Proceedings of the EUROCOALASH 2012 Conference,
Thessaloniki Greece, September 25-27 2012
http:// www.evipar.org/

The high – calcium fly ash as a component of self-compacting concrete

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Abstract

In the paper the basic influence trends of different composition and properties High Calcium Fly Ash (HCFA) on fresh mixture properties of Self-Compacting Concrete. HCFA was used as a replacement for a part of cement in the mixture (2 types of fly ashes, also activated by grinding) or as an additive to cement (also in combination with other additives as F-class ash and ground granulated blast furnace). Primary and secondary effects of admixtures action were investigated – in the first place: rheology (using rheometrical test). Discussion about the results covers mechanism of high - calcium fly ashes (C-class) influence on effectiveness of admixtures. The research has shown the negative influence of raw calcium fly ash (without grinding) added to concrete mix on its rheological properties and workability. Activation of fly ash (by grinding) improves its properties, and becomes positive as an additive to concrete mixes. Without a doubt, in many cases the problem is the loss of workability, but it does not concern cement composites. The current state of knowledge is not sufficient to effectively control of SCC mixtures with HCFA. Further research is needed, especially taking into consideration the impact which the changeable physical and chemical properties of HCFA and cement type have. The possibility of applying calcium fly ash as a partial replacement for cement in concrete and other cement components has been ascertained. An analysis on the effect of HCFA content on the properties of selected concretes of the new generation is the subject of this article. The paper presents test results for the self-compacting concrete SCC modified by HCFA, SCC mixes with cement modified by HCFA, high performance self-compacting concrete HPSCC modified by HCFA, and FRSCC mixes modified by selected types of steel and synthetic fibers. The results include studies on samples belonging to classes of slump flow SF, classes of viscosity T_{500}, the compressive strength tests: $f_{cm,28.}$ The concrete mix was tested with a varying amount of lime fly ash lime (10-20-30%), as equivalent of cement. The studies have confirmed the possibility of using HCFA in new generation concretes while maintaining the assumed technological parameters for concrete mixtures, especially their workability.

Keywords: calcareous fly ash, self-compacting concrete, rheology, steel fibers

1 Introduction

Mineral additives play a very important role in modern concrete technology. Their usage makes it possible to modify the properties of concrete and generate significant economic benefits as well. It is also an important element in achieving sustainable development strategy. Mineral additives are selected first of all according to the required strength and durability of concrete. Their presence, however, also has a significant effect on the rheological properties of the mixture. As mineral additives, most commonly used are fly ash, ground granulated blast furnace slag and silica fume. The basic requirement for the design and implementation of the new generation concretes is to assure their good workability during the whole process of concreting. These concretes are characterized by a high content of mineral additives which modify selected properties (eg, lime powder, silica fly ash, milled blast furnace slag, silica powder). The main effects of utilizing mineral additives have been widely shown in numerous studies [1][2][3][4][5][6][7]. The HCFA is obtained from the combustion of brown coal in conventional boilers. It is characterized by a much more complex composition than silica fly-ash, which is derived from burning coal, and commonly used in concrete technology. HCFA can be regarded as having puzzolana - hydraulic activity. Typical calcium fly ash contains from 10% to 40% reactive CaO, the specific area according to Blaine is lower than 2800 cm^2/g, and it contains some grains of unburned carbon, usually concentrated in the coarser fraction of the ash [3]. To this, a characteristic feature of the CFA is a considerable variation in chemical composition and grain size as well as revealing a high variability of chemical composition in the different grain fractions [3]. Also confirmed is the possibility of using lime fly ash as a replacement for part of the cement in concrete and as a component of cement itself [8]. One of the conditions for a wider use of calcium fly ash as an additive to cement or concrete is finding a solution to the problem of control workability of mixtures. The data in literature to date show no such complex studies in existence. There are only a few results available [2][3][4][5][6][7], usually from research carried out in a limited scope. On this basis, the only conclusion is that the introduction of calcium fly ash leads to an increase in the yield stress and plastic viscosity, and consequently, to a significant decrease in the workability of the mixture. It is still worse with a greater amount of the introduced ash. A higher content of CaO in the composition of the ash raises the yield stress, which contributes to the deterioration of the rheological properties of blends [12]. In order to obtain a specific flow limit it is necessary to add explicitly more superplasticizer - the introduction of 30% fly ash required more than double the amount of added superplasticizer [5].The presence of large amounts of unburned carbon in calcium fly ash also reduces the efficiency of the admixtures, making not only the liquidation difficult, but also, the efficient aeration of the concrete mixture [6]. This allows us to conclude that the present state of knowledge is not sufficient to effectively control the workability of mixtures of calcium fly ash. In summary, further research is needed on the effects of calcium fly ash on the rheological properties of mixtures, especially taking into account the variability in the physical and chemical properties of HCFA and of cement with their addition. Previous publications have indicated a problem of worsening of the workability of concrete mixtures containing lime fly ash [9] and fibres [10][11]. Therefore, as workability is key to the new generation of concretes, a series of tests were carried out to verify the possibility of achieving it with SCC concrete containing lime fly ash. Tests were performed on plain self-compacting concrete (SCC), high performance self-compacting concrete (HPSCC), and fiber reinforced self-compacting concrete (FRSCC). The current open issue is the use of lime fly ash in new generation concrete technology. The paper presents the methodology and results of the research on rheological properties of SCC with a calcium fly ash addition at varying degrees of milling. Additionally, the authors verified the effect of the amount of fly ash on the rheological properties of SCC with cement CEM I.

2. The assumptions and methodology of the research

The basic problem of the new generation of concretes, including those containing lime fly ash, is their workability. From the numerous studies which considered the workability of mixture it appears that it behaves under load as a viscoplastic Bingham body. The yield point g, plastic viscosity h, called the rheological parameters are material constants, characterizing the rheological properties of the mixture. Once the stress exceeds the yield point, the mixture will flow at a speed proportional to the plastic viscosity. The smaller the plastic viscosity of the mixture, the higher the velocity of flow at a given load. Issues related to rheology are more specifically discussed in the work [13]. It is assumed that yield point g corresponds to the diameter of the maximum slump flow SF, while plastic viscosity h propagation time corresponds to a diameter of 500 mm T_{500}, both parameters were measured in the propagation test (Slump-flow) according to standard EN 12350-8:2009.

The study was performed considering the effect of the following factors:

- supply of lime fly ash: batch (delivery) A and B (see Table 1);
- the degree of grinding of the lime fly ash (see Table 2);
- content of lime fly ash as cement equivalent: 10-20-30% mass of cement;
- mass ratio of steel fibers (see Table 5): 0 - 100 kg/m^3;
- mass ratio of synthetic fibers (see Table 6): 0 - 6 kg/m^3;

The study was performed in four series of research:

C1 – study on the effect of dosage HCFA into SCC concrete,

C2 – study on the effect of dosage HCFA in cements (CEM I, CEM II / BM (LL-W), CEM II / BW, CEM IV / B-W) for SCC,

C3 - study on the effect of dosage HCFA into HPSCC concrete,

C4 - study on the effect of dosage of synthetic and steel fibers into SCC concrete.

Composition of the self-compacting cement mixes tested in each test block are presented in Table 3. The characteristics of the cement ground together with additives included in the study block C2 are shown in Table 4. The research used superplasticizers based on polycarboxylen ether. Fibers used for testing were chosen from a relatively large group of all those available on the market. The selection was aimed at demonstrating the effect of fibers with various material and geometric parameters on the workability of self-compacting mixtures. A procedure for the preparation of concrete mixes was developed and implemented which allowed for maintaining the technological reproducibility of the results. The sequence applied during the preparation of concrete mixes in all blocks of research are presented in Figure 1:

3. The results and discussion

3.1. Study on the effect of dosage of HCFA to concrete mix on SCC

Figure 2 shows the effect of content of lime fly ash (supply A) and its degree of milling on the diameter of the SF propagation and on the propagation time T_{500} of self-compacting mixtures. Based on the study carried out, it can be concluded that an increase in the content of lime fly ash in the mixture reduces the diameter of the SF propagation and prolongs the propagation T_{500}. The greater the content of HCFA in the mix, the greater the scope of change. However, if the ash is subjected to mechanical activation (HCFA A1), the effect is smaller. There was also observed a certain deterioration of workability with time. Nevertheless, it should be emphasized that the loss of workability occurs to an extent that enables the preservation of properties of self-compatibility.

3.2. Study on the effect of dosage of HCFA to cement on SCC

Figure 3 shows the influence that the type of cement having HCFA additive have on the diameter of the SF propagation and on the propagation time T_{500} for SCC mixtures of various classes of self-compatibility. Based on the survey it can be concluded that the increase in the content of lime fly ash in cement does not cause a significant reduction in diameter of the propagation SF in SCC mixtures with its addition. Similar values of SF were observed for all tested cements in individual classes of self-compatibility of the SCC mixtures. However, the increase in the content of lime fly ash in cement composition contributed to a rise in the time of propagation T_{500} of SCC mixes with its addition. The plastic viscosity of SCC mixes increased, the lower the consistency class of compound of tested SCC. The increase in the content of lime fly ash in cement composition also affected a decrease in compressive strength $f_{cm,7}$ of SCC concrete with its addition in all classes of self-compatibility (Fig. 4).

3.3. Study on the effect of dosage of HCFA on concrete HPSCC

Figure 5 shows the effect of the content of HCFA (supply A) and the degree of milling have on the diameter of the propagation SF and propagation time T_{500} of HPSCC. With the increase in the content of lime fly ash in the mixture there was a small decrease in diameter of the propagation SF. Adding milled lime fly ash does not cause loss of workability of the mix HPSCC. An increase in the content of lime fly ash in the mixture contributed to the rise in the time of propagation T_{500} in SCC mixes with its addition, but not by much.

There was also observed a certain deterioration of workability over time but to a degree sufficient to maintain the properties of self-compatibility.

Similar effects were observed in the case of dosing HCFA (supply B) to HPSCC compound, shown in Figure 6. The increase in the content of lime fly ash in concrete HPSCC affects a decrease in their compressive strength $f_{cm,28}$ (Fig. 7). This effect is greater as the content of HCFA in the concrete increases. Adding HCFA B1 also resulted in a decline in the value $f_{cm,28}$ of concrete HPSCC with its addition, but to the smallest degree.

3.4. Study on the effect of dosage of synthetic and steel fibers into concrete FRSCC.

The paper also presents selected research on self-compacting concrete SCC with fibers. Figure 8 shows the effect of the type and volume ratio of synthetic fibers on the diameter of the SF propagation and propagation time of self-compacting mixtures T_{500}. It has been found that there is reduction in the diameter of the propagation of self- compacting mixtures with increasing fiber content in the mixture. This effect is greatest for the SCC mixtures with polymer-basalt fibers SBF 25. Increasing the content of macro-FS-25 polyethylene fibers showed no major changes in the values of SF and T_{500} of SCC concrete with their addition.

Figure 9 shows the effect of the type and volume ratio of steel fibers on the diameter of the SF propagation and propagation time of self-compacting mixtures T_{500}. Generally, the effect of deterioration on the workability of SCC mixes with the addition of steel fibers is small, in the range of research 60-80-100 kg/m^3. The mixture is easy to apply, workable, but there is a phenomenon of an uneven distribution of fibers in the concrete. This effect is greater when the volume ratio of fibers in the mixture SCC increases and greatest in the SCC mix containing 100 kg/m^3 of steel fibers.

Figure 10 shows the effect of the type and volume ratio of steel and synthetic fibers on the compressive strength $f_{cm,28}$ of SCC concrete. The effect of the fiber being tested on the value of $f_{cm,28}$ is small and with the increase their volume ratio, it is even negative. In the case of SCC concrete, such an effect can be explained by the irregular distribution of fibers in the matrix of concrete. Low fiber content does not cause such problems and the value of $f_{cm,28}$ for the tested concrete SCC increased. With higher fiber content the effect of unevenness in their distribution became larger and resulted in a decline in the value of $f_{cm,28}$ in the tested SCC concrete. The phenomena concerning the impact of dispersed reinforcement on the properties of SCC are currently being more widely studied by the authors.

4. Summary

The presented study confirmed the possibility for use of HCFA in concretes of the next generation when maintaining the required parameters of concrete mix technology, and above all, their workability.

A deterioration in workability was observed with the increase of the content of lime fly ash in concrete SCC and HPSCC. A decline in workability of concrete mixtures occurs, but to an extent that preserves the properties of self-compatibility.. The study showed no significant influence of activation of lime fly ash to improve the workability and mechanical parameters of concrete SCC and HPSCC with their addition. Activation of the ashes (the milling) certainly improves their properties, but studies have shown a similar effect of HCFA, both milled and not milled, on the tested properties of concrete mixes SCC and HPSCC.

The use of selected cements with lime fly ash in their composition showed poorer, but sufficient workability of concrete with the addition of SCC. The self-compatibility and mechanical properties of concretes with lime fly ash modified cement were satisfactory and met the established standards.

The influence of fiber types and content of the deterioration of the workability of SCC mixtures was proven. The self-compatibility of concrete mixtures deteriorates with an increasing volume ratio of fibers in a mixture of self-compacting concrete. It should be noted that, despite the deterioration in the workability, it is possible to attain self-compatibility for mixtures with the addition of steel and synthetic fibers.

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Acknowledgments

The results presented in the paper have been obtained within the project “Innovative cement binders and concretes with addition of high calcium fly ash” (project no POIG.01.01.02-24-005/09 with the Polish Ministry of Science and Higher Education) in the framework of the Operational Programme Innovative Economy 2007-2013.

Table 1. Chemical composition of calcareous fly ash

	Constituent, %								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	CaO_w
HCFA batch A	40,17	24,02	5,93	22,37	1,27	3,07	0,15	0,20	1,46*
HCFA batch B	40,88	19,00	4,25	25,97	1,73	3,94	0,13	0,14	1,07

* glycol method

Table 2. Physical properties of fly ashes

Ash		Density, g/cm^3	Residue on sieve 45μm, %	Blaine specific surface, m^2/g	Bulk density, kg/m^3
			Batch A		
A0	Unground	2,64	55,6	190	1060
A1	Ground 20 min	2,71	20,0	410	Nd
			Batch B		
B0	Unground	2,60	46,3	240	1030
B1	Ground 15 min	2,67	20,8	350	nd

Table 3. Compositions of self-compacting concrete mixtures used in particular research series

Constituent / Designation	Concrete Mixture			
	C1	C2	C3	C4
	kg/m^3			
CEM I [CI]	490,0	-	490,0	-
CEM I, CEM II/B-M (LL-W), CEM II/B-W, CEM IV/B-W [CII]*	-	600,0	-	-
CEM II B-W [CIII]	-	-	-	600,0
Sand 0-2 mm [S]	800,0	800,0	756,0	800,0
Natural aggregate 2-8 mm [Na]	800,0	800,0	-	800,0
Basalt aggregate 2-8 mm [Ba]	-	-	944,4	-
Silica fume [SF]	-	-	49,0	-
High - calcium fly ash (10-20-30% m.c.) [CFA]	49-98-147	-	49-98-147	-
Steel fibres [Sf]	-	-	-	60-80-100
Polietylene and polymer-basalt fibres [Pf]	-	-	-	2-4-6
Superplasticizer Glenium ACE 48 (3.5 % m.c.) [SP A]	-	-	17,0	-
Superplasticizer Glenium SKY 592 (1,1 - 2,5 % m.c.) [SP B]	16,2	6,8 – 15,0	-	12,0
Stabilizer RheoMatrix (0.4 % m.c.) [ST]	1,6	2,73	1,6	1,95
Sand equivalent (%)	50,0	50,0	45,8	50,0
W/C	0,42	0,31	0,42	0,31
Consistency class (SF)	SF3	SF 1-2-3	SF3	SF3

* C2 series included 12 mixtures with cements according to second row in this table

Table 4. Characteristics of co-ground cements used in C2 research section

Parameters		Cement type			
		CEM II/B-M (LL-W)	CEM II/ B-W	CEM IV/ B-W	CEM I
Constituents, %	Portland clinkier	66	66,5	48	94,5
	Asf W	14	29	48	-
	Calcium LL	14	-	-	-
	Gypsum	6	4,5	4	5,5
Settingtime, min	Initial	201	198	280	129
	Final	331	358	420	244
Compressive strength, MPa	2	21,7	19,8	12,8	29,0
	7	37,3	36,4	24,0	47,2
	28	47,4	50,4	39,3	59,9
Bending strength, MPa	2	4,4	4,3	3,2	5,4
	7	6,5	6,2	4,8	6,8
	28	8,1	8,2	6,9	7,8
Water demand, % of mass		29,4	33,0	34,6	26,4
Pasteflow, cm		17,9	15,9	14,7	18,4

Table 5. Characteristics of steel fibres used in C4 research section

Type	Length (mm)	Diameter (mm)	Cross-section	Shape	Material	Tensile strength N/mm^2
DM 6/0,17	6±10%	0,17±10%	round		Low-carbon steel	2100±15%
SW 35/1.0	35±10%	2,30±2,95 [1)]	part of circle		Low-carbon steel	800±15%

Designation: [1)] width (mm);

Table 5. Characteristics of synthetics fibres used in C4 research section

Type	Length (mm)	Diameter (mm)	class	Shape	Material	Tensile strength (N/mm^2)
SBF 25	12±10%	0,16	round	straight	Polymer-basalt	1 680
FS 25	25±10%	0,66	II; macro-fibres	deformable	Polypropylene, Polythene	600

Fig. 1 The order of the constituents adding in the procedure of concrete mixtures production in four series

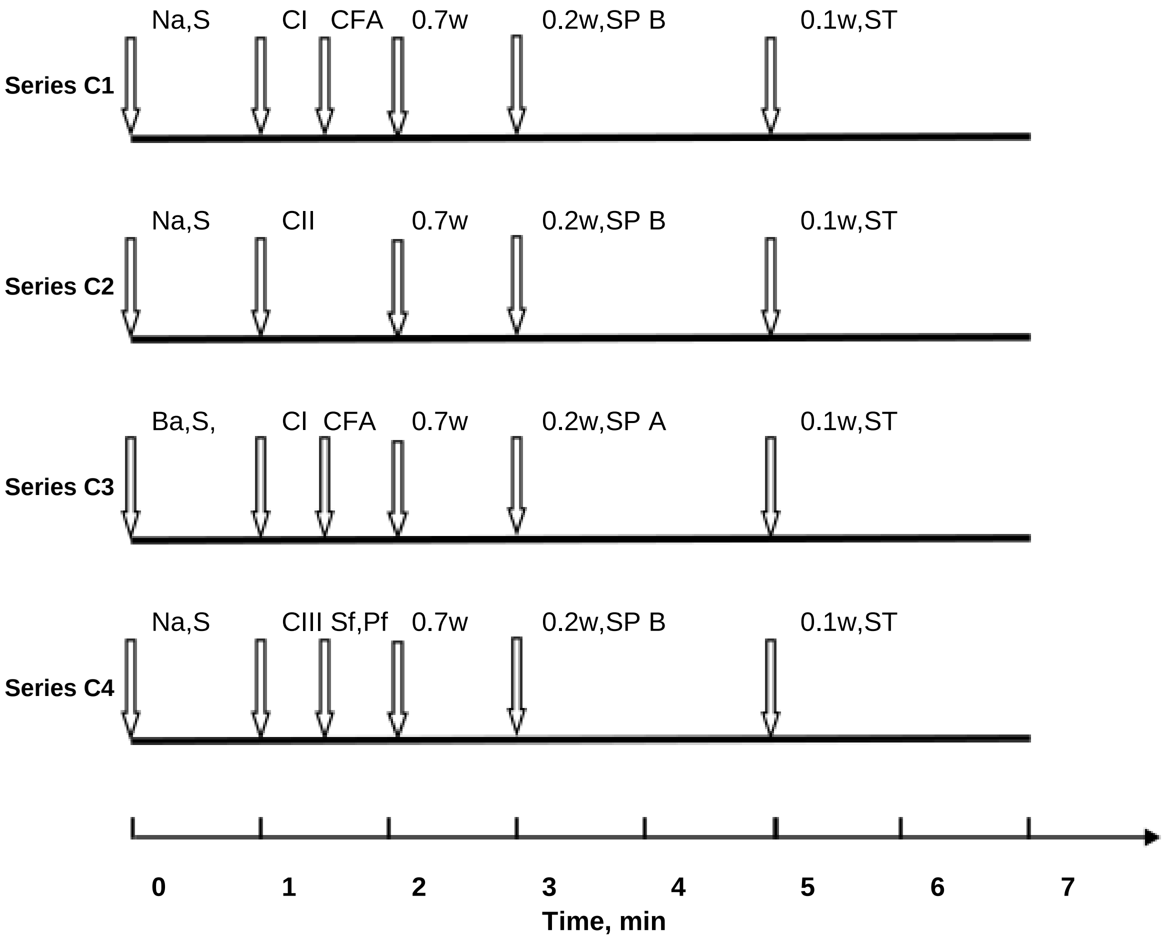

Fig. 2 The influence of calcareous fly ash content and its fineness on flow diameter SF and flow time T_{500} of SCC mixture, including the effect of time

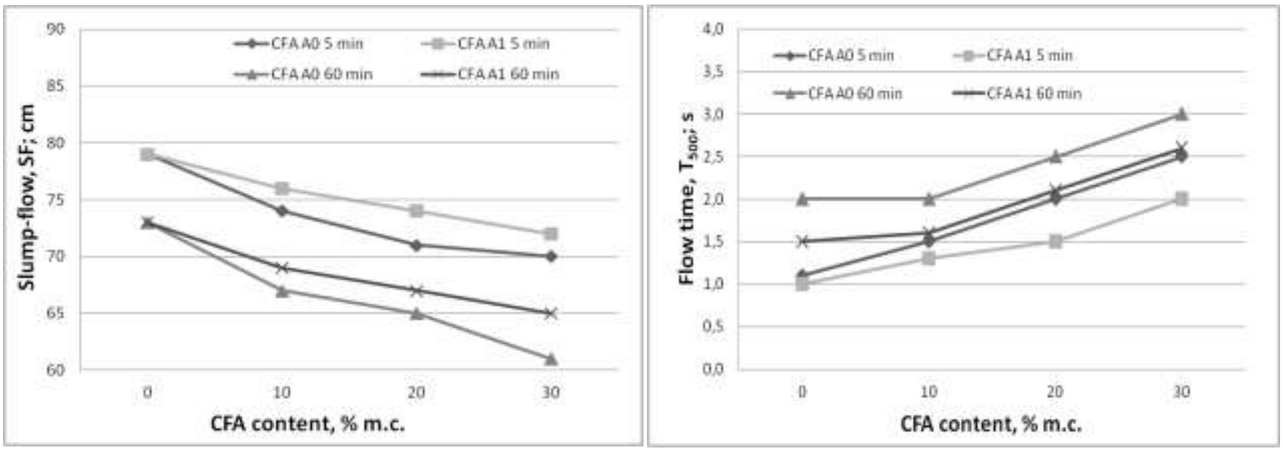

Fig. 3 The influence of cement type with HCFA addition on flow diameter SF and flow time T_{500} of SCC mixture (C2) for different self-compacting classes

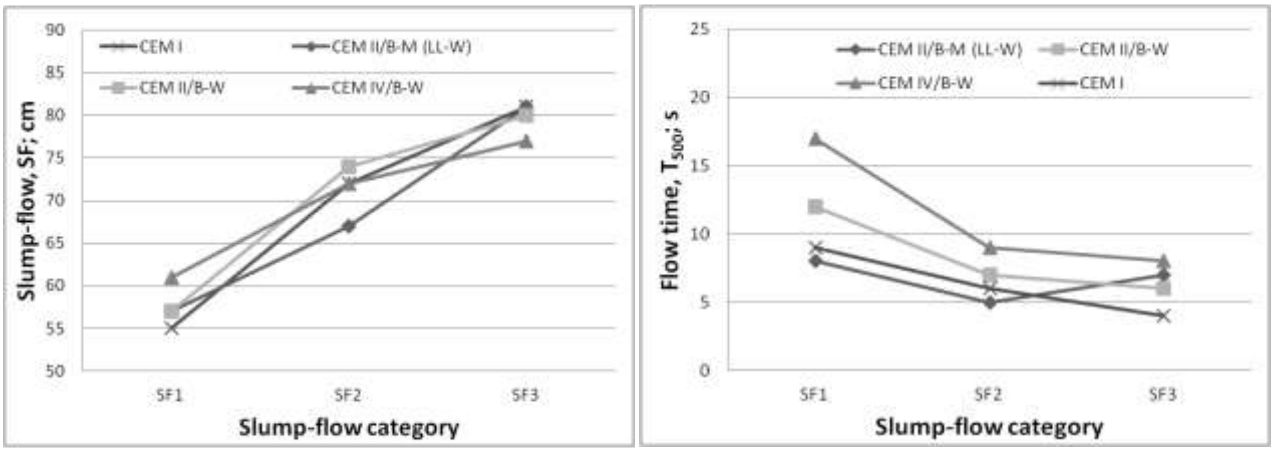

Fig. 4 The influence of cement type with HCFA addition on compressive strength $f_{cm,7}$ of SCC for different self-compacting classes

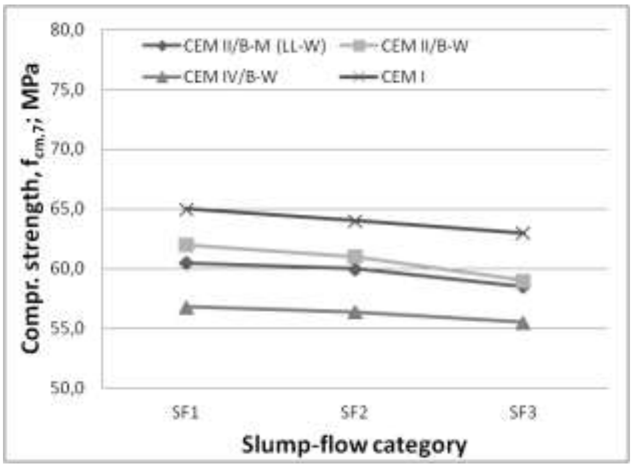

Fig. 5 The influence of HCFA content (batch A) and its fineness on flow diameter SF and flow time T_{500} of HPSCC mixtures

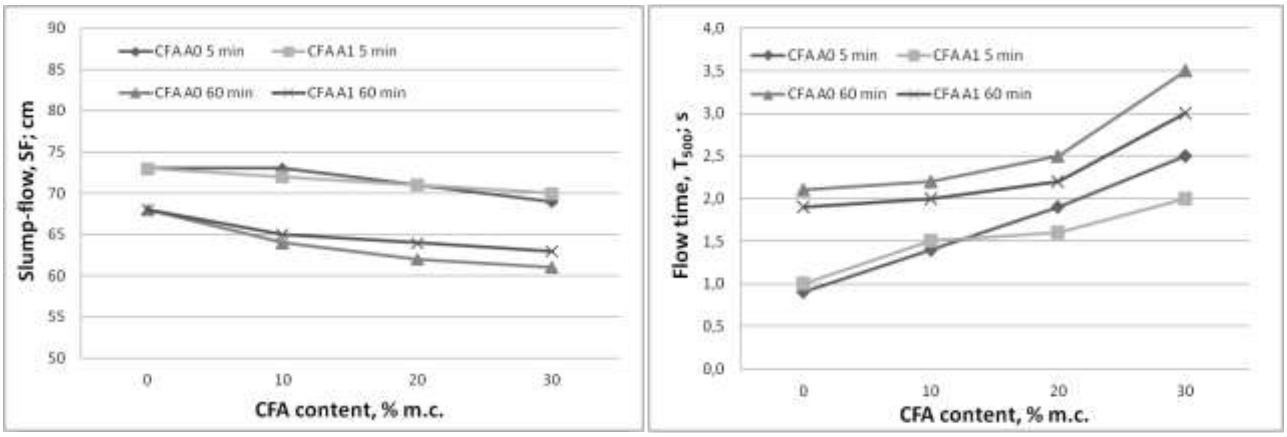

Fig. 6 The influence of HCFA content (batch B) and its fineness on flow diameter SF and flow time T_{500} of HPSCC mixtures

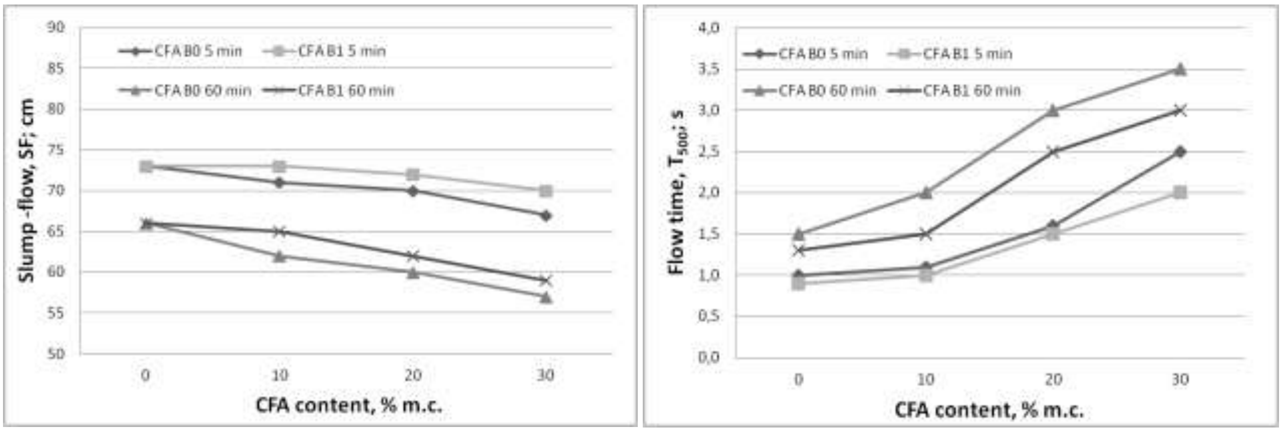

Fig. 7 The influence of HCFA content and its fineness on compressive strength $f_{cm,28}$ of HPSCC

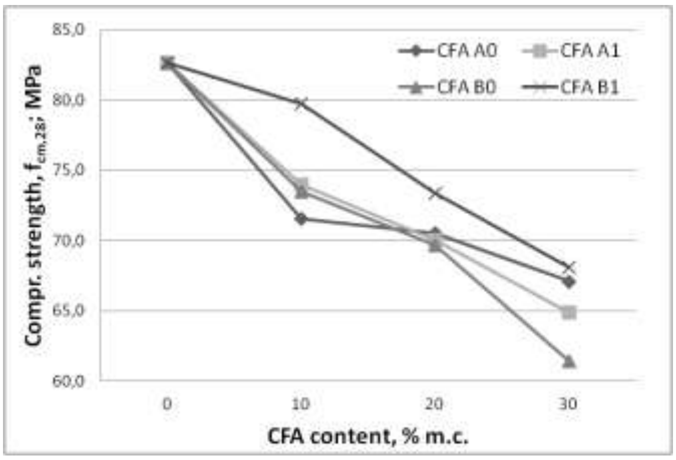

Fig. 8 The influence of type and contents of synthetic fibres on flow diameter SF and flow time T_{500} of FRSCC mixtures

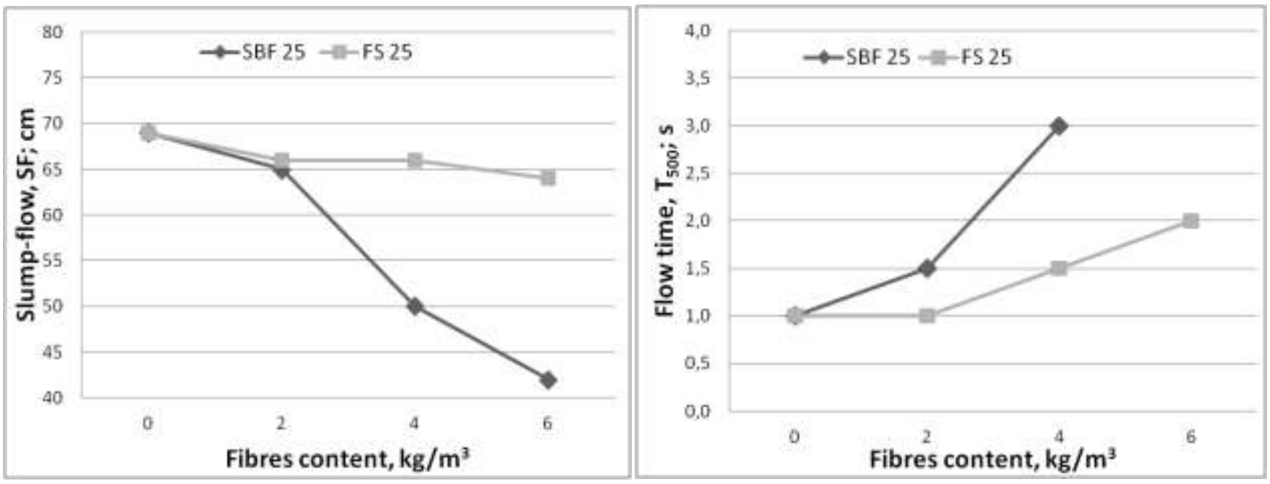

Fig. 9 The influence of type and contents of steel fibres on flow diameter SF and flow time T_{500} of FRSCC mixtures

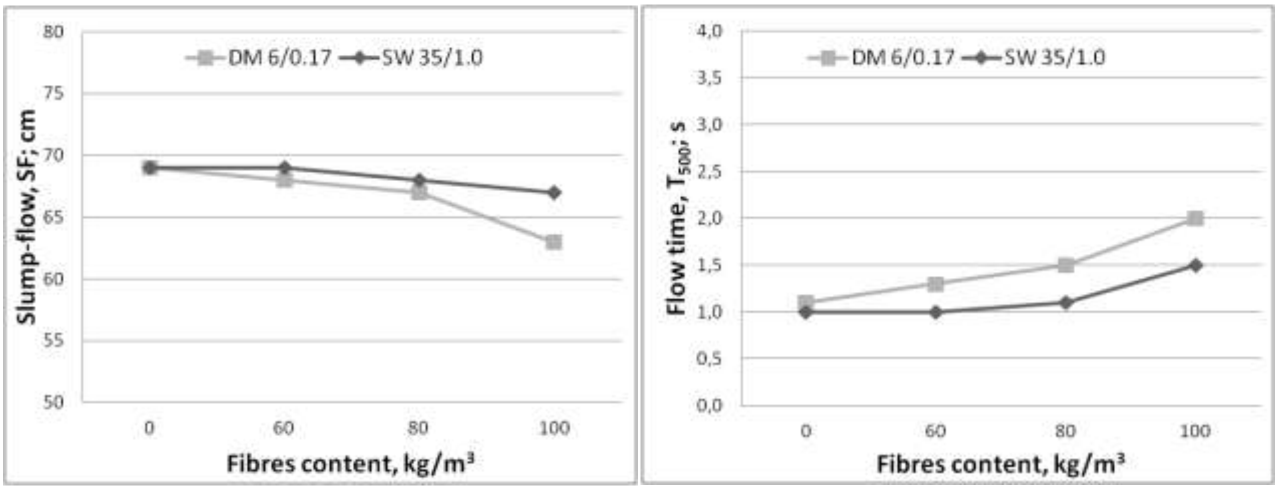

Fig. 10 The influence of type and contents of steel and synthetic fibres on compressive strength $f_{cm,28}$ of FRSCC