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X-ray computed tomography harnessed to determine 3D spacing of steel fibres in self compacting concrete (SCC) slabs

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HIGHLIGHTS

- Engineered steel fibre are important type of concrete reinforcement.
- SCC and FRC are combined into one type of cement composite.
- We examine fibre spacing in FRC–SCC slabs.
- X-ray computed tomography is harnessed to conduct the tests.
- Distribution and spacing analysis of fibre has been performed.

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ABSTRACT

The conducted research programme was focused on fibre spacing in SFR-SCC slabs. SCC slabs with two steel fibres types and different casting points were examined. A distribution and spacing analysis of fibres has been performed. Their number and volume were evaluated along the slab main axis. The distribution of fibres in slabs cast using different techniques have been compared. The amount of fibres in the upper and lower slab halves has been analysed. The uniformity of spacing of fibres was assessed. The angles between the fibres and the beam main axis were examined. Graphical visualization using 4D spherical histograms for quick assessment of fibres orientation is also presented.

1. Introduction

Steel fibre mixed into the concrete can provide an alternative to the provision of conventional re-bars or welded fabric in many applications of concrete. The concept has been in existence since 1874 when the first patent was applied for in California by Berard [23]. During 1970s the commercial use of steel fibre reinforced concrete (SFRC) began to gather momentum, especially in Western Europe, USA and Japan. Current increasing widespread of SFRC is observed due to its hassle free casting while preserving mechanical properties similar to traditionally reinforced concrete using bars and stirrups. There are many areas of civil engineering where SFRC is the main construction material. It has been widely adopted for industrial floors (both ground-supported and pile supported), external pavements, sprayed concrete and precast elements [12,23]. The newest trend in development of technology of SFRC is creation of a self-compacting SFRC. The first self-compacting concrete (SCC) also known as self-consolidating concrete or self-levelling concrete was pioneered in late 1970s and early 1980s in Germany, Italy and Japan [24]. This flowing concrete is able to completely fill the formwork (even in the presence of dense reinforcement) whilst maintaining homogeneity and consolidate under its own weight without the need of any additional compaction [10,20,22,35]. Combining both non-conventional concretes (SFRC and SCC) into a new type of fibre cement composite

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(SFR-SCC) would create a material opening wide range of future applications, especially in case of structures vulnerable to blast, harmonic and fatigue loading [4,5,16,32,33]. The new composite potentially gives previously unknown flexibility in designing and creating concrete structures. It could also be viable in purely economic terms due to eliminating both most laborious processes: placing bar-stirrup reinforcement and consolidating fresh mix. To fully utilize the composite its technology and mechanical properties have to be thoroughly tested and described. The properties of fresh mix and hardened SFR-SCC strongly depend on fibre spacing within cast element [7,13,14,27]. The dependence of casting methods and mix composition on fibre spacing and mechanical properties of SFR-SCC is a subject of multiple on-going research programmes [3,15].

The core idea behind the research programme was to assess fibre spacing of hardened SFR-SCC. To achieve this goal slabs were cast using only one type of SFR-SCC. The only variable was the location of the concrete casting points (CCP). The aim of the research programme was to denominate the correlation between the location of CCP and fibre spacing in hardened SFR-SCC element. The authors decided to harness X-ray computed tomography (CT) as an efficient and flexible tool in the non-destructive high-resolution characterization of the microstructural configuration of materials [19,21,36]. CT technology widely used in medicine allows to assess the air voids spacing and porosity characteristics of the concrete specimens.

2. Used materials, mix design and specimens

The test were conducted on the SFR-SCC modified by one type of steel fibres. Crimped steel fibres characterized by length of 50 mm were chosen as the most suitable for planned research programme. The choice of fibres was based on previous experience with steel fibre reinforced concrete and SCC. The commercial availability and commonness of civil engineering applications of specific fibre types were also studied and taken into consideration [18]. The geometry and other parameters of used steel fibres are presented in Table 1.

The composition of the mix characterized by W/C ratio equal to 0.41, was fixed for all castings (see Table 2). CEM I 42.5R was utilized as a binder and its content was equal to 490 kg/m^3. Such cement content was successfully harnessed by multiple researchers [3,7,25]. The cement was characterized by initial and final setting time of 170 min and 250 min respectively. Fineness of the cement was equal to 3400 cm^2/g. There were used two admixtures: superplasticizer and stabilizer. The superplasticizer based on polycarboxylate ether (concentration 20%) and characterized by density equal to 1.07 g/cm^3 was applied into the mix in the amount of 3.5% (of the mass of cement) [9]. The stabilizer in a form of a synthetic co-polymer and characterized by density equal to 1.01 g/cm^3 was added in the amount of 0.4% (of the mass of cement). Utilized aggregate was in a form of natural sand (median diameter d_m = 0.435 mm [17]) and natural subrounded gravel.

The authors applied mix proportioning system described by Okamura and Ozawa [26] which assumes general supply from ready-mixed concrete plants. The coarse and fine aggregate contents are fixed so that self-compatibility is achieved easily by adjusting only the water-powder ratio and superplasticizer dosage [25]. The details of mixing procedure is presented in Fig. 1.

The specimens were in a form of slabs (150 mm × 1210 mm × 1240 mm). The fresh mix was poured to the forms from two different concrete casting points. Slab C1 was prepared while pouring concrete on the edge of a mould. Slab C2 was prepared while pouring concrete in a centre of a mould. Both slabs were reinforced by addition of 1% of fibres (80 kg/m^3). The location of both CCP and mould/specimen sizes are presented in Fig. 2. After hardening, slabs were cut into 16 beams with dimensions 150 mm × 150 mm × 600 mm each which were non-destructively tested using X-ray computed tomography.

3. Research programme

The research programme consisted of three main stages. Stage one covered properties of fresh mix such as density tested according to PN-EN 12350-6: 2011 [29] and consistency assessed with the help of the slump-flow test according to RILEM TC 145-WSM [1]. During the slump flow test two parameters were measured: the diameter (SFD in mm) of the concrete pat after removal of the slump cone and the time (T_{500} in seconds) in which the flowing mix formed a 500 mm concrete pat.

Stage two of the research programme covered non-destructive tests harnessing X-ray computed tomography conducted on beams. The applied computed tomography scanner was equipped with 64 rows of detectors, and the thickness of a series of reconstructed native CT scan was 0.625 mm. The penetration factor was an X-ray beam. The examined surface of each layer of concrete was 150 mm × 150 mm. For each beam the result consisted of a native series written in DICOM (Digital Imaging and Communications in Medicine) format with at least 950 images, and reconstructed series with at least 1500 images taking into account the interval in the range 50 ÷ 80% of the thickness of the native layer. Parameters of acquisition were not less than: 140 kV lamp voltage and 400 mA s current strength. Acquired CT volumetric images were processed by in-house built software using C++ libraries for

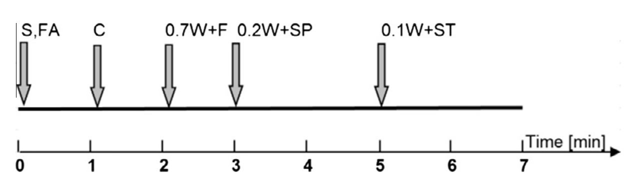


Fig. 1. Mixing procedure. (S – sand, FA – fine aggregate, C – cement, W – water, F – fibre, SP – superplasticizer, ST – stabilizer).

Table 1
Characteristics of steel fibres.

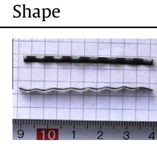
Fibre type	Length (mm)	Width (mm)	Cross section	Shape	Material	Tensile strength (N/mm^2)	Number of fibres per kg
F 50	50 ± 10%	2.30/2.95	Segment of a circle		Low carbon steel wire	800 ± 15%	1128

Table 2
Composition of SFR-SCC mix.

Cement CEM I 42.5R (kg/m^3)	Sand (0–2 mm) (kg/m^3)	Fine aggregate (2–8 mm) (kg/m^3)	Water (kg/m^3)	Steel fibres (% by volume) (kg/m^3)	Superplasticizer (kg/m^3)	Stabilizer (kg/m^3)	W/C
C	S	FA	W	F	SP	ST	–
490	807.3	807.3	201	80 (1.02)	17.2	1.96	0.41