The Relationship Between the Parameters of the Electric and the Acoustic Signal with the Destruction of Concrete Under Cyclic Freeze-Thaw

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Abstract. The paper presents the research results of the effect of formation crack process on the parameters of the electric and acoustic response to impact excitation. The physical basis of mechanoelectric transformations is described. It was found that with increasing number of freeze-thaw cycles observed increase of the attenuation coefficient of energy of the electric and acoustic response by a linear relationship. Differences in the dynamics of change of attenuation coefficient of energy of the electric and acoustic response associated with differences in formation and registration of electric and acoustic response.

1. Introduction

Building structures made of concrete are often exploited in significant seasonal temperature fluctuations, which lead to cracking. Concrete damage caused by freeze-thawing is the main problem in cold climate. These damages caused by freeze-thawing can be of two different forms: internal destruction [1] and surface cracking [2]. Therefore, timely detection of cracks in concrete products and tracking the dynamics of their development is an important task to prevent destruction of concrete structures. Many new methods of concrete products control developed to solve this problem. One of these methods is based on the use of the generation of electromagnetic fields by heterogeneous non-metallic materials during mechanical excitation.

By now gained a large amount of experimental results on the study of the generation of alternating electric fields by mechanical excitation of heterogeneous non-metallic materials. Much of the research is devoted to studying the mechanisms of appearance of alternating electromagnetic fields in the quasi-static mechanical excitation. Most authors attribute the appearance of alternating electromagnetic fields with the processes of cracking. Labors [3–5] are devoted to research of electromagnetic emission in the process of formation cracks in different materials (such as rocks, grout, composite materials, ice and others). Along with the research of occurrence of electromagnetic fields by the quasi-static mechanical excitation over a number of years the research of generating the alternating electromagnetic fields by the pulse mechanical excitation of heterogeneous non-metallic materials is conducted [6, 7].

On the basis of the use of this phenomenon the non-destructive testing of structural and mechanical properties of concrete is being developed.

To identify the informative parameters of the electric response carrying information about the cracking evolution process in the concrete the information about the basic laws of mechanoelectric transformations and their physical basis is needed.

2. Physical bases of the method

The method based on mechanoelectrical transformations can be used to solve the problem of defect detection. The principle of this method is that the object under research is subjected to the elastic shock excitation which leads to propagation of the acoustic waves in the sample. The electric response is caused by the deformation and shift of the elastic wave due to the pulsed mechanical excitation of the signal sources in material. The previous research has established that piezoelectric inclusions play the crucial role in the mechanoelectrical transformation in concrete [8]. Piezoelectric quartz is contained in sand and gravel which were used to manufacture the samples. Under the mechanical stresses caused by acoustic waves, charge formation occurs on the faces of the piezoelectric quartz owing to direct piezoelectric effect. As a result, an external electric field occurs and it is detected by the signal receiver placed near the test object.

Piezoelectric source–dipole charge is proportional to the mechanical stress value induced by acoustic longitudinal at the location point of the piezoelectric source and the magnitude of the piezoelectric quartz module. The number of sources is determined by the number of grains of sand and coarse aggregate that have piezoelectric quartz in their structures. The aggregate grains are evenly distributed over the whole volume of the concrete sample. Piezoelectric axes of quartz inclusions have different direction relatively to the receiving point and the direction of the longitudinal waves formed in the sample during its shock excitation. The total electric field at the location point of receiving electrode is a result of vector addition of the fields from each source.

Current starts to flow through the input impedance of the measuring circuit as a result of the free charge carriers occurrence on the receiving electrode surface which were induced by an electric field (figure1).

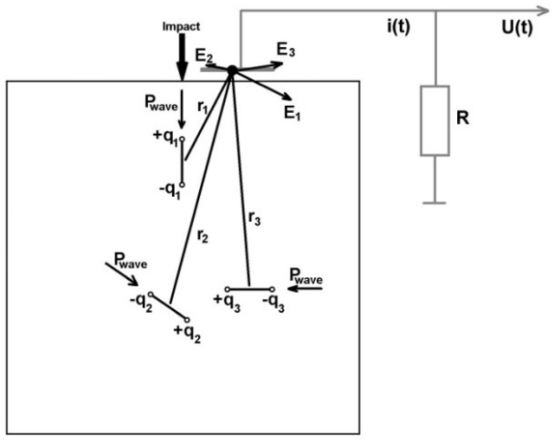

Figure 1. Measuring circuit.

An electric receiver is a metal plate located close to the sample surface within the range of the electric field generated by internal sources and grounded through the input resistance (*R*).

The charge (*Q*), induced on the surface of a conductor (electrical receiver) placed into electric field is:

$$Q = DS_d = \varepsilon_0 \varepsilon E S_d \quad (1),$$

where S_d – the electric receiver area; D – electric displacement vector.

Then the measured voltage from a single source is determined by:

$$U(t) = \varepsilon_0 \varepsilon \frac{\partial E(t)}{\partial t} R S_d \quad (2),$$

where R – input impedance.

Consequently, the value of the recorded electrical signal is determined by the change of the electric field strength in the area of the receiver, receiver area size and the value of the input resistance.

Using classical electrodynamics and mechanics relations the model of mechanoelectrical transformations in heterogeneous materials containing piezoelectric inclusions was developed [9]. Within the model the electric field rate change at acoustic excitation of piezoelectric sources was calculated:

$$E'(t) = \frac{dSMl_P}{4\pi\varepsilon_0\varepsilon L}\frac{V_y(t)}{r^3(t)}\left(\frac{3h^2}{r^2} - 1\right) \quad (3)$$

Inserting (4) into (3) we obtain that the value of the measured voltage from a single source is given by:

$$U(t) = \frac{dSMl_P}{4\pi L}\frac{V_y(t)}{r^3(t)}\left(\frac{3h^2}{r^2} - 1\right)\cdot RS_d \quad (4),$$

where S_d is the area of the measuring electrode; M is the elastic modulus; L is the model size in the excitation direction; $V_y(t)$ is the displacement rate in the excitation direction; h is the depth of the piezoelectric source position; r is the distance from the source to the receiving electrode; l is the thickness of the piezoelectric quartz crystals; d is the piezoelectric modulus of quartz; and S is the sample cross-sectional area; and R is the input impedance.

Therefore, the parameters of the electrical response and elastic waves are interrelated.

The presence of large amount of piezoelectric sources with different directions of the electric axes can reliably reflect the transformation structure of the acoustic waves parameters within the interaction with different configurations defects.

3. Technique of research

The experimental research was carried out at a laboratory hardware–software complex that performs pulse mechanical excitation of samples, and records electrical response signals. Figure 2 shows a photo of the measurement system used.

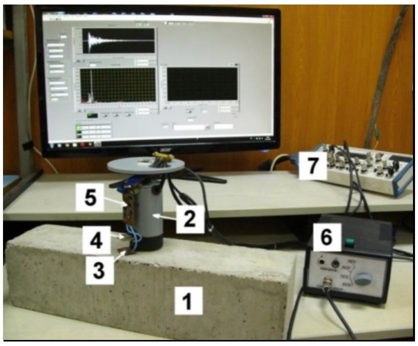

Figure 2. The measuring system photo: 1 – sample; 2 – electromechanical impact device; 3 – measuring electrode; 4 – compensation electrode; 5 – differential amplifier; 6 – power supply; 7 – NI board terminal block.

The pulsed mechanical excitation of samples (1) is performed with electromechanical impact device (2) with a normalized impact force. The electromagnet was used as the impact device. The differential electrical sensor was used for the measurement of electric response. Electrical measuring sensor (3) is placed at the distance of 2 mm from the sample surface, thus conditions for a non-contact measurement are created. The compensating receiver (4) is placed at the height of 30 mm from the measuring receiver. Then the signals come to the input of differential amplifier (5), are subtracted and amplified. The signals from the differential electrical sensor were registered using multifunction input/output board "NI PCI 6253" installed into the PC. The signal recording is performed with a special program in LabVIEW. The measurement technique of the electric response to mechanical excitation is described in more detail in [10].

Along with electrical signal measurement, we measured the acoustic signal using a standard Olympus V1011 piezoelectric transducer.

4. Experimental research and discussion

For this research the products made from heavy concrete sized of 100×100×300mm were used.

The samples manufacturing process complies with GOST 7473-2010. The mass ratio of cement / sand / coarse aggregate was 1:2:4, with a maximum aggregate size of 20 mm. The water-cement ratio was 0.6.

Studies of the influence of cyclic freeze-thaw on the parameters of electric and acoustic response were conducted. To accelerate of structure degradation at cyclic freeze-thawing, each sample was penetrated by water. Then cyclic freeze-thawing was performed. Freezing was carried out in a climatic chamber at –40 °C, thawing was carried out at 20 °C (± 5) °C and humidity of 95%.

After every fourth cycle of freeze-thaw the electric and acoustic response from concrete sample were measured. Twelve measurements of both responses at each stage of cyclic freeze-thawing were conducted. Responses were measured from four different sides of the sample. The sampling frequency of measurement was 1 MHz.

Along with electrical and acoustic signals measurement the samples surfaces were photographed for visual tracking of the surface cracking processes.

Figure 3 shows a photograph of the end surface of the concrete sample after 32 freeze-thaw cycles.

Figure 3. Photo of the sample surface.

As seen in figure 3 during the process of cyclic freezing and thawing on the sample surface formed a net of cracks.

Cracks have different directions and complicated configuration.

The carried out studies showed that during the cyclic freeze-thawing of concrete samples the temporal characteristics of the electric response change. Figure 4 shows typical electric responses of a concrete sample during cyclic freeze-thawing process.

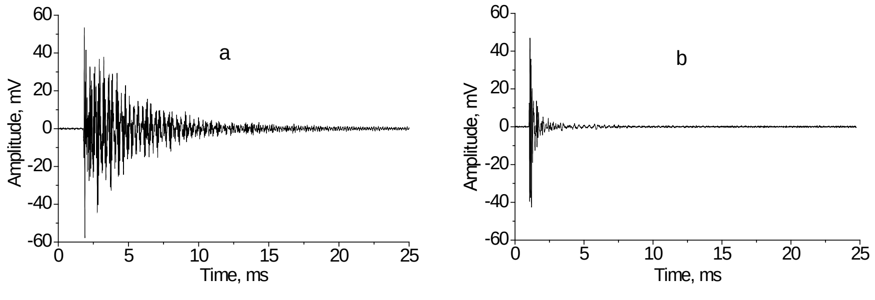

Figure 4. Changes in the electric responses of a concrete sample during cyclic freeze-thawing: a – the response of the sample in the initial state; b – the response of the same sample after 32 freeze-thawing cycles.

Cracks in the concrete sample start growing during the cyclic freeze-thawing. Scattering of elastic waves across cracks reflects their attenuation in time.

To study the behavior of the attenuation coefficient of the electric response energy from the concrete samples depending on the number of freeze-thawing cycles, the time-frequency analysis is used as described in [11, 12]. This technique allows tracking the signal energy attenuation as the time function in any selected range of frequencies. The experimental data were processed using the program routine developed in a LabView software.

Figure 5 shows the dependence of the electric response energy attenuation coefficient from the number of cycles.

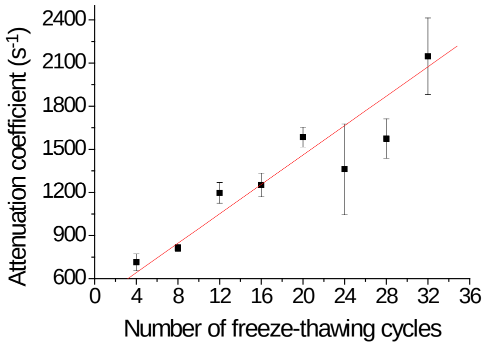

Figure 5. Dependence of the attenuation coefficient on the number of freeze-thawing cycles.

The dependencies of the attenuation coefficient (β) on the number of freeze-thaw cycles (n) are well approximated by a linear dependence of the form: $\beta = 437 + 51n$ with a correlation coefficient of 0.96.

In a similar way, the acoustic signals were processed from the samples. Figure 6 shows the dependence of the attenuation coefficient of the acoustic signal energy on the number of freeze-thawing cycles.

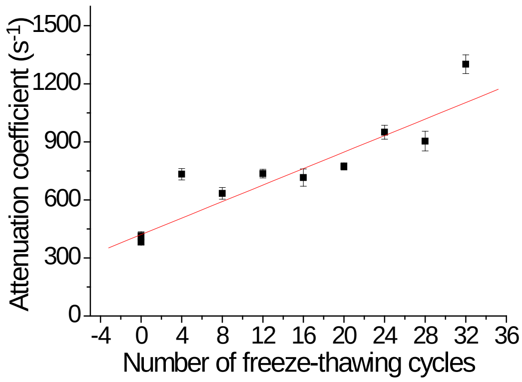

Figure 6. Dependence of the attenuation coefficient of the acoustic signal energy on the number of cycles.

As can be seen from a comparison of figures 5 and 6 dependencies have different tilt angle. That is, the increase in the attenuation coefficient of energy of electric response during the process of cyclic freeze-thaw is more intense compared to the acoustic response.

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5. Conclusions

The purpose of research presented in this paper was the studying the laws of transformation of parameters of electric and acoustic response during the process of formation cracks caused by freeze-thaw cycling.

It is found that with increasing number of freeze-thaw cycles is increased attenuation coefficient of energy of both electrical and acoustic response. Studies have shown that with increasing the number of freeze-thaw cycles is observed more intensive increase of the attenuation coefficient of energy of electric response as compared with the acoustic response.

Electric response reliably reflects the interaction of longitudinal waves with cracks having different orientation due to the large number of piezo sources that have different directions of electric axes. In contrast, piezoelectric receiver detects the waves propagated in a perpendicular direction relatively to the receiver plane. As a result, the acoustic signal is not sensitive to cracks, which are perpendicular to the sensor plane.

The increase of attenuation coefficient of energy of electric and acoustic response can serve as diagnostic features for evaluation of violations in concrete during the process of cyclic freeze-thaw.

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