https://doi.org/10.21122/2227-1031-2022-21-5-392-396

UDC 691.32:69.04:693.554-486:691.327

Nanofiber Concrete: Multi-Level Reinforcement

S. N. Leonovich[1], E. A. Sadovskaya[1]

[1]Belarusian National Technical University (Minsk, Republic of Belarus)

Abstract. Concrete is the most commonly used building material worldwide. One of its main disadvantages is the fragility of fracture and low crack resistance. The use of dispersed reinforcement of concrete composites is a promising direction in solving this type of problem. Dispersed fibers, evenly distributed over the entire volume of the material, create a spatial frame and contribute to the inhibition of developing cracks under the action of destructive forces. In order to increase the fracture toughness of concrete, dispersed fiber reinforcement is increasingly used in practice. The beginning of crack nucleation occurs at the nanoscale in the cement matrix. Thus, the use of nano-reinforcement with dispersed nanofibers can have a positive effect on the crack resistance of the cement composite. It is proposed to consider carbon nanotubes as such nanofibers. The presence of carbon nanofibers changes the microstructure and nanostructure of cement modified with carbon nanotubes. The result of the processes occurring in capillaries and cracks are deformations in the intergranular matrix, the free flow of which is prevented by rigid clinker grains and nanocarbon tubes, which creates a certain stress intensity at the tips of the separation cracks. The working hypothesis is confirmed that the required fracture toughness of structural concrete is provided by multi-level reinforcement: at the level of the crystalline aggregate of cement stone – carbon nanotubes, and at the level of fine-grained concrete – various macro-sized fibers (steel, polymer). Reinforcement of a crystalline joint with carbon nanotubes leads to an increase in the fracture toughness of the matrix (cement stone) by 20 %, compressive strength by 12 %, and tensile strength in bending by 20 %. When reinforcing at the level of fine-grained concrete, we obtain a composite – nanofibre-reinforced concrete with fracture toughness.

Keywords: nanoparticles, concrete, fracture toughness, fiber

For citation: Leonovich S. N., Sadovskaya E. A. (2022) Nanofiber Concrete: Multi-Level Reinforcement. *Science and Technique*. 21 (5), 392–396. https://doi.org/10.21122/2227-1031-2022-21-5-392-396

Нанофибробетон: многоуровневое армирование

Докт. техн. наук, проф. С. Н. Леонович[1], магистр Е. А. Садовская[1]

[1]Белорусский национальный технический университет (Минск, Республика Беларусь)

Реферат. Бетон является наиболее распространенным строительным материалом во всем мире. Основными его недостатками являются хрупкость при растяжении и низкая трещиностойкость. Применение дисперсного армирования бетонных композитов – перспективное направление в решении такого рода задач. Дисперсные волокна, равномерно распределенные по всему объему материала, создают пространственный каркас и способствуют торможению развития трещин под действием разрушающих сил. Для повышения трещиностойкости бетона на практике все чаще применяют армирование дисперсными волокнами. Начало зарождения трещины происходит на наноуровне в цементной матрице. Таким образом, применение наноармирования дисперсными нановолокнами может положительно сказаться на трещиностойкости цементного композита. В качестве таких нановолокон предлагается рассматривать углеродные нанотрубки. Присутствие углеродных нановолокон изменяет микроструктуру и наноструктуру цемента, модифицированного углеродными нанотрубками. Результатом процессов, происходящих в капиллярах и трещинах, являются

Адрес для переписки
Леонович Сергей Николаевич
Белорусский национальный технический университет
просп. Независимости, 65,
220013, г. Минск, Республика Беларусь
Тел.: +375 17 368-61-56
sleonovich@mail.ru

Address for correspondence
Leonovich Sergey N.
Belarusian National Technical University
65, Nezavisimosty Ave.,
220013, Minsk, Republic of Belarus
Tel.: +375 17 368-61-56
sleonovich@mail.ru

деформации в межзерновой матрице, свободному течению которых препятствуют жесткие зерна клинкера и наноуглеродные трубки, что создает в вершинах разделительных трещин некоторую интенсивность напряжения. Подтверждена рабочая гипотеза, что требуемая трещиностойкость конструкционного бетона обеспечивается многоуровневым армированием: на уровне кристаллического заполнителя цементного камня – углеродными нанотрубками, на уровне мелкозернистого бетона – различными видами макроразмерной фибры (стальные, полимерные). Армирование углеродными нанотрубками кристаллического сростка приводит к повышению показателя вязкости разрушения матрицы (цементного камня) на 20 %, прочности на сжатие на 12 %, прочности на растяжение при изгибе на 20 %. При армировании на уровне мелкозернистого бетона получаем композит – нанофибробетон с вязкостью разрушения.

Ключевые слова: наночастицы, бетон, трещиностойкость, волокно

Для цитирования: Леонович, С. Н. Нанофибробетон: многоуровневое армирование / С. Н. Леонович, Е. А. Садовская // *Наука и техника*. 2022. Т. 21, № 5. С. 392–396. https://doi.org/10.21122/2227-1031-2022-21-5-392-396

Introduction

Concrete is the most commonly used building material worldwide. One of its main disadvantages is the fragility of fracture and low crack resistance. The use of dispersed reinforcement of concrete composites is a promising direction in solving this type of problem. Dispersed fibers, evenly distributed over the entire volume of the material, create a spatial frame and contribute to the inhibition of developing cracks under the action of destructive forces.

The beginning of crack nucleation occurs at the nanoscale in the cement matrix. Thus, the use of nano-reinforcement with dispersed nanofibers can have a positive effect on the crack resistance of the cement composite. Carbon nanotubes (CNTs) can be considered as such nanofibers. The influence of CNTs on the microstructure and nanostructure of the modified cement stone depends on the type of carbon material, its physical and chemical characteristics, the geometrical parameters of the fibers, and the uniformity of dispersion in the composite body.

Ensuring the required fracture toughness (crack resistance) of structural concrete is solved in a complex way: we reinforce the crystalline intergrowth of cement stone with carbon nanotubes, and fine- and coarse-grained concrete are reinforced with steel, polymer, basalt fibers or their combination of various concentrations. If concrete is considered as a multilevel structure, then the onset of crack nucleation occurs at the nanoscale in the cement matrix, followed by growth to the size of macrocracks (Fig. 1). Dispersed fibers, evenly distributed over the entire volume of the material, create a spatial frame and contribute to the inhibition of developing cracks under the action of destructive forces [1–8].

Carbon nanotubes are used as nanofibers, the effect of which on the microstructure and nanostructure of the modified cement stone depends on the type of carbon material, its physical and chemical characteristics, the geometric parameters of the fibers, and the uniformity of dispersion in the composite body. The presence of carbon nanofibers changes the microstructure and nanostructure of CNT-modified cement. A decrease in capillary and total porosity was recorded, followed by an improvement in the pore structure.

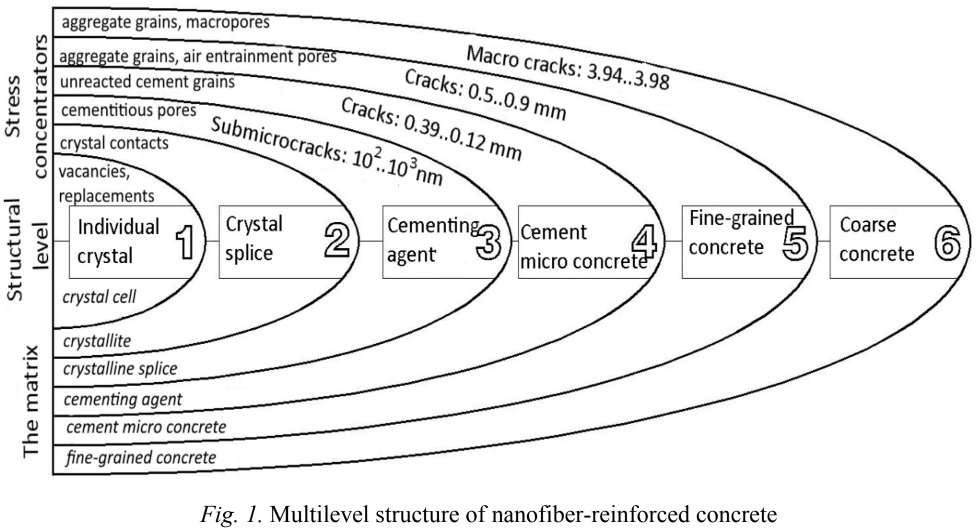


Fig. 1. Multilevel structure of nanofiber-reinforced concrete

The result of the processes occurring in capillaries and cracks are deformations in the intergranular matrix, the free flow of which is prevented by rigid clinker grains and nanocarbon tubes, which creates a certain stress intensity at the tips of the separation cracks. The stress intensity, as well as the stress-strain state near the tops of capillaries and cracks, are determined by the crack resistance criterion (K_C) and stress intensity factors (K_{IC}, K_{IIC}) [9, 10].

Materials

The main components of concrete mixtures are: binder – Portland cement PC 500 D0; modifying substance – carbon nanomaterial (CNM): average diameter of tubes and fibers 10–300 nm, average length of tubes and fibers 0.01–20.00 μ, bulk density 0.15–0.22 g/cm^3, ash content not more than 5 %, specific adsorption surface from 60 m^2/g; superplasticizer (SP) in the form of an aqueous solution – a polycarboxylate copolymer with a density of 1.1–1.14 g/ml, pH = 6–8, viscosity 230–330 cP, non-volatile substances content 39–41 %, water-reducing capacity over 40 %; water for mixing and subsequent hardening (Tab. 1).

The results of testing the studied compositions for fracture toughness are shown in Fig. 2a, by the method of nanoindentation (Fig. 2b), strength indicators (Fig. 3).

The presented results indicate that the introduction of carbon nanotubes contributes to an increase in the fracture toughness index of cement stone by 50 % relative to the unmodified composition (No 1) and by 21 % relative to the composition with a plasticizer (No 2).

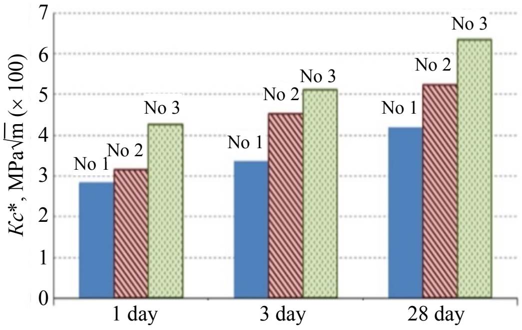
An analysis of the obtained strength indicators indicates the effect of carbon nanotubes on the compressive and flexural strength of the cement stone. The increase in compressive strength with the introduction of CNTs was 12 % relative to composition No 2 containing a plasticizer without CNTs as an additive. The joint effect of the plasticizer and CNT (composition No 3) had an increase in compressive strength by 21–23 % relative to the composition without additives (composition No 1). The increase in the flexural strength of the cement stone was 21 % (37 days) with the introduction of CNTs into the plasticizer (composition No 3 relative to composition No 2) and 51 % (37 days) with the addition of CNTs and a plasticizer (composition No 3) relative to the composition without additives (composition No 1).

Table 1

The composition of the raw mixture of nanocement stone

Composition	The composition of the raw mixture, mass %		The amount of additive introduced from the mass of cement, %	W/C	The composition of the additive		Normal density ratio
	Cement	Additive			Mass fraction SP to cement, %	Mass fraction of solid nanocarbon to cement, %	
1	99.2	0.8	–	0.26	–	–	0.26
2			0.8	0.21	0.4	–	0.21
3			0.8	0.21	0.4	0.0004	0.21

a



b

Indicator		Sample 1	Sample 3
Modulus of elasticity, GPa / Standard deviation	Phase 1	13.0/3.3	21.2/4.9
	Phase 2	23.2/10.6	30.7/9.1
	Phase 3	50.6/8.6	62.8/10.7
Rigidity, GPa / Standard deviation	Phase 1	0.93/0.21	1.04/0.23
	Phase 2	1.84/0.74	1.59/0.87
	Phase 3	2.95/1.45	4.94/1.28
Volume fraction of the phase, %	Phase 1	61.9	46.9
	Phase 2	34.0	44.1
	Phase 3	4.1	9.0

Fig. 2. Test results: a – histogram of the change in the conditional critical stress intensity factor at different ages for composition 1 (without additive), composition 2 (SP), composition 3 (SP + CNT); b – average values of the modulus of elasticity and stiffness in three phases (after the dividing line, the standard deviation in this phase is indicated)

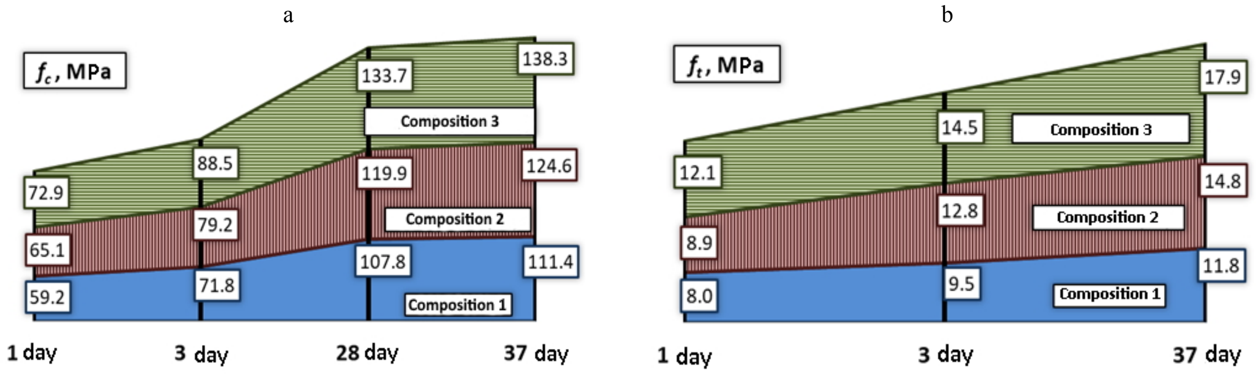


Fig. 3. The results of tests of cement stone for: a – axial compression; b – stretching in bending

Studies of heavy nanofiber-reinforced concrete

For the strength and fracture toughness of nanoconcrete, 100×100×400 mm prism samples were made, differing in different contents of the main components of the mixture (Tab. 2). Different types of fiber reinforcement were introduced into each of the nanoconcrete matrices to contain cracks at the level of fine-grained concrete: F1 – fiber from sheet steel with a wave profile (volume fraction $\mu_V = 1$ %); F2 – steel anchor fiber ($\mu_V = 1$ %); F3 – wavy polymer fiber ($\mu_V = 0.44$ %). The obtained values of the stress intensity factor in the studied compositions are shown in Fig. 4.

Table 2

Formulations of nanofiber-reinforced concrete compositions

Composition	Component consumption, %					
	The ratio of the components of the concrete matrix, %				Additive modified CNT, %	
	Cement	Rubble faction		Sand	By weight of binder	By mass fraction of solid nanocarbon to cement
		5–10	5–20			
A	18	–	45	37	0.8	0.00060
B	19	–	45	36	0.5	0.00038
C	20	38	–	42	0.7	0.00038
D	23	39	–	38	0.7	0.00060

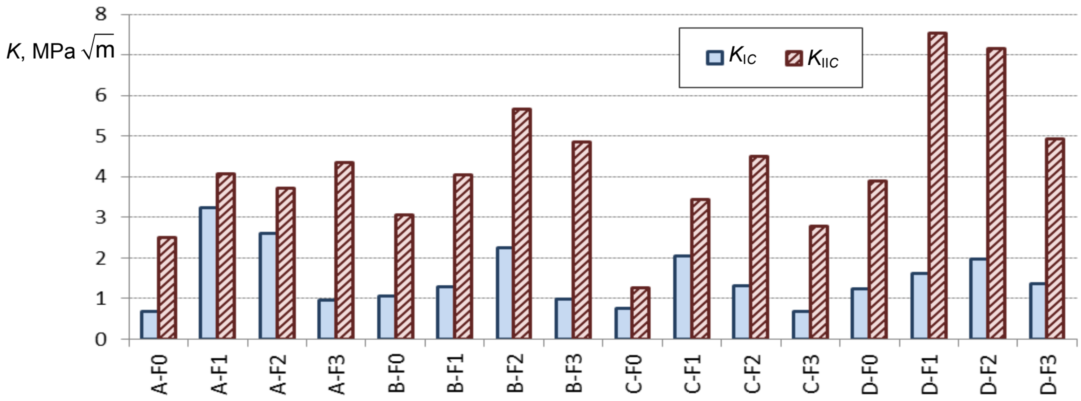


Fig. 4. Results of testing nanofiber-reinforced concrete for fracture toughness: K_{IC} – normal separation; K_{IIC} – transverse shear

Fiber reinforcement has a positive effect on the crack resistance of nanofiber-reinforced concrete. The increase in fracture toughness K_{IC} and K_{IIC} with the addition of fiber may be due to the fiber's resistance to slip of crack surfaces. Nanofiber-reinforced concretes with multi-level dispersed reinforcement are promising materials for use in structures with increased requirements for crack resistance, frost resistance, water resistance, and, in combination, durability [11].

CONCLUSION

The working hypothesis is confirmed that the required fracture toughness of structural concrete is provided by multi-level reinforcement: at the level of the crystalline joint of cement stone – carbon nanotubes, and at subsequent levels – macro-sized fiber fibers. Reinforcement of a crystalline joint with carbon nanotubes leads to an increase in the fracture toughness of the matrix (cement stone) by 20 %, compressive strength by 12 %, and tensile strength in bending by 20 %. When reinforcing at the level of fine-grained concrete, we obtain a composite – nanofibre-reinforced concrete with fracture toughness K_{IC} = (1.3–3.5) MPa$\sqrt{\text{m}}$, K_{IIC} = (3.4–7.5) MPa$\sqrt{\text{m}}$. This will make it possible to switch to the production of nanofiber-reinforced concrete for industrial, housing and communal and road construction facilities.

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Received: 14.04.2022
Accepted: 29.06.2022