Acoustic method for measurement of crack width in concrete

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Abstract. The article presents the results of research and experimental studies aimed at measurement of crack width in concrete under the impact of mechanical loading. During the research, the author simultaneously measured load, deformation, crack width, acoustic emission gross counting by tensiometric and acoustic methods and obtained full diagrams of concrete deformation. The experiments resulted in regression equations and their combined diagrams showing relation between acoustic emission gross counting and mechanical loading level. The author identified the parameters of macro-crack initiation and their width in lightweight concrete depending on the value of the applied load. The conducted experiments and statistic processing of the data produced the correlation between the crack width and acoustic emission gross counting.

1. Introduction
Concretes that have an increased quantity of defects such as pores, cracks and other discontinuities under the influence of external load produce a defect (a crack) in the most dangerous cross-section that grows until the destruction of concrete. In order to control the crack growth it is necessary to identify the initial moment of its opening and identify critical load at which the growth and width of the most dangerous defect initiate high-speed deformation [1].

2. Relevance
A number of experiments on the identification of crack growth borders performed earlier demonstrated data variability depending on the type and composition of concrete and mainly on the selected study methodology. Accuracy and reliability of these studies were limited by the use of ultrasonic control of concrete destruction. However, it is known that detection limit of acoustic emission (AE) method is significantly higher than that of ultrasonic method. There are few studies on the identification and measurement of crack and deformation width in concrete by means of AE method [2-10].

During loading of such heterogeneous material as concrete bonds at the matrix-aggregate contact break because of local stress that reaches critical values. When using AE method, the accumulated energy in the form of an instant pulse increase, i.e. acoustic emission signal, can be identified [8].

Combination of destructive and non-destructive control of the crack growth and other similar surveys that determine the corresponding dependences allows reducing costs for the structures monitoring. This results in creation of a complex survey method. Thus, such researches are very relevant and require additional experiments.
3. Problem statement
The current work included study of concrete crack toughness (crack resistance) and simultaneous
determination of the parameters of the crack growth by tensiometric and acoustic emission methods.
These studies aimed to create a complex method for the evaluation of crack resistance. It is required to
create dependences allowing the use of non-destructive control methods.

This research included complex studies of cracks width in concrete having a large amount of
defects (pores, cracks). Such defects were assessed by integral porosity.

Experiments assumed simultaneous measurement of such parameters as load, crack width, acoustic
emission gross counting by tensiometric and acoustic methods and obtaining of full diagrams of
concrete deformation [1].

4. Theoretical part
The research assumed measurement of crack width during the whole process of the specimen loading.
For that a thin-wall elastic metal plate with earlier attached tensiometer for measurement of
deformations appearing during the initiated crack opening was placed nearby the cut of the bar
specimen. The signal from the tensiometer increasing because of loading was sent to the x/y-plotter
that recorded the process diagram in the following coordinates: “time – crack width”. At the same
time, the same signal was sent to the high-speed oscillograph for full complex recording of crack
resistance parameters change with time. Two parallel diagrams have been obtained as a result of the
experiment with two plotters: load vs. deformation and crack width vs. time [1].

Concrete specimens were tested using hydraulic and mechanic equipment. Such parameters as load,
deformation and amplitude, pulse recurrence frequency and acoustic emission counting rate were
registered in analogue and digital forms. Loading and deformation parameters were measured by
tensiometric method for the receipt of full diagrams of concrete deformation. At the same time,
acoustic parameters were measured using special apparatuses.

Load vs. deformation diagram was recorded on the ENDIM x/y-plotter during loading of the
specimen with an elastic element [11]. At the same time, a standard AF-15 unit registered signals of
acoustic emission using two piezoceramic transducers installed from both sides of the assumed place
of crack growth and further destruction.

5. Results of experimental studies
Lightweight concrete with increased content of pores was tested according to the suggested methods
[1, 12-17]. Numerous experiments allowed developing concrete compositions with improved crack
resistance and strength and the same density [18-27]. Concrete compositions were selected using
software [28].

For instance, here we studied foam concrete, its cellular structure differs having a large quantity of
fine pores due to the use of foaming agents of synthetic surfactants in the form of industrial wastes
produced in the Volgograd Region. This exerts positive impact on density, resistance to water and
frost resistance of the obtained products. Different modifiers were introduced into the system for
expansion in order to adjust plastic properties and expansion capacity of the compositions. Porous
concrete structure created with the use of foaming agents has rather strong pore baffles.

Concretes with light aggregates such as especially light claydite gravel and corncobs without seeds
have fine-aggregate structure, too. One of the most widely used coarse aggregates for the production
of lightweight concrete is claydite. It has in its structure pores in different quantities and of different
form (open and closed). Claydite concrete prepared with such aggregate demonstrates relatively low
strength and crack resistance.

In order to improve these parameters the authors developed raw mixture compositions for the
production of claydite with increased strength and minimum density. This is reached by introduction
into the raw mixture for the production of claydite of the following components, mass %: argillous
raw material – (98-85.5); sapropel (1-4); preliminary treated dry-cleaning wastes (0.5-1.0).
Introduction of dry-cleaning wastes into the composition helps forming a homogeneous inner structure
of the claydite – closed pores and void-free outer surface that jointly increase strength and reduce water uptake.

Concrete having in composition strong and at the same time plastic aggregates can demonstrate high crack resistance. Such conditions are significantly met by the developed lightweight concrete with organic aggregates in the form of cut corncobs without seeds.

A chopper first cuts corncobs without seed to the particle size not more than 40 mm. A mineralizing agent $\text{CaCl}_2$ or bischofite ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) are introduced during the production of the concrete mixture, they accelerate the concrete hardening process and impregnate the corncobs protecting them from decay and gnawing animals. Due to fibrous structure, aggregates of cut corncobs have increased resistance to the formation of cracks under the influence of loads because they demonstrate higher elastic-plastic deformations.

Concrete specimens with dimensions 100x100x400 mm with a central cut having a length equalling 0.5 of the specimen height were used for testing. Full deformation diagrams and quantitative data of the crack width during the specimens loading were obtained by three point bending scheme.

Regression equations and their combined diagrams showing relation of AE gross counting and loading level $\sigma/\sigma_{\text{max}}$ as well as of crack width and $\delta/\sigma_{\text{max}}$ were obtained as a result of the performed experiments. According to the obtained diagrams foam concrete demonstrated the earliest initiation of the crack at the load equalling 30 % of the maximum value with the crack width around 0.1 mm. Concretes with organic aggregates and especially light claydite gravel demonstrate approximately equal level of loading (around 40 % of $\sigma_{\text{max}}$) at which the crack initiated. However, the crack width equalled around 0.3 mm. Acoustic emission gross counting depending on the moment of the crack initiation ranged within $2.3 \div 4 \cdot 10^{-3}$ pulses. Table 1 presents quantitative values of the obtained parameters.

The later initiation was, the wider the fracture and the more intensive acoustic emission were.

The obtained regression equations for different types of lightweight concrete are as follows:

- **foam concrete:**
  
  $N = 0.0126 \cdot \sigma / \sigma_{\text{max}}^{1.32}$
  
  $\delta = 0.63 \cdot \sigma / \sigma_{\text{max}}^{1.78}$
  
  where $N$ is AE gross counting, pulses; $\delta$ - crack width, mm; $\sigma / \sigma_{\text{max}}$ - loading level.

- **concrete with organic aggregate:**
  
  $N = 0.015 \cdot \sigma / \sigma_{\text{max}}^{1.31}$
  
  $\delta = 0.78 \cdot \sigma / \sigma_{\text{max}}^{1.49}$

- **concrete with especially light claydite gravel:**
  
  $N = 0.017 \cdot \sigma / \sigma_{\text{max}}^{1.58}$
  
  $\delta = 0.76 \cdot \sigma / \sigma_{\text{max}}^{1.67}$

Analysis of the obtained power-law dependences showed that the character of the AE and crack width curves almost did not change depending on the loading level for all types of the studied lightweight concrete.

However, concrete with organic aggregate in the form of crushed corncobs without seeds demonstrated a smoother change of the AE and crack width parameters. Despite the increased compared to claydite concrete total porosity (52 % vs. 38.5 %), use of fibrous materials allowed increasing plasticity of concrete, especially for experiencing tensile loading. Crack width at the moment of destruction was almost the same as for claydite concrete.
### Table 1. Dependence between AE gross counting-N and crack width δ on loading level $\sigma/\sigma_{\text{max}}$ during testing of lightweight concretes.

| Foam concrete | Concrete with organic aggregate | Claydite concrete |
|---------------|---------------------------------|------------------|
| $\sigma/\sigma_{\text{max}}$ | N, Pulse | $\delta$, mm | $\sigma/\sigma_{\text{max}}$ | N, Pulse | $\delta$, mm | $\sigma/\sigma_{\text{max}}$ | N, Pulse | $\delta$, mm |
| 0.1           | 0.002 | 0.3 | 0.1 | 0.1          | 0.0025 | 0.4 | 0.3       | 0.2       | 0.0037 | 0.4 | 0.25 |
| 0.15          | 0.0021 | 0.35 | 0.13 | 0.15         | 0.0026 | 0.45 | 0.3       | 0.25       | 0.0038 | 0.45 | 0.26 |
| 0.2           | 0.0022 | 0.40 | 0.15 | 0.2          | 0.0028 | 0.50 | 0.31      | 0.3       | 0.0039 | 0.50 | 0.28 |
| 0.25          | 0.0024 | 0.45 | 0.16 | 0.25         | 0.0029 | 0.55 | 0.33      | 0.35       | 0.0039 | 0.55 | 0.29 |
| 0.3           | 0.0025 | 0.50 | 0.18 | 0.3          | 0.0030 | 0.60 | 0.35      | 0.40       | 0.0040 | 0.60 | 0.30 |
| 0.35          | 0.0027 | 0.55 | 0.19 | 0.35         | 0.0031 | 0.65 | 0.36      | 0.45       | 0.0041 | 0.65 | 0.32 |
| 0.4           | 0.0029 | 0.60 | 0.20 | 0.4          | 0.0034 | 0.7  | 0.38      | 0.50       | 0.0042 | 0.7  | 0.35 |
| 0.45          | 0.003  | 0.65 | 0.22 | 0.45         | 0.0036 | 0.75 | 0.42      | 0.55       | 0.0045 | 0.75 | 0.38 |
| 0.5           | 0.0035 | 0.7  | 0.25 | 0.5          | 0.004  | 0.8  | 0.45      | 0.6        | 0.0048 | 0.8  | 0.4  |
| 0.55          | 0.0038 | 0.75 | 0.3  | 0.55         | 0.0045 | 0.85 | 0.51      | 0.65       | 0.0051 | 0.85 | 0.45 |
| 0.6           | 0.004  | 0.8  | 0.4  | 0.6          | 0.005  | 0.9  | 0.67      | 0.7        | 0.0056 | 0.9  | 0.61 |
| 0.65          | 0.0045 | 0.85 | 0.46 | 0.65         | 0.0056 | 0.95 | 0.81      | 0.75       | 0.0061 | 0.95 | 0.82 |
| 0.7           | 0.005  | 0.9  | 0.53 | 0.7          | 0.0061 | 1.0  | 0.98      | 0.8        | 0.007  | 1.0  | 1.05 |
| 0.75          | 0.0055 | 0.95 | 0.63 | 0.75         | 0.0066 |          |          | 0.85       | 0.0081 |          |          |
| 0.8           | 0.006  | 1.0  | 0.75 | 0.8          | 0.0073 |          |          | 0.9        | 0.0091 |          |          |
| 0.85          | 0.0064 |          | 0.85 | 0.0008      | 0.95  | 0.01    |          | 1.0        | 0.011  |          |          |
| 0.9           | 0.007  |          | 0.9  | 0.0089      | 1.0   | 0.011   |          |           |        |          |          |
| 0.95          | 0.0074 |          | 0.95 | 0.0096      |          |        |          |           |        |          |          |
| 1.0           | 0.008  |          | 1.0  | 0.0106      |          |        |          |           |        |          |          |

The conducted experiments and statistic processing of the data allowed producing the correlation between crack width $\delta$ and acoustic emission gross counting $N$:

$$N = 1.6 \times 10^{-3} + 5.9 \times 10^{-3} \cdot \delta \quad (7)$$

### 6. Conclusions

Analytic and graphic dependences that show relation between tensiometric and acoustic methods for measurement of growth parameters of cracks in concrete have been obtained in the course of the performed experiment.

Thus, more reliable data on the process of opening of the most dangerous cracks in concrete have been received by using a highly sensitive acoustic method. The crack initiation moment coincides with the start of an abrupt increase of the AE gross counting.

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