Table 3. The minimum target values for each test are based on guideline recommendations (EFNARC 2002).

Table 3. Properties of fresh SCC mixtures

Material	Reference (CEM I42.5N)	30% HCFA1	50% HCFA1	30% HCFA2	50% HCFA2	Target value
Slump-flow (mm)	670	560	720	580	700	> 550
T_{500} (s)	3	10	5	3.5	3	> 2
L-box (H_2/H_1)	0.90	0.85	0.90	0.80	0.90	> 0.80
Segregation (%)	2.8	2.6	8.8	2.4	9.2	< 15%

With increased use of superplasticizer, the fluidity of high HCFA mixtures is very high, however when the admixture is kept constant (as in the case of 30% HCFA mixtures) it is clear that the use of HCFA reduces flow of fresh concrete, while T_{500} time, on the other hand, is increased. Both effects, however, occur within the limits of the target values and do not alter fresh concrete robustness significantly. Also, no significant change is observed regarding passing ability, as measured by the L-box test. It should also be noted that, although HCFA, used with suitable amount of superplasticizer and VMA, seems to contribute towards more viscous mixtures (increased flow time and reduced flowability), segregation might still occur, especially if the amount of water and chemical admixtures used is not optimum.

Following mixing and fresh concrete testing, specimens were cast from all the test mixtures. The specimens cast were 150 x 150 x 150 mm cubes used for compressive strength testing, 150 x 300 mm cylinders used for the determination of split tensile strength and elastic modulus, 100 x 100 x 1000 mm prisms used for the determination of the modulus of rupture and 100 x 100 x 1000 mm prisms used for the measurement of early shrinkage deformations. All the specimens were cured at 20°C and 95% RH until testing except for the prisms used for the determination of shrinkage deformations which were stored at 20°C and 50% RH, in order to simulate drying conditions.

2.3 Hardened concrete properties

Compressive strength, modulus of rupture and splitting tensile strength were measured, as well as the elastic modulus of concrete, based on stress-strain diagrams. Compressive strength tests were carried out both at 7 and 28 days in order to assess the strength development rate. The dynamic modulus of elasticity was also estimated, based on ultrasonic pulse velocity measurements. The results are shown in Tables 4 and 5. Figure 2 shows the early shrinkage deformations for the mixtures with 50% HCFA replacement, where the effect of fly ash addition were more evident.

Table 4. Mechanical and elastic properties of SCC mixtures

Material	Reference (CEM I42.5N)	30% HCFA1	50% HCFA1	30% HCFA2	50% HCFA2
28-d cubic compressive strength (MPa)	47.4	46.5	49.9	40.5	38.3
28-d split tensile strength (MPa)	2.08	1.91	2.02	2.83	2.87
28-d flexural strength (MPa)	7.80	7.00	7.45	7.56	6.87
28-d elastic modulus (GPa)	36.9	36.2	39.6	33.1	31.3
28-d dynamic modulus of elasticity (GPa)	54.0	52.8	55.1	48.5	45.2

Table 5. Rate of strength development of SCC mixtures

Material	Reference (CEM I42.5N)	30% HCFA1	50% HCFA1	30% HCFA2	50% HCFA2
7-d cubic compressive strength (MPa)	40.8	39.6	36.5	33.6	30.9
28-d cubic compressive strength (MPa)	47.4	46.5	49.9	40.5	38.3
Increase (%)	16.1	17.4	36.9	20.5	24.0

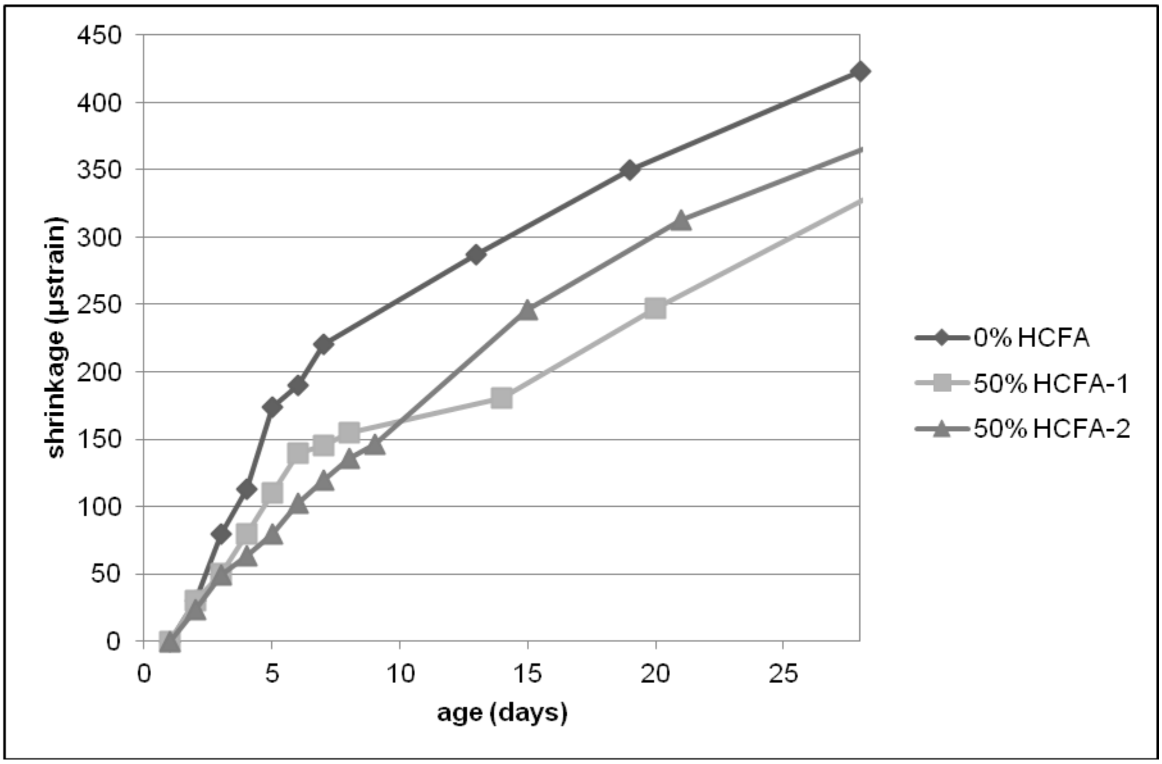

Fig. 2 Early shrinkage deformations of SCC mixtures at 20°C and 50÷60% RH

3 Results and Discussion

A 28-d compressive strength of about 50 MPa has been achieved with a 50% cement replacement by HCFA, keeping a low water to cementitious ratio (0.51) by using almost a 2% wt. of cementitious dosage of PC superplasticizer. The 7-day compressive strength of this SCC mixture corresponds to 72% of the 28-day strength. The 30% HCFA-1 SCC mixture with 30% of the total cementitious material HCFA has developed 28-day compressive strength comparable to that of the control mixture (46-50 MPa), by keeping the water to cementitious ratio equal to 0.49 and also by increasing the PC superplasticizer dosage by 20%. However, when HCFA-2 was used, strength development was 15-

20% lower than that of the reference mixture, reaching a 28-day compressive strength of 40.5 MPa and 38.3 MPa for 30% and 50% HCFA replacement, respectively. As far as the rheological characteristics of the fresh mixtures are concerned, it seems for both fly ashes that a higher dosage of superplasticizer must be used in order to achieve flowable and robust SCC mixtures.

Early shrinkage deformations of HCFA SCC mixtures are clearly lower than those of the control mixture. This behavior of HCFA SCC mixtures is considered to be related to the constituents of HCFA, reacting as expanding agents for the period from demoulding until hardening.

4 Conclusions

Research on the use of HCFA as supplementary material in SCC mixtures is very limited and according to the results of this research work it seems that a selected HCFA may replace high volume of cement in such mixtures. The extra water demand due to the incorporation of HCFA in the mixture can be confronted by increasing the superplasticizer dosage, while the very low price of HCFA (about 5% of the cement price) allows for such modifications of the SCC proportioning or for the improvement of HCFA quality. The different results obtained from different fly ashes highlight the need to select a fly ash prescribed in regulations, so as to know its potential and performance. Although water demand was increased for both fly ashes tested, the increase was greater for HCFA-1, with higher CaO content. Thus, adequate fluidity without segregation may be achieved in fresh mixtures. Also, the mechanical and elastic properties of the hardened SCC with 50% CEM I42.5N and 50% HCFA-1 as cementitious material was comparable to that of the control mixture, while HCFA-2 mixtures had also sufficient mechanical and elastic properties. Both fly ashes used in the SCC mixtures seem to reduce early shrinkage deformations, although HCFA-1, with higher CaO content, produced concrete with lower early shrinkage deformations. Overall, a highly reactive fly ash with high content in free lime can be used to achieve higher strength results and also to compensate for shrinkage deformations, while a HCFA with lower free lime content could be used in cases where cost reduction and lower strength levels are required. Consequently, the production of high volume HCFA SCC seems feasible and technically advantageous, provided that the HCFA with suitable characteristics is chosen.

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