Measurement of crack growth speed in concrete by acoustic emission and mechanics of damage methods

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Abstract. The article presents the results of research and experimental studies aimed at measurement of crack growth speed in concrete of different types and composition. The study included complex methods to measure the parameters of concrete destruction under the impact of mechanic loads and aggressive factors. The experiments were performed using mechanics of damage methods and acoustic measurement of such parameters as acoustic emission gross counting and counting rate. The experiments resulted in regression equations showing change of acoustic emission gross counting depending on the speed of a specimen loading. Data on slow growth of cracks in heat-resistant concrete during heating up to 800°C have been obtained by acoustic emission and mechanics of damage methods. The performed studies and statistic processing of the obtained data allowed identifying that parameters of acoustic emission are directly related to the characteristics of mechanics of damage that reveals a considerable capacity of acoustic emission as a method for forecasting destruction of concrete.

1. Introduction
Concrete crack resistance mainly depends on the speed of load application. Formation and stepwise propagation of the crack tip at the subcritical stage of its development result in the change of acoustic emission (AE) signals. AE parameters increase with the increase in the speed of the crack growth [1].

2. Relevance
So far, there are no experiments on the influence of a wide range of loading speed values on the change of AE gross counting values. This can be explained by technical difficulties. In order to forecast the destruction taking into account high sensitivity of the AE method, the most useful is the ratio between the crack growth speed and the acoustic emission counting rate. Intensity of acoustic emission reasoned by the growth of the primary crack is immediately related to the speed of its growth. There are few studies on the control of the crack growth and deformations in concrete by means of AE method [1-9]. Thus, such researches are very relevant and require additional experiments.

3. Problem statement
This article covers complex studies on the measurement of macro-crack growth speed in concrete containing different coarse aggregates. Correlations between the change of acoustic parameters and concrete specimen loading speed have been obtained. The experiments included complex measurement of such parameters as acoustic emission gross counting, specimen loading speed by
means of acoustic and mechanics of damage methods. Equations and their diagrams showing dependence between AE counting rate and stress intensity coefficient have been received [10].

4. Theoretical part
Experimental studies of AE during crack formation are performed following standard methods for mechanical testing of samples with a cut (initial crack). Receiving transducers are additionally installed on the surface of the specimen to register AE parameters during loading. The most widespread is registration of AE gross counting and counting rate.

The advantage of the AE method is the capacity to determine kinetic parameters of the growing defect under the influence of aggressive factors or if the access to the studied object is restricted. Structural defects and micro- and macro-cracks appearing during loading serve as sources of acoustic pulses for the control of strength and crack resistance parameters of concrete having irregular structure. The strength of the AE signal depends on the quantity of accumulated energy during the crystal lattice bonds breaking, and when the material loses its bearing capacity (breaking stress), energy and amplitude of the acoustic pulse are at their maximum. There is a regular dependence of acoustic emission on strength and crack resistance of materials.

With the view to test specimens by three-point bending, the author produced a special plant that allowed loading with speed ranging from 10-7 m/s to 101 m/s [10]. Transition from hydraulic press to mechanical one allowed reducing noise level during testing.

The following materials were selected for testing: lightweight concrete with organic aggregates represented by corncobs without seeds that demonstrates a relatively long crack development process and heavy concrete with granitic and limestone aggregates.

Heat-resistant concretes with different bonding materials were used to determine the parameters of slow crack growth under the impact of aggressive environment of high temperatures.

5. Results of experimental studies
According to the suggested methods [10-16], concrete specimens were tested to determine the influence of loading speed on the change of acoustic parameters; full destruction diagrams were obtained and stress intensity coefficient was determined. Similar additional experiments allowed elaborating different types and compositions of concrete with improved crack resistance, strength and life performance [17-25]. Concrete compositions were selected using own software [26].

The experiments resulted in regression equations and diagrams showing change of AE gross counting depending on the speed of the specimen loading:

- concrete with organic aggregate:
  \[ N = 0.016 \sigma^{0.21} \]  
  where \( N \) - AE gross counting, pulse; \( \sigma \) - specimen loading speed, m/s.

- concrete with limestone aggregate:
  \[ N = 0.019 \sigma^{0.55} \]  

- concrete with granitic aggregate:
  \[ N = 0.02 \sigma^{1.71} \]  

Analysis of the diagrams shows that lightweight concrete with organic aggregate demonstrates gradual increase of AE gross counting from the minimum to the maximum speed of loading that testifies to a ductile destruction, i.e. a relatively long process of crack growth. More compact and stronger heavy concrete with granitic and limestone aggregates demonstrated a slight increase of the above named parameters with the increase of loading speed from \( 10^{-7} \) m/s to \( 10^{-4} \) m/s. However, when loading speed increases up to \( 10^{-3} \div 10^{-2} \) m/s, AE characteristics abruptly increase that testifies to a high-speed growth of the formed macro-cracks. Maximum value of AE gross counting registered at a
specimen loading speed of $10^{-2}$ m/s was obtained for heavy concrete with granitic aggregate; its density and strength were the largest, too.

Thus, heavy concrete having compact and strong aggregates in composition are less subject to the changes in crack resistance with increasing speed of load application that testifies to the quasi-brittle destruction character of concrete.

Heat-resistant concrete on portland cement, aluminous cement and alkali silicate were included into the experiment to obtain more reliable data on slow crack growth by methods of acoustic emission and mechanics of damage. Before testing specimens with dimensions 100x100x400 mm having a central cut equalling 0.5 of the specimen height were heated to a temperature of 800°C and held under such temperatures for 3 hours. The concrete compositions included into the testing of heat-resistant concretes after being heated have increased plasticity and, consequently, a longer period of subcritical crack growth that proves the advantages and informativity of the offered methods.

Full diagrams of deformation by hydraulic press with a stiffener [27], the dependence between crack growth rate - $V$ and stress intensity coefficient - $K_I$ as well as acoustic emission counting rate - $N$ were obtained.

Equations and their diagrams (Figure 1) showing dependence between AE counting rate - $N$ and stress intensity coefficient - $K_I$ have been received as a result of the performed experiments.

Equations $V-K_I$ and $N-K_I$ had power dependence irrespectively of the type and composition of concrete. Heat-resistant concrete on portland cement demonstrates the following dependences at a temperature of 800°C:

$$
N = 553,2 \ K_I^{1.0} \\
V = 0,04 \ K_I^{13,35}
$$

Heat-resistant cement on aluminous cement:

$$
N = 585,7 \ K_I^{1.1} \\
V = 0,05 \ K_I^{14,8}
$$

Heat-resistant concrete on alkali silicate:

$$
N = 1904 \ K_I^{1.1} \\
V = 0,063 \ K_I^{15,46}
$$

The analysis of the obtained results shows almost complete agreement of the AE parameters and crack growth speed depending on stress intensity coefficient for all compositions of heat-resistant concrete.

Concrete on portland cement experienced the earliest formation of a macro-crack and a long period of its development that is related to the exponent value of the $V-K_I$ dependence, the smaller the exponent value is, the higher the concrete plasticity is.

For heat-resistant concrete on aluminous cement and on alkali silicate the exponent value in $V-K_I$ increases that testifies to a later formation of the macro-crack and its relatively quick development. AE parameters or concrete on portland cement ranged from $4 \times 10^2$ to $6 \times 10^3$ pulse/s with $K_I$ growing from 0.26 mN/m$^{3/2}$ to 0.59 mN/m$^{3/2}$ and crack growth speed from $9 \times 10^{-9}$ m/s to $3 \times 10^{-5}$ m/s. Heat-resistant cement on aluminous cement having the same variation of the AE parameter and crack growth speed demonstrated an increase of stress intensity coefficient from 0.34 mN/m$^{3/2}$ to 0.69 mN/m$^{3/2}$. 
Figure 1. Combined diagrams: counting rate $\dot{N}$ - stress intensity coefficient $- K_I$, crack growth speed $V$ – stress intensity coefficient $K_I$, obtained during testing of the specimens of heat-resistant concrete: 1 – on portland cement, 2 – on aluminous cement, 3 – on alkali silicate

Concrete on alkali silicate during testing demonstrated an increase of AE counting rate from $7 \times 10^2$ to $3 \times 10^4$ pulse/s and of crack growth speed from $9 \times 10^{-8}$ to $9 \times 10^{-4}$ m/s, with $K_I$ increasing from $0.3 \text{ mN/m}^{3/2}$ to $0.69 \text{ mN/m}^{3/2}$.

Statistic processing of the results of the experimental studies allowed establishing a relation between acoustic emission counting rate $\dot{N}$ and crack growth speed $V$:

$$\dot{N} = 0.78 - 0.051 \cdot V$$

(10)

On the basis of the obtained experiment results (equations 4-9) the relation of acoustic emission and crack toughness can be expressed in the following dependence like for ceramic materials [28, 29]:

$$K_I = \left( \frac{\dot{N}}{A_0} \right)^{1/n_0}$$

(11)

where $A_0$ and $n_0$ coefficients are physical constants of concrete.

6. Conclusions

Thus, the parameters of acoustic emission are directly related to the characteristics of the mechanics of damage that reveals a considerable capacity of acoustic emission as a method for forecasting destruction of concrete. The obtained results also confirm the hypothesis of the experiments and create a firm basis for the development of a universal complex method combining the mechanics of damage and acoustic emission method. This allows forecasting lifetime (time before destruction) and other properties of concrete and developing its new compositions.

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