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Multi-Parameter Methodology for Assessing Quality Indicators of Nanomodified Fiber-Reinforced Concrete for Construction Site

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Abstract. Nanomodified fiber-reinforced concrete is a building material for which the required characteristics of fracture toughness are a distinctive feature. Determination of the stress intensity factor of fiber-reinforced concrete makes it possible to correctly assess the resistance of the material during the formation and development of cracks. The proposed multi-parameter methodology for assessing the quality indicators of nanomodified fiber-reinforced concrete makes it possible to evaluate the quality of a fiber-reinforced concrete structure in construction and laboratory conditions. To carry out control at the construction site, modern and long-used methods of non-destructive testing are used: ultrasonic sounding, ultrasonic tomography, elastic rebound, separation with chipping. For laboratory studies, the technique provides for the manufacture of prism samples that can be molded or cut from the body of the structure. This methodology makes it possible to obtain in laboratory conditions such material parameters as tensile strength in bending, tensile strength in splitting, critical stress intensity factor for normal separation, critical stress intensity factor for transverse shear, energy consumption for individual stages of deformation and destruction of the sample, as well as to evaluate the uniformity of distribution fibers. Moreover, it is provided to obtain all the parameters on one sample from the series, which eliminates errors and inaccuracies in the quality indicators of the material associated with different conditions of hardening, molding, inaccuracies in duplicating the composition.

Keywords: crack resistance, nanomodified fibre-reinforced concrete, ultrasonic tomography, quality assessment technique, tensile strength, critical stress intensity factor

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Многопараметрическая методика оценки показателей качества наномодифицированного фибробетона для строительной площадки

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Реферат. Наномодифицированный фибробетон – это строительный материал, отличительной особенностью которого являются требуемые характеристики трещиностойкости. Определение коэффициента интенсивности напряжений фибробетона дает возможность правильно оценить сопротивление материала при образовании и развитии трещин. Предлагаемая многопараметрическая методика оценки показателей качества наномодифицированного фибробетона позволяет оценить качество фибробетонной конструкции в строительных и лабораторных условиях. Для осуществления контроля на строительной площадке используют современные и давно применяемые методы неразрушающего

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контроля: ультразвуковое зондирование, ультразвуковую томографию, упругий отскок, отрыв со скалыванием. Для лабораторных исследований методика предусматривает изготовление призматических образцов, которые могут быть отлиты в форму или вырезаны из тела конструкции. Эта методика позволяет получить в лабораторных условиях такие параметры материала, как прочность на изгиб, прочность при растяжении на раскалывание, коэффициент интенсивности напряжений при нормальном отрыве, коэффициент интенсивности напряжений при поперечном сдвиге, энергозатраты на отдельные стадии деформации и разрушения образца, а также оценить равномерность распределения волокон. Более того, предусмотрено получение всех параметров на одном образце из серии, что исключает ошибки и неточности в показателях качества материала, связанные с различными условиями твердения, формования, погрешностями при дублировании состава.

Ключевые слова: трещиностойкость, наномодифицированный фибробетон, ультразвуковая томография, методика оценки качества, прочность при растяжении, коэффициент интенсивности напряжений

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Introduction

The stress intensity factor is one of the most important indicators of the crack resistance of a material such as fiber-reinforced concrete [1–3], since the ability of fiber-reinforced concrete to prevent crack development is the main advantage over conventional concrete [4–7]. For this reason, methods for determining this indicator should most fully disclose all the features of work under load and the quality of nanomodified fiber-reinforced concrete [8–10].

Nanomodified fibre-reinforced concrete is a composite material with dispersed reinforcement at different structural levels. Starting from the nanoscale level (carbon nanotubes) and up to the macroscale (traditional reinforcement), effective resistance to cracking under the action of external loads is assumed [1–3].

Of particular interest in construction is the quality control of the manufacture of structures in construction conditions. Since the basis of fiber-reinforced concrete is the concrete-matrix, the control methods used for monolithic concrete structures will also be applicable to nanofiber-reinforced concrete. Due to the fact that dispersed reinforcement does not significantly affect the change in compressive strength, which is one of the main quality indicators for ordinary concrete, the quality control method for nanomodified fiber-reinforced concrete should provide for obtaining parameters that characterize the properties of the material depending on the introduction of fiber fibers (crack resistance, fracture toughness, etc.).

In this article, the authors propose a technique that allows assessing the quality of a nanomodified fiber-reinforced concrete structure and nanomodified fiber-reinforced concrete as a material (Fig. 1).

At the first stage, continuous control is performed by a combined (complex) method. As a result of measurements by the ultrasonic method and the elastic rebound method, the strength value of the concrete matrix is obtained. Sections (structures) with different (low) indicators are tested additionally at subsequent stages without fail.

At the second stage, ultrasound tomography of the structure is performed. This method allows you to determine the thickness of the structure and the adjacent base with one-way access, to detect voids and “hedgehogs” of fiber fibers. The control can be performed point and solid. Point control is mandatory on all structures. Continuous inspection can be carried out for structures with questionable strength indicators, defects (based on the results of point inspection).

At the third stage, the method of direct separation with chipping is used to determine the critical coefficient of stress intensity and strength of nanofibre concrete in the structure. This method is necessarily carried out in areas (structures) where defects, reduced strength, etc. were detected at previous stages of testing.

The fourth stage includes sampling of the material for subsequent tests in the laboratory. Test samples can be molded or cut from the body of the structure. In laboratory conditions, one sample from the series is subjected to step-by-step tests: bending tension, splitting tension, normal separation and transverse shear, non-destructive testing methods.

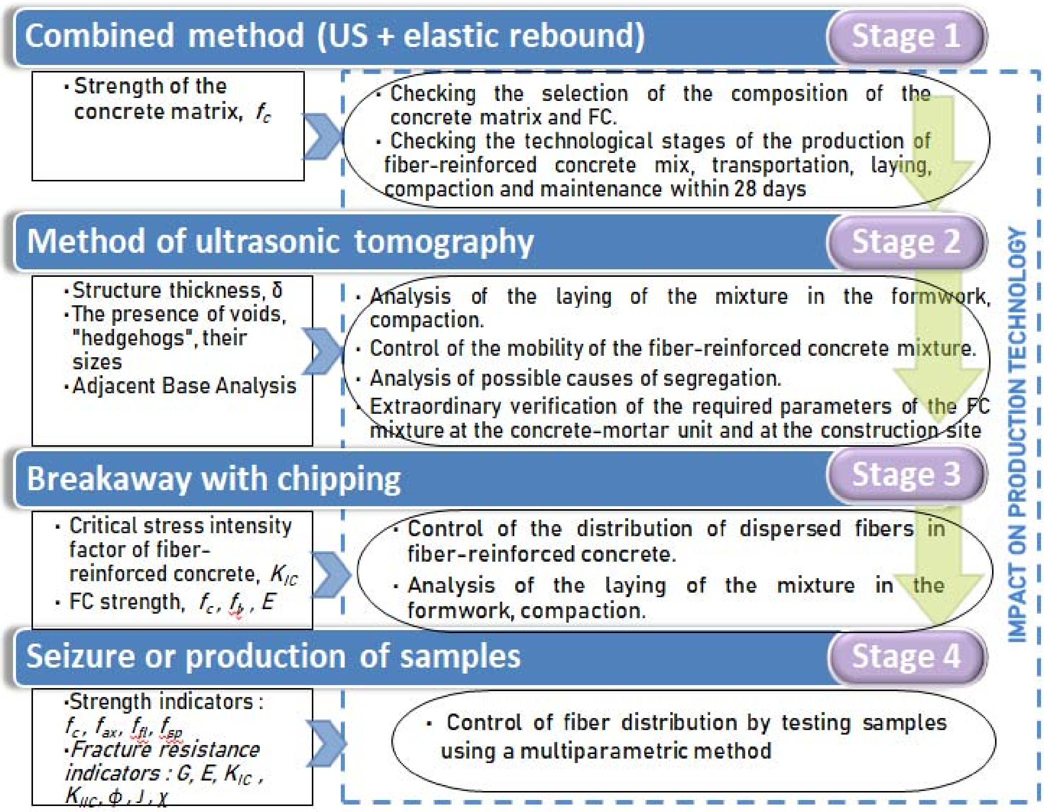

Fig. 1. The algorithm of quality control of fiber concrete in construction

Combined method

The purpose of this method is to determine the strength of the concrete matrix in the composition of the fiber-reinforced concrete material. The complex method for assessing the strength of nanofiber-reinforced concrete is based on the correction of data from the elastic rebound method according to STB 2264 and GOST 22690, an amendment that is a function of the difference in the strength estimates of nanofiber-reinforced concrete by the ultrasonic pulse method according to GOST 17624 and the elastic rebound method (Fig. 2–3). The ultrasonic pulsed method was used as a calibration method. It is used to correct the data of the dynamic indentation method [11].

In the same control zone, tests are carried out by the indentation method and the ultrasonic method; the values of the indirect parameters of these methods are I_1 and V_1. The strength of nanofiber-reinforced concrete fc of the control area is determined depending on the difference in the dynamic moduli of elasticity of the surface layer of nanofiber-reinforced concrete E^*_d and the inner area of nanofiber-reinforced concrete of the control area $E_{d,V}$ from the system of equations [12].

$$f_c = \frac{1}{1+\Theta}\left(\Theta e^{0,091(E_{\mathrm{V}}-E)} f_{c,\mathrm{I}} + f_{c,\mathrm{V}}\right); \qquad (1)$$
$$\Theta = 0,0026 f_c^2 - 0,115 f_c + 2,79,$$

f_c – strength of nanofiber-reinforced concrete of the controlled section of the structure, MPa; $f_{c,I}$ и $f_{c,V}$ – respectively, the assessment of the strength of nanofiber-reinforced concrete by the indentation method and the ultrasonic pulse method, MPa; Θ – dimensionless coefficient.

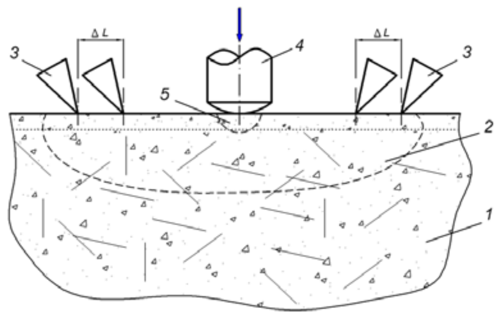

Fig. 2. Scheme of measurements by the combined method “indentation – ultrasonic pulse method” [11–13]:
1 – controlled item; 2 – area of concrete involved in the transmission of an ultrasonic pulse from the emitter to the receiver; 3 – emitting and receiving ultrasonic transducers; 4 – indenter; 5 – concrete indentation area

When testing by the method of elastic rebound, the distance from the places of testing to the reinforcement must be at least 50 mm. When performing selective control of monolithic fiber-reinforced concrete or nanofiber-reinforced concrete structures, it is necessary to test at least 60 % of the structures of the grip, floor, building [13].

The number and location of controlled areas during testing of structures may be indicated in the working drawings for monolithic structures and (or) technological control charts. Tests are carried out on a structure area with an area of 100 to 600 cm^2. The number of tests on the site is at least 5. The thickness of the structure on the test site must be at least 100 mm.

Control of nanofiber-reinforced concrete in a structure by ultrasonic tomography

The principle of operation of ultrasonic tomography devices is based on the emission of low-frequency sound vibrations. Ultrasound penetrates into the object under study and is reflected. Everything is recorded by a device that, with the help of special devices, converts simple data into a complex graphical display, which allows you to quickly read information [14–15].

To implement the method of ultrasonic tomography, an ultrasonic low-frequency tomograph A1040 MIRA can be used (Fig. 3). This device is designed to examine monolithic concrete (fiber-reinforced concrete) and reinforced concrete building structures in order to search for voids, channels, power fittings, foreign inclusions, delaminations, cracks and other cavities, both empty and filled with liquid or solid material that differs from the surrounding concrete physically-mechanical properties [14–15].

The device uses the method of synthesized focusable aperture with Raman probing, in which ultrasound is focused into each point of the half-space. The data array is formed by collecting information from all measuring pairs of the antenna device of the tomograph. The signals received by the antenna array are processed on the builtin computer directly during operation.

The total area of the sites to be controlled must be at least 10% of the total area of the controlled surface. The number and location of controlled sections should be indicated by the design organization in the working drawings of structures, depending on the geometric dimensions, purpose and technology of their manufacture. The area for measurement should be no more than: for linear structures – one section per 4 m of length; for flat structures – one plot per 4 m^2 of area; for monolithic structures of solid walls – one section per 8 m^2 of area.

Determination of the strength and critical stress intensity factor of nanofiber-reinforced concrete by the direct separation method

The objective of this method is to determine the critical stress intensity factor of the nanofibre-reinforced concrete of the operated structure at normal separation. This method is based on the method of separation with chipping according to STB 2264 and GOST 22690 (Fig. 4).

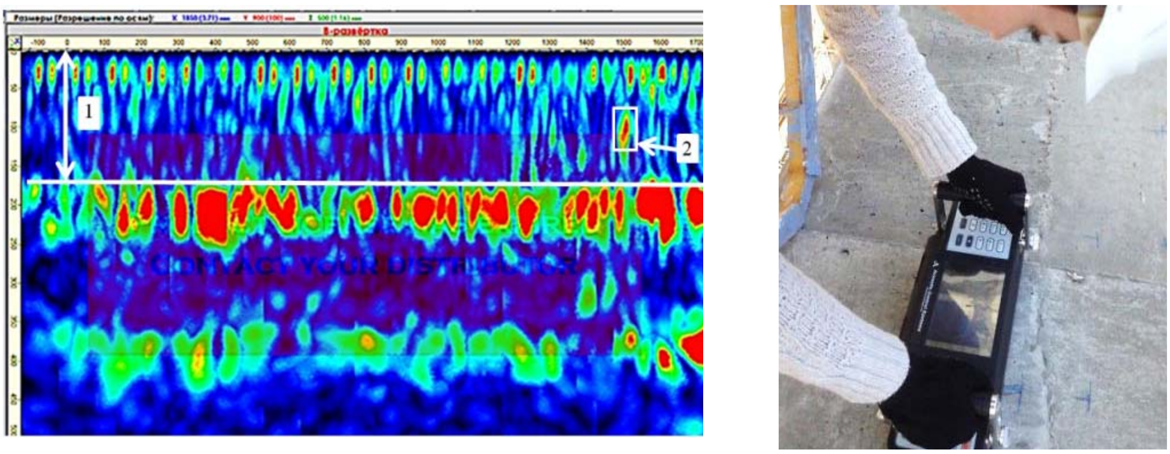

Fig. 3. Ultrasound tomography using the A1040 MIRA device in continuous scanning mode

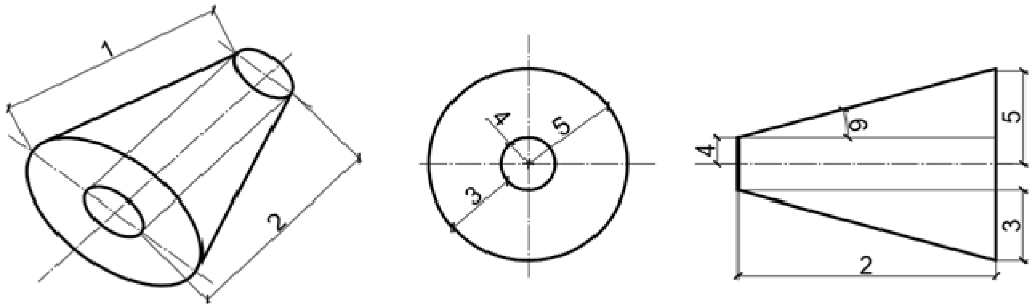

Fig. 4. Truncated fracture cone after separation with shearing: 1 – length of the generatrix of the fracture cone l; 2 – borehole length h; 3 – the difference between the maximum radius of the fracture cone and the radius of the borehole R; 4 – borehole radius r_0; 5 – maximum radius of the fracture cone r_{max}; 6 – the angle between the generatrix of the fracture cone and the side of the borehole α [16]

Depending on the stress intensity factor, directly in the structure, it is possible to predict such parameters of nanofiber-reinforced concrete as crack resistance, frost resistance, and durability of the material.

The method for determining the critical stress intensity factor of nanofibre-reinforced concrete is implemented as follows [17]. A special anchor device is installed in a hole drilled in a nanofiber-reinforced concrete mass with a radius r_0, and a part of the nanofiber-reinforced concrete is pulled out by a press pump, such as GPNS (self-centering hydraulic press pump), in the form of a truncated cone with a maximum destruction radius r_{max} and the length of the hole h. The destruction occurs along the surface of the cone, the generatrix of which coincides with the area of principal stresses.

In the process of pulling out a microvolume directly from the structure in a given area, in addition to the magnitude of the force, the dimensions of the truncated fracture cone are determined: the radius ro, the length h of the hole, the length of the generatrix l of the fracture cone, and the critical stress intensity factor K_{IC} of nanofiber-reinforced concrete is calculated according to the formula [16]

$$K_{\mathrm{IC}} = \frac{3P[\cos^2(90-\alpha) - \sin^2(90-\alpha)]}{2\pi h^2 \left(1 + \frac{r_0}{r_0 + h\,\mathrm{tg}\alpha}\right)^5} \sqrt{2\pi l} \times \left[\frac{0,8}{\left(\frac{R}{l}\right)^3 - 1} + 0,7 \right], \qquad (2)$$

where P is the pull-out force, MN; α – the angle between the generatrix of the destruction cone and the side of the hole;

$$\alpha = \mathrm{arctg}\left(\frac{R}{h}\right). \qquad (3)$$

When testing after the formation of cracks, the adhesion of the fiber to the concrete is broken, accompanied by the movement of the pulled-out microvolume relative to the body of the structure. The strength of nanofiber-reinforced concrete, which is a quality parameter, is determined by the magnitude of the force, and the calculation of the critical stress intensity factor is carried out taking into account the geometric parameters of the hole and the truncated fracture cone.

When testing by the pull-off method with shearing, the sections should be located in the zone of the lowest stresses caused by the operational load or the compression force of the prestressed reinforcement. The centers of the test sites must be at least 200 mm apart, and at least 150 mm from the edge of the structure.

Laboratory tests

A multi-parameter method for testing nanofiber-reinforced concrete in laboratory conditions makes it possible to determine the power and energy characteristics of crack resistance under static short-term loading (Fig. 5). The characteristics of crack resistance are determined during non-equilibrium mechanical tests [17].

The essence of this technique is to obtain all the declared quality indicators of nanofibre-reinforced concrete as a result of testing one sample from a series. A prism sample with a notch (stress initiator) is initially tested for tensile bending according to a four-point loading scheme (Fig. 6a). As a result of the test, the tensile strength value is determined and the complete deformation diagram is recorded. Based on the resulting deformation diagram, the energy indicators and the fracture toughness index, the quasi-static stress intensity factor (K_I) [18], are calculated.

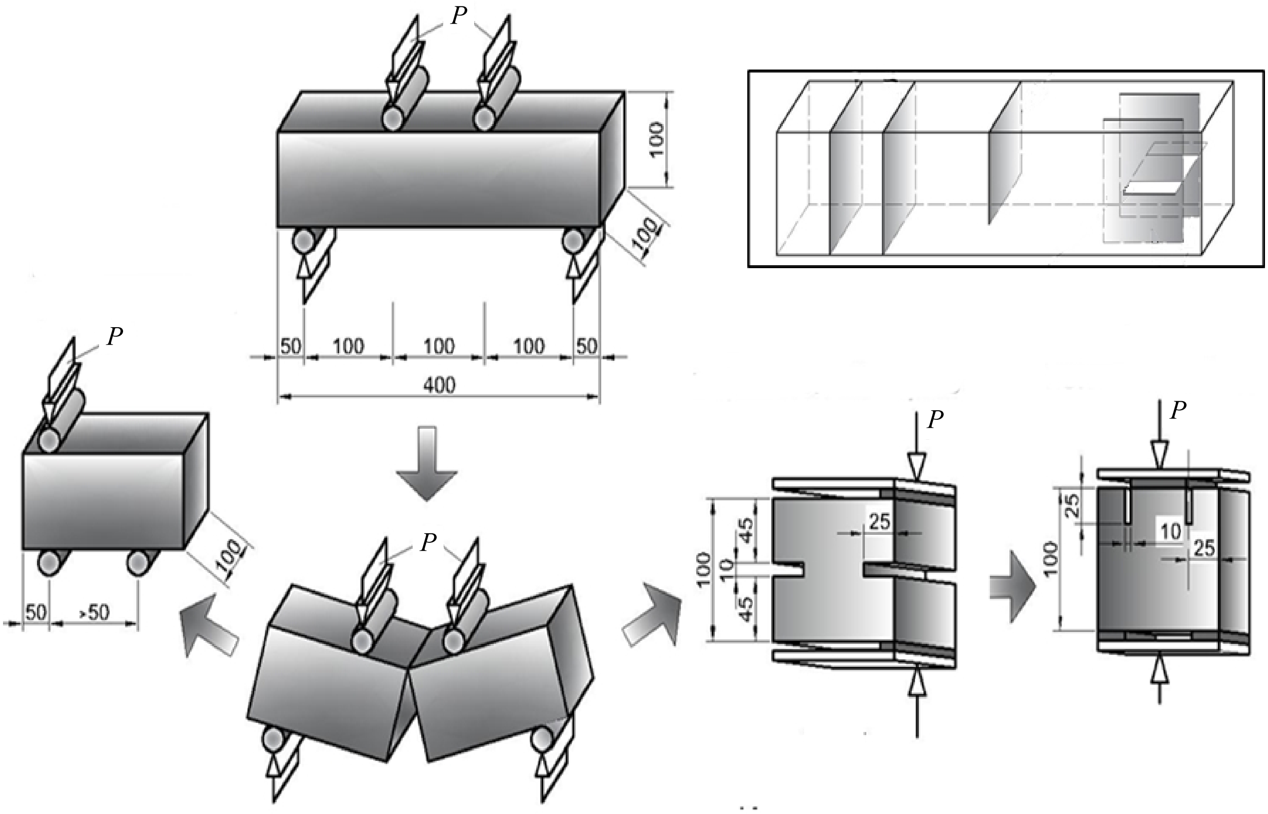

Fig. 5. Model of a multiparametric test procedure for nanofibre concrete in laboratory conditions

After the bending test, two halves of the prism specimen are formed, suitable for further tests. One half is tested for tension during splitting (Fig. 6b). The test procedure for splitting strength corresponds to the test procedure for tensile tests during splitting according to cube samples set out in GOST 10180. A sample-cube with crack initiators in the form of symmetrical cuts is formed from the second half using diamond-coated cutting tools. The resulting sample is tested for normal tear (Fig. 6c). Tests are carried out with eccentric compression. As a result of the test, the value of the critical stress intensity factor (for normal separation K_{IC}, MN/m$^{3/2}$) is determined [19].

After the normal pull test, two fragments (plates) are formed. On the obtained plates, using diamond-coated cutting tools, a stress concentration zone is made in the form of symmetrical cuts on one face of the product [18]. Plate samples are tested under central compression (Fig. 6d). As a result of the test, the value of the critical stress intensity factor (for transverse shear K_{IIC} (N/m$^{3/2}$)) is determined [20].

For testing, prism specimens are made in accordance with the requirements of GOST 10180. The ratio of the height to width (diameter) of the specimen is assumed to be 4. The recommended dimensions of the prism are 100×100×400 mm, 150×150×600 mm. The presented technique makes it possible to obtain an estimate of the fracture toughness of nanofiber-reinforced concrete on one sample from a series, which eliminates errors and inaccuracies in the quality indicators of the material associated with different conditions of hardening, molding, and inaccuracies in duplicating the composition.

Table 1 shows the results of testing according to the proposed laboratory method of nanofibre-reinforced concrete samples-prisms in the construction laboratory "Atomstroyexport" (Russian Federation) at the construction site of the Belarusian NPP in the Republic of Belarus. The compositions of concrete mixtures used in the construction of the Belarusian nuclear power plant were taken as a basis.

Fig. 6. Tests of nanofibre concrete in laboratory conditions: a – tensile in bending with registration of the fracture diagram; b – tensile during splitting; c – normal separation under eccentric compression; d – transverse shear

Table 1

Test results of nanofibre concrete samples

Options \ Fiber quantity (% by volume of the mixture)	Nanoconcrete matrix				
	Without fiber	Corrugated steel fiber (1 %)	Anchor steel fiber (1 %)	Fiber polymer wavy (1 %)	0.07 % basalt + + 0.26 % micro fiber steel straight + + 0.26 % steel anchor
Flexural elongation f_{fl}, MPa	2.8	5.9	9.4	6.2	4.2
Specific energy consumption G_i, J/m^2	208.9	800.58	1329.08	312.72	760.22
Tensile strength f_{sp}, MPa	1.7	3.1	3.2	2.8	2.3
Critical stress intensity factor K_{IC}, MN/m$^{3/2}$	0.7	3.5	2.6	0.97	1.9
Critical stress intensity factor K_{IIC}, MN/m$^{3/2}$	3.9	3.7	7.2	4.5	5.8

CONCLUSIONS

The presented technique makes it possible to evaluate the quality of nanofibre-reinforced concrete in construction conditions. According to the described method, methods based on ultrasonic sounding, shock impulse and direct separation method are used. The combination of these methods allows obtaining indicators that complement each other. So, a direct indicator of quality – the strength of nanofiber-reinforced concrete in a structure is determined by a complex method and a method based on the separation method. An indirect indicator – the speed of propagation of ultrasound (which characterizes the homogeneity of the material) is determined by a complex method and the method of ultrasonic tomography. The laboratory tests use a combination of wellknown widely used standardized test methods. The characteristics of crack resistance determined by the proposed method (along with other characteristics of mechanical properties) can be used for:

– comparison of different options for the composition, technological processes of manufacturing and quality control of nanofiber-reinforced concrete;

– comparison of nanofiber-reinforced concretes in substantiating their choice for structures;

– calculations of structures, taking into account their defectiveness and operating conditions;

– analysis of the causes of structural failures.

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