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9. The effect of steel fibres on selected properties of new generation of concrete

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The paper presents results of tests on self-compacting mixtures with the addition of steel fibers (Steel Fiber Reinforced Self-Compacting Concrete). Considered are four types of steel fibers at 3 levels of the volume ratio. The results include studies on samples belonging to classes of slump flow SF, classes of viscosity T_{500}, and to rheological tests. The studies were based on two rheometers for rheological properties of concrete mixtures - BT2 Rheometer and Viskomat XL. Additionally, a study of compressive strength ƒcm,28 and the flexural strength f_{fl} was carried out on concrete SFRSCC. These studies have confirmed the possibility of using steel fibers in concrete SCC while maintaining the assumed technological parameters for concrete mixtures and - above all - their workability. The long fibres (30 mm) are mostly oriented parallel to the flowability direction, vertically to the loading direction, and hence, they can operate efficiently under flexural loading. The orientation of fibers connected with the direction of the SFRSCC mix flow during moulding was confirmed.

Keywords: steel fibre, self-compacting concrete, rheology, flexural strength, X-ray

9.1. Introduction

The use of fibres in a cementitious system has led to many advantages in construction technology. It has been reported that fibres are effective in many ways, such as (Boulekbache *et al.*, 2010): (i) fibre reinforcement has been shown to improve the ductility, toughness, flexural strength and shear strength of cementitious materials; (ii) fibres bridge cracks during loading and transfer the load, arresting the growth and coalescence of cracks, playing the role of energy absorber; (iii) the fibres reduce the shrinkage, cracking and permeability of concrete; (iv) the fibres enhance fatigue and impact resistance; (v) the fibres take up internal stresses through their tension resistance and hence ensure the transfer of the loads, provided that a good bond exists between the fibres and the hardened cement matrix.

Analysis of the influence of fibers on the self-compacting and mechanical properties of concrete is one of the new tendencies in investigations of cement composites (Barragán *et al.*, 2004),(Ding *et al.*, 2004). The general improvement in the hardened self-compacting concrete properties with increased fiber volume is accompanied by lowered workability on casting. Other problems present themselves while dealing with the production of steel fiber modified SCC and their application. Therefore the workability of SFRSCC as well as the effect of fibres on the properties of fresh and hardened concrete mixture should be well recognized. The SCC mix design is not a simple task; every decrease in precise dosage of components, variable materials and curing conditions can result in manufacturing of material with no assumed properties: fluidity, ability to flow between the reinforcing bars as well as the resistance to segregation (Kaszyńska, 2003).

Short fibres with lengths of 10–30 mm are generally adopted in fibre reinforced concrete. These fibres are dispersed randomly in all directions so as to exhibit isotropic behavior. However, the real fibre distribution is strongly influenced by various factors such as fibre characteristics (diameter, length, and volume fraction), the fluidity of the matrix, placing method, and shape of the form (Kang *et al.*, 2011). The previous studies on random distribution of steel fibres in SFRSCC have not provided systematic experimental data to enable their design for their assumed mechanical parameters as well as the distribution and orientation of the dispersed reinforcement (Zerbino e*t al.*, 2012), (Kim *et al.*, 2008), (Ding *et al.*, 2012). This causes the discrepancy between the projected and obtained mechanical parameters of the modified concretes (Ding *et al.*, 2008), (Kang and Kim, 2011). It is important to determine the degree of variation in the mechanical properties of SFRSCC caused by the location and orientation of the dispersed reinforcement (Pająk and Ponikiewski, 2013), (Kang and Kim, 2011), (Tanikella and Gettu, 2008). Other studies have confirmed the variable and directional when using steel fibres in SCC during technological processes (Pająk and Ponikiewski, 2013), (Torrijos *et al.*, 2008), (Vandewalle *et al.*, 2008), (Yardimci *et al.*, 2008). The problems, also in the case of fiber reinforced cement composites, appear as technological difficulty during their production as well as with the formed concrete elements (Grünewald, 2004), (Rudzki et al., 2013), (Ponikiewski and Gołaszewski, 2012). Recognition of the real nature of workability and a definition of the impact that added fibers have on the phenomena occurring in fresh and hardened cement composites are needed. With the use of different type, shape, and strength of fibres, SCC can be tailored for more possible applications (Akcay and Tasdemir, 2012). At this point, however, it is vital to determine the effect of fibres on workability properties of SCC. The rheology parameters of the flowing material, particularly the yield stress and the wall effect generated by the geometry of the formwork, are the greatest influences on the orientation of the fibres within the fresh concrete. The distribution and orientation of fibres is, in turn, the parameter which influences the most the ductility of fibre concretes (Boulekbache *et al.*, 2010).

The current technological problems when applying cement composites modified with steel fibers as dispersed reinforcement are being discussed in the article. An analysis of fiber randomness influencing the workability and mechanical properties of fiber reinforced cement composite is dealt with as well. The concrete mixture was modified with steel fibers of various length and volume ratio. The results of workability tests of fiber reinforced cement mixes in the rheological context will be also presented. Research carried out by the rheometrical workability test was conducted with a new rheometer for concrete mixes Viscomat XL. The approximation of measurable results was done by the two-parameter Bingham rheological model, which allowed determination of two basic rheological parameters – yield value g and plastic viscosity h. The flexural tensile and compressive strengths of SFRSCC will be presented as well.

Self-compacting concrete technology allows one to form engineering structures in a faster and safer way than in the case of concrete with traditional characteristics. The technological procedures for forming structures from the self-compacting concrete are simpler by far with the final results enabling a broad display of hardened structures.

Equally important is the problem of uneven distribution of fibers in the volume of hardened concrete after completing the technological processes, indicated in the literature (Pająk and Ponikiewski, 2013), (Kang and Kim, 2011), (Grünewald, 2004). The problem with the application of mixtures using modified binders - fiber-cement, lies in the need to ensure even distribution of fibers in the volume of the molded component.

Past studies have shown the impact that the dimensions of a formed element have on the direction of fibers in the concrete mix. Uneven and directional deployment of reinforcements in the technological process brings some problems tied to the randomness of fiber distribution in the volume of concrete. The analysis of mutually exclusive factors occurring with the addition of steel fibers to self-compacting concrete, namely the deterioration of workability, or even a complete loss of self-compatibility from one side to an increase in compressive concrete strength on the other, is discussed in this paper. The present work aims at investigating experimentally the relation between rheology, fibre distribution and mechanical properties of SFRSCC.

9.2. Experimental Procedure

The basic problem of the SCC, including those containing fibres, is their workability. From numerous studies which have considered the workability of mixture, it appears that it behaves under load as a viscoplastic Bingham body (Ponikiewski and Gołaszewski, 2012). The yield stress g and plastic viscosity h, called the rheological parameters are material constants, characterizing the rheological properties of the mixture according the formula:

$$\tau = \tau_o + \gamma\, \eta_{pl} \tag{9.1}$$

where τ (Pa) is the shear stress at shear rate γ (1/s), τ_o (Pa) is the yield value and η_{pl} (Pa·s) is the plastic viscosity (Tattersall and Banfill, 1983). The physical interpretation of yield value is that of the stress needed to be applied to a material in order to start flowing. When the shear stress is higher then yield value the mix flows and its flow resistance depends on plastic viscosity. Rheological parameters of fresh mortar, like those of fresh concrete, can be measured using Two Point Workability Test (TPWT), by applying a given shear rate and measuring the resulting shear stress. Because of the nature of the rheological behaviour of cement mixtures, the measurements should be taken at no less than two considerably different shear rates. The rheological parameters are determined by regression analysis according to the relation:

$$\mathrm{T} = \mathrm{g} + \mathrm{N}\,\mathrm{h} \tag{9.2}$$

where T is the shear resistance of a sample measured at rotation rate N and *g* (Nmm) and *h* (Nmms) are constants corresponding respectively to yield value τ_o and plastic viscosity η_{pl}. By suitable calibration of the rheometer, it is possible to express g and h in fundamental units. The principles of TPWT and rheological properties of fresh cement mortars and concretes are presented in existing literature (Tattersall and Banfill, 1983). The uniformity of distribution of steel fibers has been studied in SFRSCC molded as bars with dimensions of 600x150x150 mm.

9.3. Assumptions And Methodology Of Research

Results of workability tests of self-compacting cement mixes modified with steel fibres in rheological context are presented in this paper. Research was carried out with the rheometrical workability test (RWT) conducted with a rheometer for mortars and concrete mixes - Rheometer BT2 and Viskomat XL. RWT method was discussed in detail in literature (Tattersall and Banfill, 1983). An approximation of measurement results conducted by two-parameter Bingham rheological model. It allowed two basic rheological parameters - yield value *g* and plastic viscosity *h* to be determined by use of a two-parameter model. The composition of SFRSCC is shown in Table 9.1. Four types of steel fibres were used in the study (Table 9.2, Fig. 9.1). The self-compacting behavior was met by all tested concretes, according to adopted mixing procedure (Fig. 9.2). The obtained results are presented for samples with the fiber content 0.5 to 2.25% (40 to 180 kg/m^3). The self-compacting behavior was verified by the time and flow diameter measurements with Abrams cone as well as by the measured rheological parameters. 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 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 are presented in Figure 9.2.

Table 9.1. Composition of SFRSCC mixture, kg/m^3

Component	Symbol	Content kg/m3
CEM I 42,5 R	C	490,0
Sand 0–2 mm	S	756,0
Aggregate 2–8 mm	B	944,4
Water	W	226,4
Steel fibres – kg/m3 (% by volume)	F	20 – 160 (0.25 – 2.0)
Superplasicizer Glenium ACE 48 (3.5 % m.c.)	SP	17,0
Stabilizer RheoMatrix (0.4 % m.c.)	ST	1,6
W/(C+SF)	-	0,42
Slump-flow (SF)	-	SF1 – SF2

Table 9.2. Characteristics of applied steel fibres

Name	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%
DG 12.5/0.4	12.5±10%	0.40±10%	round		low-carbon steel	1250±15%
KE 20/1.7	20±10%	1.70±10%	rectangular		DC01	770±15%
ST 30/0.5	35±10%	2.30±2.95	part of circle		low-carbon steel	800±15%

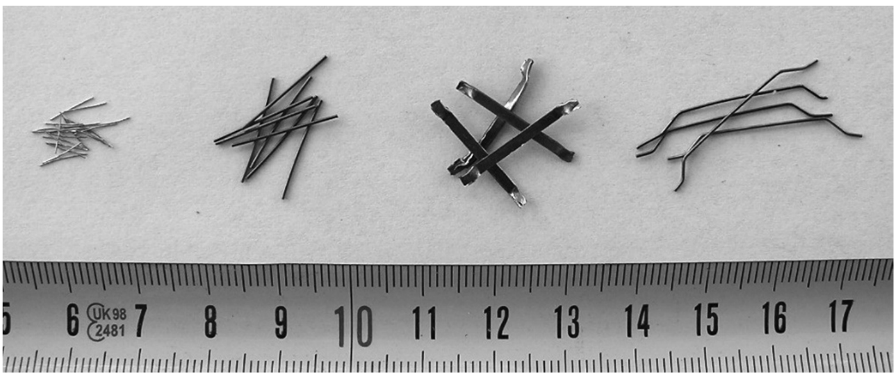

Fig. 9.1. Type of steel fibres used in the study: DM 6/0.17 ; DG 12.5/0.4 ; KE 20/1.7 ; ST 30/0.5

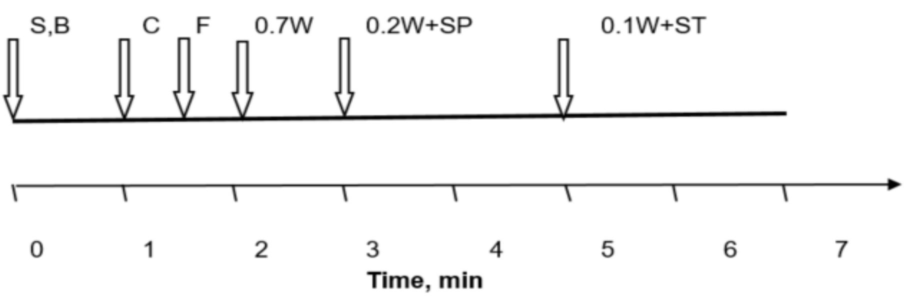

Fig. 9.2. Mixing procedure of SFRSCC

The basic problem of the new generation of concretes, including those containing fibres, 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. 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 uniformity of distribution of steel fibers has been studied in SFRSCC molded and tested as bars with dimensions of 600x150x150 mm (RILEM TC162-TDF, 2000). The static flexural strength tests were conducted on a 200 kN servo-controlled actuator and the specimens were loaded at third points. A minimum of two samples were tested for each combination of fibers.

9.4. Study on the effect of dosage of steel fibers into SCC

Workability and rheological properties

The paper also presents selected research on self-compacting concrete with steel fibers. Figure 9.3 shows the effect of the type and volume ratio of steel fibers on the diameter of the SF propagation and on the propagation time T_{500} of SFRSCC mixtures. Based on the study carried out, it can be concluded that an increase in the content of steel fibres in the mixture reduces the diameter of the SF propagation and prolongs the propagation T_{500}. The shorter fibres in the mix, the greater the scope of change. Generally, the effect of deterioration on the workability of SFRSCC mixes with the addition of steel fibers is small, in the range of research 40-80 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.

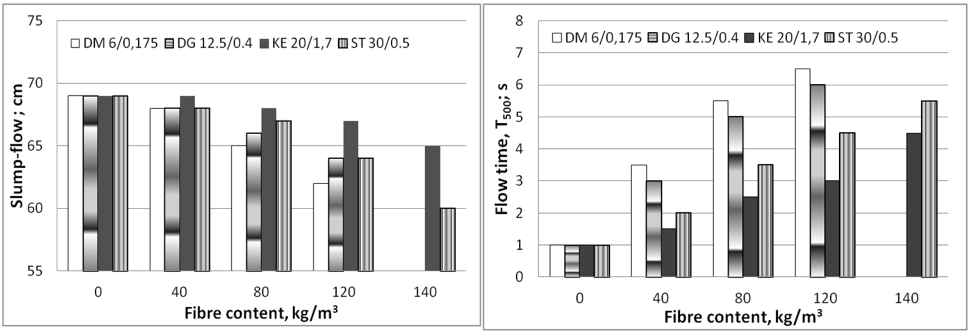

Fig. 9.3. Effect of steel fibres type and volume on slump-flow properties of SFRSCC; a) - slump-flow *SF* value; b) - flow time T_{500} value

Figure 9.4 shows the effect of the type and volume ratio of steel fibers on the rheological properties of SFRSCC according Viskomat BT2 research. It has been found that there is increasing rheological parameters yield value *g* and plastic viscosity *h* of self-compacting mixtures with increasing fiber content in the mixture. This effect is greatest for the SCC mixtures with ST 30/0.5 and DM 6/0.17 fibres. Increasing the content of KE 20/1.7 fibres showed no major changes in the values of *g* and *h* of SFRSCC with their addition.

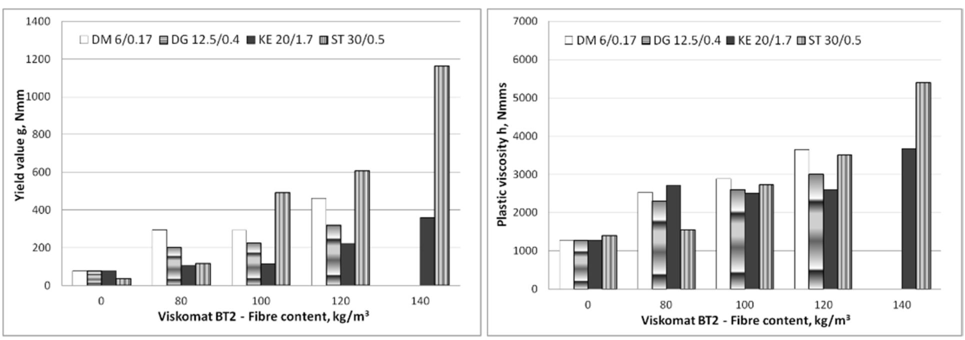

Fig. 9.4. Effect of steel fibres type and volume on rheological properties of SFRSCC according Viskomat BT2 research; a) - yield value g; b) - plastic viscosity h

Figure 9.5 shows the effect of the type and volume ratio of steel fibers on the rheological properties of SFRSCC according Viskomat XL research. It has been found that there is increasing rheological parameters yield value *g* and plastic viscosity *h* of self-compacting mixtures with increasing fiber content in the mixture as well. This effect is greatest for the SCC mixtures with DM 6/0.17 fibres.

Increasing the content of KE 20/1.7 fibres showed no major changes in the values of *h* of SFRSCC with their addition.

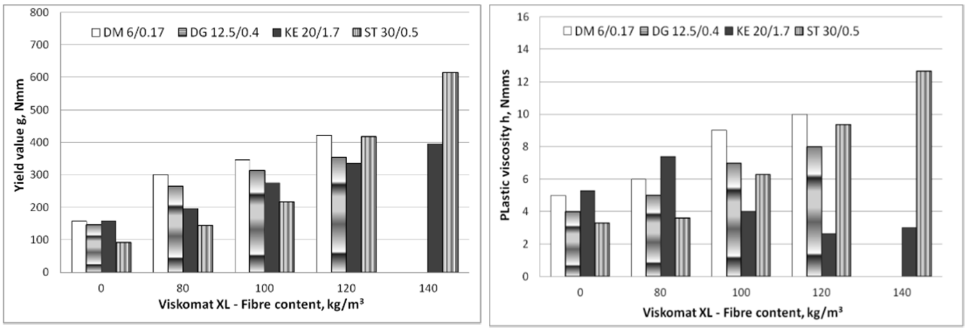

Fig. 9.5. Influence of steel fibres kind and volume on rheological properties of SFRSCC according Viskomat XL research; a) yield value g; b) plastic viscosity h

Flexural Strength Test and Compressive Strength Test Results

Flexural strength f_{fl} results for SFRSCC mixes with different type of fibres at different fibre volume fractions are shown in Fig. 9.6. The load-deflection curves obtained in this investigation for SFRSCC with different type of fibres at different fibre volume fractions are presented in Fig. 9.7 – 9.10. Figure 9.7 presents the load-deflection curves and compressive strength tests for SFRSCC with 40-80-120 kg/m^3 of DM 6/0.17 fibres. Figure 9.8 presents the load-deflection curves and compressive strength tests for SFRSCC with 40-80-120 kg/m^3 of DG 12.5/0.4 fibres. Figure 9.9 presents the load-deflection curves and compressive strength tests for SFRSCC with 100-140-160 kg/m^3 of KE 20/1.7 fibres. Figure 9.10 presents the load-deflection curves and compressive strength tests for SFRSCC with 40-80-120 kg/m^3 of St 30/0.5 fibres.

It can be seen from Fig. 9.7-9.10 that the maximum increase in flexural strength with respect to plain concrete was obtained for SFRSCC with St 30/0.5 fibres.

Figures 9.7 – 9.10 show the effect of the type and volume ratio of steel fibers on the compressive strength $f_{cm,28}$ of SCC. 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.

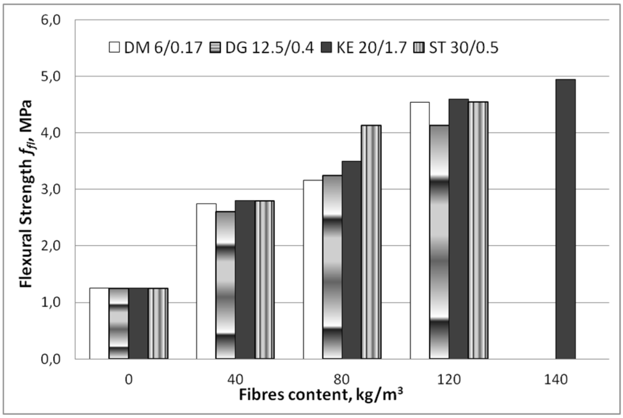

Fig. 9.6. Flexural strength ffl of SFRSCC with different fibres type and volume fractions

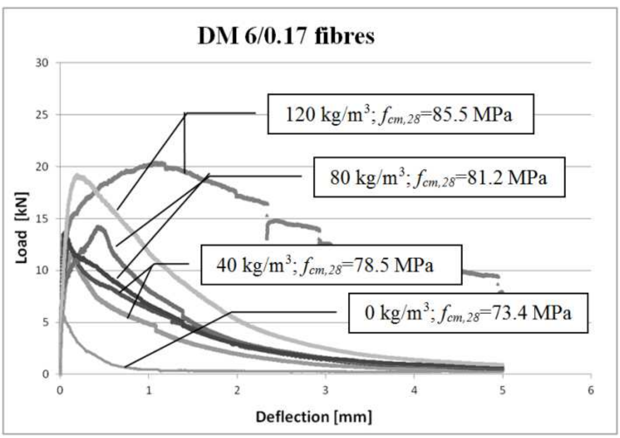

Fig. 9.7. Load-deflection curves and compressive strength tests for SFRSCC with DM 6/0.17 fibres (0 - 40 - 80 - 120 kg/m^3)

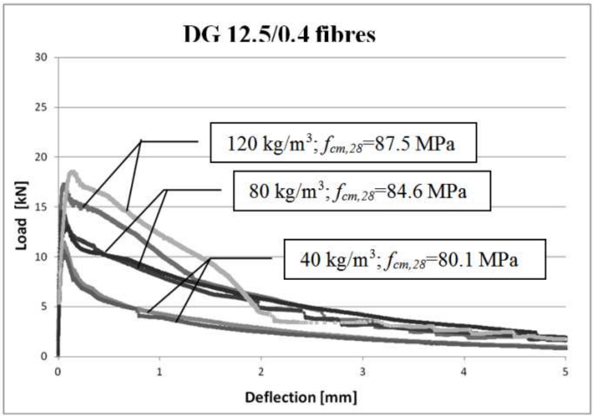

Fig. 9.8. Load-deflection curves and compressive strength tests for SFRSCC with DG 12.5/0.4 fibres (40 - 80 - 120 kg/m3)

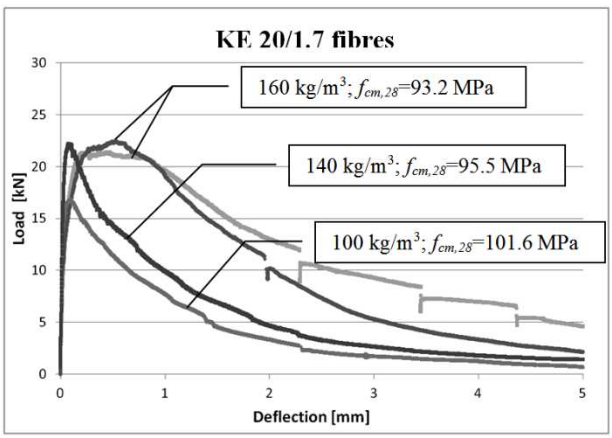

Fig. 9.9. Load-deflection curves and compressive strength tests for SFRSCC with KE 20/1.7 fibres (100 - 140 - 160 kg/m3)

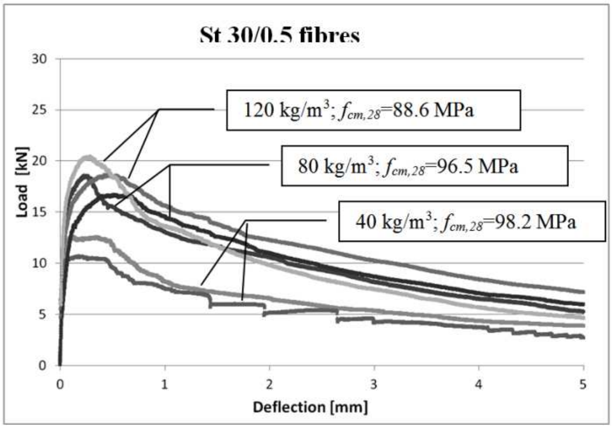

Fig. 9.10. Load-deflection curves and compressive strength tests for SFRSCC with ST 30/0.5 fibres (40 - 80 - 120 kg/m^3)

Figure 9.11 presents the flexural strength f_{fl} - yield value g curves for SFRSCC with all detected steel fibres.

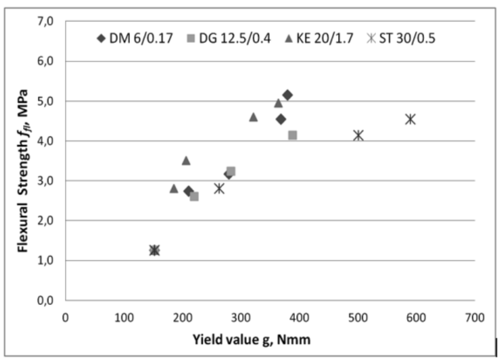

Fig. 9.11. Flexural strength f_{fl} - yield value g curves for SFRSCC with steel fibres

In general, increasing yield value g causes linear increase of flexural strength f_{fl} of SFRSCC but the increasing number of fibres affects the rheological properties of the mix and its strength, while there is no cause and effect relationship between these properties. So, the optimal fibre content and type according rheological and mechanical can be used.

The computed tomography X-ray of 2D sections of SFRSCC beams, with F 30x0.7 mm fibres are presented in Figures 9.12 and 9.13. The 2D cross-section of the concrete with ST 30x0.5 fibres, located at 0 - 10 - 20 - 30 - 40 cm from concreting places is shown in Figures 9.12. In general, increasing distance between forming places causes the trend of the orientation of fibres and irregular distributed in

SFRSCC. Fig. 9.13. X-ray 2D images of SFRSCC beams sections with ST 30x0.5 fibres located at 1 - 3 - 7 - 10 - 14 cm from its down surface.

The 2D image confirms the trend of the orientation of fibers in a matrix of concrete. The fibres are generally evenly distributed in concrete, with the exception of selected sections of the edge of the concrete.

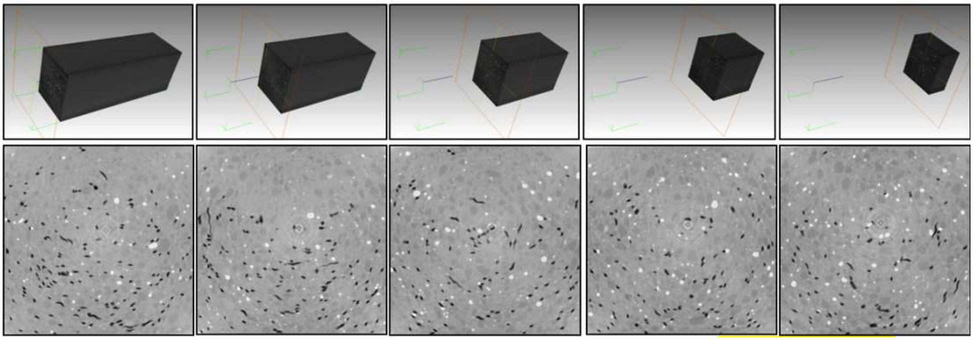

Fig. 9.12. X-ray 2D images of SFRSCC beams sections with ST 30x0.5 fibres; located at 0 - 10 - 20 - 30 - 40 cm from concreting places

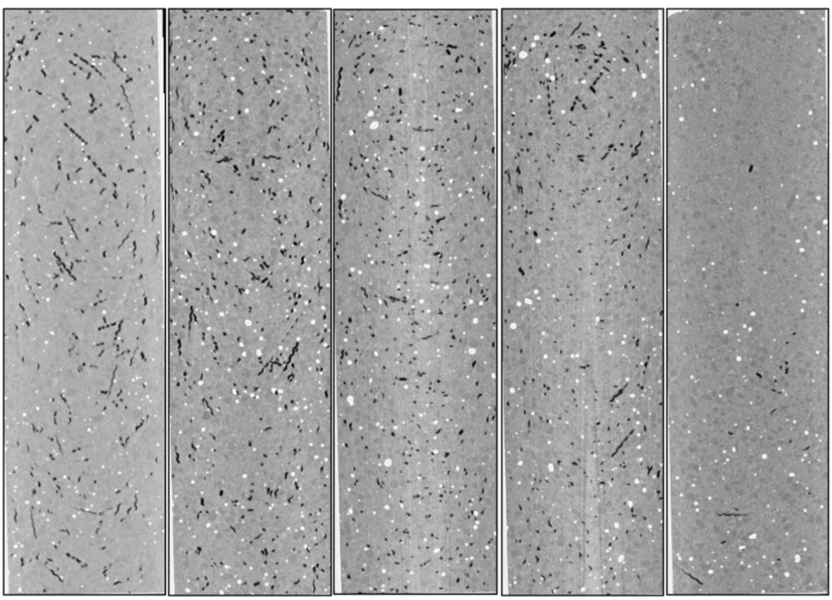

Fig. 9.13. X-ray 2D images of SFRSCC beams sections with ST 30x0.5 fibres; located at 1 - 3 - 7 - 10 - 14 cm from its down of beam

The 3D cross-section of the concrete with KE 20/1.7 fibre, laying between 400-500 mm from the surface of the sample, is shown in Figures 9.14. 3D image confirms the trend of the orientation of fibres in a matrix of concrete. The fibres are generally evenly distributed in concrete, with the exception of particular sections on the edge of the concrete.

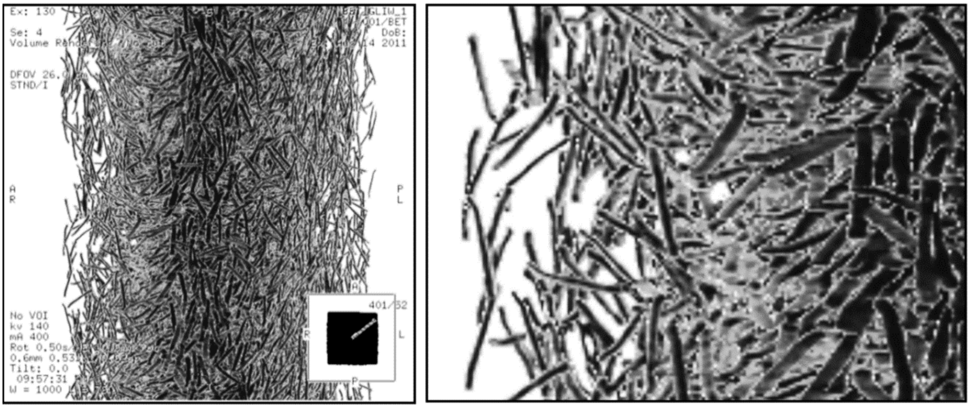

Fig. 9.14. X-ray 3D image of SFRSCC bars sections with KE 20/1.7 fibres located at 400 ÷ 500 mm from its surface

3.5. Conclusions

The main scope of the paper was to examine the characterization of rheology and mechanical properties of SFRSCC and to establish the optimal relationships between rheology and mechanical properties. Rheological properties, slump-flow workability, compressive strength and flexural strength of SFRSCC were investigated. Basing on experimental research, with application of the new rheological equipment and computed tomography, some preliminary results were obtained in the undertaken realm of investigation.

Decline in workability of concrete mixtures occurs, but to a certain extent the properties of self-compatibility are maintained.

The self-compatibility of concrete mixtures deteriorates with an increasing volume ratio of fibers in the mixture of self-compacting concrete. Despite the deterioration in the workability, it is possible to attain self-compatibility for mixtures with the addition of steel fibers and with good mechanical properties.

It was also shown that using the rheological properties of matrix with the content and geometry of fibre it is possible to predict the flexural strength of SFRSCCs.

The orientation of fibers connected with the direction of the SFRSCCs mix flow during moulding was confirmed. Proved as well was the uniform distribution of fiber in the produced concrete element.

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