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Impact of the Heat Load of Concrete on the Propagation of Ultrasound Waves

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Abstract. Due to fires of building structures, there has been a growing interest in investigating the properties of concrete at high temperatures. In the fire, a temperature of up to 1400 °C may be measured. Such high temperatures will bring about changes in the structures of the entire construction. Ultrasonic methods such as acoustic emission method can be used to monitor changes in the structure caused by a fire. Two similar concrete mixtures after thermal degradation are evaluated using an impulse ultrasonic method.

Introduction

Interest in the behaviour of concrete under high temperatures has recently been fuelled by fires of industrial, government- or private-owned buildings, tunnels, and other building structures. In a fire, the temperature may reach up to 1400 °C [1]. Due to such heat, changes occur in structures that may alter the mechanical properties and structures of materials through macro- and micro-cracks.

The resistance to fire of reinforced concrete may be defined as its capacity, in the event of a fire, to keep the concrete's native function, its structural properties, to protect the steel reinforcements, and protect the immediate environment against toxic gases [2]. Damage to concrete due to a fire is not regarded as a degradation mechanism, but rather as an accident and direct external influence. However, the driving forces that cause explosive crumbling of concrete exposed to a fire may be related to the microstructure and transport mechanisms of the cement material, as is the case with other degradation mechanisms [3]. A major difference is that the damage results in a much shorter time and that concrete may be destroyed within an hour or even a shorter interval [4].

The mechanisms causing explosive crumbling or disintegration in the event of fire include concrete humidity and material microstructure. At 100^{o} C, the water contained in concrete will turn to steam. As the temperature grows, the pressure of the steam in concrete will mount, too. With the concrete microstructure being rather open, i.e., with an interconnected system of pores (high water coefficient), the steam pressure will drop as the steam is leaking rather fast. If, however, the concrete structure is rather dense, the steam pressure may reach values exceeding 3 N/mm^2. As a result of high internal pressure, a thin surface layer of concrete may abruptly be torn off, which is called explosive crumbling [5].

The paper aims to evaluate the concrete properties monitored at different temperatures of up to 1200 °C [6]. The observed changes in the propagation of ultrasound waves through degraded concrete material may be used to quickly assess the quality of a concrete structure after being exposed to heat from a fire [7]. Acoustic or ultrasound methods are among the non-destructive methods that may often enable an early detection of material failures in a structure [8,9].

Experimental set up

This paper presents evaluation of ultrasound signals when testing their passage through the material of concrete specimens after a heat load. The used specimens were a prism of 100 mm by 100 mm and length of 400 mm, Each specimen was placed in an oven to be exposed for one hour to one of the temperatures of 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C, and 1200 °C. Two similar mixture was made - cement CEM I 42.5R of 350 kg/m^3, sand 0/4 of 820 kg/m^3, water of 160 kg/m^3, super plasticizer of 3 kg/m^3. The mixture A contains coarse aggregate 8/16 which mixture B makes compensate of coarse aggregate 11/22 of 1000 kg/m^3.

The PUNDIT ultrasound device with a classic ultrasound probe placed on a 100 mm by 100 mm square wall was generated an impulse signal. Four sensors were pick up ultrasound signals as shown in Fig. 1. The two sensors are placed of 50 mm from the opposite wall of the exciter.

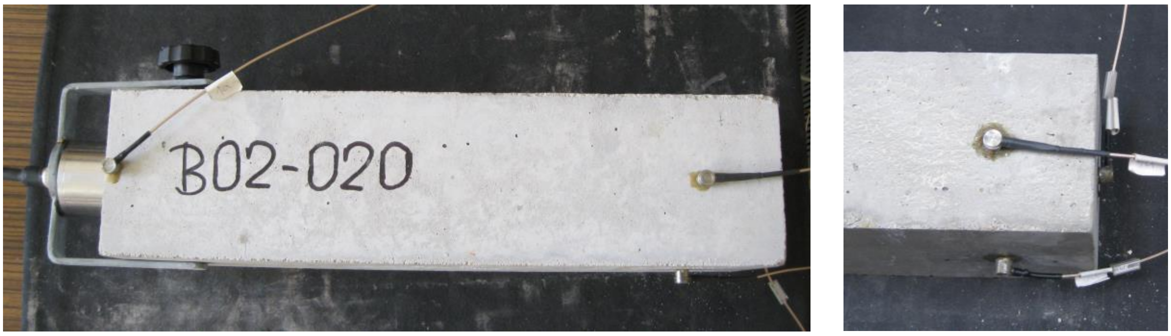

Figure 1 Location of the exciter and the sensors on specimens.

By impact acoustic emission tests, for each temperature degradation, twenty specimens were put to an impact acoustic emission test. Each specimen was loaded with three different pulse amplitudes of 250 V, 500 V, and 1200 V, respectively. The errors of the values measured are below five percentage points.

Monitored properties

The values measured of selected material properties obtained from destructive and non-destructive tests are illustrated in Fig. 2, 3 and 4 and in Table 1. The bar diagrams show the temperature-dependent trends between the compressive strengths, the flexural bending strengths, maximal amplitudes of the impact acoustic emission and the linearity of increasing loading impulse. Similar trends were observed between the monitored properties and the temperature, that is, with an increasing temperature, the value measured will drop down to a degrading temperature of 1000 ^{o}C at which the sample structure begins to change significantly.

The compressive strengths of both mixtures are similar except at degraded usually temperature as shown in Fig. 2 left graph. However, the flexural bending strengths shown in Fig. 2 right graph are a little different; here mixture B contains higher values except for degradation temperature of 1200 ^{o}C.

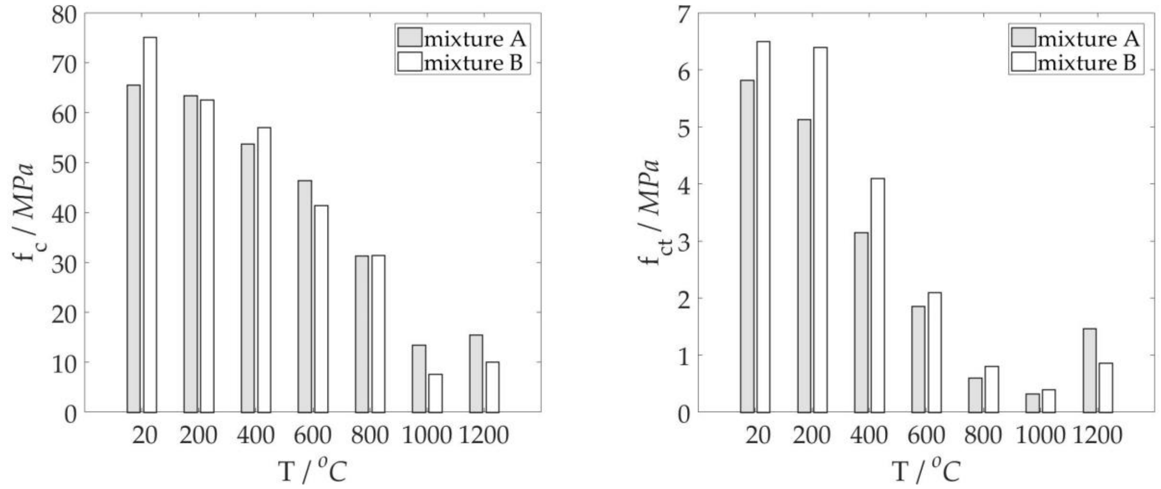

Figure 2 The compressive strength f_c and the flexural bending strength f_{ct} at the different degradation temperatures T

To describe the response emission signals, which are formed during the impact test in the specimens, we focused on the selected parameters of these signals such as maximal amplitude. In Fig. 3 frequency spectral responses of sensor No 4 of mixture A (left graph) and of mixture B (right graph) dependent on the degraded temperature at the loaded impulse of 1200 V will be evaluated in a next article. A response sample were recorded by 4 MHz, therefore the frequency are up to 200 kHz contains higher values of spectra. This sampled frequency was applied for point of view of higher time resolution.

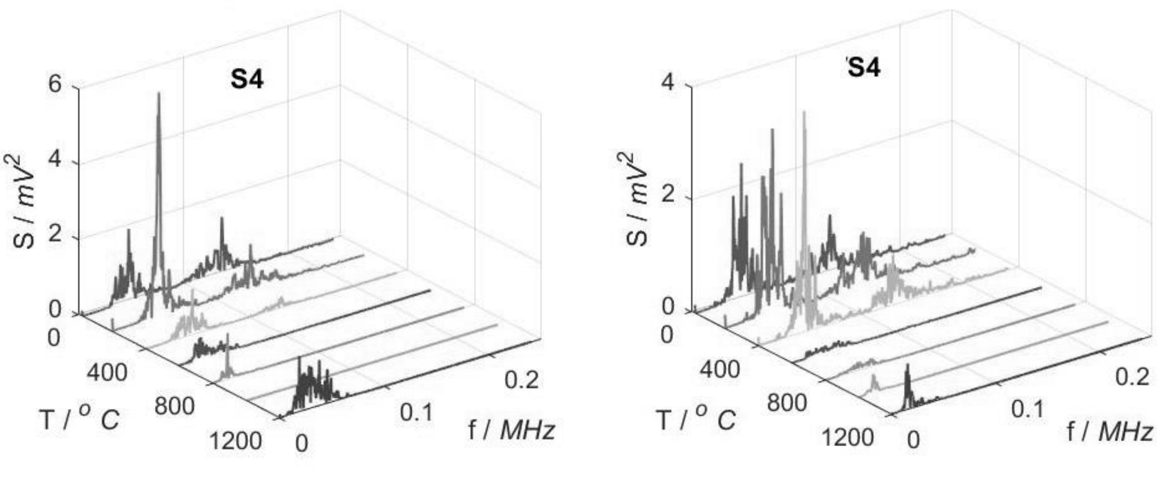

Figure 3 The spectral response S at the different degradation temperature T and the frequency f for specimens of mixture A in the left and of mixture B in the right

The bar graphs in the Figure 4 show seven groups of columns. Each group of six columns shows pairs, that is, for each mixture, different excitation voltages, the first pair 250 V, the second 500 V and the third 1200 V. The degrading-temperature-dependent character of the resizing of the maximum amplitude (see Fig. 4) is similar to that in the case of changes in the compressive strength or the flexural bending strength (see Fig. 2).

There are two areas of interest in the range of temperatures of up to about 200°C and around 1000°C. In the first temperature region of up to 200°C, the maximum amplitude increases, thus the compressive strength does not change significantly. The minimum value is reached both by the maximum pulse amplitude of the impact acoustic emission and the compressive strengths and flexural bending strengths at temperatures around 1000°C, at which the structure of cement mixtures changes.

The changes up to temperature of 200°C are the effect of loss of free water occurs at about 100 °C. Here is formatted Calcium-Silicate-Hydrate (C-S-H) and Calcium Hydroxide $Ca(OH)_2$ - Portlandite. During further raising temperatures of up to 200 °C begins dehydration cementing compound. The main phenomena for decreasing properties until about temperature of 600 °C are decomposition of calcium hydroxide ($Ca(OH)_2 \rightarrow CaO + H_2O$) takes place at about 450 °C and the crystal structure of quartz transforms at temperature of 573 °C from α- to the β- form and at temperature of 900°C calcite starts shrinking due to decomposition. The next phenomena, that affects the mechanical properties, is that the volume and surface of pores increase up to a temperature of 500°C and decrease with further increase of temperature. Whenever the temperature was increased to of 800 °C were the second phase decomposition C-S-H took place and also decomposition of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$). When the temperature is above 1000 °C, it changes the overall structure of the concrete mixture to rocks melt, therefore a structural change, accompanied by the creation of new crystal phases (Wollastonit β - $CaO.SiO_2$).

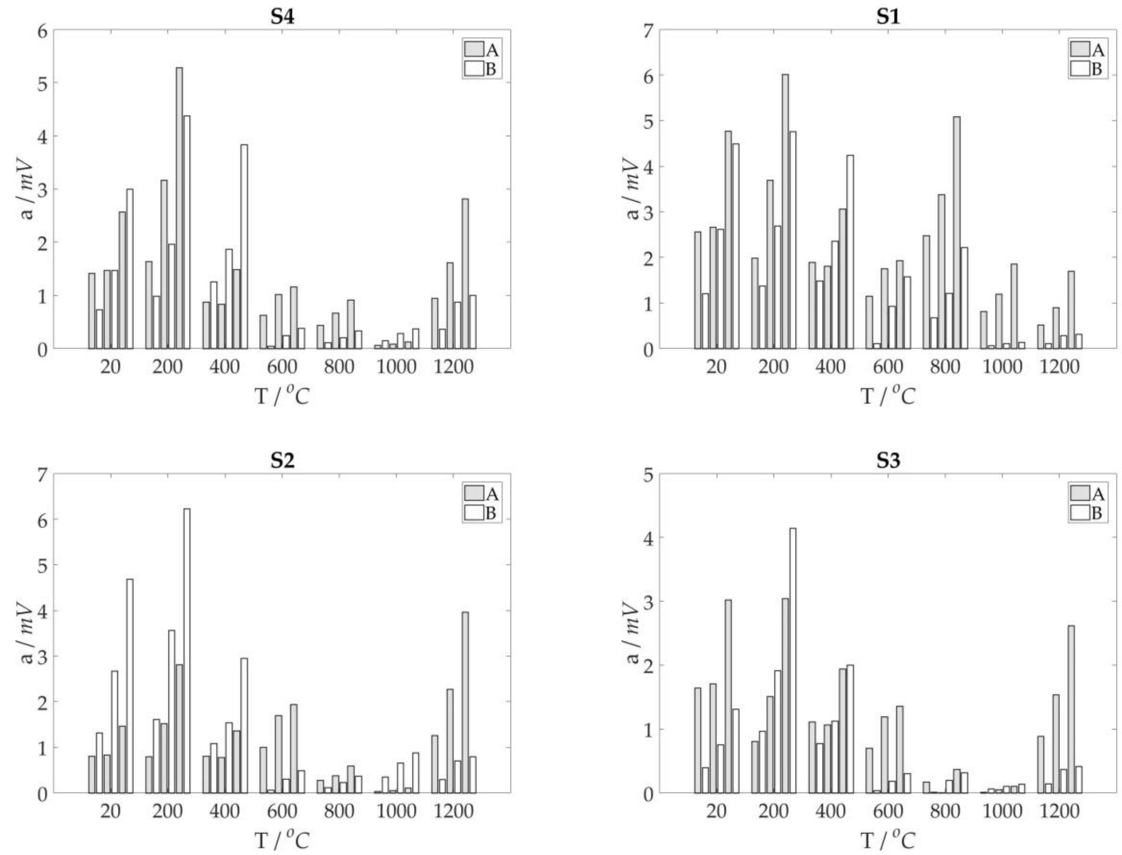

Figure 4 Maximal amplitudes a depending on degraded temperature T and excited voltage (each group contained 250 V, 500 V and 1200 V)

The correlation coefficients of the linear increase in the maximum amplitude due to the rising pulse excitation voltage according to Table 1 are very close to one, which means that the behaviour of the sample is linear. Lower values of the correlation coefficients occur at degradation temperatures of above 600 °C.

Table 1 The correlation coefficients

	Degraded temperature [°C]	20	200	400	600	800	1000	1200
Sensor 1	Mixture A	0.977	0.984	0.951	0.901	0.996	0.994	0.998
	Mixture B	0.983	0.991	0.998	0.945	0.995	0.915	**0.786**
Sensor 2	Mixture A	0.976	0.995	0.953	0.906	0.999	0.998	0.993
	Mixture B	0.988	0.984	1.000	0.940	0.979	0.939	0.811
Sensor 3	Mixture A	0.977	0.998	0.954	0.907	**0.752**	0.982	0.992
	Mixture B	0.990	0.999	1.000	0.944	0.921	0.923	0.805
Sensor 4	Mixture A	0.997	0.985	0.952	0.905	0.970	0.981	0.995
	Mixture B	0.998	1.000	1.000	0.931	0.981	0.929	0.824

Conclusions

The paper describes an analysis of the impact acoustic emission tests carried out on temperature degraded concrete specimens. The evaluations of the experiments imply the possibility of using the impulse acoustic emission method to describe the changes of concrete structure after its fire degradation. The outputs of the impulse acoustic emission method can help for more accurate input parameters for numerical models. As can be seen in Table 1 for mathematical modelling, it can be assumed that increasing the excitation amplitude is a linear process.

The replacement of the coarse aggregate 8/16 by the coarse aggregate 11/22 can improve the fire resistant properties of concrete.

Based on the above results it can be concluded that the monitoring history of concrete using the impulse acoustic emission method can approximately determine the degradation of a structure due to thermal loading. However, in practice, there are many more factors influencing the transport of waves through an observed structure, especially a heterogeneous one.

The above method of acoustic emission combines the advantages of the ultrasound impulse method and the signal recording by the acoustic emission method with valuable information about the longitudinal, transversal, and surface wave obtained from a single impulse. The change in the input pulse shape and the the different levels of the excitation voltage yield comprehensive information on the observed structure.

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