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The bond strength by pull-off and direct tensile strength of concrete damaged by elevated temperatures

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Abstract. This paper presents the results of an experimental study of selected characteristics of concrete following its exposure to high temperatures. The monitored parameter was the influence of high temperatures on the bond strength and tensile strength of concrete. The bond strength was tested by a pull-off test, the tensile strength was determined as the direct tensile strength. Experimental concrete panels of 2300 × 1300 × 150 mm were exposed to high temperatures (corresponding to the temperatures in a normal fire) using a fire test furnace at the AdMaS Science Centre of the Faculty of Civil Engineering, Brno University of Technology. The direct tensile strength test was performed on cylinders (diameter of 100 mm and length of 100 mm) made from core samples taken from the panel. The pull-off test was performed on the surface exposed to high temperatures. The results of the experiment show a significant influence of high temperatures on the examined characteristics, and both characteristics were found to significantly decrease with a growing thermal load.

1. Introduction

At present, concrete ranks among the most commonly used building materials. The most important mechanical property of concrete, according to the current practice, is the compressive strength, according to which the concrete is classified into individual strength classes. Another important and no less significant role is played by the tensile characteristics of concrete, because they have a major influence on the occurrence and development of cracks in concrete structures [1,2]. When evaluating building structures made from this composite material, according to the recommendations given in ČSN ISO 13822 [3], the actual characteristics of the material are considered. It is also necessary to take into account material degradation caused by extraordinary influences which also include a load in the form of fire. Elevated temperatures cause damage of the concrete internal structure [1].

The direct tensile strength test of concrete is used very little in common practice due to its complicated execution. In order to achieve the required type of failure caused by direct tension, it is necessary to achieve a strict parallelism of the contact areas of the specimen (by grinding), and the specimens in the press must be perfectly centered [4,5].

For the testing, series of large-format experimental concrete panels were made as part of the experimental research, which were exposed with one side to the action of high temperatures in the furnace for fire tests of building materials and small-scale elements in the AdMaS Centre (Advanced Materials, Structures and Technologies), Faculty of Civil Engineering in the Brno University of Technology. Apart from the characteristics tested in this paper, also a number of other important properties of the thermally damaged concrete were assessed. The published partial outcomes include the results of both non-destructive [6,7] and destructive tests [8–12].

2. Methods

To determine the influence of high temperatures on the bond strength and tensile strength of concrete, a series of large-format experimental panels were made, which were subsequently thermally loaded.

2.1. Fire experiment

A total of 5 experimental panels (with dimensions of 2300 × 1300 × 150 mm) were made from standard concrete with a strength class of C30/37, with standard characteristics in terms of fire resistance. The mixture of fresh concrete consisted of Portland cement CEM I 42.5 R (335 kg/m^3), water (170 kg/m^3), silica sand 0–4 (840 kg/m^3), silica aggregate 8–16 (880 kg/m^3), fly ash (50 kg/m^3), and superplasticizer (2.67 kg/m^3). The concrete panels were reinforced with a mesh reinforcement near the bottom side.

In order to measure the temperatures achieved during the fire test, type K thermocouples were embedded into the panels. In each panel, a total of 10 thermocouples were placed along the longitudinal axis, three near the upper (unheated) side, three near the bottom (heated) side, three in the middle of the panel width, and one at a quarter of the panel width from the bottom side.

The test panels were placed on the upper side of the fire furnace, which guaranteed a one-sided heating of the panel from its bottom side. The upper side and lateral sides of the panel were left to have a spontaneous heat exchange with the surrounding environment. Loading with high temperatures was performed in accordance with EN 1992-1-2 [13] according to the standardized temperature curve specified in ISO 834 [14], because this chosen type of a sharp increase in the furnace temperature corresponds to the action of a real fire [13]. To achieve the prescribed maximum nominal temperatures (550, 600, 800 and 1000 °C), the level of thermal load specified for individual panels was always kept for the following 60 minutes. Then the panel was left on the furnace until cooling down to the environment temperature. One of the panels was left as a reference panel without thermal loading. The age of panels at the time of starting the fire tests was approximately 160 days, and thus the experiments were in accordance with the recommendations of RILEM TC 129-MHT [15] requiring the age of concrete of at least 90 days. Details of the fire test are given in the earlier publication [8].

2.2. Pull-off bond strength test

The strength test was performed in accordance with standard EN 1542 [16]. The procedure is based on a direct pull-off of a disc, which is glued onto the surface of the tested material. The pull-off area was defined in advance by making a core drill through the surface layer of the specimen. On each panel, 8 testing points were tested, and therefore, a total of 40 tests were performed.

At first, the tested surface was levelled by means of a grinding machine. A metal disc with a diameter of 50 mm was glued to the tested surface using a two-component adhesive. The metal disc provided with a thin continuous layer of an adhesive was attached to the surface of the drilled area concentrically with the core axis and pressed (air removal must be ensured). The potential adhesive running outside the disc area was immediately removed. The adhesive was left to set in accordance with the manufacturer's guidelines. Into the glued disc, a special screw with a small ball on one end was screwed, thanks to which the strength from the device is transferred to the pull-off area. The used Proceq DY-216 pull-off tester (Figure 1) is able to exert a maximum tensile force of up to 16 kN. The result of the test is then directly the value of bond strength in MPa, on the basis of the known area of the disc used.

Figure 1. Proceq DY-216: pull-off bond strength automated tester.

Figure 2. Pull-off bond strength test: a) selected panel (panel P7 loaded with 1000°C) after performing the pull-off test, b) detail of testing point P4-8 on the thermally unloaded panel P4 after performing the pull-off test, c) detail of testing point P7-3 on the thermally most loaded panel P7 after performing the pull-off test.

2.3. Direct tensile strength test

Specimens for the direct tensile strength test were obtained by core drilling from the experimental panels. The nominal diameter of the drilled core was 100 mm. Bases of the extracted cylinders were levelled from the side of the temperature action (therefore, we removed material with a width of several millimeters, so that the damaged part of the specimen was preserved as much as possible), and subsequently, the specimens were shortened also on the upper base, to 100 mm. The final test specimen was thus a cylinder with a diameter of 100 mm and a length of 100 mm. From each panel, 3 specimens were taken for this test. In total, we tested five series of three specimens, i.e. 15 specimens.

Bases of the test specimens were glued with a fast-setting two-component Sikadur adhesive to steel plates, which have a thread for screwing a joint with a holding rod serving for transmitting load from the tensile machine through the steel plate to the test specimen.

The direct tensile strength is determined on specimens, which are loaded by an axial tension of the tensile machine in the longitudinal direction. The tensile test was performed using a Heckert FPZ 100/1 mechanical press (see Figure 3).

Figure 3. Heckert FPZ 100/1 mechanical press for the direct tensile strength test (specimen 8C_P3).

During the test, a maximum tensile force is recorded. The direct tensile strength is then determined using the equation (1):

$$f_t = F_{max}/A \quad (1)$$

where f_t represents the direct tensile strength of concrete [MPa], F_{max} represents the size of load at failure of the test specimen [N], and A represents the cross-sectional area of the test specimen [mm^2].

3. Results

The tensile characteristics were used to evaluate the conditions of the concrete after high temperature exposition simulating fire load of structures. Direct tensile strength and pull-off bond strength were determined.

The results of experimental work are summarized in the form of average values and standard deviations in Figure 4 for bond strength determined by a pull-off and in Figure 5 for direct tensile strength of concrete.

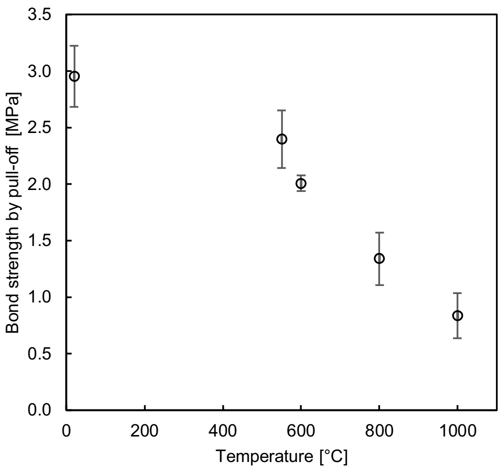

Figure 4. Dependence of the concrete bond strength determined by a pull-off test on temperature.

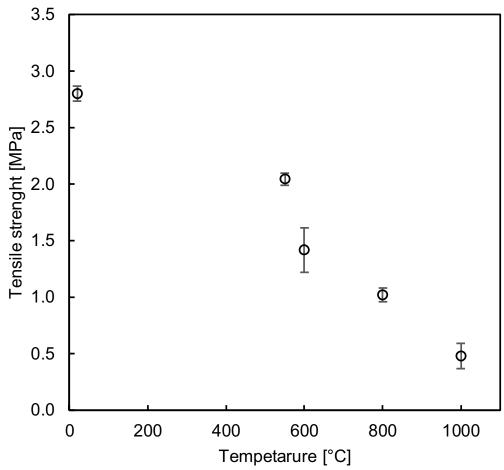

Figure 5. Dependence of the concrete direct tensile strength on temperature.

Table 1 and Figure 6 compares percentage changes of the tested characteristics, where the value determined on concrete without thermal loading (panel P4_T20) is considered a reference value (100 %). The rate of decrease of the direct tensile strength with increasing temperature is higher than for the pull-off bond strength. The characteristics declined the most significantly for temperature 1000 °C, the bond strength drops to 28.2 % and the direct tensile strength decreased to 17.1 % compared to the unloaded concrete.

Table 1. Percentage change in the characteristics of concrete depending on temperature – comparison of the bond strength by pull-off and the tensile strength.

Temperature (max.) [°C]	Bond strength by pull-off [%]	Tensile strength [%]
20	100.0	100.0
550	81.1	73.0
600	67.9	50.5
800	45.3	36.3
1000	28.2	17.1

In Figure 7, mutual comparison of the bond strength and the tensile strength values is shown. The strengths significantly decrease with increasing temperature. The direct tensile strength values are slightly higher than the bond strength by pull-off over the entire applied thermal load range.

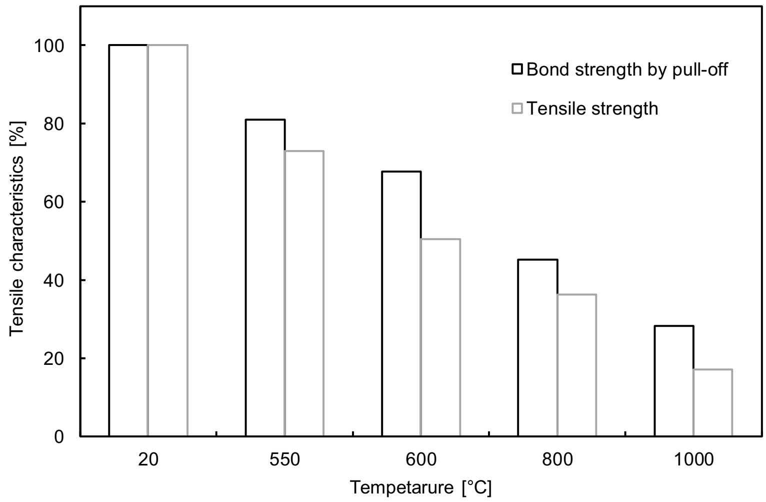

Figure 6. Percentage change in the tensile characteristics of concrete depending on temperature – comparison of the bond strength by pull-off and the direct tensile strength.

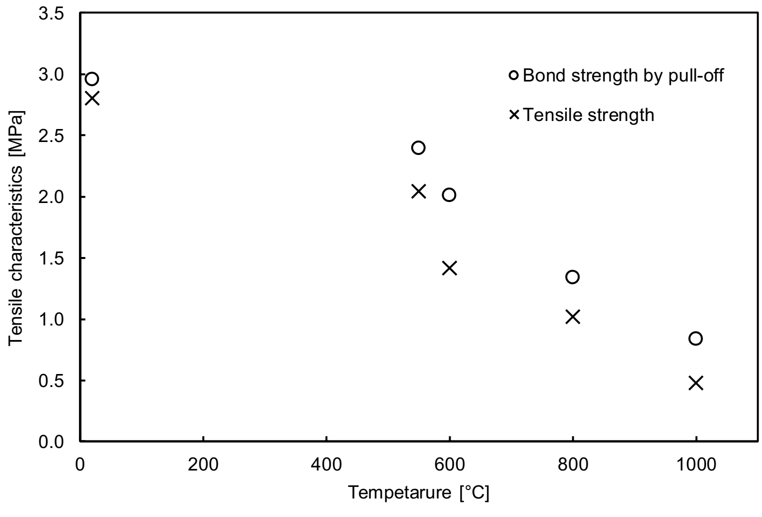

Figure 7. Mutual comparison of the bond strength and the tensile strength values.

4. Conclusion

The experiment examined the state of concrete after its thermal load with high temperatures. The values determined were the bond strength by a pull-off test and the direct tensile strength. The used methods proved a significant change in these characteristics due to exposure to high temperatures.

The bond strength of concrete determined by a pull-off test gradually decreases with a growing thermal load. In comparison with the reference specimens, there was almost a 72 % decrease in the most heavily loaded panel. No significant trend in the variability of individual measurements was observed, and its values were not particularly significant.

Similar behaviour was observed also for the direct tensile strength of concrete. The decrease in strength was even more significant, the strength for the highest temperature decreased by almost 83 %. The measurement variability also does not display significant changes caused by growing temperatures.

A mutual visual comparison of the determined characteristics suggests the possibility of a certain relation between the tensile strength of concrete and its bond strength. In order to arrive at valid conclusions, it would be appropriate to focus on examining also this option in future.

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