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Mechanical behaviour of steel fibre reinforced SCC after being exposed to fire

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Abstract. The focus of this paper is given to the investigation of mechanical properties of steel fibre reinforced self-compacting concrete after being exposed to fire. The research programme covered tests of two sets of beams: specimens subjected to fire and specimens not subjected to fire. The fire test was conducted in an environment mirroring one of possible real fire situations where concrete surface for an extended period of time is directly exposed to flames. Micro-cracking of concrete surface after tests was digitally catalogued. Compressive strength was tested on cube specimens. Flexural strength and equivalent flexural strength were tested according to RILEM specifications. Damages of specimens caused by spalling were assessed on a volumetric basis. A comparison of results of both sets of specimens was performed. Significant differences of all tested properties between two sets of specimens were noted and analysed. It was proved that the limit of proportionality method should not be used for testing fire damaged beams. Flexural characteristics of steel fibre reinforced self-compacting concrete were significantly influenced by fire. The influence of fire on properties of steel fibre reinforced self-compacting concrete was discussed.

Keywords: concrete; fire; fibre; SCC; SFRC; mechanical properties

1. Introduction

One of the key advantages of using steel fibre reinforced concrete (SFRC) instead of traditionally reinforced (by re-bars and stirrups) concrete is their much higher resistance to fire. The presence of a dispersed steel in the whole volume of concrete influences its thermal conductivity. SFRC can reach thermal conductivity up to 40% higher than ordinary concrete (Blesak *et al.* 2016). High thermal conductivity allows SFRC to quickly dissipate heat in much larger volume than in ordinary concrete. This way, significantly longer time is needed by SFRC to start chipping and spalling (Maidl 1995).

Explosive spalling is also limited by the presence of fibre (Ding *et al.* 2016) which influence

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the volume of trapped air in a concrete mix. The coefficient of thermal expansion is not influenced by fibre reinforcement (Firmo and Correira 2015). All the above facts make SFRC particularly suited for specialised applications where fire resistance is the key factor for the safety of a structure. Traditionally, underground structures were considered as especially vulnerable to fire, thus SFRC is becoming a popular main construction material for shield tunnel segments and similar elements (Yan *et al.* 2015). Currently, terrorist-proof structures are quickly becoming the main application of SFRC due to its desired dynamic characteristics (Cichocki and Ruchwa 2015). These structures, apart from being resistant to impact and blast loadings are also foreseen to resist effects of subsequent fire. The characteristics of fire taking place in confined underground or closed space and fire taking place in open air is very different especially in terms of temperature gradient profiles (Taylor *et al.* 1992). So far, the majority of fire tests of ordinary concrete and SFRC have been realized to mimic the conditions in confined underground or closed space (Šimonová *et al.* 2018a, Šimonová *et al.* 2018b). There is a need to fill the gap in knowledge about behaviour of SFRC in an open air fire scenario. One should also take into account new types of concrete matrix used for creation of fibre concrete. The newest trend in development of SFRC is utilizing self-compacting concrete (SCC) as a matrix for fibre reinforcement. The concept of SCC was born in Japan in late 1980s and first full scale applications took place in the 1990s (Okumura and Ozawa 1996). Combining SFRC and SCC (SFR-SCC) has a wide range of potential of previously unknown structural applications (Ponikiewski and Katzer 2015). Fibre spacing in SFR-SCC is different than in ordinary SFRC (especially when considering thin elements). It was also proven that fibre spacing in SFR-SCC elements varies due to the casting process, mix flow rate, the wall effect, the location of mix casting point and the proximity to the bottom of a mould (Bui *et al.* 2003, Bywalski and Kamiński 2011, Martinie and Roussel 2011). The mix composition of SFR-SCC differ significantly from ordinary SFRC due to fineness of used aggregate, amount of used: cement, water, fine fillers and volume of added chemically active admixtures. The volume and spacing of air pores is also different in hardened SFR-SCC than in ordinary SFRC (Ponikiewski and Gołaszewski 2016, Ponikiewski and Katzer 2016). All the above facts influence behaviour of SFR-SCC when exposed to fire. Multiple differences between internal structure of SFRC and SFR-SCC disable utilizing knowledge about behaviour of SFRC under fire loading for forecasting behaviour of SFR-SCC under fire loading. Moreover, majority of research programmes focused on fire resistance of SFRC were conducted using only high temperature environment (Abdallah *et al.* 2017, Arioz 2009, Dugenci *et al.* 2015, Guerrieri *et al.* 2009, Hager *et al.* 2015). Such tests gave us thorough knowledge about thermo-hydral processes taking place inside concrete but do not reflect majority of real fire situation. Specimens placed in a lab oven with uniformed and stable high temperature conditions are useful for following the phenomenon of generating high pore pressure and pressure gradients but do not mirror exposure of concrete surface to flames which takes place in many of real fire scenarios. Such scenarios are particularly important in case of open air civil engineering structures vulnerable to terrorist attacks such as bridges, dams, towers, large scale retaining walls, piers etc. Taking into consideration the above facts, authors decided to conduct a research programme focused on SFR-SCC which would create fire test environment as close to a real fire scenario as possible, including extinguishing process. On the other hand SFR-SCC specimens were prepared using casting procedures used on an average construction site. The size of cast specimens was in scale of 1:2 of a real-life precast elements. Different types of surfaces exposed to fire were of interest, too. The main aim of the research programme was to test mechanical properties of hardened SFR-SCC being exposed to fire for one hour and then extinguished using cold water. Mechanical characteristics of SFR-SCC subjected to fire and extinguishing were compared with properties of reference specimens. Discussion was conducted and conclusions were drawn.

2. Used materials and mix composition

The SCC in question was based on two types of natural aggregate: sand (0 mm-2 mm) and sub-rounded gravel (2 mm-16 mm). Sand and gravel were characterized by median diameter (Katzer 2012) d_m equal to 0.36 mm and 1.79 mm, respectively. The aggregates were mixed in weight proportion 1 to 1. The resulting aggregate was characterized by d_m=0.75 mm. Calculated values of fineness moduli by Kuczynski (U_K), Hummel (U_H) and Abrams (U_A) were equal to 4.77, 111.2 and 3.70, respectively. Portland Cement CEM II/B-M(V-W) 32.5 was utilized as a binder. This cement contains silica, fly ash and lime fly ash in the amount of 15% each. The setting time of the cement is equal to 220 min±10 min. Two admixtures were harnessed to prepare the concrete mix. As a superplasticizer an admixture based on polycarboxylate ether was chosen (ρ=1.07 kg/dm^3, concentration 20 %). The role of a stabilizer was played by admixture based on synthetic co-polymer (ρ=1.01 kg/dm^3). SCC mix was reinforced by the addition of crimped steel fibre.

This type of fibre proved to be compatible with SCC mixes (Ponikiewski and Katzer 2016). The geometric shape and properties of the used engineered steel fibre (Zarzycki *et al.* 2017) are presented in Fig. 1. The last material used for mix creation was ordinary tap water. The mix composition of a cubic meter was as follows: cement -490.0 kg, water -200.9 kg, aggregate -1614.6 kg, superplasticizer -9.8 kg, stabilizer -2.0 kg, fibre -80 kg. The achieved w/c ratio was equal to 0.41 and fibre volume (V_f) was equal to 1%.

3. Mix and specimens preparation

Length [mm]	50±1
Width [mm]	2.30-2.95
Cress-section	segment of a circle
Type of steel	low-carbon
Tensile strength [MPa]	800±120
Number of fibre per 1 kg	1128

Fig. 1 Engineered steel fibre used as reinforcement (mean values with standard deviation)

Fig. 2 Casting, cutting of the slabs and assigned numbers of the beams

SCC mix was prepared in 350 dm^3 rotary drum mixer. The procedure of mix creation was divided into five steps. Initially, dry ingredients were mixed for 2 min. Subsequently, 50% of water was added and the mixing was continued for 2 min. Then 35% of water with all the superplasticizer was added and the mixing was continued for 2 min. Next the remaining 15% of water and the stabilizer were added and the mixing was continued for 2 min. Fibre was added to the mix as the last step of mix preparation. The final part of mixing of all the ingredients lasted 3 min. This procedure was successfully utilized during multiple previous research programmes focused on SCC (Ponikiewski and Katzer 2015, Ponikiewski and Gołaszewski 2016). The mix proved to be of a very good quality during these research programmes thus currently it was controlled only by the means of a basic slump flow test. EFNARC (2002) requirements for SCC were used as a reference point. SCC mix in question was characterized by the slump flow diameter (SFD) of 775 mm±5 mm fulfilling the minimum EFNARC requirement of 650 mm. It can be classified as SF3. The volume of prepared batch was equal to 260 dm^3. There were cast two large scale specimens in a form of slabs with dimensions 1210 mm×1240 mm×150 mm. The specimens were coded as slab 4 and slab 5. The slabs were prepared using the same concrete mix. The utilized casting procedure (pouring fresh mix in the centre of the mould) was based on previous technological experience (Ponikiewski and Katzer 2015, Ponikiewski and Katzer 2016). Cast slabs were tightly covered with polyethylene sheets. After the first 24 hours of curing slabs were demoulded, sprayed with water and again tightly covered with polyethylene sheets. On the 7th day of curing slabs were cut into 16 beams (600 mm×150 mm×150 mm) each. The beams were numbered, notched and again covered with polyethylene sheets. The curing process was continued for the next 21 days. The air temperature for the whole length of the curing process was equal to +20℃ ±2℃. The casting process, cutting of slabs into beams and assigned numbers of the beams are presented in Fig. 2. In this way 32 beams were created with two different external surfaces achieved by the contact with the mould and by cutting. Quality of the external surface depended on the original location in a slab.

4. Research methods

The planned research programme was organized in three work-packages (WP). WP1 was dedicated to exposing specimens to fire and following the development of specimens' temperature and destruction. The fire test was conducted after 28 days of curing. Only half of the beams was exposed to fire. The other half was used as a reference. Basically, specimens created through cutting slab 4 were the reference and specimens created through cutting slab 5 were exposed to fire. Mechanical properties of both slabs were checked and compared using NDT methods before the tests (Katzer and Kobaka 2009). The difference in compressive strength was assessed to be less than 2% between the slabs. The fire test was conducted outdoors, at university testing grounds under the tight control of the local Fire Department. The fire was created using wood logs put under the specimens. The specimens were placed over the wood logs in the same way as they were placed in the original slab. The gaps of 50 mm were left between beams allowing air and flames to move and penetrate freely. At the end of the test, the whole testing setup was extinguished by Fire Brigade using cold water. The exact setup of the fire testing is shown in Fig. 3.

The beams subjected to the fire were slowly cooling for a few days at the testing grounds to meet requirements of university health and safety department. Then, they were transported to the laboratory for full tests of mechanical properties. WP2 was dedicated to these lab tests. The tests were scheduled for 90th day of curing and consisted of traditional mechanical tests including compressive strength and flexural test (span of 500 mm) according to RILEM TC 162-TDF (2002). Due to the fact that specimens subjected to fire test were considerably damaged (very bad quality of the bottom surface - notch missing et cetera) it was impossible to conduct full CMOD

(a) (b)

Fig. 3 Specimens during the fire test (a) and extinguishing the testing setup (b)

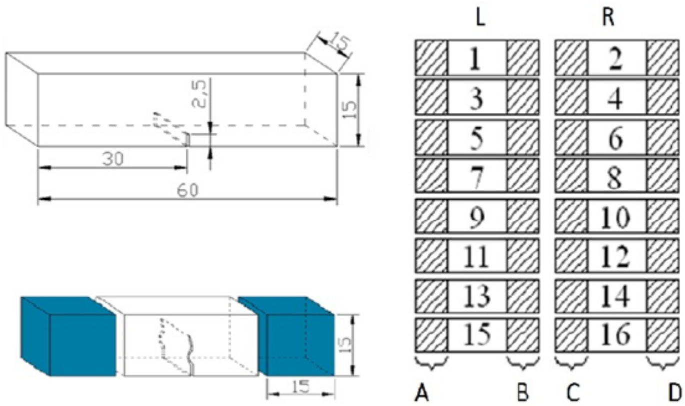
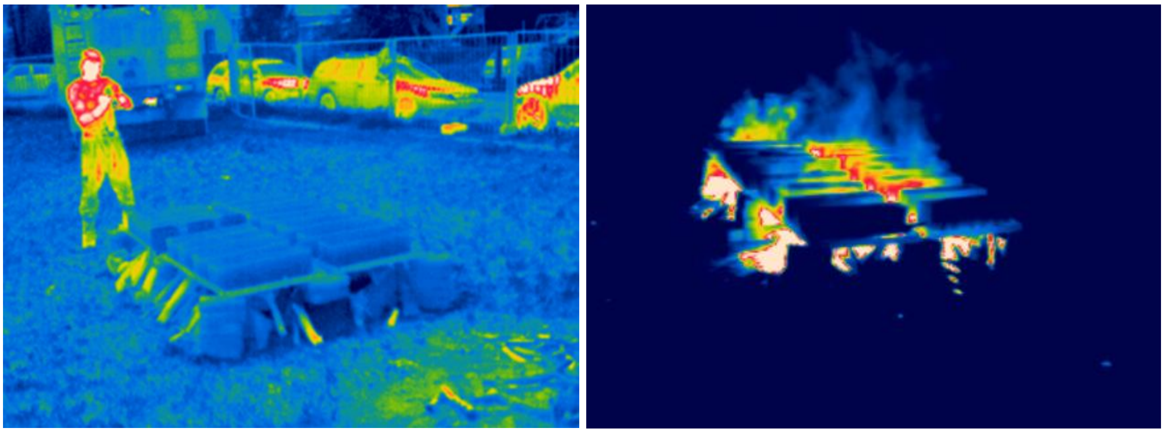


Fig. 4 A specimen before and after flexural test, partition of a specimen and cubes numbering



(a) (b)

Fig. 5 Digital thermal images taken before (a) and during the fire test (b)

measurements. Authors decided to compute flexural strength (f_L) and equivalent flexural strength (f_{eq}) using the obtained load-deflection relations. The compressive strength test was conducted on cube specimens (150 mm×150 mm×150 mm). These specimens were obtained after the flexural test. The initial geometry of a tested beam and its partition into cube specimens are presented in Fig. 4. This technique of obtaining cube specimens was thoroughly described in previous publications (Ponikiewski *et al*. 2015, Ponikiewski and Katzer 2015). Mechanical properties of specimens located in the same place in original slabs were compared. In this way specific spacing of fibre and air pores in different areas of the slabs caused by casting fresh SFR-SCC mix (Ponikiewski and Katzer 2015) were taken into account. The whole fire test was registered using thermal imaging digital camera. The camera is sent to the producer on a yearly basis for factory calibration (blackbody calibration and non-linearity correction). Before each field use it is also briefly checked using ice and boiling water as reference points. In this way temperature measurements and digital thermal imaging with the nominal accuracy of the apparatus are assured. The digital thermal images were taken in one minute intervals. In total, there were created 82 JPEG files with definition of 320 pixels×240 pixels. The registered temperature was ranging between +23.5℃ (before starting the fire) and +900℃ at its highest. Digital thermal images for those two temperatures are presented in Fig. 5.

During the test thermal boundary conditions were variable mainly due to changing roughness of the SFR-SCC surfaces and influence of the wind. Moreover, spalling of concrete was influencing the very geometry of the tested beams. This phenomenon was further changing a heat flux. All three phenomena take place during real fire of a concrete structure. Thus, the conducted test realistically mimicked variable boundary conditions which take place during real fire.

The temperature of +550℃ was achieved after 10 minutes of fire. Subsequently, the fire was temporally reaching peak temperatures from +800℃ to +900℃ between 15th and 45th minute of fire. Between 46th and 75th minute the temperature of the fire was stable and equal to +550℃. Measurement of the temperature of the specimens was conducted during the 60th minute of the test when the temperature was stable. First spalling of concrete took place after 12 minutes of fire. WP3 covered the analysis of specimens subjected to fire and the comparison of their properties with properties of reference specimens.

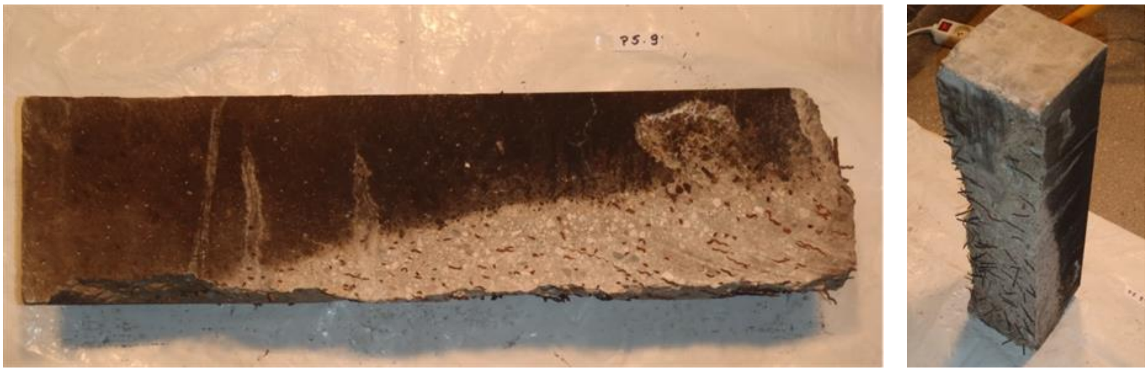
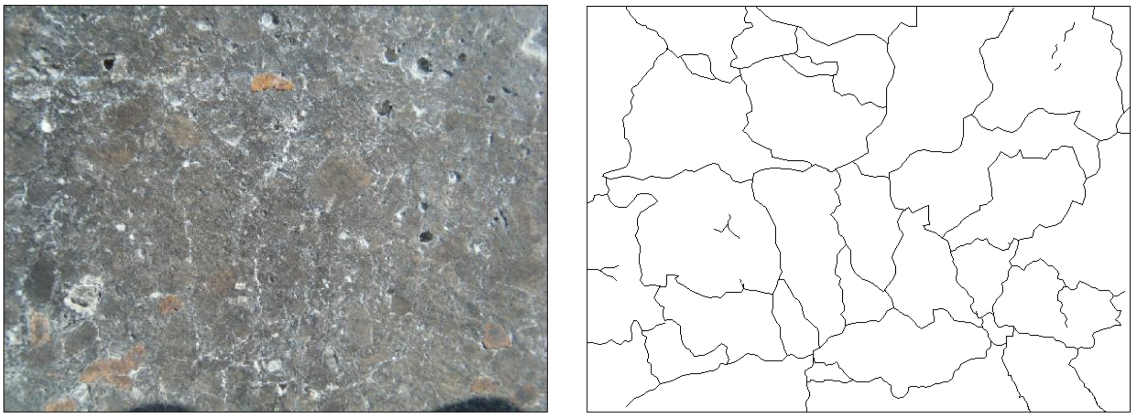


Fig. 6 Beam after the fire test



(a) (b)

Fig. 7 Micro-cracking of concrete surface (a) and its digital representation (b)

5. Results

After the fire all specimens were subjected to visual inspection. Significant damages of all tested beams could be observed. The bottom surface of beams was the most damaged one. The explosive spalling took place in this area. The thickness of missing concrete cover was from 5 mm to 25 mm. The colour of the concrete was of lighter shade in comparison to reference specimens. Multiple surface cracks and protruding steel fibre were observed. In Fig. 6, an exemplary beam after fire with all described damages is presented. Surface micro-cracking of specimens was digitally catalogued (see Fig. 7).

Compressive strength of SFR-SCC after 90 days of curing is presented in Fig. 8. The temperatures in Fig. 8 correspond to Slab 5 and are surface temperatures of the concrete. The average value of the compressive strength for slab 4 was equal to 73.2 MPa with standard deviation of 3.5 MPa. The difference between the smallest strength value and the highest strength value was 13 MPa. In case of slab 5 the average value of the compressive strength was equal to 54.6 MPa with standard deviation of 4 MPa.

The difference between the smallest strength value and the highest strength value was 19 MPa. Cubes located in area B and C were exposed to the highest temperatures resulting in the largest

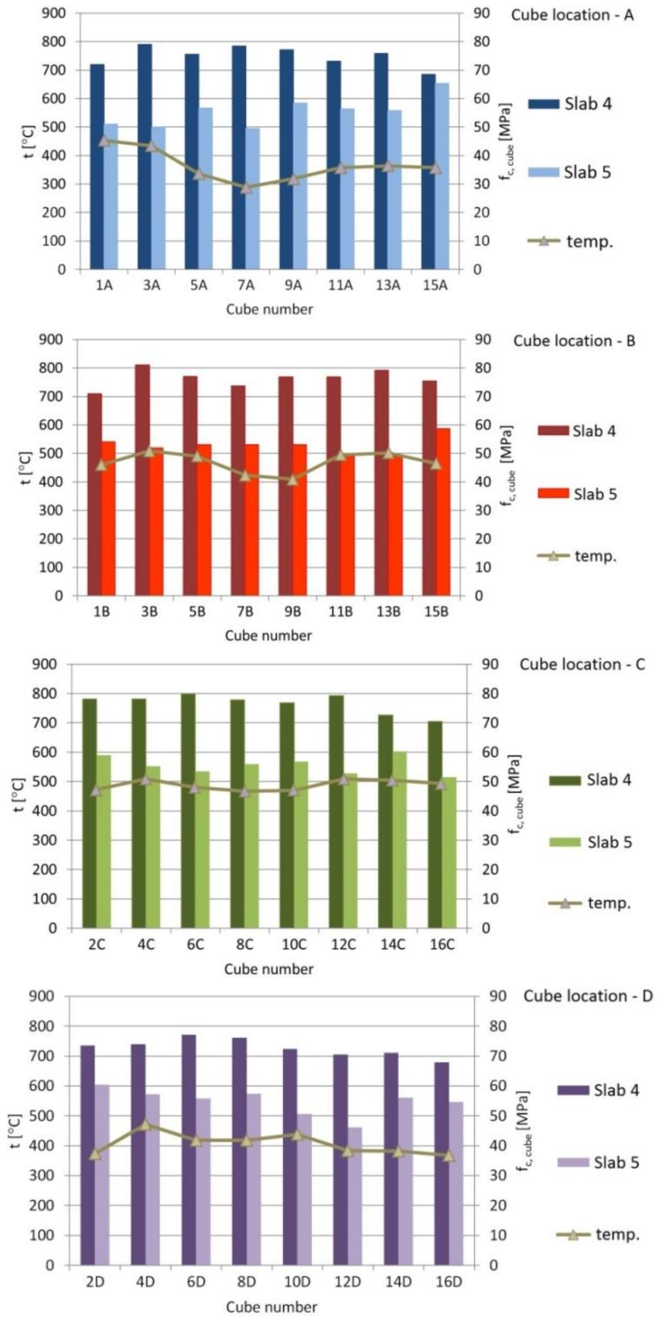


Fig. 8 Compressive strength after 90 days of curing

average loss of compressive strength equal to 30 %. Cubes located in area A and D were exposed to lower temperatures which resulted in smaller loss of average compressive strength equal to 25%. In Fig. 8, apart from compressive strength, values of registered temperatures are presented. One can follow changes in compressive strength and temperature simultaneously. The average

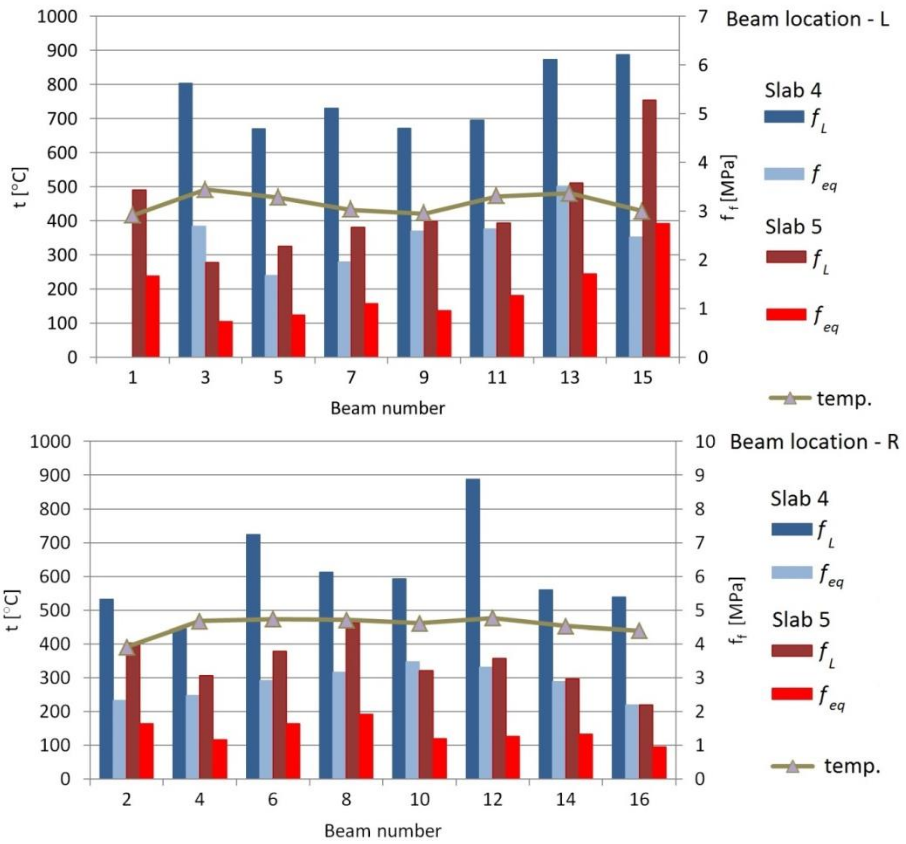


Fig. 9 Flexural strength f_L and equivalent flexural strength f_{eq} of beams

temperature registered on the surfaces of all tested specimens is equal to +442℃. There are no clear tendencies of temperature differences influencing the compressive strength. Some irregularities can be observed like in the case of cube 7A. This specimen was exposed to the lowest registered temperature of +289℃ and at the same time the specimen is characterized by the largest loss of compressive strength (37%) in comparison to the reference specimen.

Flexural characteristics of tested SFR-SCC are presented in Fig. 9. The temperatures in Fig. 9 correspond to Slab 5 and are surface temperatures of the concrete. The difference of average value of f_L between reference specimens and specimens subjected to fire is equal to 2.5 MPa. The maximum loss of flexural strength took place in the specimen number 3 and was equal to 65%. The maximum registered temperature for this specimen was equal to +493℃. The smallest difference between flexural strength of reference specimen and specimen subjected to fire was noted for the specimen number 15. The value of f_L was smaller by 15% in this case and the maximum registered temperature for this specimen was equal to +428℃. In case of equivalent flexural strength the largest loss took place in the specimen 10 and was equal to 66% (max. temp. +461℃). There were also some anomalies observed like the specimen number 15 and the specimen number 2. The value of f_{eq} for the specimen 15 was by 11 % higher after subjecting to fire than the reference result. The lowest temperature was registered for the specimen number 2, but it wasn't characterized by the largest loss of any of either strengths f_L or f_{eq}.

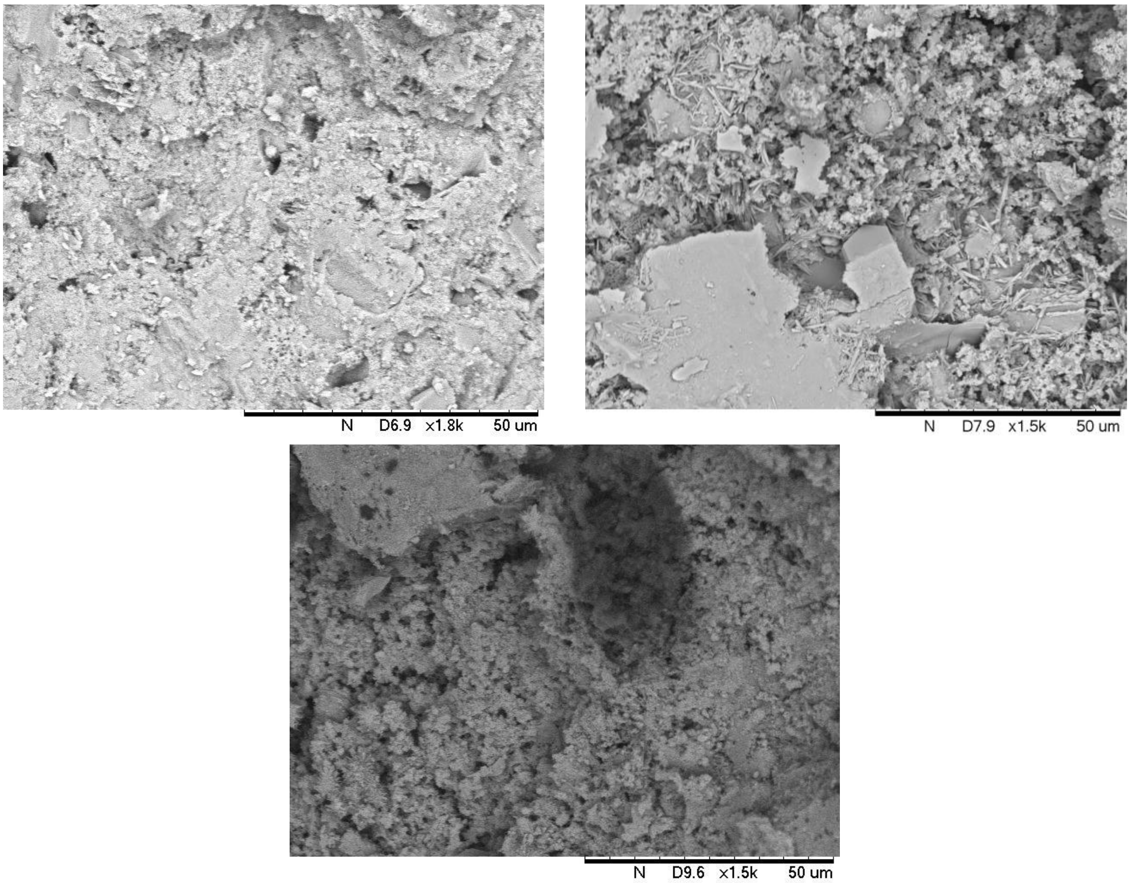


Fig. 10 SEM images of tested cubes

6. Discussion

During the test, the achieved temperatures of the SFR-SCC were only temporary (on the surface of a concrete element) reaching +900℃, thus had no influence on mechanical properties of the steel reinforcement (Fike and Kodur 2011). The stress-strain curves of steel, and bond/slip characteristics between steel and concrete, have a significant influence on the fire resistance of a reinforced concrete element (Cashell *et al.* 2010). At +600℃ ordinary concrete is assumed to have no tensile strength while SFRC retains significant tensile strength (and continues beyond +800℃) (Fike and Kodur 2011). SFRC is also characterized by much higher ductility (up to 75%) throughout the temperature range in comparison to ordinary concrete. The average difference in compressive strength between Slab 4 and 5 is equal to 25.4%. The influence of fibre reinforcement on compressive strength tested on cube specimens is limited and usually ranges from 0% to 10% (Ponikiewski and Katzer 2016, Domski 2016). It means that even if all of fibre lost their load bearing capabilities the difference in compressive strength would be much smaller. One should keep in mind all above facts while analysing results presented in Figs. 8 and 9. The lost in both compressive strength and flexural strength should be considered as a result of a matrix deterioration and subsequent total failure (Tang 2017).

Cement paste is the most vulnerable part of hardened concrete while being exposed to high temperatures (Jameran *et al.* 2015). The key ingredient of the hydrated cement paste is calcium silicate hydrate (C-S-H). It is the most important phase of concrete governing the majority of its properties (Park *et al.* 2015). Therefore, C-S-H of tested concrete was studied using scanning electron microscope (SEM). In Fig. 10, exemplary SEM images of tested cubes are presented. There were taken images of internal concrete structure in top, middle and bottom parts of cubes.

In top area, apart from some air pores (created during mixing a fresh concrete), a well crystallized C-S-H can be observed. Middle area is characterized by higher porosity than the top one. This phenomenon is caused by high temperature. One can also observe needle-like crystals of ettringite lining air voids. The presence of ettringite proves that the temperature of this area did not exceeded +100℃. The temperature of the concrete surface located 75 mm away was equal to +421℃. In the bottom area crystaline structure is "blurred". It is difficult to point out single crystals which are aggregated into larger chunks. The needle-like crystals of ettringite are not present thus temperature in this area was higher than +100℃. In terms of compressive strength tested, SFR-SCC can be described by strength class C55/67 and C40/50 for reference specimens and specimens subjected to fire, respectively.

Flexural characteristics of SFR-SCC was also significantly influenced by fire. In case of reference specimens, the highest and the lowest value of flexural strength was achieved by the beam 12 (f_L=8.9 MPa) and the beam 6 (f_L=4.5 MPa), respectively. The average value of flexural strength was equal to 5.8 MPa. Beams subjected to fire were characterized by lower values of flexural strength than reference beams. The maximum strength was registered for the beam 15 (f_L=5.3 MPa) and the lowest strength was registered for beam 3 (f_L=1.9 MPa). The average value of flexural strength was equal to 3.3 MPa. On average flexural strength of SFR-SCC subjected to fire is lowered by 42%. One can notice that both populations of results overlap. Two beams subjected to fire (the beam number 8: f_L=4.6 MPa and the beam number 15: f_L=5.3 MPa) were characterized by flexural strength higher than the lowest registered result for reference specimens. Similar overlapping takes place in case of populations of results of equivalent flexural strength. The average value of f_{eq} for reference beams and beams subjected to fire is equal to 2.7 MPa and 1.4 MPa, respectively. The lowest and highest values of f_{eq} are as follows: reference beams 1.7 MPa and 3.5 MPa; beams subjected to fire 0.7 MPa and 2.7 MPa. On average equivalent flexural strength of SFR-SCC subjected to fire is lowered by 48%.

Properties of all fibre reinforced concrete are influenced by fibre spacing (Domski 2016). Randomness of fibre spacing is a major factor formatting homogeneity of achieved population of results. Therefore testing fibre reinforced concrete is more demanding than testing ordinary concrete. Apart from issues of the uniformity of results there are specific properties of fibre reinforced concrete like flexural characteristics which have to be tested in a special way. Some of these testing procedures (e.g., testing notched beams) proved to be impossible to utilize for testing beams after being exposed to fire. During the research programme fibre spacing was a key problem due to the comparison of properties of reference specimens with properties of specimens exposed to fire. Authors were well aware of the importance of fibre spacing and decided to compare only properties of specimens located in the same place in original slabs. The location of specimens during the fire test was fixed in the same way, so the possible differences caused by fibre spacing were supressed. Nevertheless, identical fibre spacing and fibre volume wasn't guaranteed in any pair of compared specimens. Taking into account all the above facts some irregularities in achieved results were expected, but not to such an extent. During the research programme it became obvious that much larger populations of specimens would be needed to get unambiguous results. “Natural” randomness of fibre spacing in concrete matrix combined with randomness of natural fire resulted in scattered and overlapping results populations.

5. Conclusions

The conducted research programme allow to draw the following conclusions:

• Mechanical characteristics of SFR-SCC is significantly influenced by fire. The decrease of three strength classes was noted during the research programme. The loss of flexural strength is equal to 42%.

• It is impossible to harness LOP method for testing specimens subjected to fire due to spalling, thus assessing strength class according to fib Model Code (2010) is disabled.

• The analysis of SEM images doesn’t give firm answer to what was happening with SCC concrete matrix during fire.

• Tests conducted using much larger populations of specimens are needed. More data and analysis on the actual boundary conditions are needed for achieving good repeatability of the conducted test.

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