Investigation of Mechanical Properties of Steel Fibre-Reinforced Concrete

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Abstract. Steel fibre-reinforced concrete (SFRC) is widely used in the structural elements of buildings: industrial floors, slabs, walls, foundation, etc. When a load is applied to a fibre-reinforced composite consisting of a low-modulus matrix reinforced with high-strength, high-modulus fibres, the plastic flow of the matrix under stress transfers the load to the fibre; this results in high-strength, high-modulus material which determines the stiffness and stress of the composite. In this study the equivalent flexural strength, equivalent flexural ratio $R_{e,3}$ and the compressing strength of SFRC are investigated. Notched test specimens with five different dosages of steel fibres (20, 25, 30, 35, 40 kg/m$^3$) were prepared using industrial concrete. Determination of flexural tension strength was carried out according to the EU norm EVS-EN 14651:2005+A1:2007. The equivalent flexural strength and subsequent equivalent flexural ratio $R_{e,3}$ of SFRC with a dosage of 20, 25, 30, 35 kg/m$^3$ similar to their average values and with a dosage of 40 kg/m$^3$ were 31% higher than their average values. The compressive strength of the steel fibre-reinforced concrete was slightly higher compared to plain concrete, except specimens with the dosage of 40 kg/m$^3$ where the increase was 30%.

1. Introduction
Steel fibre-reinforced concrete (SFRC) is currently used in a wide range of applications, including bridges, industrial floors, walls, tunnels and structural slabs [1,2,3]. The FRC is a concrete made primarily of hydraulic cements, aggregates and discrete reinforcing fibres. A variety of tests have been performed to determine the actual characteristics and advantages of fibrous materials [4,5,6]. Fibres suited to reinforcing composites are made of steel, glass and organic polymers [7]. Different fibres differently affect the properties of concrete. Addition of synthetic fibres prevents cracking caused by plastic shrinkage and plastic setting, and provides tensile strength in the initial phase of hardening [7].

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Synthetic fibres do not affect the load-bearing capacity of construction elements. Addition of steel fibres provides concrete with higher flexural tensile strength, higher cracking resistance, higher impact resistance and higher resistance to volume shrinkage [7]. Steel fibres are effectively used for reinforcement of edge and corner regions, where shear stresses are higher. In the case of using steel fibres as primary reinforcement, cracking of concrete caused by plastic setting under reinforcement rods is eliminated.

The SFRC has advantages over traditionally reinforced concrete in civil engineering. Steel fibres are added to concrete mix and become an integral part of fresh concrete. Thus SFRC can be then pumped like plain concrete and there is no need for preparing the reinforcement frame. Reinforcement by steel fibres can improve resistance to shrinkage cracking and durability of reinforced concrete structures. Addition of steel fibres sufficiently improves the post-cracking process of concrete [1,2,8,9]. High wearing of the concrete pumping equipment can be mentioned as a disadvantage of SFRC.

The design and analysis of structures containing SFRC depend on its mechanical parameters. The objectives of the present study were: 1) to determine the flexural behaviour of industrial C25/30 class of concrete with five different steel fibre dosages: 20, 25, 30, 35, 40 kg/m³; 2) to determine the effect of steel fibre dosage on the ultimate compressive strength.

Fracture energy is an important characteristic in describing the properties of concrete and in determining the design criteria for concrete structures with SFRC. Fracture energy is defined as the area under the load-deflection curve per unit fractured surface area [4].

2. Experimental work

2.1. Test specimens

Test specimens with five dosages of crimped steel fibres SAVEX 1/50 (20, 25, 30, 35, 40 kg/m³) were manufactured by the concrete production company Rudus AS, they represented industrial class C25/30 concrete with water/cement ratio of 0.5. The mix details of concrete are presented in table 1. Twelve specimens were prepared with each dosage of fibres.

| Material     | Quantity (kg/m³) |
|--------------|------------------|
| Cement       | 258              |
| Sand         | 843              |
| Gravel 4-12  | 362              |
| Gravel 4-16  | 288              |
| Water        | 142              |

Specimens for bending tests were prisms conforming to EN 12390-1 [10] with a nominal size: section width 150 mm and depth and length 600 mm. The mould was filled up to approximately 90% of the height of the test specimen and the mix was compacted by external vibration. After compacting the mould was topped up and levelled off. All specimens were demoulded after about 48 h and stored in water at room temperature up to 28 days, and were then removed and stored until testing. All specimens were notched before testing. Test specimens were rotated by 90° around their longitudinal axis and were then sawn through at the mid-span of the specimen. The width of the notch was 5 mm and the depth 25 mm (figure 1b).
The test specimens for the compressing tests with dimensions 150×150×150 mm were sawed out after bending tests from the parts of beams. Four specimens were prepared with each dosage of fibres. Specimens for determination of the compressing strength of the plane concrete were cast at the same time as were casted beams for bending tests.

2.2. Experimental procedure
Experiments were carried out in accordance with EN 14651:2005+A1:2007 [11]. An Instron 3369 testing machine (figure 1a) with a capacity of 50 kN was used for the bending tests. The specimens were tested at deflection control rates so that deflection increased at a constant rate of 0.08 mm/min. When deflection equalled to 0.13 mm, the machine was operated so that deflection increased at a constant rate of 0.21 mm/min. The test was terminated at a deflection value of 5 mm. Deflection was measured at the mid-span by means of a video extensometer to 0.001 mm.

The yoke arrangement was designed and manufactured for holding the assisting equipment of the video extensometer at the mid-span of the specimen. A schematic diagram illustrating the test set-up is presented in figure 1. Holes were introduced using a masonry drill at the mid-height of the beams at the supports to install screws to hold the yoke arrangement. The yoke arrangement held assisting equipment so that deflections were measured directly from the specimen. Mid-span deflection readings depending on the load were recorded at the rate of 5 Hz.

Compressing tests were carried out in accordance with EVS-EN 12390-3:2002 [12].

![Figure 1](image)

**Figure 1.** (a) Testing machine Instron 3369 and (b) test set-up for a notched beam specimen.

3. Results and discussion
Five experiment series S20, S25, S30, S35, S40 were carried out with a steel fibres content of 20, 25, 30, 35, 40 kg/m³, respectively. A typical bending diagram representing the dependence of central deflection on the load is shown in figure 2. Strain is obtained according to basis b (figure 1b) of video extensometer.
One of the advantages of using steel fibres is improvement of the post-cracking behaviour of concrete. The appearance of the first crack during flexural loading is clearly the evidence of the ultimate stress of plain concrete. After the first crack, the strength of the specimen diminishes. During this process steel fibres bridge the crack preventing its propagation. A specimen with a bridged crack can successfully carry on external load which in some cases can even be higher than the ultimate load of plain concrete.

In accordance with the standard EVS-EN 14889-1:2006 [13], the minimum dosage of fibres in concrete must be such that a residual flexural strength ($f_{0.47}$) of 1.5 MPa is achieved at 0.47 mm of central deflection and a residual flexural strength ($f_{3.02}$) of 1.0 MPa at 3.02 mm of central deflection. $F_L$ is the load at the limit of proportionality, which corresponds to the formation of the first crack. The results of experiments and the calculations of five experiment series are presented in table 2.

**Table 2.** Data of specimens and results of experiments.

| Series No | Dimensions of section (mm) | Residual flexural strength (MPa) | Equivalent flexural strength | $R_{e,3}$ (%) |
|-----------|----------------------------|---------------------------------|-----------------------------|---------------|
|           | Height | Width | $f_L$  | $f_{0.47}$ | $f_{3.02}$ | $f_{e,3}$ (MPa) | $R_{e,3}$ (%) |
| S20       | 126    | 155   | 4.23±0.13 | 2.20±0.34 | 1.68±0.26 | 2.24±0.29 | 53±7   |
| S25       | 125    | 156   | 4.30±0.13 | 2.20±0.44 | 1.78±0.35 | 2.18±0.37 | 51±8   |
| S30       | 126    | 155   | 4.39±0.08 | 2.18±0.30 | 1.74±0.27 | 2.14±0.29 | 49±7   |
| S35       | 125    | 154   | 4.47±0.13 | 2.35±0.16 | 1.94±0.16 | 2.30±0.15 | 51±2   |
| S40       | 125    | 154   | 4.42±0.14 | 2.90±0.49 | 2.48±0.43 | 2.91±0.47 | 65±9   |

The equivalent flexural strength of SFRC was determined according to the code of the Japanese Society of Civil Engineers – JSCE-SF4 [14]. The equivalent flexural strength ($f_{e,3}$) is determined from the area below the load-deflection curve until measured deflection becomes 1/150 of the specimen’s span. This value of stress can be used directly for designing SFRC elements. Further toughness of SFRC can be estimated by the equivalent flexural ratio $R_{e,3} = f_{e,3}/f_L$. The higher is the value of $R_{e,3}$, the higher is load capacity and ductility.

Compressing tests were carried out on concrete samples at the age of eight months and the results are presented in table 3.
Table 3. Results of compressing tests.

| Series No | Average dimensions of section (mm) | Ultimate load (kN) | Average compressing strength (MPa) |
|-----------|-----------------------------------|--------------------|-----------------------------------|
| S20       | 151.2 153.1                       | 924                | 39.9                              |
| S25       | 151.4 153.5                       | 990                | 42.6                              |
| S30       | 150.8 153.6                       | 841                | 36.3                              |
| S35       | 150.4 155.0                       | 886                | 38.0                              |
| S40       | 150.7 150.8                       | 1069               | 47.0                              |

Four specimens from each series were tested under the compressive load. Compared to compressive strength $f_c = 36.0$ MPa of plain concrete, there is a slight increase in the compressive strength of SFRC specimens. Highest compressive strength is observed for the specimens of series S40.

It has been shown [15] that failure in compression occurs in a localized zone as a shear or cleavage fracture. The failure mode of concrete specimens can be considered as resulting from local tensile mechanisms, or from a combination of tensile and shear mechanisms. Mainly three-dimensionally distributed steel fibres can markedly reinforce both shear failure (oblique cracks) and splitting failure (vertical cracks). At early age, in comparison with plain concrete, steel fibres can significantly increase the duration of the peak load. In the long term, for hardened concrete, steel fibres have no influence on the duration at peak load. Damage of concrete is initiated because of distributed micro-cracks caused by the shrinkage of cement paste around aggregates [4].

4. Conclusions
The equivalent flexural strength, equivalent flexural ratio $R_{e,3}$ and compressive strength of SFRC with steel fibres Savex 1/50 were determined in this study. The equivalent flexural strength and subsequently equivalent flexural ratio $R_{e,3}$ of SFRC with a dosages of 20, 25, 30, 35 kg/m$^3$ were similar and with dosage of 40 kg/m$^3$ was 31% higher compared to their average values. In all cases, the obtained stress values can be used directly for designing of SFRC elements, as results meet the requirements of code [13]. The compressive strength of the steel fibre-reinforced concrete was slightly higher compared to plain concrete, except S40 where increase was 30%.

5. References
[1] Banthia N, MacDonald C and Tatnall P 1999 Structural Applications of Fiber Reinforced Concrete. ACI International, SP-182 (Mich: Farmington Hills) p 257
[2] Altun F, Haktanir T and Ari K 2007 Effects of steel fiber addition on mechanical properties of concrete and RC beams Construction and Building Materials 21 654–661
[3] Chiaia B, Fantilli A P and Vallini P 2009 Combining fiber-reinforced concrete with traditional reinforcement in tunnel linings Engineering Structures 31 1600–06
[4] Köksal F, Sahin Yu, Gencel O and Yigit I 2013 Fracture energy-based optimisation of steel fibre reinforced concretes Engin. Fracture Mechanics 107 29–37
[5] Kim J, Kim D J and Zi G 2013 Improvement of the biaxial flexure test method for concrete Cement & Concrete Composites 37 154–160
[6] Pajak M and Ponikiewski T 2013 Flexural behavior of self-compacting concrete reinforced with different types of steel fibers Construction and Building Mat. 47 397–408
[7] Andrzej M B 2008 Fibre reinforced cement-based (FRC) composites after over 40 years of
[8] Khaloo A R and Afshari M 2005 Flexural behavior of small steel fibre reinforced concrete slabs *Cement & Concrete Composites* **27** 141–149

[9] Altun F, Haktanir T and Ari K 2007 Effects of steel fiber addition on mechanical properties of concrete and RC beams *Construction and Building Mat.* **21** 654–661

[10] EVS-EN 12390-1:2012 Testing hardened concrete. Part 1: Shape dimensions and other requirements for specimens and moulds *Estonian centre for standardisation* (Tallinn)

[11] EVS-EN 14651:2005+A1:2007 Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual) *Estonian centre for standardisation* (Tallinn)

[12] EVS-EN 12390-3:2009 Testing hardened concrete - Part 3: Compressive strength of test specimens *Estonian centre for standardisation* (Tallinn)

[13] EVS-EN 14889-1:2006 Fibres for concrete - Part 1: Steel fibres - Definitions, specifications and conformity *Estonian centre for standardisation* (Tallinn)

[14] JSCE-SF4 1984 Methods of tests for flexural strength and flexural toughness of fibre reinforced concrete *Japan Society of Civil Engineers*

[15] Ding Y and Kusterle W 2000 Compressive stress-strain relationship of steel fibre-reinforced concrete at early age *Cement & Concrete Composites* **30** 1573–79