Material properties of various types of fibre reinforced concrete exposed to elevated temperature

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Abstract. This paper presents experimental program focused on determination of material properties of various types of fiber reinforced concrete exposed to elevated temperatures up to 1000° C. Material properties were measured by several methods which are described and compared. The resulting changes of material properties depending on temperature are presented. The values are compared with values from literature and standards. The aim of this paper is to provide a comprehensive overview of material properties of these types of concrete depending on elevated temperature and possibility of their measurement.

1. Introduction
The requirements on durability and resistance of structures increase, together with requirements on their fire resistance. The fire resistance of concrete structures depends on the properties of the main component. These properties are defined by dimensions of the specimen, method of reinforcement and by material properties of concrete. Therefore, material properties of concrete are measured and evaluated in many experimental programs. However, usually only partial measurements of several characteristics are undertaken.

This paper presents an experimental program which was focused on determining the material properties of three types of concrete. Basic mechanical and thermal properties were measured: bulk density, thermal conductivity, specific heat capacity, porosity, permeability and compressive strength. The description and results of the tests are presented in the following chapters.

As mentioned above, the material properties are studied by many experimental programs and the results may be found in literature. Basic summary of material properties at normal temperature is presented in [1]. Description of the material characteristics at high temperatures are given in [2]. The book [2] describes material properties and their changes, defines basic mathematical relations between all properties. On the other hand, [3] deals with material characteristics and their influence on fire resistance of structure. Reference [4] focuses on the use of material characteristics to determine the behavior of elements at high temperatures. [5] and [6] can serve as an example of an experiment focused on measurement of only one characteristic. The first paper deals with commonly used techniques for measuring thermal conductivity of concrete. The second paper presents the results of measurement of thermal conductivity of eight materials. The paper [7] describes one type of measurement method for compressive strength and its results for some cement materials.
2. Materials
Material properties were measured for the following types of concrete:

- Common concrete C30/37 – C marked
- Concrete with polypropylene fibres – P marked
- Ultra-high performance concrete with steel fibres – U marked

Common concrete was chosen as a reference material to be used for further comparison.

3. Material properties and their measurement
Some material properties were measured by more than one method to compare and validate the results (or methods). All used methods are described in the following paragraphs.

3.1. Bulk density
The first measured characteristic was the bulk density depending on elevated temperature. Bulk density was measured using two methods. The first measurement (marked TZ) was carried out according to EN 993-1 [8]. For the second time, bulk density and matrix density were measured by the helium pycnometry (Pycnomatic ATC device) combined with gravimetric method (marked MA). The samples dimensions were 50 x 50 x 100 mm.

3.2. Compressive strength
The compressive strength of the concrete depending on elevated temperature was measured using a common hydraulic press. The system was installed in an electric furnace. A sample was placed in the furnace and then heated to the required temperature. After reaching of required temperature, the normal test of compressive strength was performed in the furnace. For the measurement of one temperature level, three cylinder specimens with 200 mm high and 100 mm diameter were used.

3.3. Thermal conductivity
Thermal conductivity depending on elevated temperature was measured by two methods. The first method (marked TZ) uses the heating wire is described in EN 993-15 [9]. For the measurement, three specimens with dimension 150 x 150 x 700 mm were used. The second method (marked MA) uses series of thermocouples, which record increasing temperature in the element. This method is described in [8]. This method is based on an approach taking into account moisture transport, radiative modes of heat transport and other reactions. The dimensions of samples were 50 x 50 x 50 mm and three samples were used.

3.4. Specific heat capacity
Specific heat capacity was determined using a water calorimeter (mixing vessel with water). The method used is described in [9] and [10]. It is a type of non-adiabatic method. The samples with dimensions of 50 x 100 x 100 mm were exposed to elevated temperature and heated to required temperature. After heating, the specimen was placed into mixing vessels and continuously stirred. Temperature of water was measured by system of five thermocouples, which were connected to monitoring systems. By this system specific heat capacity of used materials was defined.

3.5. Porosity
Porosity was measured by two methods. Using the first method, the porosity was calculated as ratio of weight dried samples and saturated samples (marked TZ). Using the second method, the porosity was calculated as ration of mean of matrix density and bulk density (marked MA).

3.6. Permeability
In this case, gas permeability was measured according to EN 993-4 [13]. The measurement was performed for three pressure levels. During the test, amount of gas passing through the specimen, was
recorded. Three cylinder specimens with 50 mm high and 50 mm diameter were used for each tested pressure level.

4. Results of material properties measurement

All data obtained from the experimental measurement were compared. Results from literature were added to the comparison. The data from available and valid standards were also used. The results of each test are listed in this chapter.

4.1. Bulk density

Bulk density was measured by two methods. The results of both measurements are shown in Figure 1. The measured values were compared with the assumed values based on the parameters defined by the valid standard.

As expected, the bulk density of all materials decreased with increasing temperature affecting the specimen. Results of the both types of measurements were comparable for all materials up to 600 °C. From 600 °C to 1000 °C bulk density still decreased, but for measurement marked MA decreased much faster. Bulk density at 1000 °C of all materials was one quarter lower than initial value.

![Change of Bulk Density Depending on Elevated Temperature](image)

**Figure 1.** Results of bulk density measurement. [14], [15]

4.2. Compressive strength

The compressive strength of the concrete was measured by one method. The results are shown in Figure 2. The results were compared with the assumed values based on the parameters defined by the valid standard and the available literature. The results were comparable with standards values. The exception is the area between 100 °C and 200 °C where the values were different. Standards indicated no changes in this area, but experimental values were increasing. This may be because the standard conservatively neglects the increase in strength at lower temperatures. However, the resulting compressive strength at the highest temperature reached the expected values. The only exception was high-performance concrete with fibres (marked U), where the measured compressive strength was in all cases lower than expected.
The resulting compressive strength of all materials used decreased to 20% of the initial compressive strength.

**Figure 2.** Results of compressive strength measurement. [6], [15], [16], [17], [18], [19]

### 4.3. Thermal conductivity

The thermal conductivity was measured by two different methods but with an incomparable result as shown in Figure 3.

The thermal conductivity determined according to the method specified in the standard (marked TZ) corresponded to the assumed values based on the parameters defined by the valid standard and the available literature. Thermal conductivity decreased with increasing temperature. However, the values obtained by the second measurement method (marked MA) were completely different. After reaching the temperature approximately 250 °C, the thermal conductivity stopped decreasing and started slowly increasing. For ultra-high performance, concrete with steel fibres it was growing at all measured points. The final thermal conductivity at the highest temperatures significantly exceeded the thermal conductivity of the material at normal temperature.

### 4.4. Specific heat capacity

Specific heat capacity was measured by one method and the results are shown in Figure 4. The results were compared with the assumed values based on the parameters defined by the valid standard. They were compared with curve for 0% moisture. This corresponds with the measurement because the samples were dried before the test.

The specific heat capacity of all materials used increased to 600 °C, respectively 700 °C, and then decreased. However, the final specific heat capacity was higher than its initial values. The specific heat capacity was affected by the moisture of the material in all its forms. This was reflected in its resulting course.
Figure 3. Results of thermal conductivity measurement. [15], [6], [14]

Figure 4. Results of specific heat capacity measurement. [15]
4.5. Porosity
Porosity was measured by two different methods and the results are shown in Figure 5. The results of both measurements were comparable and reached approximately the same values. The only exception was high-performance concrete with steel fibres (marked U), where one measurement showed almost double porosity than the other. The porosity of the material increased to maximum elevated temperature. The final porosity at 1000 °C was more than two times higher than initial value for all materials.

![Change of Porosity Depending on Elevated Temperature](image)

**Figure 5.** Results of porosity measurement.

4.6. Permeability
Permeability is closely related to porosity. As porosity increases, the amount of open pores also increases, causing increased permeability. In this case, the permeability was measured as gas permeability. The results are shown in Figure 6.

The results were compared with those obtained from the literature. The permeability increased with increasing temperature and increased most at high temperatures above 600 °C. Final permeability at the highest temperature was many times higher than initial value. That indicates significant damage of samples during its heating.

The lowest permeability was measured for ultra-high performance concrete with steel fibres (marked U). This material had zero permeability up to temperature 400 °C.
5. Conclusion
This paper presents the results of an experimental program focused on experimental evaluation of material properties of various types of (fiber) concrete. Material characteristics of three types of concrete were measured at elevated temperatures up to 1000 °C. The reference material was common concrete, the second material was common concrete with polypropylene fibres and the last material was high-performance concrete with steel fibres. The material properties of common concrete are described in the valid standards and are also measured in many experimental programs. Concrete with polypropylene fibres is a commonly used material with high fire resistance. Therefore, it is important to know its behavior and material properties at high temperatures. The high-performance concrete is used mainly for its high load carrying capacity but with low fire resistance and high probability of spalling.

Methods of measurement and the results are presented in this article. According to assumptions with increasing temperature, bulk density, compressive strength and thermal conductivity of all materials decreased. On the other hand, the specific heat capacity, porosity and permeability of all materials increased. All these changes are mainly influenced by the moisture (and its transport) through the material. Moisture transport affects the pore pressure in the element. High pore pressure can damage the material (small cracks can be formed). Due to the small cracks, the air can pass to material structure and affect all thermal properties. Air and moisture have a major influence on thermal properties. On the other hand, cracks has a major influence on mechanical properties especially the compressive strength of material. The influence on the material properties is also the temperature itself. When the critical temperatures of material are reached, some material components can be changed.

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