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The Rheological and Mechanical Properties of Self-Compacting Concrete with High Calcium Fly Ash

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ABSTRACT

The paper presents test results on the self-compacting concrete (SCC) modified with High Calcium Fly Ash (HCFA), SCC mixtures with cement modified by HCFA and high performance self-compacting concrete (HPSCC) modified by HCFA. HCFA was used as a replacement for a part of cement in the mixture (2 types of HCFA, also activated by grinding) or as an additive to cement. 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 mixtures. The results include studies on samples belonging to classes of slump flow SF, classes of viscosity T_{500}, compressive strength and flexural strength tests. The concrete mixture was tested with a varying amount of HCFA (10-20-30%), as equivalent of cement.

Keywords. High Calcium Fly Ash, self-compacting concrete, rheology, activated HCFA

INTRODUCTION

Mineral additions play an extremely important role in current concrete technology, as they enable the improvement of concrete properties, especially in relation to its immunity to aggressive environment and obtaining significant economic benefits. Furthermore, the use of mineral additive is also an important element in the strategy of sustainable development, enabling i.a. effective management of wastes, lowering energy consumption in cement production and lowering CO_2 emission. Usually, in production of concrete, fly ashes from hard coal, grinded blast-furnace slag or, if high durability is needed, silica fume are used; in self-consolidating concrete, rock dusts are used (i.e. grinded limestone, dolomite), which are, however, considered as neutral additions. The mineral additions are selected in regard to concrete strength and durability requirements, and its presence significantly influences rheological properties of the mixture. The main effects of mineral additions use are widely presented in numerous works e.g. (Neville, 2000; Giergiczny, 2006).The main effects of utilizing mineral additives have been widely shown in numerous studies (Aitcin, 1998; Neville, 2000; Giergiczny, 2006; Tsimaset al., 2005; Yazici, 2008; Wei et al., 2003; Yamei et al., 1997). 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% of 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 (Giergiczny, 2006). To this, a characteristic feature of the HCFA is a considerable variation in chemical composition and grain size as well as revealing a high variability of chemical composition in different grain fractions, (Giergiczny, 2006). Also, the possibility of using lime fly ash as a replacement for part of the cement in concrete and as a component of cement itself is confirmed (Gołaszewski, 2012). One of the conditions for a wider use of calcium fly ash as the additive to cement or concrete, is finding the solution to the problem of control workability of mixtures. The existing data in literature show no such complex studies in existence. There are only a few results available (Neville, 2000; Giergiczny, 2006; Tsimas et al., 2005; Yazici, 2008; Wei et al., 2003; Yamei et al., 1997), 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 the increase in the yield stress and plastic viscosity, and consequently, to a significant decrease in workability of the mixture. It is still worse with a greater amount of the introduced ash. 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 (Grzeszczyk, 2002). 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 (Yazici, 2008).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 (Wei et al., 2003). This allows us to conclude that the present state of knowledge is not sufficient to control effectively 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 cement with their addition. Previous publications have indicated a problem of worsening of the workability of concrete mixtures containing lime fly ash (Ponikiewski, 2012). Therefore, as workability is a key to the new generation 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) and high performance self-compacting concrete (HPSCC). The current open issue is the use of HCFA in new generation concrete technology. The paper presents the methodology and results of the research on rheological properties of SCC with HCFA addition at varying degrees of milling. Additionally, the authors verified the effect of the amount of fly ash on rheological properties of SCC with cement CEM I.

RHEOLOGICAL PROPERTIES OF SELF-COMPACTING MIXTURE AND THEIR MEASUREMENTS

Given definition of self-compacting concrete states three main requirements for rheological properties of the mixture: high fluidity, its ability to pass the reinforcement and the resistance to segregation both during the transport and laying. High fluidity of the mixture determines the possibility of automatic removal of the air accidentally caught in during the production and transport from the mixture. Rheological properties of the self-compacting mixture are characterized by the parameters of Bingham material model – the yield value and plastic viscosity. Their value depends mostly on constituents properties and mixture composition, time passed from the moment of mixing the constituents, and temperature. Once the stress passes the yield value, the mixture flow occurs with velocity proportional to plastic viscosity.

The lower yield value and plastic viscosityare, the easier the mixture will flow and deaerate, but, at the same time, the more vulnerable to segregation is. While designing the self-compacting concrete mixture, one usually aims for relatively low yield value and at the same time optimizes the plastic viscosity of the mixture, making it high enough to prevent segregation, and low enough to enable self-deaeration. The issues of self – compacting mixture rheology were presented in detail in (De Schutter et al., 2008; Szwabowski et al., 2010). Measurements of the rheological parameters of the self-compacting mixture are best carried out with rheometer (De Schutter, 2008; Szwabowski et al., 2010). However, it is relatively expensive, it requires highly qualified staff and moreover it can be used only in laboratory conditions. For those reasons, in technological practise special tests are used that which simulate particular conditions occurring during laying the SCC mix. According to EN 206-9 standard, following tests are recommended: slump flow (EN 12350-8), J-ring (EN 12350-12), V-funnel (EN 12350-9) and L-box (EN 12350-10). These tests have been described in detail in, i.a. (De Schutter, 2008; Szwabowski et al., 2010). They enable to determine mixture fluidity, viscosity and ability to flow through the reinforcement bars. Correlation between the tests used and rheological parameters and the consistency class of SCC mixture is shown in table1. According to EN 206-9 standard, the basis for determining the resistance to segregation is the penetration test (EN 12350-12). However, according to (ACI 237 R-07; 2007) for determining the degree of segregation, use of Visual Stability Index (VSI) is recommended. There are four classes of stability that describe the resistance of the mixture to segregation and water outflow from the mixture which are estimated by visual assessment of the mixture appearance after slump-flow test. The stability of SCC mixture in the research was estimated by VSI.

Table 1. Tests used for determining the rheological properties of the SCC mix according to EN 206-9 and their correlation with rheological parameters according to (De Schutter, 2008; Szwabowski et al., 2010)

Test	Measured feature, unit	Consistency class	Yield Value	Plastic Viscosity
Slump flow	Slump flow, mm	SF1 - 500 ÷ 650 mm SF2 - 660 ÷ 750 mm SF3 - 760 ÷ 850 mm	↘	-
	Time when the concrete has flowed to a diameter of 500 mm, s	VS1 - < 2 s VS2 - > 2 s	-	↗
V-funnel	Flow time, s	VF1 - < 8 s VF2 - > 9 ÷ 25 s	-	↗
L-box	Flow time needed to reach the 20 and 40 cm distance from outflow aperture, s	3 - 6 s	-	↗
	The passing ability ratio – ratio of heights at the bars to heights at box end	PA1 - ≥ 0,80 for 2 bars PA2 - ≥ 0,80 for 3 bars	-	

THE ASSUMPTIONS AND METHODOLOGY OF THE RESEARCH

The basic problem of the new generation concretes, including those containing lime fly ash, is their workability. From 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 is, the higher the velocity of flow at a given load. Issues related to rheology are more specifically discussed in the work (Szwabowski, 2010). 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 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 HCFA: batch (delivery) A and B (see Table 2);
• the degree of grinding of the HCFA (see Table 3);
• content of HCFA as cement equivalent: 10-20-30% mass of cement;

Table 2. Chemical composition of HCFA

	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 3. Physical properties of HCFA

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	-
			Batch B		
B0	Unground	2.60	46.3	240	1030
B1	Ground 15 min	2.67	20.8	350	-

The study was performed in three series of research:
C1 – study on the effect of HCFA dosage into SCC concrete,
C2 – study on the effect of HCFA dosage in cements (CEM I, CEM II / BM (LL-W), CEM II / BW, CEM IV / B-W) for SCC,
C3 - study on the effect of HCFA dosage into HPSCC concrete,
The composition of the self-compacting cement mixtures tested in each test block are presented in Table 4. The characteristics of the cement ground together with additives are included in the study block C2 are shown in Table 5. The research used superplasticizers based on polycarboxylen ether. A procedure for the preparation of concrete mixtures was developed and implemented which allowed for maintaining the technological reproducibility of the results. The sequence applied during the preparation of concrete mixtures in all blocks of research are presented in Figure 1.

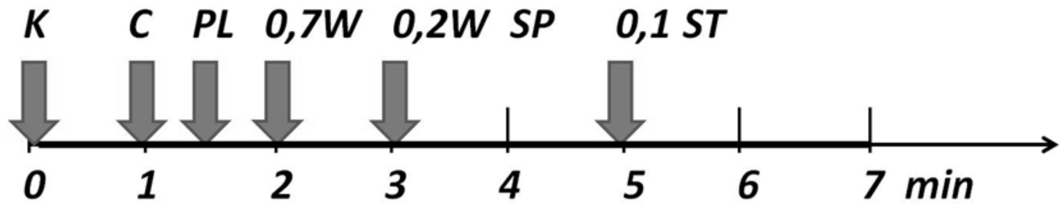

Figure 1. Procedure of mixing the concrete mixture constituents K – aggregate, C – cement, W – water, PL - HCFA, SP – superplasticizer, ST – stabilizer.

Table 4. Compositions of SCC mixtures used in particular research series

Constituent / Designation	Concrete Mixture		
	C1	C2	C3
		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	-
Sand 0-2 mm [S]	800,0	800,0	756,0
Natural aggregate 2-8 mm [Na]	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
Superplasticizer (3.5 % m.c.) [SP A]	-	-	17,0
Superplasticizer (1,1 - 2,5 % m.c.) [SP B]	16,2	6,8 – 15,0	-
Stabilizer RheoMatrix (0.4 % m.c.) [ST]	1,6	2,73	1,6
Sand equivalent (%)	50,0	50,0	45,8
W/C	0,42	0,31	0,42
Consistency class (SF)	SF3	SF 1-2-3	SF3

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

Table 5. 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
Flexural 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
Paste flow, cm		17.9	15.9	14.7	18.4

THE RESULTS AND DISCUSSION

STUDY ON THE EFFECT OF DOSAGE OF HCFA TO CONCRETE MIXTURE ON SCC

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

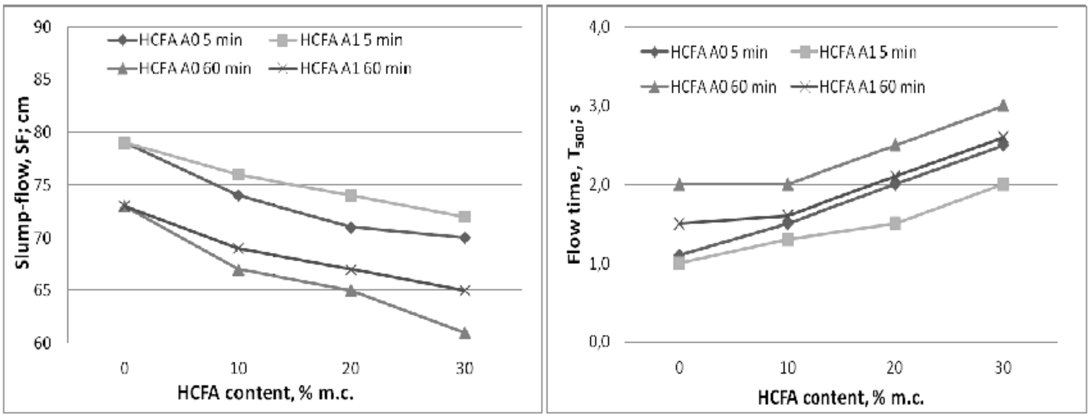

Figure 2. The influence of HCFA content and its fineness on flow diameter SF and flow time T_{500} of SCC mixture, including the effect of time

STUDY ON THE EFFECT OF DOSAGE OF HCFA TO CEMENT ON SCC

Figure 3 shows the influence that the type of cement with HCFA additive has on the diameter of SF propagation and on propagation time T_{500} for SCC mixtures of various self-compatibility classes. 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 SF propagation in SCC mixtures with its addition. Similar values of SF were observed for all tested cements in individual classes of self-compatibility of SCC mixtures. However, the increase in the content of lime fly ash in cement composition contributed to a rise in time of propagation T_{500} of SCC mixtures with its addition. The plastic viscosity of SCC mixtures increased, when the consistency class of compound of tested SCC was lower. The increase in the content of HCFA in cement composition also affected a decrease in compressive strength of SCC concrete with its addition in all classes of self-compatibility (Fig. 4).

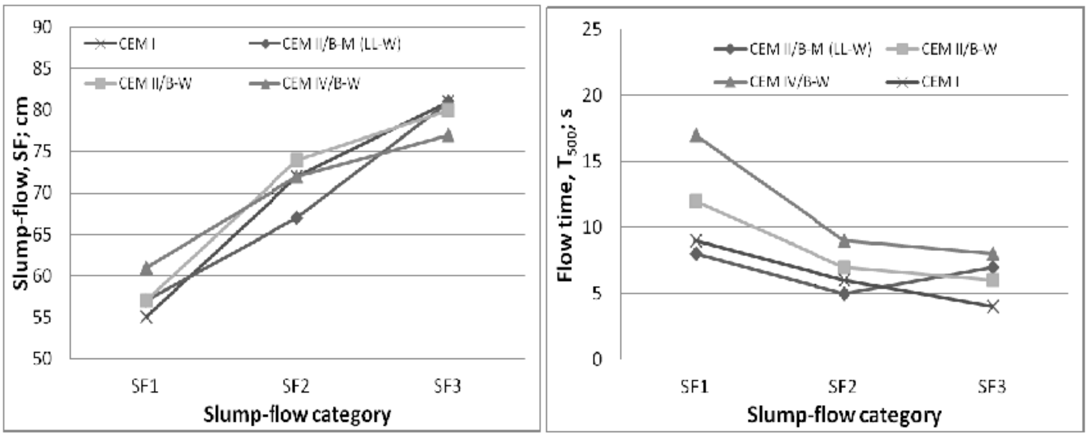

Figure 3. The influence of cement type with HCFA addition on flow diameter SF and flow time T_{500} of SCC mixture (C2) for different self-compacting classes

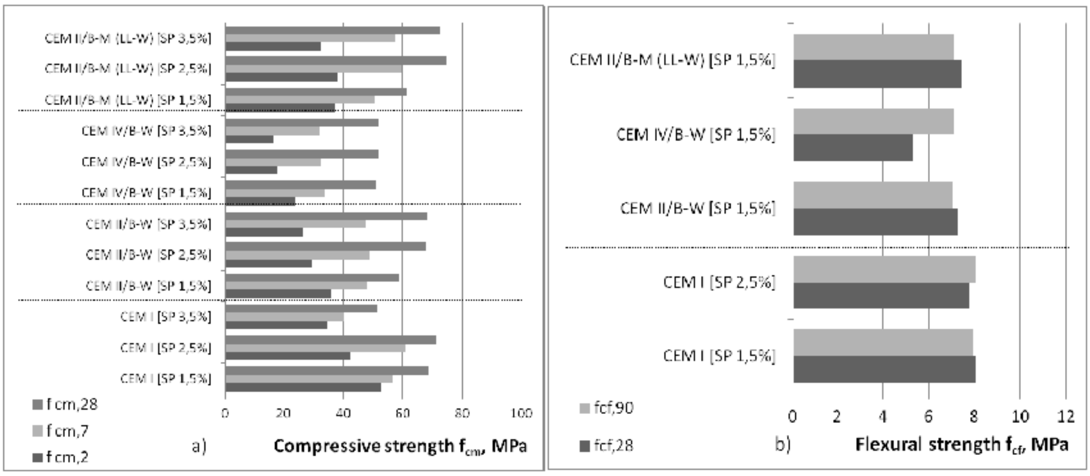

Figure 4. The influence of cement type with HCFA addition for different SP dosage on: a) compressive strength; b) tensile strength of SCC

STUDY ON THE EFFECT OF DOSAGE OF HCFA ON HPSCC CONCRETE

Figure 5 shows the effect of HCFA content (supply A) and the degree of milling they have on the diameter of SF propagation 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 SF propagation. Adding milled HCFA does not cause loss of workability of HPSCC mixture. An increase in the content of HCFA in the mixture contributed to the rise in time of propagation T_{500} in SCC mixtures with its addition, but not much.

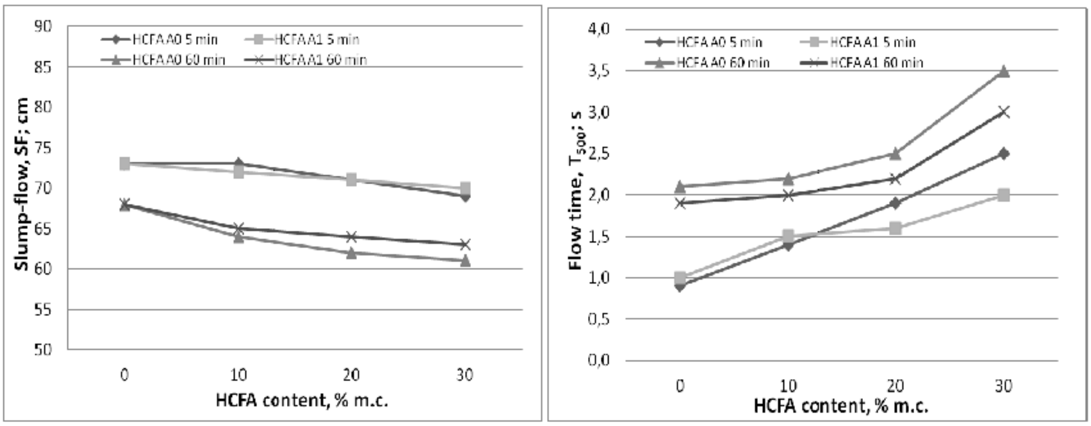

Figure 5. The influence of HCFA content (batch A) and its fineness on flow diameter SF and flow time T_{500} of HPSCC mixtures

A certain deterioration of workability but to a degree sufficient to maintain the properties of self-compatibility was also observed over time. Similar effects were observed in case of HCFA dosing (supply B) to HPSCC compound, shown in Figure 6. The increase in the content of lime fly ash in HPSCC concrete affects a decrease in their mechanical properties (Fig. 7). This effect is greater as the content of HCFA in concrete increases. Adding HCFA B1 also resulted in a decline in the value $f_{cm,28}$ of HPSCC concretewith its addition, but to the smallest degree.The effect of the HCFA modified cement being tested on the value of $f_{cm,2}$, $f_{cm,7}$, and $f_{cm,28}$ is small and with the increase in their volume ratio, it is almost the same values (Fig. 8a). In case of 28 and 90 days flexural strength of HPSCC concrete, content does not cause such problems andflexural strength value for tested HPSCC concrete decreased with HCFA in cement addition (Fig. 8b).

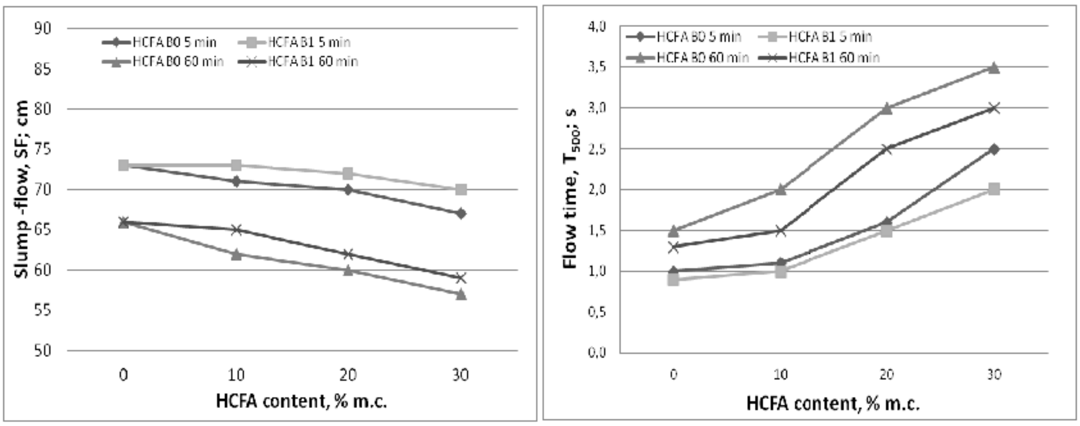

Figure 6. The influence of HCFA content (batch B) and its fineness on flow diameter SF and flow time T_{500} of HPSCC mixtures

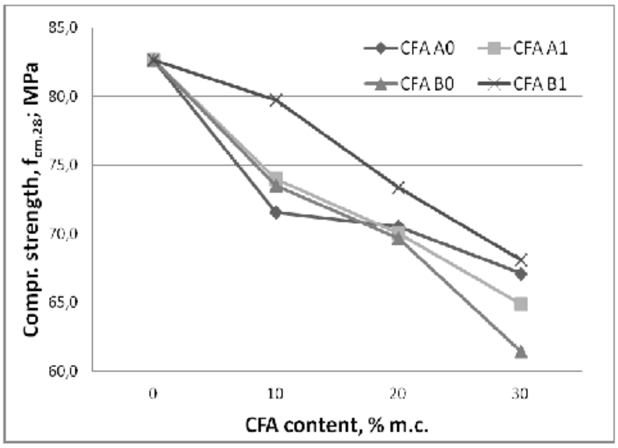

Figure 7. The influence of HCFA content and its fineness on compressive strength $f_{cm,28}$ of HPSCC

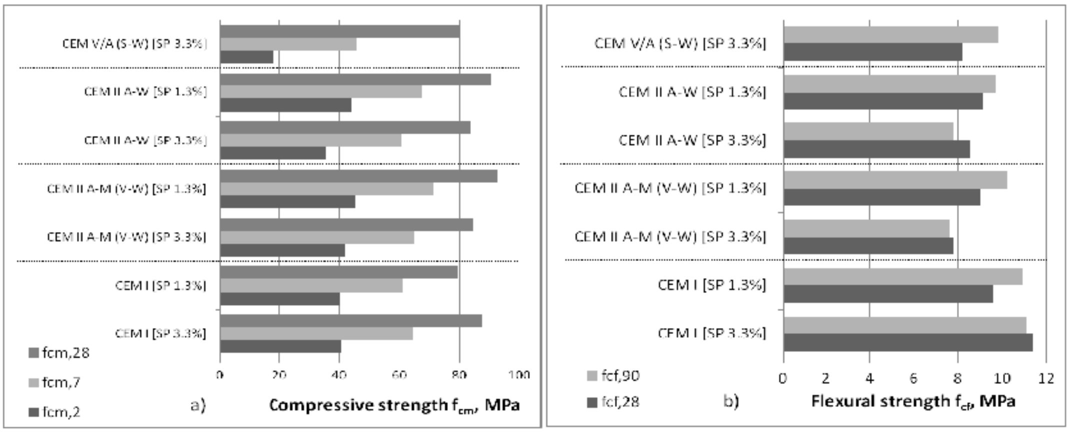

Figure 8. The influence of HCFA content and its fineness on:a) compressive strength and b) flexural strength of HPSCC

SUMMARY

Presented study confirmed the possibility for the use of HCFA in concretes of the next generation when maintaining the required parameters of concrete mixture 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 tested properties of concrete mixtures 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.When the addition of ash in concrete is bigger than 20%, the problem with enhanced workability loss in time might appear. During the research, with the adequately chosen, big dose of superplasticizer, mixtures with 30% addition of ash were obtained that meet the self-compaction requirements even after 60 min. While using the cement with high-calcium fly ash, problems with self-compacting properties are smaller and might occur if the amount of ash ion cement is higher than 30%. The research confirms, that treating the high – calcium fly ash by grinding or using it as a cement constituent, especially in multi-component cement, allows to reduce the negative influence of the ash on the flow of self-compacting mix. The compressive strength of concrete from cements modified with high – calcium fly ash and with the addition of the ash does not differ significantly from the analogue concretes from CEM I, if the classes of mentioned cements are comparable. In early stages of concrete maturing the presence of HCFA slows down the development of compressing strength.

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Acknowledgments

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