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The Acoustic Emission Parameters Obtained during Three-point Bending Test on Thermal-stressed Concrete Specimens

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Abstract

Fire response of concrete structural members depends on thermal, mechanical, and deformation properties of concrete. These properties vary significantly with temperature and also depend on the composition and characteristics of the concrete batch mix as well as heating rate and other environmental conditions. Concrete structures could be exposed to extreme temperature conditions. Examples of such conditions are concrete foundations for launching rockets carrying spaceships, concrete structures in nuclear power stations or those accidentally exposed to fire, for instance in the case of tunnel fires. This paper analyses acoustic emission signals captured during three-point bending test on thermal-stressed concrete specimens. The method of acoustic emission is an experimental tool suitable for monitoring the failure processes in materials. The typical parameters of acoustic emission signal were identified during the acoustic emission records for different concrete specimens to further describe the under-the-stress behaviour and failure development. The amount of crack growth was continuously monitored using four acoustic emission sensors mounted on the specimens.

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Keywords: acoustic emission method; three-point bending test; plain concrete; high-temperature degradation; modulus of elasticity;

1. Introduction

After the terrorist attacks, the worldwide interest in the design of structures for fire greatly increased. Currently, the structural fire safety is one of the key considerations in building applications. When subjected to heat, concrete responds not just to instantaneous physical changes, such as expansion, but by undergoing various chemical changes.

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This response is especially complex due to the non-uniformity of the material. Concrete contains both cement and aggregate elements, and these may react to heating in a variety of ways. First of all, there are a number of physical and chemical changes which occur in the cement subjected to heat [1,2].

Some of these are reversible upon cooling, but others are non-reversible and may significantly weaken the concrete structure after a fire. Most porous concretes contain a certain amount of liquid water in them. This will obviously vaporize if the temperature significantly exceeds the moisture level range of 100 - 140 °C or so, normally causing a build-up of pressure within the concrete. If the temperature reaches about 400 °C, the calcium hydroxide in the cement will begin to dehydrate, generating further water vapor and also bringing about a significant reduction in the physical strength of the material. Other changes may occur in the aggregate at higher temperatures, for example, quartz-based aggregates increase in volume, due to a mineral transformation, at about 575 °C and limestone aggregates will decompose at about 800 °C. In isolation, the thermal response of the aggregate itself is more straightforward but the overall response of the concrete due to changes in the aggregate may be much greater. For example, differential expansion between the aggregate and the cement matrix may cause cracking and spalling. These physical and chemical changes in concrete will have the effect of reducing the compressive strength of the material. Generally, concrete will maintain its compressive strength until a critical temperature is reached, at which point it will rapidly drop off. This generally occurs at around 600 °C. This is only a little higher than critical temperatures for steel, but because of the much lower conductivity of concrete the heat tends not to penetrate very far into the depth of the material, meaning that the structure as a whole normally retains much of its strength (timber is similar in being able to retain strength in its depth once surface layers have been attacked by fire) [3,4].

The dynamic modulus of elasticity was determined by means of two non-destructive methods. The first was the ultrasonic (US) pulse velocity test, which determined the dynamic elastic modulus E_{cu}. The static modulus of elasticity was determined by means of the compressive test, which is ended by measuring the specimens' compressive strength (i.e. specimen failure).

The principle of the ultrasonic pulse velocity test is the repeated releasing of ultrasonic impulses into the specimen and measuring the time T required for them to travel through, which is then used in the determination of the velocity of ultrasonic wave propagation v_L through the concrete. In the end, the dynamic modulus of elasticity is calculated using the equation:

$$E_{cu} = \rho \cdot v_L^2 \cdot \frac{1}{k^2} \cdot 10^{-6}, \tag{1}$$

where E_{cu} is the dynamic modulus of elasticity in MPa, ρ is the material's bulk density in kg/m^3, v_L is the ultrasonic pulse velocity in m/s and k is the dimensionality coefficient.

The dimensionality coefficient k equals 1 for a one-dimensional environment, and in the cases of two- and three-dimensional environments it depends on the value of Poisson's ratio μ, which can be determined by means of the resonance method (as was done in the experiment described here).

The time for which the ultrasonic pulse travelled through each specimen was measured longitudinally in three positions. The ultrasonic wave velocity was calculated for each position and the average of the results was used as the velocity v_L in the calculation of the elastic modulus according to (1). The procedure of E_{cu} determination was in accordance with the standard [5].

The static modulus of elasticity of each specimen was determined in accordance with the standard [6] using 200 mm resistance strain gauges and a testing press FORM+TEST ALPHA 3-3000. The resulting values of the elastic modulus E_c were calculated according to the equation:

$$E_c = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b}, \tag{2}$$

where E_c is the static compressive modulus of elasticity in MPa, σ_a is the upper loading stress in MPa, i.e. $1/3f_c$, σ_b is the basic loading stress, i.e. 0.5 MPa, ε_a is the average relative deformation at upper loading stress and ε_b is the average relative deformation at basic loading stress.

Acoustic emission method is a powerful technique for non-destructive testing and materials evaluation. Acoustic emission (AE) is the term for the noise emitted by materials and structures when they are subjected to stress. Stress can be tensile, compressive or shear and can have components in all three dimensions. Under the action of stress, the material expands contracts or shears elastically: this is known as “strain”. These waves travel from the source to the sensors where they are converted to electrical signals. The AE instrumentation measures these signals and produces data displays from which the operator evaluates the condition and behaviour of the structure under stress [7]. This emission is caused by the rapid release of energy within a material due to events such as crack formation, and the subsequent extension occurring under an applied stress, generating transient elastic waves which can be detected by piezoelectric sensors. Acoustic emission method can monitor changes in materials behaviour over a long time and without moving one of its components i.e. sensors [8,9].

2. Material and experimental setup

For experimental part, concrete samples with dimensions of 0.1 x 0.1 x 0.4 m were prepared. Specimens were prepared according to the following mix design (for $1m^3$): 345 kg Portland cement CEM I (42.5 R Mokrá), 848 kg sand (Žabčice 0/4), 980 kg gravel aggregate (Olbramovice 8/16), 2.8 kg superplasticizer (Sika Viscocrete 2030) and 160 kg water in laboratory of the Institute of Technology of Building Materials and Components, Faculty of Civil Engineering, Brno University of Technology. Seven sets of test specimens were manufactured. Each set was labelled with an ID number which corresponds to the temperature conditions maintained in the laboratory furnace during its heating. Specimens labelled 20 represent concrete specimens which dried freely in laboratory conditions with a temperature of (21±1) °C and were not further heated.

The specimens (except for samples labelled 20) were immersed in a water bath for 28 days. Then, they were dried first in the laboratory conditions and then in a ceramic furnace at temperature 110 °C for another 48 hours. The concrete specimens were heated in a programmable laboratory furnace Rhode KE 130B at the heating rate of 5 °C/min. Selected temperatures T= 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C and 1200 °C were maintained for 60 minutes.

Three-point bending (3PB) tests were performed after the specimens were exposed to prescribed thermal-stress levels. Ten specimens from each set were tested. During the tests, an acoustic emission activity was recorded. Four acoustic emission sensors were attached to the surface by beeswax – see in Fig. 1. Acoustic emission signals were taken by measuring device DAKEL XEDO with four acoustic emission sensors IDK-09, which included 35 dB preamplifier. To eliminate the mechanical and electrical noise, the guard sensor was used.

The loading tests were carried out using a Heckert FPZ 100/1 testing machine at a laboratory in the Institute of Building Testing, Faculty of Civil Engineering, Brno University of Technology. Beam specimens with initial central edge notches were loaded under a 3PB test using the displacement-controlled method which is more suitable for monitoring the behaviour of specimens after crack initiation and during its propagation. The initial notch was made by a diamond blade saw before testing. The depth of the notches was about 33 mm for all specimens.

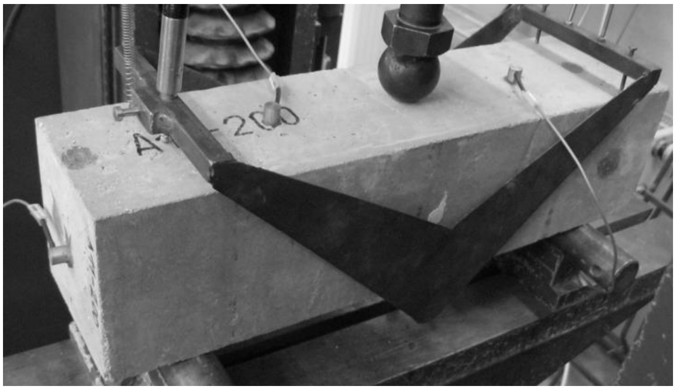

Fig. 1. The arrangement of acoustic emission sensors on specimen during the three-point bending test.

3. Results and discussions

The measured values of selected material properties obtained from destructive and non-destructive tests (compressive cube strength, static and dynamic modulus of elasticity) are summarized in Table 1. This table also introduces informative changes of bulk density values. It was observed that the concrete modulus of elasticity is significantly affected by the thermal stress and its value decreases with rising temperature [9,10]. At high temperature, the disintegration of hydrated cement products and breakage of bonds in the microstructure of cement paste reduce the elastic modulus. The range of reduction depends on moisture loss, high-temperature creep, and type of aggregate [11]. The static modulus of elasticity was non-measurable for specimens burned at 1000 °C.

Table 1. The selected properties of thermally degraded concrete.

	Specimens ID						
Properties	20	200	400	600	800	1000	1200
Average bulk density [kg/m^3]	2353	2306	2275	2312	2244	2146	2038
Compressive cube strength [MPa]	52.50	41.80	30.90	26.00	14.00	3.80	10.80
Static modulus of elasticity E_c [GPa]	32.50	30.70	15.10	7.52	3.62	–	4.39
Dynamic modulus of elasticity E_{cu} [GPa]	39.80	36.70	17.80	9.64	2.71	0.94	6.10

To describe acoustic emission signals which are formed during the three-point bending test in the specimens, the focus was on the selected parameters of these signals, e.g. number of events, AE amplitude and AE energy. Amplitude is the greatest measured voltage in a waveform. This is an important parameter in AE inspection because it determines the detectability of the signal. Signals with amplitudes below the minimum threshold will not be recorded. Another monitored parameter, acoustic emission energy, is directly proportional to the area under the acoustic emission waveform. Results of analysis of acoustic emission signals captured during three-point bending tests are introduced in Fig. 2, Fig. 3 and Fig. 5 where mean values (obtained from 10 independent measurements) and standard deviations (as error bars) of investigated parameters are displayed.

Fig. 2 and Fig. 3 presents the dependence of a number of AE events and amplitude of AE signals on the thermal stress level. The waves which emerge and propagate within the sample during the three-point bending test, can affect the material element oscillations. The exposure to elevated temperatures causes a change of structure, leading to the change in number of AE events and amplitudes of AE signals. All specimens, which were heated in the range of 200 to 800 °C, showed very similar behaviour. The structural changes did not have a significant influence on the value of amplitudes of AE signals recorded from the start of measurement up to the time when the specimens reached their ultimate tensile capacity, which means that micro cracks formed during the loading was of the same size in all cases. The explanation of this phenomenon can be found in process of concrete decomposition during the thermal stress application. Heating the concrete up to 100 °C results in the dehydration (conversion of loosely bound to water chemically bound) and the formation of Calcium-Silicate-Hydrate (C-S-H) and calcium hydroxide $Ca(OH)_2$ – Portlandite occurs. During further raising of heating temperature up to 200 °C, dehydration of cementing compound begins which results in the release of physically bound water along with the concurrent decomposition of hydrate. The first stage of decomposition of C-S-H and decomposition of gypsum $CaSO_4.2H_2O$ culminates between 150 °C and 170 °C. However, a number of AE events is lower than in the case of specimen labelled 20 (unheated), which indicates a lower quantity of new formed micro cracks. At a temperature above 200 °C, the release of physically bound water occurs. Between 250 - 300 °C, the hydrated cement phases are decomposed. Further increase of temperature above 300 °C results in decomposition of Portlandite [$Ca(OH)_2 \rightarrow CaO + H_2O$] and the significant formation of micro cracks. The formation of micro cracks and Portlandite decomposition resulted in a significant increase in the amount of micro cracks which arose before the reaching the ultimate tensile capacity of the test specimens during three-point bending test.

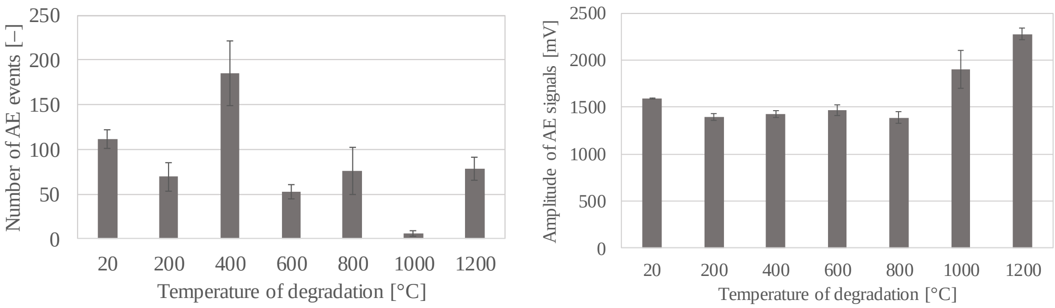

Fig. 2. The dependence of number of AE events (left) and amplitude of AE signals (right) on thermal stress level (record to ultimate tensile capacity).

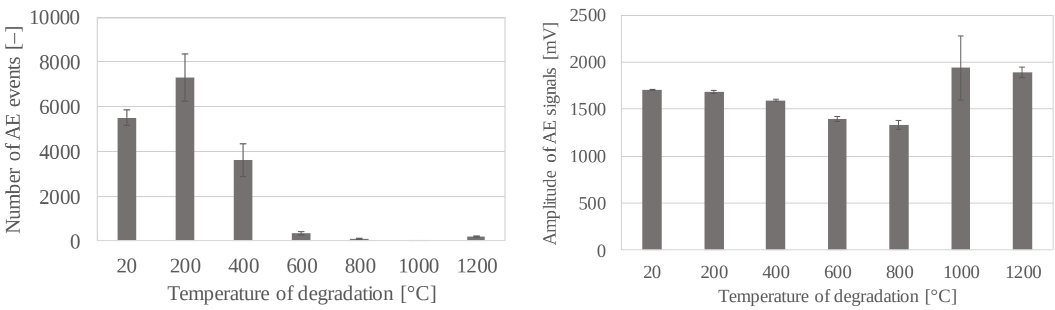

Fig. 3. The dependence of number of AE events (left) and amplitude of AE signals (right) on thermal stress level (record a whole of measurement).

The decrease of a number of AE events and values of amplitude of AE signals is caused by quartz phase transition (in the silicate aggregate) from triclinic system to the hexagonal system (β at α 573 °C) after burning up to (at) 600 °C (Fig. 3). This resulted, together with the influence of a difference in thermal expansion disruption bonds between aggregate and cementing compound, in the creation of a small number of micro cracks during 3PB test.

When the burning temperature is increased to 800 °C, the second phase of C-S-H and also of calcium carbonate [$CaCO_3 \rightarrow CaO + CO_2$] decomposition occurs. This decomposition leads to a decrease in the number and size of arising micro cracks (see Fig. 3). In conjunction with the total decomposition of the cementing compound at the temperature of 1000 °C, the lowest value of the number of AE events (the smallest number of arising micro cracks) was recorded for the specimens labelled 1000.

For the specimens which were exposed to a thermal stress at a temperature of 1200 °C, a larger number and size of forming micro cracks were recorded again. This is due to a structural change, accompanied by the creation of new crystal phases [Wollastonite β ($CaO.SiO_2$)], which takes place in the specimen's structure at temperatures of above 1000 °C. In the photos (Fig. 4) of selected specimens are visible cracks which were formed by burning.

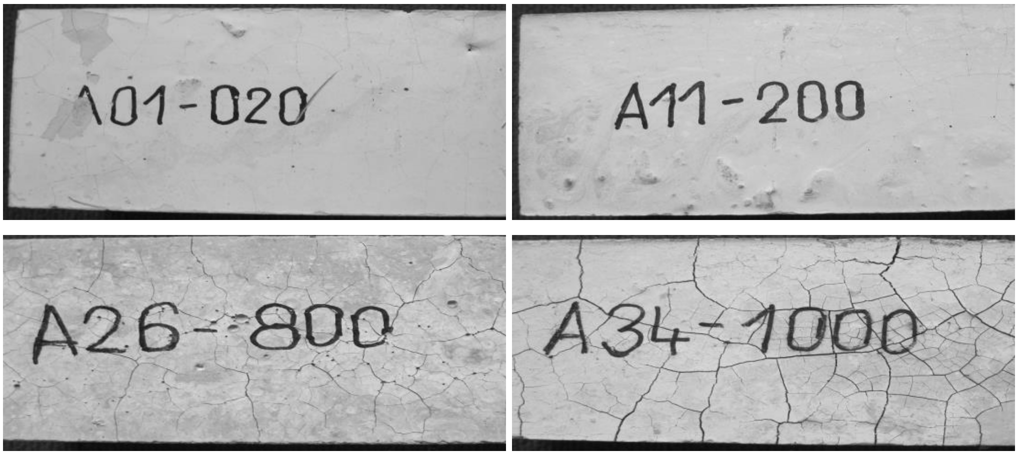

Fig. 4. The photo of selected specimens after the three-point bending test.

The values of AE energy (Fig. 5) are in correlation with the toughness of the particular set of concrete specimens. The highest value of AE energy was recorded for specimens exposed to the temperature of 200 °C which may indicate that also the toughness of the specimen is high (in comparison with no heated specimens labelled 20). This implies that structural changes prevent from the crack growth, because more energy is needed for fracture. Generally speaking, the rising burning temperature above 200 °C causes a decrease in the quantity of AE energy released during the three-point bending test that indicates the raising brittleness of the material. This behaviour of concrete is changed with the temperature of above 1000 °C, when the Wollastonite is created and the increase in concrete toughness can be observed.

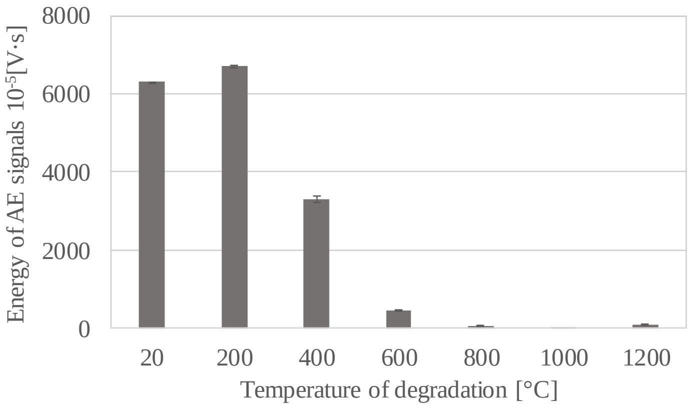

Fig. 5. The dependence of energy of AE signals on degradation thermal stress level (record a whole of measurement).

4. Conclusions

In this work, several experimental tests were carried out and analysed on thermal-stressed concrete specimens loaded up to failure are analysed. Specimens with central notch were subjected to the three-point bending test. During the experiments, the AE technique was used to monitor the progress of the specimens' failure. It is obvious, that different types of cracks generate different AE signals. These differences can be related to the degree of damage of the structure. It can be assumed that higher value of amplitude indicates better mechanical properties of concrete which have a better bond of the matrix. A small number of cracks generate a small number of events before the failure occurs. The different burning temperature has a significant influence on monitored signal parameters of AE. From the AE method measurement, the following conclusions may be drawn:

- The more brittle material, the less AE events are recorded before a visible crack is created.
- The increased AE energy and AE amplitude recorded for the specimens exposed to the temperature above the 1000 °C is probably connected with increase in toughness of concrete specimens after Wollastonite was created.

In summary, the results of the experiments performed as part of the research project focused on thermal-stressed concrete can be used for the prediction of properties of thermal-stressed cement materials as well as the specific characteristics of micro cracks. The properties of the micro cracks can be linked to the overall fracture behaviour of the materials.

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