Assessment of the fresh self-compacting concrete properties utilizing different types of additives

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Abstract

Self-compacting concrete (SCC) is characterized by unique workability properties. Stagnation or segregation of SCC must be avoided to obtain a homogenous and stable mixture. When SCC is produced, it is essential that the concrete has all the adequate fresh properties at the time of placement. For a successful and reliable application of SCC, the predication of SCC fresh state properties is of crucial importance. This predictability is determined by the sensitivity of the rheological properties towards the affecting parameters in the mixture composition. Experimental work was conducted to clarify the effects of the volumetric water to powder ratio and additives on the behavior of SCC from the rheological point of view. Therefore, the aim of this paper is to analyze the effect of different types of additives and paste contents on the fresh state response of SCC; powder type. It was found that the additives can greatly influence the concrete workability. Along that, an extension of the workability window of SCC is updated according to the acceptance criterion for.

Keywords: Self-compacting concrete; Fresh properties; Sustainability; Additives

Kulcsszavak: Öntömörödő beton; Frissbeton jellemzők; Fenntarthatóság; Kiegészítő anyagok

1. Introduction

Self-compacting concrete (SCC) was developed to meet the durability requirements of concrete structures and tackle the casting difficulties in challenging geometries [1].

The primary fresh properties of SCC have been the filling ability, passing ability and segregation resistance. These properties must be taken into consideration in the design phase of SCC. The essential rheological properties of SCC have been based on low yield stress, moderate viscosity and retention of the kinetic energy of the flowable mixture by reducing the content of coarse aggregates. These measures have been required to reach the targeted filling ability, viscosity and segregation resistance. A low yield stress is achieved by the use of adequate dosages of superplasticizer. The flow characteristics are further modified by changing the aggregate volume fraction, coarse-to-fine aggregate volume, and the composition of the other ingredients. The viscosity has been controlled by the contents of the free water, superplasticizer, and the volume fraction of the solids in the mixture. The basic strategies for ensuring a moderate viscosity are based on either inclusion of high amounts of powder materials; i.e. total content of cementitious materials (referred to as powder type SCC) or addition of viscosity modifier agents (referred to as VMA type SCC) [2-5].

The filling ability is a fresh property of SCC that permits it to flow into the formwork under self-weight, and without vibration or any other means of consolidation. SCC filling ability is controlled through its rheological parameters such as the yield stress and the plastic viscosity. In general, high range water reducing admixture (HRWRA) improves the filling

ability of SCC by reducing the yield stress and plastic viscosity. On the other hand, extreme dosages of HRWRA could result in very high fluidity that may cause concrete segregation. The use of additives is a great alternative to improve the segregation resistance. Therefore, the stability of the mixture could be maintained along with a good filling ability. Additives such as ground granulated blast-furnace slag, metakaolin (MK), silica fume (SF), fly ash and others have been used to produce SCC with a good filling ability [4-7].

Passing ability has been defined as the ability of fresh SCC to flow through small openings and fill the spaces within the reinforcements. In case of heavily reinforced structures, an adequate passing ability of SCC enables it to be placed and consolidated through dense reinforcing bars without any aggregate blockage [4]. The filling and passing ability have been directly connected. Also, the passing ability is affected by the number and spacing of the reinforcing bars. A good passing ability can be achieved by increasing the filling ability of fresh concrete and by limiting the segregation of coarse aggregates. Table 1 summarizes the slump flow classes according to EFNARC recommendations and European standards [4, 7].

Slump flow classes	Mean slump flow diameter (mm)
SF1	550 – 650
SF2	660 – 750
SF3	760 – 850

Table 1. Slump flow classes [4, 7]

1. táblázat Roskadási területi osztályok [4, 7]

The segregation resistance of SCC has been defined as its ability to remain uniform during and after placement without any loss of stability due to bleeding, mortar separation and coarse aggregate settlement [2, 4]. In particular, the distortion of aggregates becomes non-uniform if SCC did not have the necessary segregation resistance. A good segregation resistance of SCC could be obtained by the proper selection of material constituents and fractions. SCC with good segregation resistance quality is characterized by a high amount of powder material, a limited content of well-graded coarse aggregates, a small nominal maximum size of aggregate, and a low water to binder ratio [2,3]. Also, a viscosity modifying agent could assist in the segregation resistance of SCC. The characterization of the viscosity of SCC could be determined using the V-funnel time test. The test procedure has been clearly described in EFNARC guidelines [4].

Since there has been a large amount of recommendations and guidelines in the literature. Table 2 and 3 help to summarize the viscosity classes (VF).

Viscosity class	V-funnel time (s)
VF1	≤ 8
VF2	9 – 25

Table 2. Viscosity classification for V-funnel time test [4, 7]
2. táblázat Viskozitási osztályok töltésrés kifolyási vizsgálat alapján [4, 7]

References	Recommended V-funnel time (s)
BRL 1801 recommendations [8]	9-25
EFNARC guidelines [5]	6-12
Domone [9]	3-15

Table 3. Recommendation for V-funnel time by several authors
3. táblázat Töltésrés kifolyási idő javaslatok különböző szakirodalmi forrásokban

During the development of the mixture composition of SCC, the optimum workability ranges were established for the fresh state. Fig. 1 illustrates the workability ranges as suggested by DAfStb [10]. This could help to limit the targeted values based on the upper and lower limits of the slump flow and for the V-funnel flow time.

Fig. 1. Processing window for SCC as suggested by DAfStb [10]
1. ábra DAfStb [10] javaslat öntőmördő beton optimális reológiai jellemzőire

2. Experimental work

2.1 Materials, mix design and testing methods

A total of seventy-two SCC mixtures were designed and placed with common constant and variable parameters to

obtain an objective evaluation between the fresh properties. Local natural quartz river sand and gravel with a maximum nominal size of 16 mm were used in the mixtures. Blast furnace slag cement CEM III/A 32.5 R (C) with a compressive strength grade of 32.5 MPa and a clinker content in the range of 41–58 wt% was applied for the present study. MK and SF were the supplementary cementitious materials (SCMs) implemented separately to enrich the mechanical properties. Waste perlite powder (WPP) originating from raw perlite rock was used as a filler material for SCC. Two types of WPP, which mainly differed in terms of their specific surface areas (WPP-C and WPP-SZ), were generated from cutting the raw perlite rock and applied with the following content (75% WPP-C and 25% WPP-SZ). Limestone powder (LP) was the non-pozzolanic filler applied in this study. The physical and chemical compositions of the mentioned fine materials are shown in Table 4, and grading fractions are provided in Fig. 2. A HRWRA, Sika Viscocrete 5, was used and adjusted to keep an SF3 slump flow class in a range of 740-850 mm [7].

Fig. 2. Particle size distribution of the cement (C), metakaolin (MK), silica fume (SF), limestone powder (LP), waste perlite powder (WPP-C) and waste perlite powder (WPP-SZ)

2. ábra Szemeloszlási görbék; cement (C), metakaolin (MK), szilikapó (SF), mészkőpor (LP), hulladék perlit C (WPP-C), hulladék perlit SZ (WPP-SZ)

Chemical composition	C	MK	SF	LP	WPP-C	WPP-SZ
SiO ₂	25.53	52.79	95.09	5.63	73.80	73.2
Al ₂ O ₃	6.3	42.07	0.24	1.4	13.80	16.6
Fe ₂ O ₃	2.29	1.25	0.06	0.9	1.57	2.6
CaO	55.59	0.37	0.91	50.32	1.17	1.06
MgO	4.05	0.38	0.32	0.65	0.11	0.2
SO ₃	2.34	< 0.01	0.07	0.08	-	-
K ₂ O	0.78	1.22	0.51	0.29	4.01	3.5
Na ₂ O	0.33	0.02	0.2	0.07	2.66	1.5
TiO ₂	0.28	0.2	< 0.01	0.08	0.083	0.09
P ₂ O ₅	0.03	0.06	0.07	0.02	-	-
Physical properties						
Specific gravity	3.1	2.6	2.35	2.69	2.33	2.33
Specific surface area (cm ² /g)	3450	15244	20450	3470	843.3	4159
Loss on ignition (%)	2.15	1.59	2.49	40.55	2.8	1.21

Table 4. Chemical and physical characteristics of binders and filler materials
4. táblázat Alkalmazott anyagok kémiai és fizikai jellemzői

Mix ID	w/c _a	w/p _b	a/p _c	MK, kg/m ³	SF, kg/m ³	LP or WPP _d , kg/m ³	HRWRA, kg/m ³	V-funnel time, s	Slump flow, mm	Reference
T1	0.56	0.84	2.7			300	2.24	7.5	730	-
T2	0.50	0.85	2.8			260	2.34	14.6	580	-
T3	0.45	0.85	2.8			220	2.60	8.5	630	-
SCC-1	0.56	0.84	2.7	40		260	2.20	9.5	610	[13]
SCC-2	0.50	0.84	2.8	40		220	2.70	7.7	720	[13]
SCC-3	0.45	0.85	2.8	40	40	180	2.80	9.3	690	[13]
SCC-4	0.56	0.83	2.7		40	260	4.00	8.2	710	[13]
SCC-5	0.50	0.84	2.7		40	220	3.60	12.0	725	[13]
SCC-6	0.45	0.85	2.8			180	3.20	9.5	720	[13]
T4	0.56	0.90	3.0			260	0.96	16.5	530	-
T5	0.50	0.91	3.1			220	1.26	9.5	630	-
T6	0.45	0.92	3.1			180	3.20	3.7	890	-
SCC-7	0.56	0.90	3.0	40		220	2.40	13.2	680	[13]
SCC-8	0.50	0.91	3.0	40		180	2.63	6.8	820	[13]
SCC-9	0.45	0.92	3.1	40		140	4.00	7.0	850	[13]
SCC-10	0.56	0.89	3.0		40	220	2.88	10.8	835	[13]
SCC-11	0.50	0.90	3.0		40	180	3.13	8.4	835	[13]
SCC-12	0.45	0.91	3.0		40	140	3.70	9.9	820	[13]
R1	0.56	0.84	2.7			300	3.04	5.0	800	[11, 14]
R2	0.50	0.85	2.8			260	3.06	6.3	795	[11, 14]
R3	0.45	0.85	2.8			220	3.56	5.9	790	[11, 14]
M1	0.56	0.84	2.7	40		260	3.36	7.1	775	[11, 14]
M2	0.50	0.84	2.8	40		220	3.96	8.6	800	[11, 14]
M3	0.45	0.85	2.8	40		180	4.40	11.0	755	[11, 14]
S1	0.56	0.83	2.7		40	260	5.44	5.3	765	[11, 14]
S2	0.50	0.84	2.7		40	220	4.86	6.3	780	[11, 14]
S3	0.45	0.85	2.8		40	180	5.20	6.7	770	[11, 14]
R4	0.56	0.90	3.0			260	1.92	5.7	740	[11, 12]
R5	0.50	0.91	3.1			220	2.02	5.4	760	[11, 12]
R6	0.45	0.92	3.1			180	2.72	4.6	780	[11]
M4	0.56	0.90	3.0	40		220	2.72	9.7	775	[11, 12]
M5	0.50	0.91	3.0	40		180	2.92	10.3	780	[11, 12]
M6	0.45	0.92	3.1	40		140	4.00	8.6	810	[11]
S4	0.56	0.89	3.0		40	220	2.88	6.3	760	[11]
S5	0.50	0.90	3.0		40	180	3.17	5.0	770	[11]
S6	0.45	0.91	3.0		40	140	3.76	5.1	790	[11]
R7	0.56	1.01	3.5			200	1.74	5.2	780	[11]
R8	0.50	1.03	3.6			160	1.55	7.7	750	[11]
R9	0.45	1.04	3.6			120	1.76	5.9	770	[11]
M7	0.56	1.01	3.5	40		160	2.27	7.5	770	[11]
M8	0.50	1.02	3.6	40		120	2.34	8.7	785	[11]
M9	0.45	1.03	3.6	40		80	2.84	9.7	800	[11]
S7	0.56	1.00	3.5		40	160	2.31	6.7	765	[11]
S8	0.50	1.01	3.5		40	120	2.34	6.0	780	[11]
S9	0.45	1.02	3.6		40	80	2.72	3.6	850	[11]
NA1	0.56	0.84	2.7			300	3.68	4.9	790	[14]
NA2	0.50	0.85	2.8			260	3.42	6.1	760	[14]
NA3	0.45	0.85	2.8			220	3.92	6.1	780	[14]
MA1	0.56	0.84	2.7	40		260	4.80	9.5	790	[14]

Mix ID	w/c _a	w/p _b	a/p _c	MK, kg/m ³	SF, kg/m ³	LP or WPP _d , kg/m ³	HRWRA, kg/m ³	V-funnel time, s	Slump flow, mm	Reference
MA2	0.50	0.84	2.7	40		220	5.76	11.2	800	[14]
MA3	0.45	0.85	2.8	40		180	6.20	10.1	790	[14]
SA1	0.56	0.83	2.7		40	260	4.64	6.6	750	[14]
SA2	0.50	0.84	2.7		40	220	5.04	5.9	770	[14]
SA3	0.45	0.85	2.8		40	180	4.80	6.4	760	[14]
N1-P1	0.56	0.78	2.6			300	7.17	8.0	850	[15]
N2-P1	0.50	0.79	2.7			260	9.31	7.6	825	[15]
N3-P1	0.45	0.81	2.7			220	7.57	10.1	780	[15]
M1-P1	0.56	0.78	2.6	40		260	7.65	10.3	760	[15]
M2-P1	0.50	0.80	2.7	40		220	8.10	12.5	725	[15]
M3-P1	0.45	0.81	2.7	40		180	8.40	8.3	840	[15]
S1-P1	0.56	0.78	2.6		40	260	7.58	5.0	810	[15]
S2-P1	0.50	0.79	2.7		40	220	7.20	7.8	750	[15]
S3-P1	0.45	0.81	2.7		40	180	10.56	8.7	780	[15]
N1-P2	0.56	0.84	2.9			260	6.40	6.1	785	[12, 15]
N2-P2	0.50	0.85	3.0			220	7.56	5.5	800	[12, 15]
N3-P2	0.45	0.87	3.0			180	7.96	11.7	790	[15]
M1-P2	0.56	0.84	2.9	40		220	7.42	8.6	800	[12, 15]
M2-P2	0.50	0.86	3.0	40		180	8.10	6.4	790	[12, 15]
M3-P2	0.45	0.88	3.0	40		140	8.40	7.9	765	[15]
S1-P2	0.56	0.84	2.9		40	220	7.04	5.5	785	[15]
S2-P2	0.50	0.86	2.9		40	180	7.95	8.1	770	[15]
S3-P2	0.45	0.87	3.0		40	140	8.88	8.0	790	[15]

Table 5. Mixtures parameters
5. táblázat Keverék összetételek

To better imitate SCC types used in practice, several factors were considered in the mix design, including the total fine content (sum of cement, fillers, and SCM), SCMs, and filler type. The cement content (320, 360, 400 kg/m³), total fine content (620, 580, 520) kg/m³ and SCM (none, 40 kg/m³) dosages were set as variables. Aggregate particle-size distribution (three nominal grading fractions) was used as: sand 0/4 mm (45%), small gravel 4/8 mm (25%), and medium gravel 8/16 mm (30%). The amount of water (W), 180 kg/m³ was held as constant parameters. The mixture compositions of all the studied concretes is summarized in Table 5. In this study, the cement was defined as the main binder, with MK or SF as the SCMs, and WPP or LP as filler materials.

Because of the scope of the comparison, parameters related to the rheological properties of SCC mixtures were collected from previous studies [11-15].

To examine the adequacy of SCC mixtures deformability and viscosity, slump flow diameter and V-funnel time tests were carried out according to European Standards [16-17]. Refereeing to EFNARC guidelines for SCC [4], the aim of the study was to obtain a slump flow criterion which belong to SF3 category. The latter could be achieved by the proper addition of HRWRA and maximum aggregate size of 16 mm.

X_a: water to cement ratio by weight; X_b: volumetric water to powder ratio; X_c: Volumetric aggregates to powder ratio; X_d: Mixtures with WPP filler are those from N1-P1 to S3-P2

3. Range of SCC- “Window solution”

According to the measures from Table 5, a processing window similar to Fig. 1 for the studied SCC mixtures was derived. Note that all studied mixtures were having the same grading fraction of aggregates with a maximum nominal size of 16 mm. Based on the positively evaluated SCC mixtures given in Table 5 and the limitation given by EFNARC [4], an update for the processing window has been created (Fig. 3). This was done in four directions. First, the V-funnel time was enlarged to 14 s, to account for the higher friction and viscous SCC mixtures. Stagnation was noticed by visual inspection when the V-funnel time was greater than 14 s and the slump flow diameter was less than 600 mm. These mixtures were lacking the flow ability characteristic of SCC. Referring to Fig. 4, cases with stagnation corresponded to mixtures with low volumetric water to powder ratio (Mixtures T2 and T4; see Table 5), and by that, enhancing the plastic viscosity of the concrete. However these mixtures were reproduced with the same mixture composition but with a higher content of HRWRA (Mixtures R2 and R4), providing adequate flow ability and viscosity properties. Therefore, the requirement of V-funnel time greater than 14 s and slump flow less than 600 mm might be an appropriate limitation for a highly viscous SCC. Note that this workability window was applied to the range of temperature around 20 °C.

On the other hand, the slump flow axis is enlarged up to 850 mm, to account for the highly flow able mixtures. When

it comes to mixtures holding a V-funnel time less than 4 s, segregation of concrete was visually observed. The V-funnel time axis is enlarged also in the direction of shorter funnel times. Here at least, the mark of 4 s should be included as lower funnel time limit. It has been shown that SCC mixtures with low V-funnel time values, as low as 4.6 s (Mixture R6), could be successfully produced while also fulfilling all other requirements. This is of special relevance in particular for mixtures with low yield stress, thus with large slump flows.

Fig. 3. Suggested processing window for SCC (corresponding data are collected from Table 5) in terms of V-funnel time and slump flow (in green); The red window corresponds to EFNARC limitations [4]

3. ábra Javasolt SCC reológiai jellemzők (az 5. táblázat adatai alapján) tölcéses kifolyási vizsgálatra és roskadási területre (zöld színnel); a piros vonallal határolt mező EFNARC [4] javaslat

Fig. 4. Suggested processing window for SCC (corresponding data are collected from Table 5) in terms of V-funnel time and volumetric water to powder ratio (in green); The red window corresponds to EFNARC limitations [4]

4. ábra Javasolt SCC reológiai jellemzők (az 5. táblázat adatai alapján) tölcéses kifolyási vizsgálatra és térfogat szerinti víz-kötőanyag arányra vonatkozóan (zöld színnel); a piros vonallal határolt mező EFNARC [4] javaslat

The workability ranges for all collected SCC mixtures are shown in Fig. 4 in terms of their volumetric water to powder ratio and V-funnel time. These mixtures differ in the total powder content, water to cement ratio, and different types of fillers and SCMs (see Table 5). It can be noticed that the workability ranges fluctuate between 750 and 850 mm since the targeted slump flow classification was SF3 for the following mixtures (starting with mixture “R1” to S3-P2; see Table 5). The exact position of the targeted workability highly depended on the implemented materials and their physical properties.

EFNARC guidelines [3] classified the viscosity of SCC into two classes (see Table 3), Figs. 3 and 4 compared all mixtures that were arranged according to their viscosity class (VF1 or VF2) [3]. It can be noticed that several mixtures shared the same slump flow value but with a different V-funnel time. For instance, if SCC mixture containing MK (mixture M2) or SF (mixture S2) were compared with their corresponding reference mixture R2, almost a common slump flow diameter (800 ± 20 mm) is shown yet with significant difference in the V-funnel time value. MK enhanced the plastic viscosity of the mixture by 36% in V-funnel time, while adding SF does not appear to have any effect on the viscosity. Same response pattern is noticed for mixtures M5 and S5 as compared with mixture R5. The high cohesiveness of MK bearing mixtures seemed to be the reason for the high V-funnel time. On the other hand, shorter V-funnel times were recorded in SF incorporated mixtures. This could be explained by the ball bearing effect and additional lubrication provided by spherical and smooth-textured of SF particles. This finding is consistent with the following references [18-20].

To avoid the risk of segregation in SCC from excess amount of HRWRA, Fig. 5 shows a curve where the minimum amount of HRWRA is indicated in accordance with the volumetric water to powder ratio derived from the data's in Table 5. The replacement of aggregates by fine powders (lower volumetric water to powder ratio) increased the HRWRA demand of when compared to mixtures with higher volumetric water to powder ratio. The risk of obtaining very viscous, unworkable SCC mixture could be reduced by increasing the w/p. The causes of the increase in HRWRA demand upon SCMs were studied by several researches [19]. They concluded that the very small size SCMs particles with high specific surface area, tended to agglomerate resulting in a high demand of HRWRA. Thereby, excess of HRWRA deflocculated the fine agglomerate particle, and lubricated the flowing system.

Fig. 5. Relationship between the high range water reducing admixture content and the volumetric water to powder ratio

5. ábra Összefüggés a folyósítószer adagolás és a térfogat szerinti víz-kötőanyag arány között

4. Conclusions

Self-compacting concrete (SCC) is sensitive to small changes in the material properties and proportions used in the mix design. An experimental approach for assessing the fresh

properties of SCC has been developed which represents the workability window of SCC in a diagram (slump flow diameter as a measure of the flow ability and the V-funnel flow time as a measure of the viscosity).

Based on the effects of the different mix design parameters (Volumetric water-to-powder ratio, high range water reducing admixture content and additives) on the fresh properties of examined SCC mixtures, the following conclusions could be drawn:

1. The optimum ranges of workability for self-compacting concrete SCC and its corresponding limits (stagnation and segregation) have to be tested and specified for the adequate fresh behaviour. That's could be achieved by varying the volumetric water to powder ratio and high range water reducing admixture. Thereby, this helped us to identify the range of workability within the workability window diagram.
2. V-funnel time of the SCC mixtures incorporating metakaolin was higher than of the mixtures with SF or reference mixtures.
The minimum V-funnel time for VF1 classification should be 4 s; otherwise concrete segregation would occur.
3. For the same slump flow diameter values, mixtures containing metakaolin or silica fume showed higher demand of HRWRA as compared to that of.
4. reference mixtures.

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Öntömörödő beton frissbeton-tulajdonságainak vizsgálata különböző kiegészítő anyagok alkalmazása esetén

Az öntömörödő betonok frissbeton tulajdonságai eltérnek a hagyományos betonokétól. Megfelelő beton összetétellel kell elérni, hogy a keverék homogén legyen, megfelelően mozogjon, és ne osztályozódjon szét. Az öntömörödő beton sikeres alkalmazásához szükség van a megfelelő frissbeton tulajdonságokra a bedolgozás során. Az öntömörödő betonok előállításának egyik legnagyobb kihívása az adott helyszínen elérhető alapanyagok minősége. Laboratóriumi kísérleteket végeztünk öntömörödő betonok reológiai tulajdonságainak vizsgálatára különböző cement kiegészítő anyagokkal. Jelen cikk azt vizsgálja, hogy a különböző cement kiegészítő anyagoknak milyen hatása van az öntömörödő betonok frissbeton tulajdonságaira. Az eredmények rávilágítottak, hogy a cement kiegészítő anyagok nagy hatást gyakorolnak a bedolgozhatóságra, és új elfogadási feltételek vezethetők be erre vonatkozóan.