Fibre reinforced concrete exposed to elevated temperature

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Abstract. Although concrete when subject to fire performs very well, its behaviour and properties change dramatically under high temperature due to damaged microstructure and mesostructure. As fibre reinforced concrete (FRC) represents a complex material composed of various components with different response to high temperature, to determine its behaviour and mechanical properties in fire is a demanding task. The presented paper provides a summary of findings on the fire response of fibre FRC. Namely, the information on steel fibre reinforced concrete (SFRC), synthetic fibre reinforced concrete and hybrid (steel + synthetic) fibre reinforced concrete have been gathered from various contributions published up to date. The mechanical properties including the melting point and ignition point of fibres affect significantly the properties of concrete composites with addition of fibres. The combination of steel and synthetic fibres represents a promising alternative how to ensure good toughness of a concrete composite before heating and improve its residual mechanical behaviour and spalling resistance as well as the ductility after heating. While synthetic fibres increase concrete spalling resistance, steel fibres in a concrete mix leads to an improvement in both mechanical properties and resistance to heating effects.

1. Introduction

Fiber reinforced concrete (FRC) is a building material whose utilization in the concrete industry has been rapidly increasing. This development is motivated by its physical and mechanical properties which contribute to traditional concrete elements and structures various economical benefits such as structure subtlety, part or full elimination of conventional reinforcement, enhanced impact resistance, resistance to mechanical loads and environmental loads. Recently, many comprehensive studies have been undertaken with the aim to observe the mechanical behaviour of FRC exposed to elevated temperature.

Although concrete is well-known for a high degree of fire resistance, high temperature seriously damages microstructure and mesostructure which results in generalised mechanical decay of a concrete composite [1]. As a consequence, the extensive knowledge of mechanical properties of FRC exposed to elevated temperature seems to be decisive for a wider utilization of the material. There are two fundamental types of a methodological procedure used for observing the mechanical properties of specimens at elevated temperature. Most of experimental investigations [2-28] were conducted on test specimens at ambient temperature after high temperature exposure and only a few was performed on heated test specimens [29-31]. Such approach to experimental testing is used mainly due to a simple way of testing as tests are easier to conduct on test specimens at ambient temperature. However, if the results obtained from the tests on specimens after high temperature exposure correspond enough to the
mechanical properties of a tested material at a certain temperature level has not been still fully understood. Bamonte and Gambarova belong to authors which very intensively deals with such issue and states in their publications [32,33] that the hot and residual (after high temperature exposure) behaviour in compression are very close, the only difference was observed in case of the peak strain in compression which is larger on heated specimens in comparison with specimens after temperature exposure.

The fire response of concrete composites is closely associated with concrete composition, particularly with a type and content of concrete components used. Generally speaking, concrete made of siliceous aggregates, such as granite, shows unfavourable mechanical properties at high temperature compared to concrete composed of calcareous aggregates such as dolomite and limestone [34]. Recently, a lot of interest is also being paid on the possible use of metakaolin, fly ash and silica fume as partial cement replacement in concrete subjected to high temperature [2,7,8]. Owing to silica fume and fly ash fineness, concrete composites with such additions have denser microstructure and as a consequence their explosive spalling tendency increases [8].

2. Fire resistance of FRC

A number of experimental investigations have been conducted up to date with the aim to observe the fire response of concrete composites. Particularly, the studies are focused on the effect of a type, shape and content of fibres on the mechanical properties of concrete composites, mostly compressive and tensile strength including elastic modulus. Namely, it concerns steel fibers [2,5,6,8-11,14,16,19-22,24,27-30], synthetic fibers [2,4,6-9,11,12,15,17,19,22,27,29,30] and a mix of steel and polypropylene fibres [2,6,11,13,19,22,27,29,30] which are widely used in the concrete industry. There also a few investigations which deals with carbon fibres [3,12] and glass fibers [12].

2.1. SFRC

As the melting point of steel is relatively high in comparison with other materials, the use of steel fibers seems to be beneficial for concrete composites exposed to high temperature. Incorporating steel fibers into concrete composites remains advantageous even when the concrete composites are exposed to high temperature up to 1200 °C, particularly 1% content has no deleterious effect on heated concrete. In fact, the inclusion of steel fibers in a concrete mix leads to an improvement in both mechanical properties and resistance to heating effects in comparison with unreinforced concrete [5,16,22,23,27]. Some experimental investigations [10,14,21] even demonstrate the compressive strength of steel fiber reinforced reactive powder concrete and geopolymer concrete gradually increases when the material is heated up to 200–300 °C (figure 1), but starts to decrease as temperatures further increase. The compressive strength of reactive powder concrete with 1% steel content is higher between 200°C and 400°C than at room temperature and subsides when temperature exceed 500°C. Furthermore, 2% and 3% steel fiber content significantly increase compressive strength from 200°C to 300°C which then gradually decreases as the temperatures reach 400 °C and beyond. However, a higher content of steel fibers cannot improve the compressive strength of concrete composites at elevated temperatures [24]. On the contrary, it has been also demonstrated that steel fibers have negligible effect on high temperature compressive strength and only improve tensile strength when temperature up to 400°C is considered [29]. The tensile behavior of SFRC subjected to elevated temperature is more sensitive to the volume fraction and the aspect ratio of the fiber than to its type [20].

SFRC also has the higher toughness after the high-temperature exposures when compared to the initial values of unheated concrete [2]. As temperature increases, SFRC weakens and shows reduced stiffness with the degradation depending on the type, aspect ratio, and volume fraction of the fiber [20] and the reduction in modulus of elasticity is more pronounced than the reduction in compressive strength for the same heat treatment [24]. Steel fiber reinforced recycled aggregate concrete exhibits the identical behavior and loses stiffness much faster than strength after exposure to elevated temperature [16]. As a consequence, peak strains gradually increases together with temperature. The
increase in peak strains along with steel fiber content does not significantly differ between ambient temperature and 200 °C. When temperatures exceed 200 °C, a higher steel fiber content generally is associated with a higher peak strain [10]. Moreover, the addition of steel fibers does not eliminate the spalling tendency of concrete mixtures [8].

Figure 1. Residual compressive strength (left) and tensile strength (right) of SFRC

2.2. Synthetic fibre reinforced concrete

In the concrete industry, synthetic fibers, regardless of the type, shape and length, are mostly utilized with the aim to increase concrete spalling resistance when concrete structures exposed to elevated temperature [15,30]. As the melting point of synthetic fibers is relatively low, the presence of fibers in a concrete composite subjected to elevated temperature affects the mechanical properties of the concrete composite, particularly residual compressive strength, modulus of elasticity and splitting tensile strength [4]. While the presence of polypropylene fibers slightly increase ductility and the specific toughness, defined as the ratio of the area under the stress–strain curve, and the compressive strength of unheated concrete, after heating all the enhanced characteristics are lost [2,22]. Many contributions even demonstrate that polypropylene fibers have negative effect on the residual mechanical properties of polypropylene fiber reinforced concrete (PPFRC) after high-temperature exposure as they significantly decrease the residual compressive strength (figure 2), elastic modulus and tensile strength as well as they increase peak strain [8,15,29]. On the other hand, some experimental investigations show that polypropylene fibers can improve the relative residual compressive strength of a concrete composite after the exposure to fire [27]. While the presence of polypropylene fibers at different dosages does not affect the residual compressive strength at 200°C and 400°C, it considerably increases the residual compressive strength of concretes after exposure to 600 °C [17]. Moreover, some even shows that compressive strength of concrete with polypropylene fiber additions is greater than unreinforced concrete without additions, when subjected to temperature up to 400 °C [23]. In comparison with SFRC, polyvinyl alcohol fibers reduce the uniaxial compressive strength but cause no appreciable change in elastic modulus in reactive powder concrete [30].

Figure 2. Residual compressive strength (left) and tensile strength (right) of synthetic fiber reinforced concrete
2.3. **Hybrid (steel + synthetic) fibre reinforced concrete**

The combination of steel and synthetic fibers represents a promising alternative how to ensure good toughness of a concrete composite before heating and improve its residual mechanical behavior and spalling resistance as well as the ductility after heating [11]. Although a few contributions declare that a fiber cocktail does not have much effect on high temperature compressive strength [29], the most of presented work affirm that the incorporation of steel fibers can effectively improve the compressive properties of a concrete composite when exposed to elevated temperatures while polypropylene fibers enhance concrete spalling resistance [13,27]. Specifically, the combination of steel fibers and polypropylene fibers shows positive synergy effect on the post-peak behavior of concrete composites (figure 3) before and after exposure to high temperature [11]. However, as synthetic fibers have a low melting point and ignition point, only steel fibers provide the stability and enhanced mechanical behavior to a concrete composite after exposing to elevated temperatures [22]. Considering steel to synthetic fiber content ratio, a concrete composite containing 1% synthetic fibers and 1% steel fibers by volume seems to produce the best results, balancing performance at high temperature with consideration of initial mechanical properties [30]. As a consequence, using hybrid fiber reinforced concrete (steel and synthetic fibers) might provide necessary safe guarantee for the rescue work and structure repair during and after a fire disaster.

![Figure 3. Residual compressive strength (left) and tensile strength (right) of hybrid (steel + synthetic) fiber reinforced concrete](image)

3. **Conclusion**

The increasing utilization of FRC in the concrete industry is motivated by the physical and mechanical properties of the material which contribute to traditional concrete elements and structures various economical benefits. The extensive knowledge of mechanical properties of FRC exposed to elevated temperature seems to be decisive for a wider utilization of the material. Most of experimental investigations are conducted on test specimens at ambient temperature after high temperature exposure and only a few is performed on heated test specimens. The observed findings are as follows:

- **Steel fibers** in a concrete mix leads to an improvement in both mechanical properties and resistance to heating effects in comparison with unreinforced concrete. However, a higher content of steel fibers do not improve the compressive strength of concrete composites at elevated temperatures.
- The compressive strength of steel fiber reinforced reactive powder concrete and geopolymer concrete gradually increases when the material is heated up to 200–300 °C, but starts to decrease as temperature further increases.
- While the addition of steel fibers does not eliminate the spalling tendency of concrete, synthetic fibers enhance concrete spalling resistance.
- Polypropylene fibers have negative effect on the residual mechanical properties of PPFRC after high-temperature exposure as they significantly decrease the residual compressive strength, elastic modulus and tensile strength as well as they increase peak strain in comparison with unreinforced concrete.
The combination of steel and synthetic fibers represents a promising alternative how to ensure good toughness of a concrete composite before heating and improve its residual mechanical behavior and spalling resistance as well as the ductility after heating.

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