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RESEARCH ARTICLE

Fresh Mix Characteristics of Self-Compacting Concrete Reinforced by Fibre

Tomasz Ponikiewski [1], Jacek Katzer [2*]

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Abstract
An analysis of influence of different types of fibre and fibre content on properties of self-compacting concrete is the main subject of the paper. Presented study is focused on the effect of steel, basalt and polypropylene fibres with different geometrical parameters on workability and self-compacting abilities of fresh mixes.

Keywords

SCC, self-compacting, cement, rheology, fibre, steel, basalt, polypropylene

[1]Department of Building Materials and Processes Engineering,
Faculty of Civil Engineering,
Silesian University of Technology
44-100 Gliwice, Poland
[2]Department of Construction and Building Materials,
Faculty of Civil Engineering Environmental and Geodetic Sciences,
Koszalin University of Technology,
75-453 Koszalin, Poland
[*]Correspondinf author email: jacek.katzer@tu.koszalin.pl

1 Introduction

The current state-of-the-art of concrete technology is not sufficient to effectively shape the workability of self-compacting concrete (SCC) with the addition of fibre. Further research is needed, especially taking into account the impact of variable physicochemical properties of cement type and mineral additions (e.g. fly ash, silica fume, lime fume) on such concrete mixes.

The influence of fibre addition on properties of fresh and hardened concrete mixes was thoroughly described in multiple previous publications [1, 2, 3, 4, 5]. In general, the higher the volume of fibre (V_f) added to concrete mix the better the mechanical properties of the hardened composite are. At the same time increasing fibre volume in concrete causes the loss of workability of fresh mixes and problems with casting and forming [6]. Currently, fibre plays a very important and rapidly growing role in modern concrete technology. Harnessing fibre as concrete reinforcement allows to enhance its mechanical properties and obtaining significant economic benefits. Fibre quickly becomes an important element of sustainable development of construction industry [7]. As far as technology of fibre reinforced self-compacting concrete (FRSCC) is concerned the main problem is the technical difficulty of its preparation and implementation processes during casting. There is a real need to examine and describe the true nature of FRSCC workability and determine the effect of added fibre on multiple phenomena occurring in fresh mix and hardened SCC composite.

According to numerous researchers [8, 9] a fresh concrete mix under loading behaves like viscoplastic Bingham body. It basically behaves as a rigid body at low stresses but flows as a viscous fluid at high stresses.

Rheological parameters yield point (g) and plastic viscosity (h) are material constants, characterizing the properties of a fresh concrete mix. Once the stresses exceed the yield point, the mixture will flow at a rate proportional to plastic viscosity. The smaller the plastic viscosity of the mixture, the greater the speed of the flow at a given load. Workability-wise, the yield point parameter is the most essential for shaping workability of both ordinary and SCC fresh mixes. In case of ordinary concrete mixes (which are traditionally compacted by vibration), technological importance of plastic viscosity is secondary. In contrary, for SCC mixes their workability is defined by both yield point and plastic viscosity.

The main aim of the conducted research programme was to analyse properties of SCC influenced by growing fibre addition. There were used the most popular types of fibre used in civil and structural engineering. The process of losing workability and improvement of mechanical properties of hardened composites were of special interest.

2 Research programme

The research programme covered tests of rheological and strength properties of SCCs reinforced by different steel, basalt and polypropylene fibres. All fresh mixes were tested following ordinary slump-flow procedure according to RILEM TC 145-WSM [10]. During this test two parameters were measured: the diameter (D_{max} in cm) of the concrete pat after removal of the slump cone and the time (T_{500} in seconds) in which the flowing mix formed a 50.0cm concrete pat. Mixes with basalt and polypropylene fibres were additionally investigated following the procedure of rheometric workability test (RTU). The RTU tests were conducted using rheometer BT-2 which was presented in Fig.1.

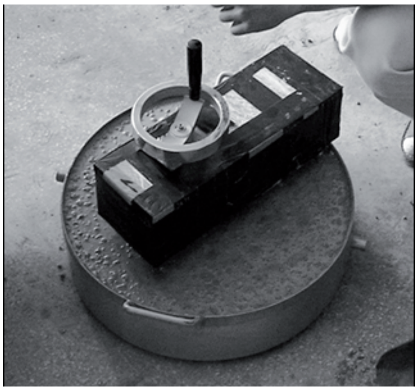

Fig. 1 Rheometer BT-2 during the testing procedure

Achieved results were approximated using dual-parameter Bingham rheological model. In this way two basic rheological parameters: *g* and *h* were established. The compressive strength was tested after 7 days of curing on cube specimens 15cm · 15cm · 15cm. The tested mixes were prepared using superplasticizers based on polycarboxylate ether. There were utilised two types of aggregate: natural sand and natural coarse aggregate. The sand point [11] was equal to 50.0%. The detailed mix compositions of tested SCC are shown in Table 1.

The study was conducted taking into account the impact of the following factors on the SCC mix:

- fibre material: steel, basalt and polypropylene,
- the geometry and shape of fibres,
- fibre addition: steel V_f = 0.25% ÷ 1.5% (20kg/m^3 ÷ 120kg/m^3); basalt and polypropylene V_f = 0.1% ÷ 1.0% (1kg/m^3 ÷ 10kg/m^3)

Table 1 Compositions of tested SCC mixes

Ingredient	kg/m3
CEM I	600.0
Natural sand 0-2 mm	800.0
Natural rounded aggregate 2÷8 mm	800.0
Superplasticizer Glenium SKY 592 (2.5 %)	15.0
Stabilizer RheoMatrix (0.4 %)	2.4
W/C	0.31
Consistency class (SF)	SF2

Fibres used during the research programme were selected from fibres commercially available on the market and commonly used for concrete production. They were solicitously chosen to represent the most popular materials and geometric shapes of fibres used in concretes for civil and structural applications. Steel fibres were dosed taking into account their geometry (volume fraction of fibre in a mixture inversely proportional to the length of the fibre). Basalt and polypropylene fibres were dosed in proportion to their volume density and the geometrical characteristics.

Table 2 Geometrical and material characteristics of used fibre

Name	Length Diameter [mm]	Cross-section Shape	Material	Tensile strength [MPa]
SW 50/1.0	50 1.000	Semicircle corrugated		1100
DM 6/0.175	6 0.170	Circle straight		2100
SF 01-32	32 3. 800	crescent hooked	Low carbon steel	980
KE 20/1.7	20 1.700	Rectangular hooked		770
SW 35	35 2.30÷2.95	Semicircle corrugated		800
SBF 5	5 0.016	Circle straight	Basalt, polymer	1680
SBF 12	12 0.016	Circle straight		1680
FS 25	25 0.660	macrofibre (II) deformed	Poly-propylene, polyethyl-ene	600
FS 40	40 0.66	macrofibre (II) deformed		600
FS 12	12 0.028	microfiber (Ia) straight	Poly-pro-pylene	600

All the mixes were prepared according to a specific procedure. The sequence of actions during SCC mix preparation was as follows:

- Dosing of coarse aggregates
- Dosing of sand
- Dosing of cement
- Dosing of fibre
- The initial mixing of the ingredients - 3 minutes
- Dosing 2/3 of water
- Dosing 1/6 of water along with a full dose of super-plasticizer

- The second mixing of the ingredients - 2 minutes
- Dosing 1/6 of water along with a full dose of stabilizer
- The third mixing of the ingredients - 2 minutes

This rigorous mix preparation regime allowed to achieve repetitively stable mixes characterized by the same properties.

3 Achieved results and discussion

The influence of basalt, polypropylene and steel fibres on properties of fresh SCC mix tested by slump-flow (D_{max} and T_{500}) are presented in Fig. 2, 3, 4 and 5 respectively. As a condition of fulfilling the self-compaction ability a value of D_{max} = 55.0 cm of slump-flow test was acquired. This condition was thoroughly described and discussed by Ponikiewski [12,13,14].

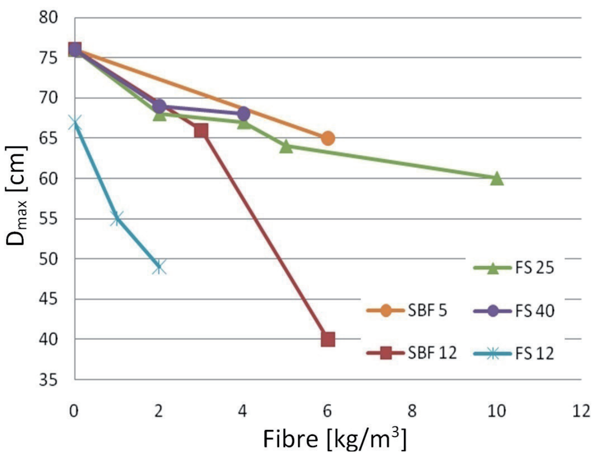

Fig. 2 Influence of polypropylene and basalt fibres on diameter D_{max}

The addition of all three (basalt, polypropylene and basalt) types of fibre deteriorates mixes' workability. A significant reduction of both measured parameters: the diameter of mix flow D_{max} and time T_{500} were observed. Along with the increasing amount of added fibre their influence on workability of fresh mixes was more visible. The smallest diameter D_{max} for steel fibre reinforced mix was observed for the addition of fibre DM 6/0.175. Mix reinforced by the maximum amount of this fibre (120kg/m^3) was characterized by D_{max} = 57.0cm. All mixes reinforced by steel fibre can be classified as self-compacting. In case of non-steel fibre reinforced mixes the smallest diameter D_{max} was observed for addition of basalt fibre SBF 12. The SCC mix modified only by 6kg/m^3 of this fibre reached the value of D_{max} equal to 40.0cm and can't be classified as self-compacting.

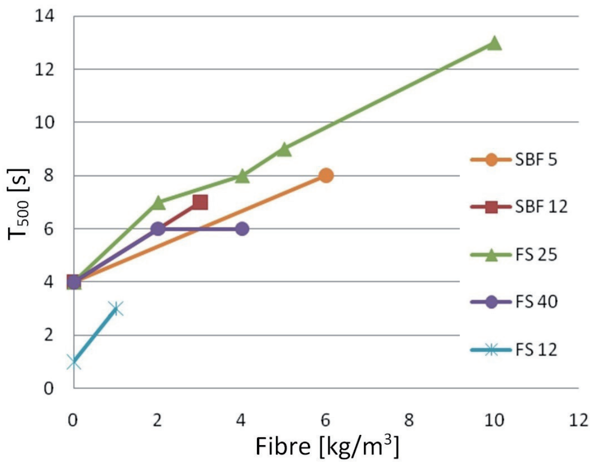

Fig. 3 Influence of polypropylene and basalt fibres on flow time T_{500}

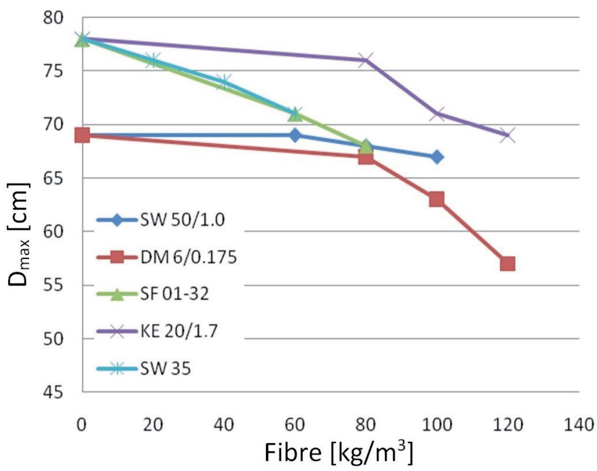

Fig. 4 Influence of steel fibres on diameter D_{max}

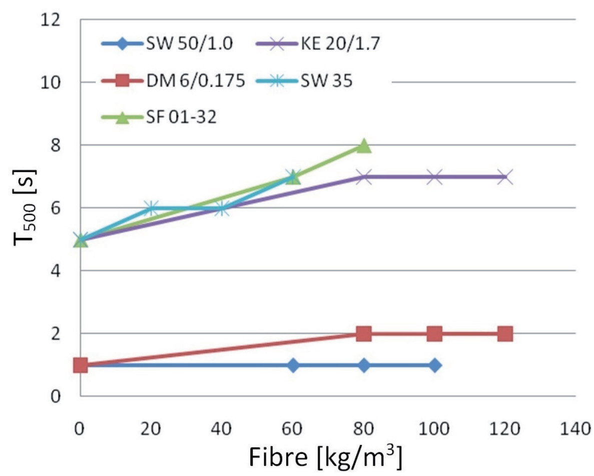

Fig. 5 Influence of steel fibres on flow time T_{500}

The second smallest value of D_{max} was achieved by mix modified by 2 kg/m^3 of polypropylene fibre FS 12. It reached D_{max} of 49.0cm and thus also can't be classified as self-compacting. All other mixes modified by 2 kg/m^3 of non-steel fibres were characterized by the diameter D_{max} larger than 67.0 cm. Flow time T_{500} is getting longer and longer with increasing amount of added synthetic fibres. Polypropylene micro-fibre influences the flow time in the most significant way. This phenomenon is particularly evident in the case the of the polymer-basalt fibre SBF 12 (loss of self-compacting properties). The impact of the growth of volume of polypropylene fibres does not translate into a significant decrease in the flow diameter. The value of the flow time T_{500} clearly increases with increasing volume of 25mm long polypropylene fibres.

The Addition of steel fibre also deteriorates workability of fresh mixes. In case of addition of 40kg/m^3 all mixes could be classified as self-compacting. Larger dosage of steel fibre of 60kg/m^3 caused more significant workability loss, especially visible in case of longer fibre (e.g. fibre SW 35, D_{max} dropped from 78cm for unreinforced mix to 72cm). The flow diameter D_{max} of mixes modified by the longest steel fibres (50mm) is almost constant over the range of dosage from 60kg/m^3 to 100kg/m^3. Only the mix modified by 120 kg/m^3 of steel fibre DM 6/0.17 (the shortest of the used steel fibre) lost its self-compacting ability. Flow time T_{500} of all tested mixes increases with increasing fibre content. When the steel fibre content exceeds 80kg/m^3 there is no increase of the flow time in the case of the three types of fibres (SW 50/1.0 DM 6/0.17 KE 20/1.7).
Results of tests of yield value g and compressive strength f_{cm7} of mix modified by synthetic fibre are shown in Fig. 6 and 7 respectively.

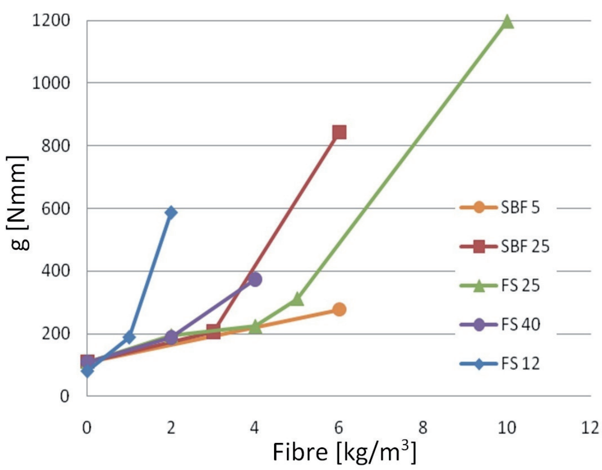

Fig. 6 Influence of polypropylene and basalt fibres on yield value *g* of SCC

The value of the yield stress increases with increasing volume of added fibre. The influence of the fibres' material on yield value is clearly visible. In the case of micro polypropylene fibres, the largest increase in the yield value g was registered for the addition of 2 kg/m^3. For the fibre content from 2 kg/m^3 to 4kg/m^3 of macro-polypropylene and basalt fibre, mixes are characterized by the relatively lowest value of the yield point. For the content of 6 kg/m^3 of short basalt fibre (characterized by length of 5mm), the mix demonstrates the smallest increment of yield stress. On contrary, the mix containing 6kg/m^3 of long basalt fibre (characterized by length of 12mm) demonstrates a relatively high increase in yield stress. The addition of 10kg/m^3 of polypropylene fibre (length of 25mm) caused an increase in the value of yield stress from 100Nmm to 1200 Nmm.

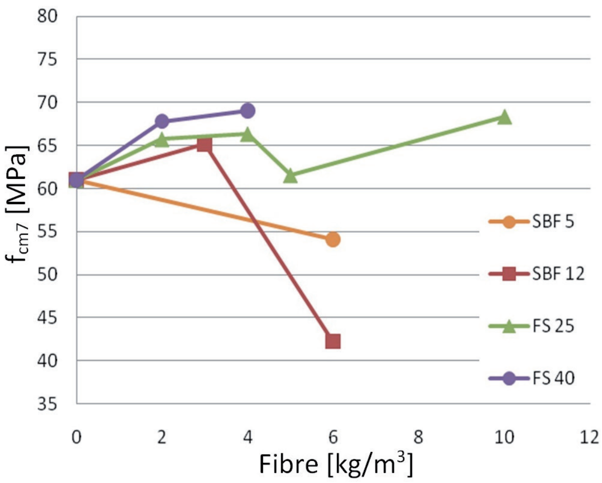

Fig. 7 Influence of polypropylene and basalt fibres on compressive strength

The highest compressive strength (f_{cm7} = 69.0 MPa) was registered for the SCC mix with the addition of 4kg/m^3 of polypropylene fibre characterized by length of 40 mm (FS 40). It was an increase of 13.1% comparing to SCC with no fibre reinforcement. A similar value of f_{cm7} (68.0 MPa) was achieved by SCC modified by 10 kg/m^3 of polypropylene fibres characterized by length of 25mm (FS 25). Both SCC mixes reinforced by 6 kg/m^3 of basalt fibre 5mm long (SBF 5) and basalt fibre 12 mm long (SBF 12) were characterized by a decrease of the f_{cm7} (11.5% and 31.1% respectively) in comparison to SCC without fibres.

The yield value g and compressive strength f_{cm7} achieved for mixes modified by steel fibre are presented in Fig. 8 and 9 respectively. The influence of the fibre addition on yield value is visible, but not as significant as in case of polypropylene and basalt fibre. Mix modified by 120 kg/m^3 of steel fibre DM 6/0.17 is characterized by the largest g value equal to 440 Nmm. Majority of mixes with steel fibre are characterized by g value ranging from 100 Nmm to 300 Nmm. The influence of steel fibre addition on SCC compressive strength is varied and depends on fibre type. In case of fibre KE 20/1.7 the larger the amount of added fibre the larger the compressive strength. For addition of 120 kg/m^3 the compressive strength exceeds 70 MPa. In case of fibre SW 50/1.0, SW 35 and DM 6/0.17 the strength characteristics of the mixes is very similar. Namely, compressive strength is getting slightly smaller alongside the increasing fibre addition. The reduction of the compressive strength for fibre addition of 100 kg/m^3 varies from 1 MPa to 4 MPa (≤5%).

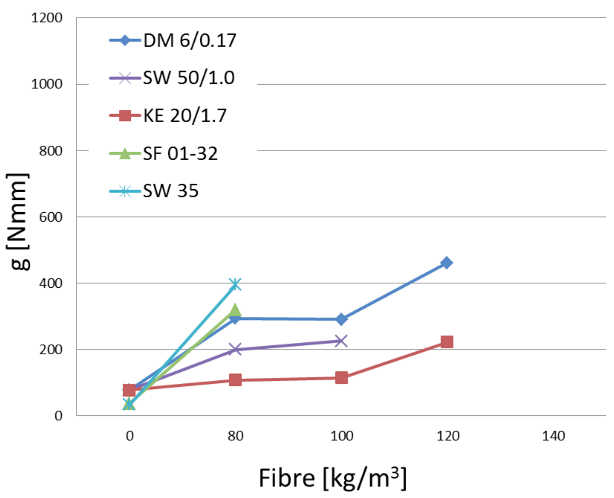

Fig. 8 Influence of steel fibres on yield value g of SCC

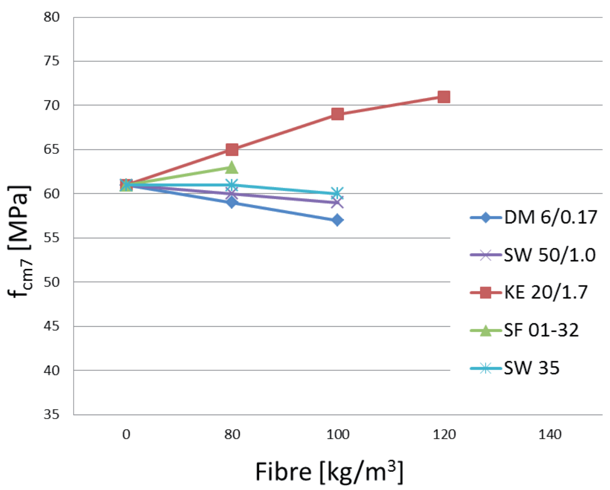

Fig. 9 Influence of steel fibres on compressive strength

4 Conclusions

On the basis of the conducted research programme it can be stated that:

- despite the deterioration in workability due to fibre addition self-compacting concrete can be successfully created,
- self-compacting ability of the tested mix deteriorates with increasing volume fraction of fibres despite their geometry, shape and material,
- reinforcing SCC mix by 80kg/m³ of steel fibre does not result in significant deterioration of workability,
- the largest deterioration of self-compacting ability of tested SCC mixes was caused by the addition of polypropylene micro fibre characterized by length of 12mm (FS 12),
- SCC mix modified by 2 kg/m³ of polypropylene micro fibre characterized by length of 12mm (FS 12) lost self-compacting properties,
- SCC mix modified by 6 kg/m³ of basalt fibre characterized by length of 12 mm (SBF 12) lost self-compacting properties,
- Addition of polypropylene and basalt fibre influence the values of D_{max} in much more significant way then steel fibre especially while considering the same volumes of added fibre e.g 0.5% (5kg/m³ and 40kg/m³ of polypropylene/basalt fibre and steel fibre respectively),
- The influence of addition of polypropylene and basalt fibre on value of T_{500} is significant and much larger than in case of steel fibre.

The conducted research programme should be continued using large scale specimen and testing mechanical properties of fibre composites according to Limit of Proportionality (LOP) method. Apart from mechanical properties tested in a static way the future research should be focused on dynamic characteristics [15, 16] of composites in question. It would allow to successfully model their behaviour under blast load and harness them for erecting "terrorist-proof" structures.

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