EFFECT OF MIXING TOLERANCES ON PERFORMANCE OF SELF-CONSOLIDATING CONCRETE (SCC)

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ABSTRACT

The objective of the paper is to present the effect of additions and admixtures on flowability and compressive strength of self-consolidating concrete. The fabrication of self- consolidating concrete requires a more rigorous quality control of materials and selection of the mixture at various stages of construction. The tests confirmed the importance of the superplasticizer quantity and compatibility between the cement and superplasticizer. It was found that the highest strength can be obtained for mixtures that satisfy the self-consolidating criterion. Increase or decrease of the slump flow beyond the accepted limits can cause a decrease of the compressive strength. This is due to poor compacting in case of reduced slump flows and segregation of components for excessive slump flows.

Keywords: Self-Consolidating Concrete, Self-Compacting Concrete, Cement, Superplasticizer**,** Silica Fume, Flowability, Passing Ability, Stability, Compressive Strength.

INTRODUCTION

Self-Compacting or Self-Consolidating Concrete (SCC) has been described as "the most revolutionary development in concrete construction for several decades". SCC can be used in precast applications or for concrete placed on site. In designing the mix, the size and the form of the structure, the dimension and density of reinforcement and cover should be taken into consideration. The development and use of self-consolidating concrete in many countries have shown that it can successfully be produced from a wide range of component materials but it is difficult and often impossible, to predict the resulting properties of the concrete[1,2,3].

There is an urgent need to develop design codes for the SCC. This concrete is very sensitive with regard to the proportions of the mix and quality of workmanship. Inaccuracies in proportions of ingredients, varying characteristics of the applied components, and varying curing conditions, can result in a failure to obtain the required properties of the SCC, i.e. its filling ability (flowability), its passing ability (free from being blocked by reinforcement) and its resistance to segregation (stability). Many different test methods have been developed in an attempt to specify the properties of SCC, but so far there is no single test available to measure all three properties.

The paper presents the results of tests performed for paste, mortar and concrete mixes with a constant content of the basic ingredients, i.e. binder, water and aggregate. The only differences were in the chemical composition of cement, and quantity and type of the superplasticizer.

MATERIALS

The tests were performed for concrete mixtures made using Portland cement CEM I 42.5 produced in three different cement plants (G, S and R). For all the mixtures, a superplasticizer and pozzolanic additives (fly ash and/or silica fume) were used. Material characteristics of these cements, fly ash and silica fume are listed in Table 1.

Table 1. Chemical analysis of the considered cements, fly ash and silica fume

Composition	**Portland Cement [%]**			**Fly Ash [%]**	**Silica Fume [%]**
	G	S	R		
SiO_2	20.9	19.6	22.1	53.0	94.0
CaO	64.7	64.4	65.2	3.3	0.00
Al_2O_3	5.1	6.2	4.8	28.0	0.64
Fe_2O_3	2.6	2.7	2.2	7.1	0.78
SO_3	3.0	2.9	3.2	0.4	0.70
MgO	1.2	1.7	2.4	2.5	0.38
Loss on ignition	0.7	1.2	1.0	1.0	0.70

Three different modified polycarboxylic ether superplasticizers were considered. The characteristics of the superplasticizers are shown in Table 2.

Table 2. Characteristics of the superplasticizers

Superplasticizer	Chemical description	Notation
Sika Visco Crete 3	Polycarboxylic ether	**Si**
Isola Polymer BV 10	Polycarboxylic ether	**B**
Addiment FM 34	Polycarboxylic ether	**F**

EXPERIMENTAL PROCEDURE

DESIGN OF THE PASTE COMPOSITION

The water to powder volume ratio has to be determined on the basis of paste and mortar flow cone test. Initially the water to powder ratio for zero flow (β_p) is determined in the paste, with the selected proportion of cement and additions. In this study, the flow cone tests were performed for the water/powder ratios of 1.1, 1.2, 1.3 and 1.4 (by volume), using one of the six selected powder compositions for each tested cement. Fig.1 shows the flow cone to determine the relative slump-flow for the paste, Γ_p, defined as

$$\Gamma_p = (r / r_o)^2 - 1 \qquad (1)$$

where r is the average diameter of the spread circle, $r = 0.5\ (r_1 + r_2)$, r_1 and r_2 are the spread circle diameters measured in two perpendicular directions, and $r_o = 100$ mm (4 in).

The powder compositions and the test results for cement G are shown in Table 3.

The test results for six powder compositions are shown in Fig. 2. For each series of tests, the relationship between the water/powder ratio and Γ_p is modelled using the linear regression analysis. The resulting straight lines are described by equations that are also shown in Fig. 2, with y representing the water/powder ratio, and x representing Γ_p. The water-powder ratio corresponding to $\Gamma_p = 0$ is designated by β_p.

Table 3. Results of Paste Flow Cone Test for Cement G

Powder composition	w/p	r[cm]	r[inch]	$\Gamma_p = (r/r_o)^2 - 1$
MIX 1 Cement G - 260 kg/m^3 (16.2 pcf) Fly Ash – 300 kg/m^3(18.7 pcf) Silica Fume ----	1.1	24.75	9.74	5.1
	1.2	29.9	11.77	7.9
	1.3	31.15	12.26	8.7
	1.4	36.6	14.41	12.4
MIX 2 Cement G - 300 kg/m^3(18.7 pcf) Fly Ash –260 kg/m^3(16.2 pcf) Silica Fume ----	1.1	15.05	5.93	1.3
	1.2	21.9	8.62	3.8
	1.3	22.95	9.04	4.3
	1.4	32.3	12.71	9.4
MIX 3 Cement G - 360 kg/m^3(22.5 pcf) Fly Ash –200 kg/m^3(12.5pcf) Silica Fume ----	1.1	13.8	5.43	0.9
	1.2	23.85	9.39	4.7
	1.3	24.95	9.82	5.2
	1.4	26.4	10.39	6.0
MIX 4 Cement G - 400 kg/m^3(25.0 pcf) Fly Ash –160 kg/m^3(10.0 pcf) Silica Fume ----	1.1	18.65	7.34	2.5
	1.2	20.0	7.87	3.0
	1.3	27.9	10.98	6.8
	1.4	31.0	12.20	8.6
MIX 5 Cement G - 450 kg/m^3(28.1 pcf) Fly Ash – 110 kg/m^3(6.9 pcf) Silica Fume ----	1.1	13.4	5..28	0.8
	1.2	21.95	8.64	3.8
	1.3	26.45	10.41	6.0
	1.4	27.75	10.93	6.7
MIX 6 Cement G - 360 kg/m^3(22.5 pcf) Fly Ash – 164 kg/m^3(10.2 pcf) Silica Fume - 36 kg/m^3(2.25 pcf)	1.1	11.3	4.45	0.3
	1.2	12.7	5.00	0.6
	1.3	14.3	5.63	1.0
	1.4	19.3	7.59	2.7

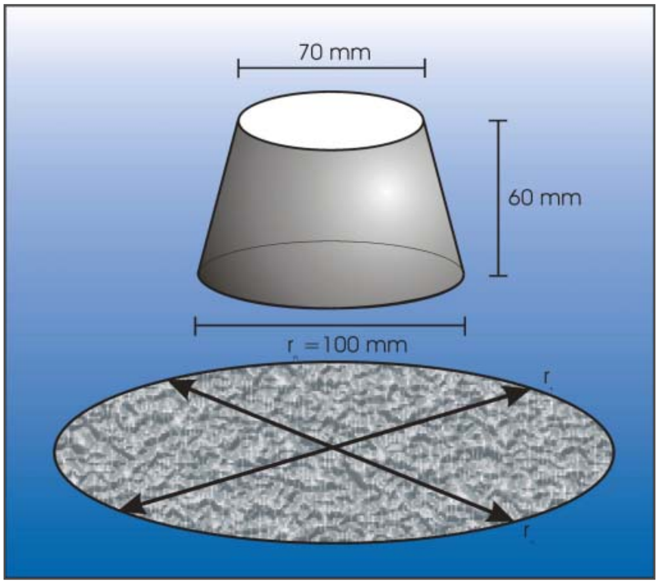


Fig.1. Paste (Mortar) Flow Cone Test

DETERMINATION OF THE MORTAR COMPOSITION

The optimum volumetric water/powder ratio and superplasticizer dosage are determined by tests using flow cone and V-Funnel. The considered water/powder ratios are in the range of $(0.8 - 0.9)\beta_p$, with varying dosages of the superplasticizer. Fig. 3 shows V-Funnel used for the mortar test.

Test results for selected mixtures (Mix 1, Mix 3, Mix 5 and Mix 6) with a constant amount of water but different amount and type of the superplasticizer are presented in Table 4. The relative slump flow for the mortar, Γ_m, is defined as

$$\Gamma_m = (r / r_o)^2 - 1 \qquad (2)$$

where r is the average diameter of the spread circle, $r = 0.5\ (r_1 + r_2)$, r_1 and r_2 are the spread circle diameters measured in two perpendicular directions, and r_o = 100 mm (4 in). The parameter R_m is defined as

$$R_m = 10/t \qquad (3)$$

where t is the flow time (sec). The resulting values of Γ_m and R_m are also listed in Table 4.

Target values for the slump-flow are from 24 to 26 cm (9.5 to 10.5 in), corresponding to $\Gamma_m = 5$, and for V-funnel tests the flow time from 7 to 11 seconds, corresponding to $R_m = 1$. The mortars with the best filling abilities are marked by a bold print.

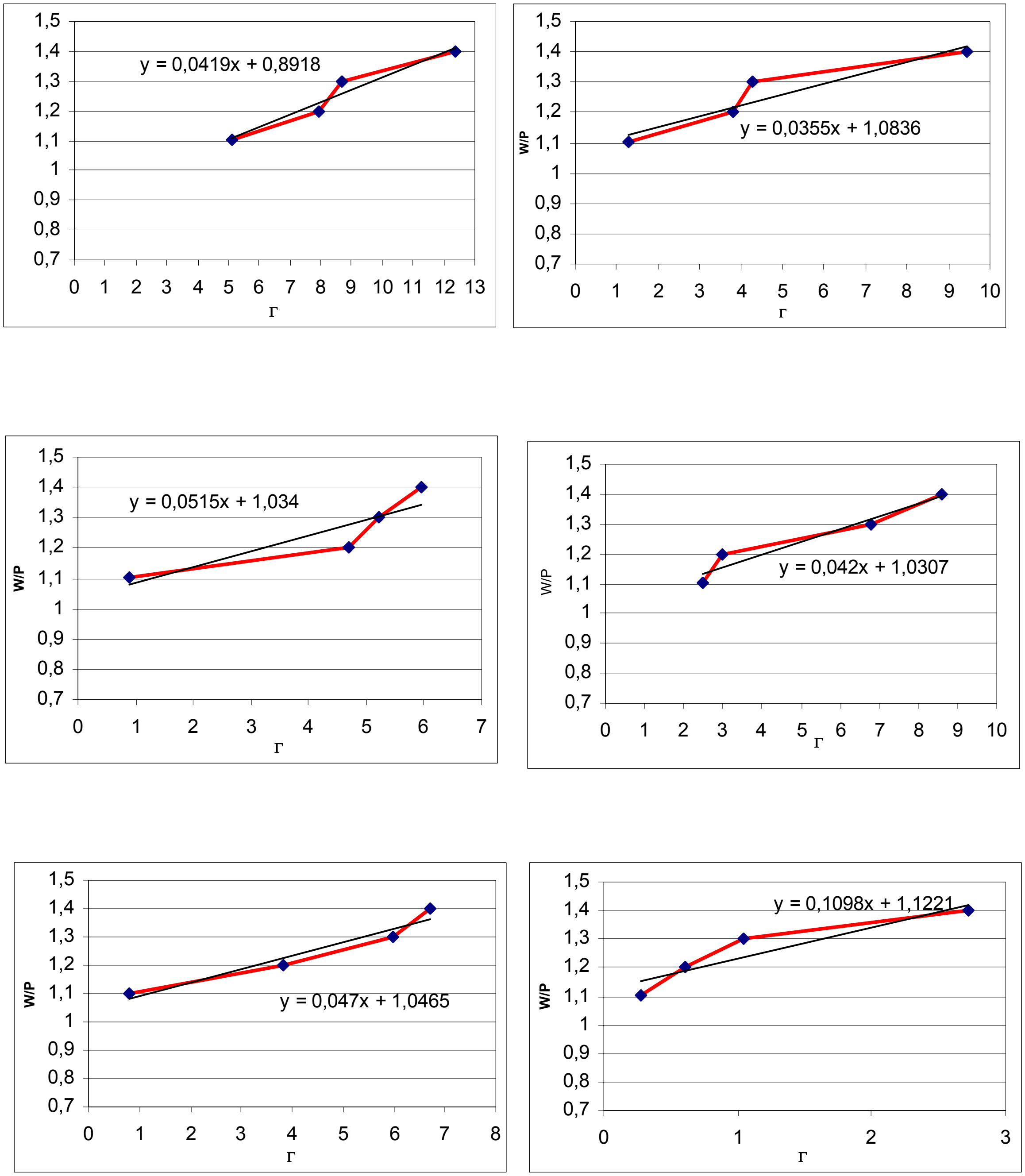


Fig.2. Relationship between the Water/Powder Ratio and Γ_p

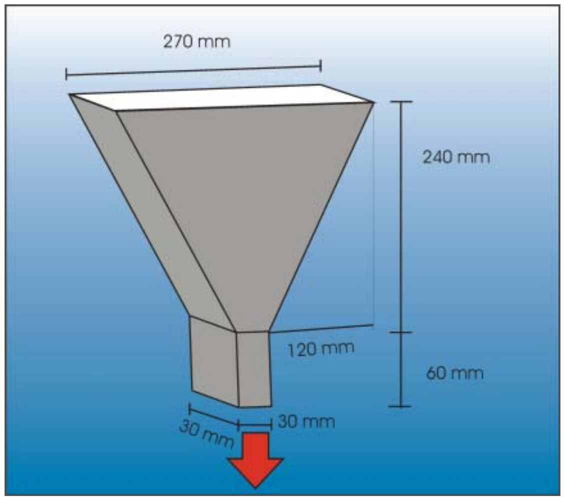


Fig.3. V- Funnel for the Flow Time Test of the Mortar

Table 4. Slump-Flow and V-Funnel Test Results for Mortar

Mixture	**Superplasticizer**		**r [cm]**	**r [inch]**	**t [sec]**	**Γ_m**	**R_m**
	type	**% of cement mass**					
G1	B	1.2	28.3	11.14	8.56	6.98	1.17
G1	**B**	**1.1**	**25.4**	**10.0**	**9.57**	**5.43**	**1.04**
G1	B	1.	22.4	8.82	12.55	4.00	0.80
G3	B	1	33.3	13.11	5.68	10.09	1.76
G3	**B**	**0.8**	**26.75**	**10.53**	**8.2**	**6.16**	**1.22**
G3	B	0.7	20.5	8.07	9.64	3.16	1.04
G5	B	1	34.35	13.52	6.7	10.8	1.49
G5	B	0.7	30.45	11.99	7.53	8.27	1.33
G5	**B**	**0.6**	**23.15**	**9.11**	**8.38**	**4.36**	**1.19**
G6	**B**	**1**	**24.95**	**9.82**	**7.69**	**5.23**	**1.30**
G1	**Si**	**1.5**	**25.8**	**10.16**	**10.2**	**5.66**	**0.98**
G3	Si	1.2	26.65	10.49	9.24	6.10	1.08
G3	**Si**	**1.1**	**24.1**	**9.49**	**10.16**	**4.81**	**0.98**
G3	Si	1	15.7	6.18	13.28	1.46	0.75
G5	Si	1	27.55	10.85	9.57	6.59	1 04
G5	**Si**	**0.9**	**25.5**	**10.04**	**9.13**	**5.5**	**1.1**
G5	Si	0.8	17.25	6.79	12.82	1.98	0.78
G6	**Si**	**1.2**	**25.9**	**10.19**	**7.56**	**5.71**	**1.32**
G6	Si	1	15.15	5.96	16.28	1.3	0.61

TEST OF CONCRETE

The determination of the mix proportion for the SCC involves the following basic steps:

- determination of air content,
- determination of coarse aggregate volume,
- determination of fine aggregate volume,
- determination of water to powder volume ratio,
- determination of superplasticizer dosage.

In the paper, the test results are presented for selected concrete mixtures (Mix. 3 without silica fume and Mix. 6 with silica fume). The same amount of cement (c = 360 kg/m^3, 22.5 pcf), water (w = 150 l/m^3, 9.4 pcf), binder (b = 560 kg/m^3, 35 pcf), sand (755 kg/m^3, 47 pcf) and gravel (924 kg/m^3, 58 pcf) were used in all concrete mixtures. A constant water-cement ratio (w/c = 0.42) and water/binder ratio (w/b = 0.27) were applied.

The study focused on the filling ability and the compressive strength of concrete. The slump flow test was performed using a slump cone. It is the most commonly used test, and it gives a good assessment of the filling ability and it may also serve as an indication of resistance to segregation. The time was measured for the concrete to reach a 500 mm spread circle (denoted by T_{50cm}). The final diameter of the concrete spread circle was measured in two perpendicular directions (the average value is the slump-flow in mm). Typical range of values for slump-flow for SCC is from 65 cm to 80 cm (26 to 32 in) and for T_{50cm} from 2 to 5 sec[4,5]. All the measurements of spread circle were performed within 10, 40 and 70 minutes after mixing concrete.

The concrete compressive strength was determined after 3, 7 and 28 days of curing. Identification and proportions of the concrete mixtures and results of compressive strength are given in Table 5.

ANALYSIS OF THE RESULTS

In the study, the following parameters were considered:

- Type of Portland cement, cement came from three different sources: G, S, R
- Type of superplasticizer, three superplasticizers were considered: Si, B, F
- Amount of superplasticizer: from 0.5% to 2.0 % of the binder mass
- Addition of silica fume: 10% of cement mass

EFFECT OF TYPE OF PORTLAND CEMENT

Comparison of the test results for the slump flow test for different types of Portland cement are presented in Fig.4 separately for different superplasticizers. The study showed that even for the same proportions of ingredients, the type of cement has a considerable effect on the slump flow and duration time for the SCC properties. After 70 minutes, some of the mixtures lost its free flow properties required for SCC. This is caused by non-compatibility problems between the cement and superplasticizer.

Table 5a. Mixture Proportions and the Compressive Strength of Concrete, f_c' (SI)

Mix (*C/SP/SF*)	Binder [kg/m^3]			Super-plasticizer [%]	Compressive Strength [MPa]		
	Cement	Fly Ash	Silica Fume		3 days	7 days	28 days
G/B1.0	360	200	-	1	32.5	41.5	89.9
G/B1.2	360	200	-	1.2	26.4	44.4	88.3
G/B1.2/M	360	164	36	1.2	30.2	50.1	76.7
G/B1.5	360	200	-	1.5	2.88	43.1	87.9
G/B2.0	360	200	-	2	-	51.1	69.4
G/Si1.0	360	200	-	1	-	50.7	60.0
G/Si1.5	360	200	-	1.5	-	42.0	68.3
G/Si2.0	360	200	-	2	-	51.6	64.7
G/F0.8	360	200	-	0.8	32.1	46,8	83.6
G/F1.0	360	200	-	1	25.7	48.4	84.3
G/F1.0/M	360	164	36	1	38.5	56.5	83.8
S/B1.0	360	200	-	1	33.7	39.2	72.1
S/B1.0/M	360	164	36	1	33.8	58.7	79.3
S/B1.2	360	200	-	1.2	30.3	37.4	65.9
S/B1.2/M	360	164	36	1.2	34.7	40.5	74.5
S/B1.5	360	200	-	1.5	41.0	41.9	77.7
S/B1.5/M	360	164	36	1.5	32.3	47.3	81.3
S/Si1.0	360	200	-	1	30.5	48.4	78.7
S/Si1.5	360	200	-	1.5	27.5	38.4	64.9
S/F0.8	360	200	-	0.8	27.5	39.8	73.2
S/F1,0	360	200	-	1	15.3	21.2	38.1
S/F1.0/M	360	164	36	1	26.3	35.4	61.6
R/B0.5	360	200	-	0.5	23.3	23.6	61.6
R/B0,8	360	200	-	0.8	21.2	26.9	67.4
R/B1.0	360	200	-	1	22.3	46.2	61.7
R/B1.0/M	360	164	36	1	23.1	32.2	54.7
R/Si0.8	360	200	-	0.8	0.9	32.3	65.5
R/Si1.0/M	360	164	36	1	14.0	30.2	61.8
R/Si 1.2	360	200	-	1.2	-	29.0	64.1

Table 5b. Mixture Proportions and the Compressive Strength of Concrete, f_c' (US)

Mix (*C/SP/SF*)	Binder [pcf]			Super-plasticizer [%]	Compressive Strength [ksi]		
	Cement	Fly Ash	Silica Fume		3 days	7 days	28 days
G/B1.0	22.47	12.49	-	1	4.71	6.02	13.04
G/B1.2	22.47	12.49	-	1.2	3.83	6.44	12.81
G/B1.2/M	22.47	10.24	2.25	1.2	4.38	7.27	11.12
G/B1.5	22.47	12.49	-	1.5	0.42	6.25	12.75
G/B2.0	22.47	12.49	-	2	-	7.41	10.07
G/Si1.0	22.47	12.49	-	1	-	7.35	8.70
G/Si1.5	22.47	12.49	-	1.5	-	6.09	9.91
G/Si2.0	22.47	12.49	-	2	-	7.48	9.38
G/F0.8	22.47	12.49	-	0.8	4.66	-	12.13
G/F1.0	22.47	12.49	-	1	3.73	7.02	12.23
G/F1.0/M	22.47	10.24	2.25	1	5.58	8.19	12.15
S/B1.0	22.47	12.49	-	1	4.89	5.69	10.46
S/B1.0/M	22.47	10.24	2.25	1	4.90	8.51	11.50
S/B1.2	22.47	12.49	-	1.2	4.39	5.42	9.56
S/B1.2/M	22.47	10.24	2.25	1.2	5.03	5.87	10.81
S/B1.5	22.47	12.49	-	1.5	5.95	6.08	11.27
S/B1.5/M	22.47	10.24	2.25	1.5	4.68	6.86	11.79
S/Si1.0	22.47	12.49	-	1	4.42	7.02	11.41
S/Si1.5	22.47	12.49	-	1.5	3.99	5.57	9.41
S/F0.8	22.47	12.49	-	0.8	3.99	5.77	10.62
S/F1,0	22.47	12.49	-	1	2.22	3.07	5.53
S/F1.0/M	22.47	10.24	2.25	1	3.81	5.13	8.93
R/B0.5	22.47	12.49	-	0.5	3.38	3.42	8.93
R/B0,8	22.47	12.49	-	0.8	3.07	3.90	9.78
R/B1.0	22.47	12.49	-	1	3.23	6.70	8.95
R/B1.0/M	22.47	10.24	2.25	1	3.35	4.67	7.93
R/Si0.8	22.47	12.49	-	0.8	0.13	4.68	9.50
R/Si1.0/M	22.47	10.24	2.25	1	2.03	4.38	8.96
R/Si 1.2	22.47	12.49	-	1.2	-	4.21	9.30

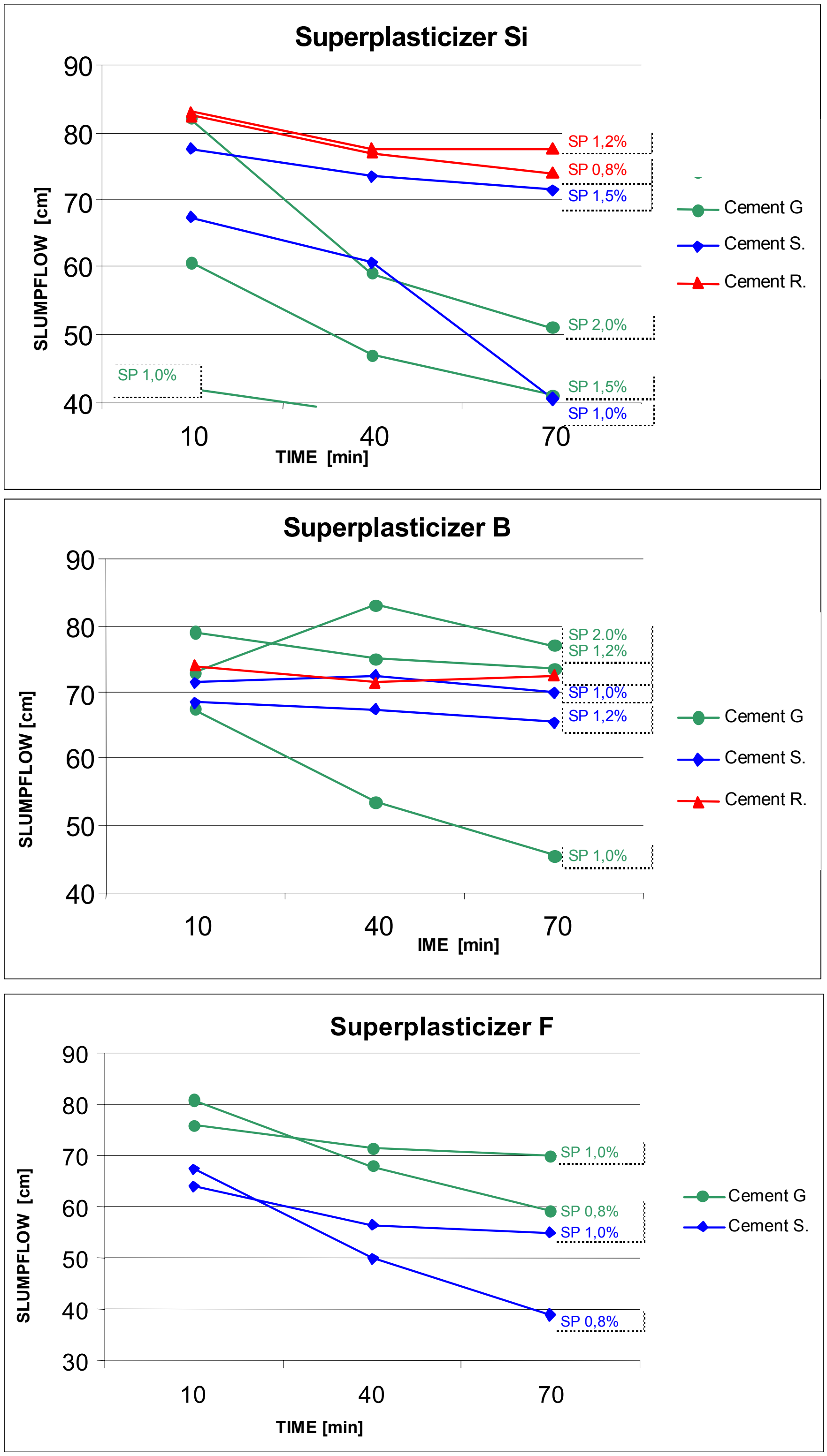


Fig.4. Test Results for Slump-Flow of Concrete for Different Types of Portland Cement

EFFECT OF TYPE OF THE SUPERPLASTICIZER

In the selection of the mixture content for the self-consolidating concrete, it is very important to select the most suitable superplasticizer for given cement. For the considered cements and mixtures, the resulting relationships between the slump flow and time are shown in Fig. 5.

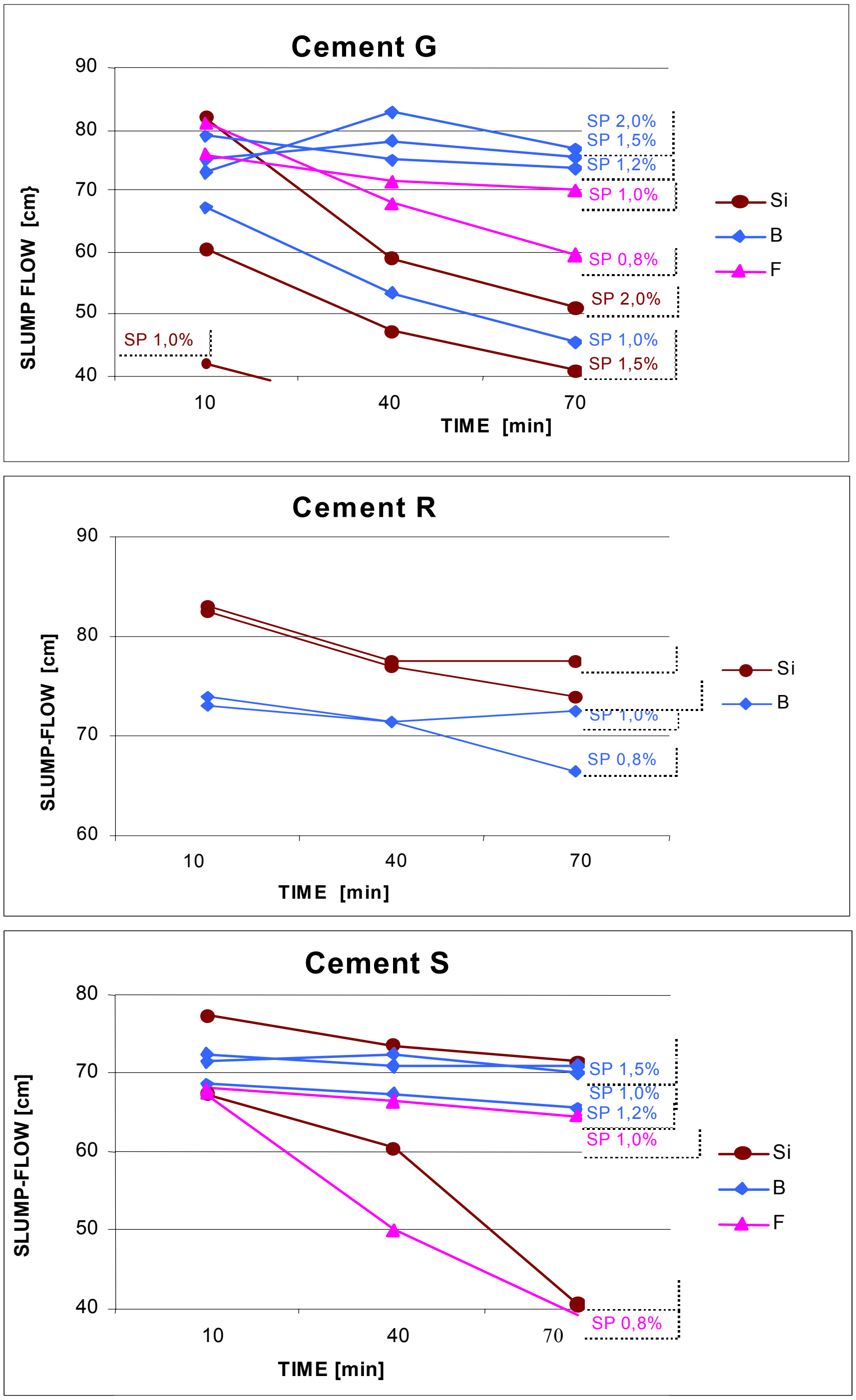


Fig.5. Comparison of the Slump-Flow Test Results for the Three Considered Cements

In addition, the considered mixtures were checked with regard to sedimentation and segregation. The best results were obtained for the following combinations of ingredients: Cement G – superplasticizer B, cement S – superplasticizer B, and cement R – superplasticizer Si.

EFFECT OF AMOUNT OF SUPERPLASTICIZER

The selection criterion for the optimum quantity of the superplasticizer was maximization of the slump flow without segregation. In Fig. 6, 7 and 8, the effect of small changes in superplasticizer's quantity on slump flow is compared for the considered cements. The maximum percentage of the superplasticizer was 2% of the binder mass, and the minimum percentage was 0.5% of the binder mass.

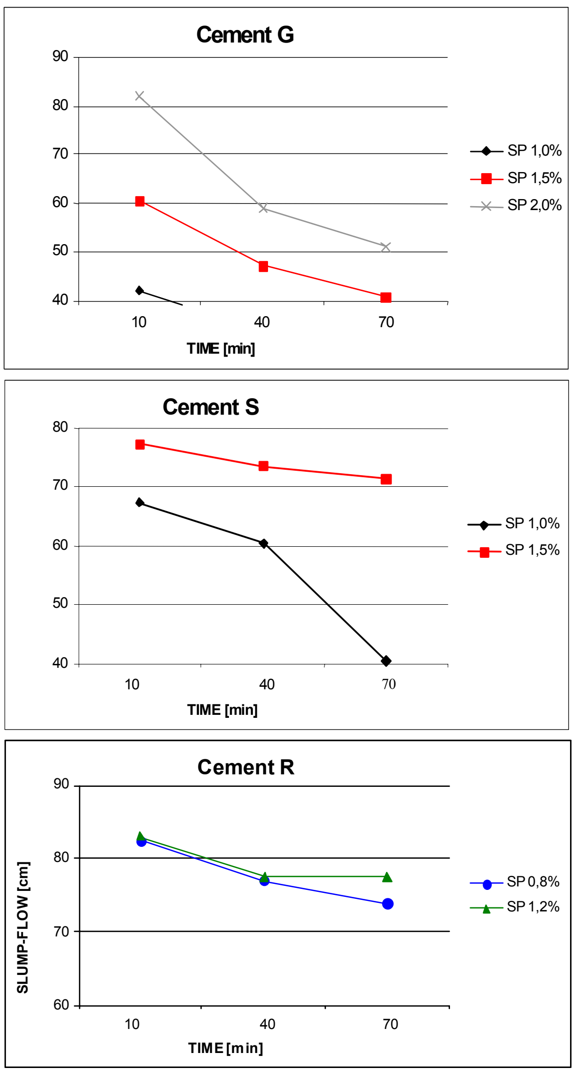


Fig. 6. Slump-Flow in Mixtures with Superplasticizer Si

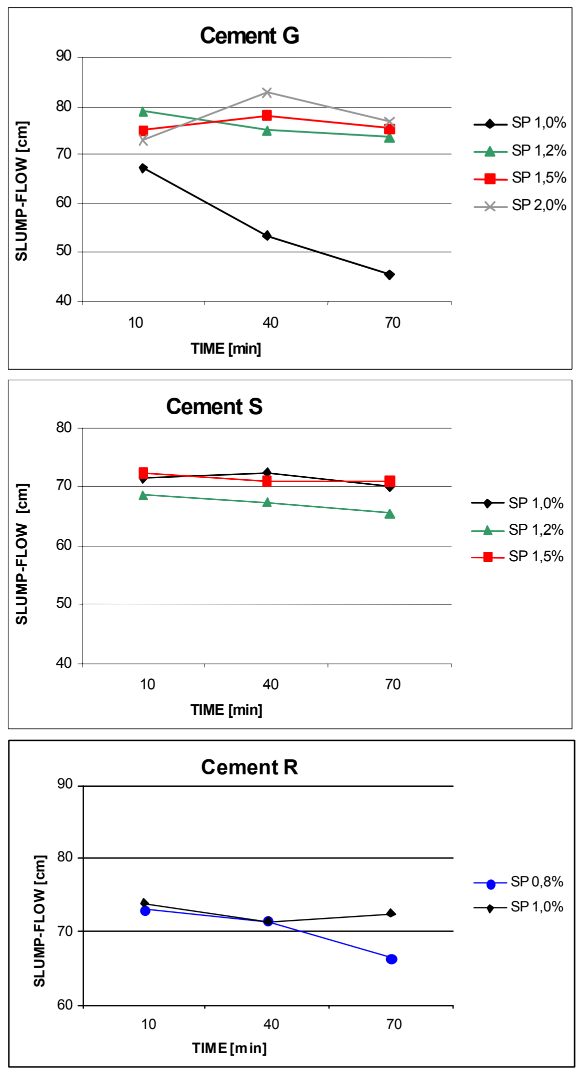
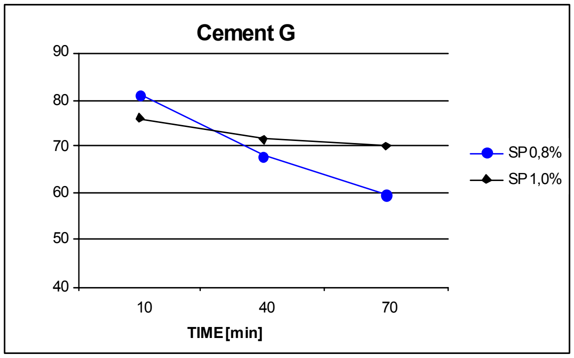


Fig. 7. Slump-Flow in Mixtures with Superplasticizer B



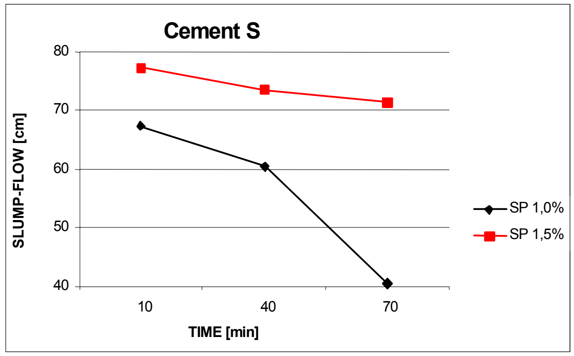


Fig.8. Slump-Flow in Mixtures with Superplasticizer F

EFFECT OF ADDITION OF THE SILICA FUME

Silica fume was added in the amount of 10 % of the cement mass and it replaced the same amount of fly ash in the considered mixtures. The comparison of test results for mixtures with addition of silica fume and without silica fume for one of the superplasticizers is shown in Fig.9 and Fig.10.

The tests showed that replacement of the fly ash with silica fume results in a reduction of the slump flow for the mixture with the same amount of the superplasticizer. It also causes an increase of the early age strength in comparison with the mixtures without silica fume.

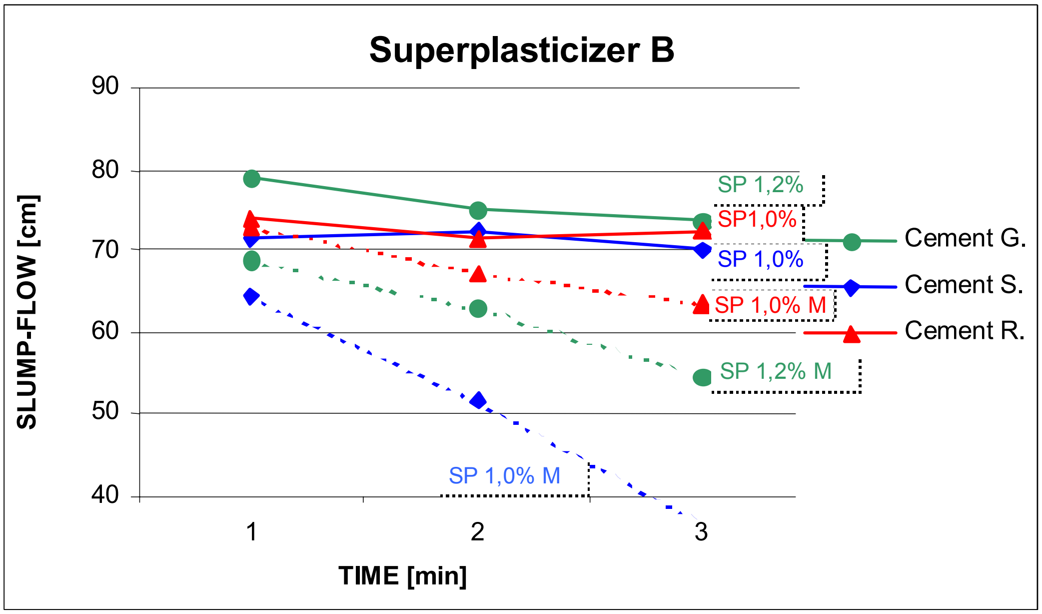


Fig. 9. Comparison of the Slump-Flow Test Results for Mixtures with Addition of Silica Fume (designated with M) and without Silica Fume

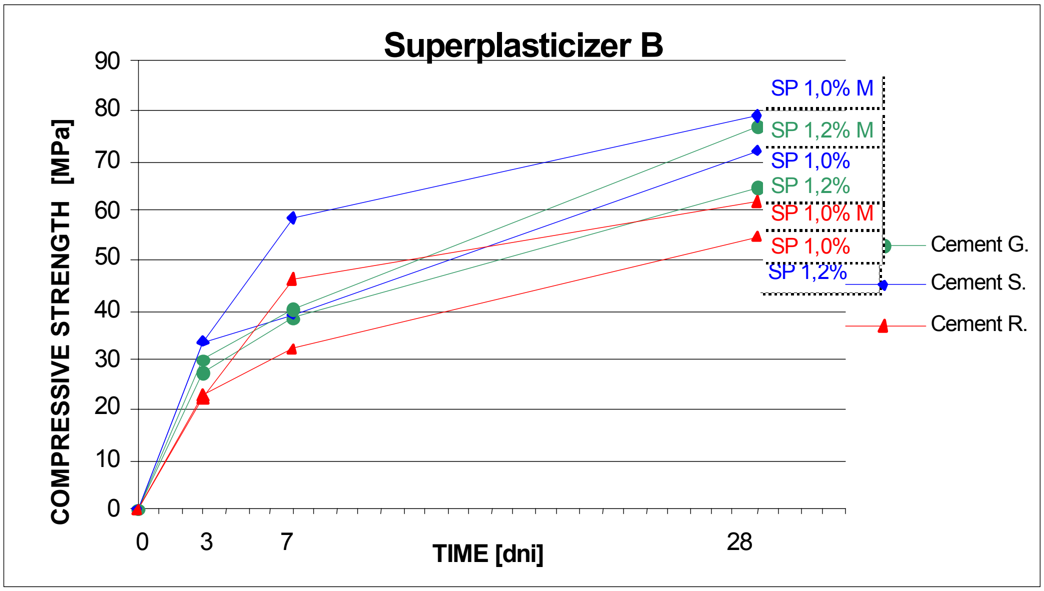


Fig. 10. Comparison of Compressive Strength Test Results for Mixtures with Addition of Silica Fume (designated with M) and without Silica Fume

CONCLUSIONS

The fabrication of self-consolidating concrete requires a more rigorous quality control of materials and selection of the mixture at various stages of construction. The tests carried out as a part of this study showed that the slump flow is from 40.5 to 83.0 cm (16 to 33 in), depending on the composition of the mixture. The optimum range for self consolidating concrete is from 65 cm to 80 cm (26 to 32 in).

It was found that the highest strength can be obtained for mixtures that satisfy the self-consolidating criterion. Increase or decrease of the slump flow beyond the accepted limits can cause a decrease of the compressive strength. This is due to poor compacting in case of reduced slump flows and segregation of components for excessive slump flows.

The best properties were obtained for the following mixtures:

- **R**/Si0.8 (cement R, superplasticizer Si) – slump-flow after 70 minutes of 74 cm (30 in) and compressive strength after 28 days of 65.5 MPa (9.4 ksi),
- **G**/F1.0 (cement G and superplasticizer F) – slump-flow after 70 minutes of 70 cm (28 in) and compressive strength after 28 days of 84.3 MPa (12.0 ksi),
- **G**/F1.0/M (cement G, superplasticizer Si and Silica Fume) – slump-flow after 70 minutes of 64 cm (26 in), compressive strength after 28 days of 83.8 MPa (12.0 ksi).

The tests confirmed the importance of the superplasticizer quantity and compatibility between the cement and the superplasticizer.

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REFERENCES

1. P. Billberg, "Mix design Model for Self-Compacting Concrete", Conference Proceedings of First North American Conference on the Design and Use of Self-Consolidating Concrete, 2003.
2. Van K. Bui, Surendra P. Shah, Yilmaz Akkaya, "A new Approach in Mix Design of self-Consolidating Concrete, Proceedings of First North American Conference on the Design and Use of Self-Consolidating Concrete, 2003.
3. Hajime Okamura, Kazumasa Ozawa, "Self-Compacting High Performance Concrete" *Structural Engineering International 4/96*
4. Specification and Guidelines for Self-Compacting Concrete, EFNARC, 2002.
5. Kazanori Takada, Galia I. Pelova, Joost C. Walraven, "Development of Self-Compacting Concrete in the Netherlands"- 1998,