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# Mechanical properties of concrete composites subject to elevated temperature

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A B S T R A C T

Fire resistance represents an important parameter which is necessary to consider during the structural design of buildings. It is defined as an ability of building components to perform their intended load-bearing functions under fire exposure. In terms of fire resistance, the right choice of a construction material plays a key role and can reduce structural damage or even save human lives. The building industry offers a wide range of materials whose structural behaviour is more or less affected by temperature. Recently, concrete has become one of the most utilized materials used for a various kind of buildings. While the knowledge and experience with concrete behaviour under ambient temperature are well-known, the behaviour under elevated temperature has to be deeply investigated.

The paper deals with observing the behaviour of concrete composites with addition of fibres under ambient and elevated temperature with the aim to determine the mechanical properties of materials. The experimental tests were conducted on three selected concrete composites which differ in a type and content of fibrous reinforcement used. The experimental work carried out was divided into several phases. First of all it was necessary to leave the produced specimens aging and drying in order to minimize the risk of unexpected damage caused by concrete spalling during heating. Time to time, the specimens were weighted with the aim to determine the loss of weight imposed by drying. Then, a heat transport test was performed on a few reference specimens in order to determine the time required for uniform heating the specimens up to 200 °C, 400 °C and 600 °C. In the last phase, conventional testing methods were undertaken to determine the mechanical properties of concrete composites at ambient and elevated temperature. A compression test and a splitting tensile test were conducted on 150 mm cubes. Based on the results, the peak and residual strength of the materials were determined for various temperature levels. The obtained findings contribute to improving the knowledge in the field of both concrete structures exposed to high temperature and structural behaviour of fibre reinforced concrete. The findings can be also utilized in case of the structural design of concrete structures with the high risk of fire loading.

## 1. Introduction

Today, a structural design represents a very complex task which includes analyzing many parameters such as ultimate bearing capacity, stability, deflection, rigidity of structure etc. The essential part, which has to be paid attention to, is also fire resistance defined as an ability of building components to perform their intended load-bearing functions under fire exposure. Although the issue of fire safety seems to be not so important, the inadequate fire design or a construction material choice can cause structural damage or even loss of human lives. For instance, in 2008 an extensive fire occurred in the 13-story Faculty of Architecture Building at the Delft University of Technology (TUD) in Netherlands [1]. Although all building occupants evacuated safely, the fire burned uncontrolled for several hours and caused the structural collapse of the major portion of the building with a reinforced concrete structural system. The key cause of the collapse is assumed to be the occurrence of spalling which rapidly and dramatically reduced reinforced concrete member capacities. A massive fire also hit the Windsor Tower in Madrid, Spain, in February 2015 [2]. The structural system of the tower was constituted of a reinforced concrete core, interior columns, waffle slab and steel exterior columns. The part of building was exposed to the fire for 20 h resulting in the extensive structural damage. As lately analyzed, a large portion of the floor slabs collapsed during the fire due to the failure of reinforced concrete elements. However, according to other sources [3]

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the collapse was induced by buckling of steel columns during the fire.

Today, there are many regulations and standards which deal with the demands for the durability and fire resistance of concrete structures [4]. The European standard EN 1992-1-2 [5] is a widely-used document which serves for designing concrete structures exposed to high temperature. Recommendations and principles stated not only in this standard are usually based on the extensive experience and experimental investigations in the field of concrete composites subject to high temperature. However, the available data does not have to accurately describe the structural behaviour of relatively new materials including fibre reinforced concrete (FRC). While the knowledge and experience with FRC behaviour under ambient temperature are well-known, the behaviour under elevated temperature has to be deeply investigated.

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 [6]. 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 methodological procedure used for observing mechanical properties of concrete at elevated temperature. Most of experimental investigations [7–33] are conducted on test specimens at ambient temperature after high temperature exposure and only a few is performed on hot test specimens [34–36]. Such approach of experimental testing is preferred mainly due to a simple way of testing as tests are easier to conduct on test specimens at ambient temperature. However, if 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 [37,38] 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 cooled down 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 [34,39]. Recently, a lot of interest is being paid on the possible use of metakaolin, fly ash and silica fume as partial cement replacement in concrete subject to high temperature [7,12,13]. 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 [13]. The amount and type of fibres also have an influence on the structural performance of a composite exposed to high temperature.

A number of experimental investigations have been conducted up to date with the aim to observe the fire response of FRC with a various type and amount of fibres. 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 fibres [7,10,11,13–16,19,21,24–27,29,32–35], synthetic fibres [7,9,11–14,16,17,20,22,24,27,32,34,35] and mix of steel and polypropylene fibres [7,11,16,18,24,27,32,34,35] which are widely used in the concrete industry. There also a few investigations which deals with carbon fibres [8,17] and glass fibres [17].

### 1.1. Steel fibre reinforced concrete

As the melting point of steel is relatively high in comparison with other materials, the use of steel fibres seems to be beneficial for concrete composites exposed to high temperature. Incorporating steel fibres into concrete composites remains advantageous even when the concrete composites are exposed to high temperature up to temperature up to 1200 °C, particularly 1% content has no deleterious effect on heated concrete. In fact, the inclusion of steel fibres in a concrete mix leads to an improvement in both mechanical properties and resistance to heating effects in comparison with unreinforced concrete [10,21,27,28,32]. Some experimental investigations [15,19,26] even demonstrate the compressive strength of steel fibre reinforced reactive powder concrete and geopolymer concrete gradually increases when the material is heated up to 200–300 °C, 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 fibre 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 fibres cannot improve the compressive strength of concrete composites at elevated temperatures [29]. On the contrary, it has been also demonstrated that steel fibres have negligible effect on high temperature compressive strength and only improve tensile strength when temperature up to 400 °C is considered [34]. The tensile behaviour of SFRC subjected to elevated temperature is more sensitive to the volume fraction and the aspect ratio of the fibre than to its type [25].

SFRC also has the higher toughness after the high-temperature exposures when compared to the initial values of unheated concrete [7]. As temperature increases, SFRC weakens and shows reduced stiffness with the degradation depending on a type, aspect ratio, and volume fraction of the fibre [25] and the reduction in modulus of elasticity is more pronounced than the reduction in compressive strength for the same heat treatment [29]. Steel fibre reinforced recycled aggregate concrete exhibits the identical behaviour and loses stiffness much faster than strength after exposure to elevated temperature [21]. As a consequence, peak strains gradually increases together with temperature. The increase in peak strains along with steel fibre content does not significantly differ between ambient temperature and 200 °C. When temperatures exceed 200 °C, a higher steel fibre content generally is associated with a higher peak strain [15]. Moreover, the addition of steel fibres does not eliminate the spalling tendency of concrete mixtures [13].

### 1.2. Synthetic fibre reinforced concrete

In the concrete industry, synthetic fibres, regardless of a type, shape and length, are mostly utilized with the aim to increase concrete spalling resistance when concrete structures exposed to elevated temperature [20,35]. As the melting point of synthetic fibres is relatively low, the presence of fibres 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 [9]. While the presence of polypropylene fibres 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 [7,27]. Many contributions even demonstrate that polypropylene fibres have negative effect on the residual mechanical properties of polypropylene fibre reinforced concrete (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 [13,20,34]. On the other hand, some experimental investigations show that polypropylene fibres can improve the relative residual compressive strength of a concrete composite after the exposure to fire [32]. While the presence of polypropylene fibres at different