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Evaluation of freeze–thaw damage in concrete by the parameters of electric response under impact excitation

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HIGHLIGHTS

- Influence of freeze–thawing cyclic on the damage of concrete was studied.
- Impact-electric nondestructive method to evaluate the damage of concrete was used.
- The diagnostic electrical parameters to evaluate of the concrete damage is proposed.
- Advantages of this method was discussed.

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ABSTRACT

The paper proposes a contactless method for assessing damages in concrete under cyclic freeze–thawing. Different sized concrete blocks with various types of aggregates (gravel, crushed stone) were researched. The evaluation procedure is based on the measurement of electrical response to impact excitation. Signal analysis in the time and frequency domain is the basis for the estimation algorithm of damages in concrete. Experimental results showed that the proposed method can be used to monitor the evolution of damage in concrete with freeze–thaw cycling. The proposed method is more effective for estimation of the concrete damage during freezing–thawing cycling in comparison with acoustic method.

1. Introduction

Concrete constructions are operated under static and dynamic loads and significant seasonal variations of temperature and humidity. As a result of mechanical and temperature–humidity effects, cracking processes occurring in concrete lead to structural damage. 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]. Methods to detect and determine damage characteristics using NDT methods are of great interest to practicing engineers. The following methods can be used to determine damages in concrete: ultrasonic velocity [3], surface-waves [4,5], nonlinear acoustic methods [6,7], acoustic and electrical emission [8–10], diffuse ultrasound [11], coda wave interferometry [12,13] and impact-echo testing [14–16]. In recent years a lot of scientists have conducted research to develop non-contact ultrasonic methods [17]. The research results of non-contact detection of the surface wave characteristics in concrete with laser are reported in [18,19]. Methods using surface waves are insensitive to deep cracks. Moreover, surface waves scatter over a rough surface. This is a drawback of monitoring and detection of cracks in materials with rough surfaces such as concrete. Built-in piezoelectric elements are proposed to be used as a non-contact method of acoustic vibrations recording in [20]. This method allows recording of the value of internal mechanical stresses at the interface with the piezoelectric transducer and making conclusions of their change.

To evaluate damages in concrete caused by cyclic freeze–thawing, the authors developed the method based on the use of characteristics of an electric response occurring in concrete under pulsed mechanical excitation. The suggested technique is based on the fact that the stress waves propagating in the sample affect the piezoelectric inclusions. This causes the electric field which is measured in our experiments. The main advantage of the method is the electric response sensitivity to the waves propagating in all directions of the sample. This is due to the fact that directions of the electrical axes of piezoelectric inclusions are different. As a result, the method is sensitive to the defects in their different orientation and configuration.

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The aim of the current research is to study the principles of electric response parameters changing during the concrete cyclic freeze–thawing, and to search for the diagnostic criteria to evaluate the cracking starting and crack dynamics. The experimental research introduced in current paper shows that the development of cracking under cyclic freeze–thawing leads to the shift of the gravity center of the electric response spectrum towards lower frequencies and increase in attenuation coefficient of the electric responses energy. Comparative analysis showed a higher sensitivity of the proposed method in comparison with the acoustic method.

2. Experimental research methodic

2.1. Physical basis of the method, its novelty and advantages

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 the result of two different processes: deformation and shift by elastic wave of electric double layers arranged on the borders of the components in the concrete; and piezoelectric quartz polarization, which is contained in sand and gravel, used for concrete manufacturing. The previous research has established that piezoelectric inclusions play the crucial role in the mechanoelectrical transformation in concrete [21].

The X-ray diffractometer ARL X'TRA was used for determining sand and gravel phase composition. X-ray analysis showed that the sand contains 90–95% of piezoelectric quartz. These investigations showed that quartz free grains were not revealed in gravel used for making heavy concrete and the fraction of grains that contained only quartz was approximately 20%.

The piezoelectric inclusions are distorted by mechanical stress caused by the elastic waves in the area of their location. As a result, they become polarized and an electric field is produced. This field is the source of the signal, recorded by the external electric sensor. Fig. 1 shows the general function principle of the internal piezoelectric source of mechanoelectrical transformations.

The Figure demonstrates a sample fragment with piezoelectric source – dipole located at a depth h from sample surface. 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 strength of the dipole field at a distance r from the receiving point is given by:

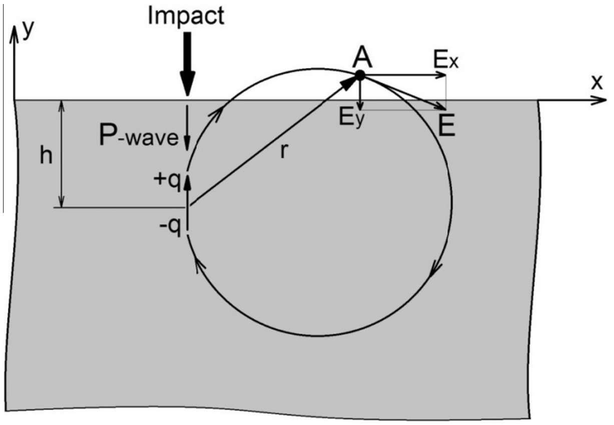

Fig. 1. To the determination of the dipole electric field component at the receiving point (A).

$$\mathbf{E} = \frac{3(\mathbf{Pn})\mathbf{n} - \mathbf{P}}{4\pi\varepsilon_0\varepsilon r^3} \tag{1}$$

where n – unit vector along r; r – the radius vector from the source to the predetermined point A at the sensor surface.

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 (Fig. 2). 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:

$$Q = DS_\mathrm{d} = \varepsilon_0\varepsilon ES_\mathrm{d} \tag{2}$$

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

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

$$U(t) = \varepsilon_0\varepsilon\frac{\partial E(t)}{\partial t}RS_\mathrm{d} \tag{3}$$

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 [22].

Within the model the electric field rate change at acoustic excitation of piezoelectric sources was calculated:

$$E'(t) = \frac{dSMl_p}{4\pi\varepsilon_0\varepsilon L}\frac{V_\mathrm{y}(t)}{r^3(t)}\left(\frac{3h^2}{r^2} - 1\right) \tag{4}$$

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

$$U(t) = \frac{dSMl_p}{4\pi L}\frac{V_\mathrm{y}(t)}{r^3(t)}\left(\frac{3h^2}{r^2} - 1\right)\cdot RS_\mathrm{d} \tag{5}$$

where S_d is the area of the measuring electrode; M is the elastic modulus; L is the model size in the excitation direction; $V_\mathrm{y}(t)$ 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.

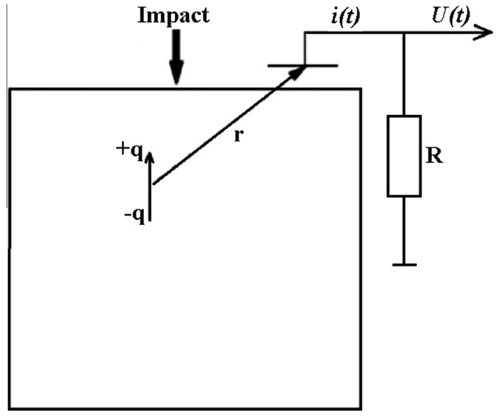

Fig. 2. Measuring circuit.