Effective non-destructive methods of evaluating quality of efficient building materials

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Abstract. The research is devoted to the analysis of available and widely used conventional measures to ensure reliable operation of the in-situ reinforced concrete structures and their compliance with legal requirements. It requires using one of the research trends of the Samara school of material sciences developed by the authors some time ago. Several stages of the work have been distinguished during the process of defining methodological foundations for effective non-destructive methods. The first stage concerned the proper mathematical apparatus of the concrete deterioration under various types of external effects. The second stage is important for determining the composition of basic physical and mechanical characteristics. Finally, the third stage is the period when the most reliable existing non-destructive methods are identified and investigation on new techniques is carried out. Thus, the combination of the A.A. Griffiths energy theory and the kinetic theory of S.N. Zhurkov has led to the formation of the mathematical apparatus that is able to simulate conditions of external effects. Testing effective methods for the concrete quality control developed by authors of this paper has been performed at the construction site. The conditions under study are characterized by a large number of ambiguous factors influencing the quantitative indicators of quality control criteria.

1. Introduction

The massive use of the in-situ reinforced concrete as a structural material leads to higher quality requirements in order to ensure the reliable operation of the designed structures during the period conforming to legal requirements. These are operating companies that almost always carry out repair work or strengthening of structures to eliminate errors that occur in the design and execution of the installation and construction work. These operations are very expensive and time-consuming. The greatest difficulties arise, of course, in the production of structures of the reinforced concrete, which is quite common nowadays. This situation can be explained in terms of the concrete manufacturing technology when the concrete structure is finally formed directly in the construction under the influence of a significant number of factors. Unfortunately, the control of the aforementioned external effects is either very time-consuming or difficult, or practically impossible. For this reason, more attention should be paid to the incoming concrete quality control, i.e. physical and mechanical characteristics (strength, frost resistance, waterproof, etc.).
2. Materials and methods
The analysis of existing standard methods for monitoring parameters of concrete leads to the generalization of the necessity of using bulky and power-consuming equipment to produce samples of the specific shape and precise size. In addition to it, all methods in question are destructive that effects the statistical reliability of measurements of controlled parameters and they are very time-consuming. Of course, in this situation the most optimal way to increase the reliability of controlled parameter measurements is to use non-destructive methods. These methods allow quick production of the unlimited number of measurements in minimal time.

Modern methods of non-destructive testing of physical and mechanical characteristics of the concrete are based either on phenomenological dependences established between the controlled parameters and an indirectly related characteristic of the material (ultrasonic wave velocity and the concrete compressive strength), or on the results of theoretical studies based on the fundamental scientific and repeatedly proven positions of the material science (theories of destruction, structuring, etc.).

3. Results
One of the areas of the Samara school of material science is the study of the concrete fracture processes based on modern provisions of the fracture mechanics and its mathematical apparatus [1-3]. All studies were conducted as a continuation of the work performed in the seventies at Moscow Institute of Civil Engineering under the leadership of G.Ya. Pochtovik.

The process of defining methodological foundations for effective non-destructive methods took several stages. The first stage concerned features of the mathematical apparatus describing the processes of the concrete destruction by various types of external influences, in particular, force, cyclic (effect of low temperature), hydrostatic, etc. The second stage dealt with the determination of the composition of major physical and mechanical characteristics affecting the values of controlled parameters. At the third stage the most reliable of the existing non-destructive methods were distinguished and the work on the development of new ones to specify physical and mechanical characteristics of concrete proceeded.

The proposed mathematical apparatus is based on the combination of the energy concept of fracture considered in A.A. Griffiths works and the kinetic theory of S.N. Zhurkov [4-7]. The specific feature of this work is the mathematical simulation of conditions of external effects on the concrete. The energy theory is applied to materials with brittle fracture character, and the mechanical theory is applied to materials with cracks development accompanied by initial plastic deformations. Moreover, the identity of the material test conditions by the standard method has also been tracked. Accordingly, for each of the considered types of external influence, the nature of the loading is close to standard conditions, hence there is a discrete, i.e. its stepwise flow, which confirms the discrete nature of the entire destruction process.

The application of the energy concept of fracture mechanics simplifies the mathematical model of concrete fracture and is successfully applied in practice.

Thus, in each of the considered types of external influence, the authors attempt to identify the dependence:

The value of the strength of concrete, when loaded uniaxial static compression,

\[
R_{\text{com}} = \frac{8Ev\alpha}{\pi \mu^2 \beta \left[ \exp(\alpha - 1) \right] \left( 1 - \mu^2 \right)}
\]  
(1)

here \( R_{\text{com}} \) – concrete compressive strength, Pa; \( E \) – modulus of elasticity of concrete, Pa; \( v \) - surface energy of concrete, J/m²; \( \mu \) - Poisson's ratio; \( \beta \) – the tendency of concrete to crack under compressive stresses, Pa/m; \( \alpha \) – the intensity of cracking at compressive stresses, the value is dimensionless.

Numerical value of freezing and thawing cycles, after which the concrete sample will lose its bearing capacity,
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\[ N = \frac{2Ev}{0.0025\mu^2R_{com}^2\beta_f\exp(0.05\alpha_f)} \]  

here \( N \) - number of freeze and thaw cycles; \( R_{com} \) – concrete compressive strength, Pa; \( E \) – modulus of elasticity of concrete, Pa; \( v \) - surface energy of concrete, J/m\(^2\); \( \mu \) - Poisson's ratio; \( \beta_f \) – tendency of concrete to crack under cyclic freezing, Pa/m; \( \alpha_f \) – the intensity of cracking during cyclic freezing, the value is dimensionless.

The value of water permeability, when testing concrete hydrostatic pressure,

\[ W = \sqrt{\frac{4Ev\alpha_w}{\pi\beta_w[\exp(\alpha_w - 1)](1 - \mu^2)}} \]  

here \( W \) – water permeability of concrete, Pa; \( E \) – modulus of elasticity of concrete, Pa; \( v \) - surface energy of concrete, J/m\(^2\); \( \mu \) - Poisson's ratio; \( \beta_w \) – tendency of concrete to crack under hydrostatic pressure, Pa/m; \( \alpha_w \) – the intensity of cracking at hydrostatic pressure, the value is dimensionless.

The follow-on estimation of values obtained as a result of mathematical simulation of processes of the concrete fracture by the uniaxial static compression, tensile and bending, hydrostatic pressure and cyclic low-temperature effects has led to the conclusion that values of the whole complex of physical and mechanical characteristics affect the concrete strength, waterproofing and frost resistance. The above-mentioned complex includes the modulus of elasticity, Poisson’s ratio and surface energy [8-5].

Non-destructive methods of defining the concrete modulus of elasticity, Poisson’s ratio and surface energy were used during development of the effective technique to determine the strength characteristics of the concrete and its frost and water resistance. In particular, the first two were determined by the results of measuring the velocity of longitudinal and shear ultrasonic waves [16-19]. The surface energy was found by the amount of the electric energy consumed in the process of drilling a hole of a certain depth and diameter [20-23].

The obtained values confirmed that the method accuracy is not inferior to that of standard ones because of the laboratory and industrial approval of the proposed method theoretical ideas. Moreover, in some experiments the accuracy was higher. The high accuracy of the proposed methods is due to the greater statistical validity because of the use of non-destructive methods that allow you to perform a statistically reasonable number of repeated measurements and reduce the material consumption of the tests.

4. Discussion
The experience has shown that the developed methods have successful application at the construction site under the final quality inspection of manufactured concrete and reinforced concrete structures. Temperature and humidity conditions of the concrete hardening are close to those in the laboratory and help to get the best results. However, temperature and humidity condition oscillations are present and affect the reliability of measurements, but they do not exceed 5...10% compared with the results of laboratory ones. This error is usually within the overall normalized error for desired characteristics and this fact reduces the performance index of effective methods [24,25].

5. Conclusion
The analysis of possibilities of application of mathematical model for the description of processes of destruction of concrete by the considered types of external influence confirms validity of application of the offered device. Moreover, it allows noticing that durability of concrete under compression, frost resistance of concrete, water permeability, depending on three initial physical and mechanical characteristics of concrete and two kinetic characteristics.

The initial physical and mechanical characteristics include surface energy, modulus of elasticity and Poisson's ratio, and kinetic characteristics include the tendency of concrete to crack under the
considered types of external influence and the intensity of crack formation under the appropriate types of external influence.

Experimental studies carried out by the authors showed good convergence of the results of theoretical studies with experimental data [25-27] and allowed to develop methods for determining the parameters under consideration, using conditions close to standard test methods.

The experience of the proposed technique approval at the construction site and in the laboratory research makes it possible to select the index that has the greatest impact on the measurement error, i.e. the humidity of the concrete. To eliminate the effect of humidity on further results it is necessary to obtain dependence curves of the measured indicators from those considered in the laboratory. The use of these dependences will allow adjusting the obtained measurement results and getting the more reliable data on controlled parameters.

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