UDC 691.3 **DOI 10.52928/2070-1683-2024-36-1-14-20**

COMPARATIVE STUDY ON THE APPLICABILITY OF NON-METALLIC NANOFIBERS AND REED FIBERS IN CONCRETE

X. WANG[1], H. YU[2], E. SADOVSKAYA[3], PhD, associate prof. S. KOVSHAR[4],
Doctor of Engineering, prof. S. LEONOVICH[5]
([1)-5)] Belarusian National Technical University, Minsk)
[1)] wxp-phd@bntu.by, [2)] yuhaoxuan2001@gmail.com,
[3)] sadovcskayea@bntu.by, [4)] kovsharsn@bntu.by, [5)] leonovich@bntu.by

This article mainly conducts mechanical and mechanical experiments on non-metallic nanofiber concrete and non-metallic reed fiber concrete. Through relevant mechanical experimental data, the mechanical properties of the two fibers are compared in detail and the structures of the two fibers in concrete are determined. Durability, environmental protection, chemical stability and physical and mechanical properties hope to provide reference for the development of non-metallic fiber concrete materials.

Keywords: *non-metallic fiber, nanofiber, reed fiber, concrete.*

Introduction. Ordinary cement composites have low tensile strength and limited strain capacity. This results in the formation of nanocracks at relatively low tensile loads. These nanocracks have a significant impact on the durability of the cement matrix. In order to achieve the Sustainable Development Goals, people have begun using nanomaterials in significant quantities in building materials. Konsta-Gedutes et al. showed that the addition of carbon nanotubes (CNTs) as reinforcement materials can control nanoscale cracks [1]. Carbon nanofibers (CNFs) can significantly enhance the mechanical properties of nanocomposites by serving as effective reinforcing materials in cement composites. This is due to their excellent material properties, such as high stiffness, tensile strength, excellent electrical and thermal conductivity, and corrosion resistance [2; 3]. In addition, the physical structure of CNF (cellulose nanofiber) presents many exposed edges along the surface. These exposed edges may create a p-region that interacts with cement hydration products, resulting in significant changes in nanoscale mechanical properties, including strength, durability, fracture resistance, and more. Reed fiber reinforced concrete is a type of concrete that utilizes reed fiber as a reinforcing material. It offers unique mechanical properties and environmental advantages. As a natural fiber material, reed fiber possesses characteristics such as lightweight, high strength, low thermal conductivity, and renewability. These qualities make reed fiber reinforced concrete highly promising for various applications in the construction industry[1]. Meheddene Machaka, Jamal Khatib, and Safaa Baydoun prepared four concrete mixtures. They added reed fiber ranging from 0% to 1,5% and used a water-cement ratio of 0,5%. Additionally, they treated the reed fibers, which were 40 mm long and 2 mm wide, with a 4% concentration of NaOH solution. Tests include compressive strength, density, total water absorption, and capillary water absorption. Studies have shown that the incorporation of reed fiber-infused concrete can decrease water absorption by up to 45% in cases of complete immersion and capillary action. There is minimal reduction in the density and strength of reed fiber reinforced concrete. The optimal addition of fiber in reed fiber reinforced concrete is 1,5%. This method is a viable approach for producing environmentally friendly materials that can be used to create sustainable building materials with adequate mechanical and durability properties [4] (Cardinale & Arleo). The addition of reed fiber can effectively enhance the tensile strength and crack resistance of concrete, resulting in improved seismic and wind resistance. It can also improve the frost resistance and durability of concrete, reduce concrete shrinkage and cracking, and prolong the service life of buildings [5]. Reed fiber can also improve the thermal insulation performance of concrete, reduce energy consumption, and achieve the goal of building energy efficiency [6]. Therefore, this paper analyzes the mechanical properties of nanofiber concrete and reed fiber-reinforced concrete. It then discusses the practical applications of these two types of fiber-reinforced concrete, providing relevant references for readers.

1. Materials and Methods

1.1 Experimental Materials

R42,5 ordinary Portland cement is used, the main chemical composition is showed in table 1, mechanical properties are showed in table 2. The natural coarse aggregate consists of ordinary gravel with a particle size of 0/5 (5–10 mm) and 1/2 (10–20 mm). The gradation is continuous. The fine aggregate is natural river sand from Minsk Sea. The mixing water used is laboratory tap water. The reed fiber used is treated with a 4% NAOH solution in wells. The reed fiber has a length of 40 mm, width of 3–5 mm, diameter of 0,45 mm, and density of 1,7 g/cm^3.The unprocessed reeds are shown in figure 1, *a*, the processed reeds are shown in figure 1, *b*. The purity of the nanofiber is greater than 99,9%. The reed fiber has an outer diameter of 200–600 nm and a length of 5–50 μm. It also has a specific surface area of 18 m^2/g and a conductivity greater than 100 sec/cm, is shown in figure 2. The mix ratio design is based on a substitution rate of 0–6%. The target design strength is C25, and the design standard slump is 180–220 mm. The material's mix ratio is shown in table 3.

Table 1. – The main component of cement, %

CaO	SiO2	Al2O3	Fe2O3	SO3	Na2O	K2O	MgO
63,11	23,32	7,43	3,36	1,1	0,75	0,56	0,37

[1] Jaafer, B.S., Majeed, A.H. & Kadhim, M.J. (2020). Physical and Mechanical Properties of Reed Fiber Cement Board // IOP Conference Series: Materials Science and Engineering. IOP Publishing, 928(2), 022054. DOI: 10.1088/1757-899X/928/2/022054.

a ***b***

Figure 1. – Reed fiber

Figure 2. – Nanofiber [13]

Table 2. – Mechanical properties

Standard Consistency Water Requirement, %	Specific surface area, m^2/kg	Coagulation time, min		Compressive strength, MPa		Flexural strength, MPa	
		Initial setting	Finalization	3 d	28 d	3 d	28 d
28	360	175	235	27,5	49,0	5,5	8,0

Table 3. – Mix ratio of materials

r, %	Water-cement ratio	The amount of concrete material is kg/m^3							
		cement	water	sand	Natural coarse aggregates		Reed fibers	Nanofibers	Water reducer
					0/5	1/2			
0%	0,45	400	180	730	330	770	0	0	4,0
1%	0,45	400	180	730	330	770	4	4	4,0
2%	0,45	400	180	730	330	770	8	8	4,0
3%	0,45	400	180	730	330	770	12	12	4,0
4%	0,45	400	180	730	330	770	16	16	4,0
5%	0,45	400	180	730	110	770	20	20	4,0
6%	0,45	400	180	730	110	770	24	24	4,0

1.2 Experimental design

According to the material design ratio mentioned above, the material ratio for a 100 mm×100 mm×100 mm mold is calculated as follows: cement, sand, water, and 1–6% nano-reed fiber in the proportions of 0,4 kg:0,6 kg:0,18 L:0,004 kg; 0,4 kg:0,6 kg:0,18 L:0,008 kg; 0,4 kg:0,6 kg:0,18 L:0,012 kg; 0,4 kg:0,6 kg:0,18 L:0,016 kg; 0,4 kg:0,6 kg:0,18 L:0,02 kg; and 0,4 kg:0,6 kg:0,18 L:0,024 kg. Compressive test specimens were subjected to axial compressive tests on standard cubic concrete specimens and fiber reinforced concrete specimens with different types and gradients using a DS2-1000N compressive strength tester. The test block is shown in figure 3 and the test is shown in figure 4.

Figure 3. – Compression test block

Figure 4. – Verification process

According to the material design ratio mentioned above, the material ratio for a 150 mm×150 mm×650 mm mold is calculated as follows: cement, sand, water, and 1–6% nano-reed fiber = 3,71 kg:5,58 kg:1,67 L:0,037 kg; = = 3,71 kg:5,58 kg:1,67 L:0,074 kg; = 3,71 kg:5,58 kg:1,67 L:0,11 kg; = 3,71 kg:5,58 kg:1,67 L:0,14 kg; = = 3,71 kg:5,58 kg:1,67 L:0,18 kg; = 3,71 kg:5,58 kg:1,67 L:0,22 kg. Conduct flexural tests on standard prismatic concrete specimens and fiber-reinforced concrete specimens with different types and gradients using the "Hydraulic Pressure Testing Machine GB/T3722" tester. The test block is shown in figure 5.

Each layer is compacted using a shaker for 30 seconds. After the casting operation is completed, the samples are demolded for 24 hours and then stored at a temperature of 23,0 ± 2,0°C and a relative humidity of 95% for 28 days. The process of destruction is shown in figure 6.

2. Results & Discussion

Figure 5. – Flexural test block

Figure 6. – Flexural test

Table 4. – Tensile failure load of the specimen

Serial number	Substitution parameter r, %	Ordinary concrete 28 d, kN	Reed fiber 28 d, kN	Nanofibers 28 d, kN
C1	1	4,1	5,0	4,8
C2	2	3,9	4,9	4,6
C3	3	4,5	5,8	5,2
C4	4	4,2	5,9	4,3
C5	5	4,2	5,4	5,6
C6	6	4,0	4,9	4,7

Table 5. – Compressive failure load of the specimen

Serial number	Substitution parameter r, %	Ordinary concrete 28 d, kN	Reed fiber 28 d, kN	Nanofibers 28 d, kN
C1	1	44,1	44,1	47,4
C2	2	42,3	45,6	46,5
C3	3	42,8	43,8	46,4
C4	4	41,5	50,7	50,1
C5	5	40,2	48,3	43,5
C6	6	42,5	43,9	44,5

2.1 Compressive strength results

2.1.1 Compressive strength of non-metallic nanofiber concrete

In the experiment, we prepared specimens of non-metallic nanofiber concrete and tested their compressive strength. The curve of figure 7 show that the compressive strength of non-metallic nanofiber concrete is approximately 15% higher than that of ordinary concrete. Specifically, the compressive strength of regular concrete is 42,23 kN, while the compressive strength of non-metallic nanofiber concrete reaches approximately 48,4 kN. This result shows that the addition of non-metallic nanofibers effectively improves the compressive strength of concrete. Non-metallic nanofiber concrete has a higher compressive strength, indicating that non-metallic nanofibers have great potential for improving the mechanical properties of concrete. This result provides a theoretical basis and practical guidance for engineering applications, helping to enhance the durability and safety of concrete structures.

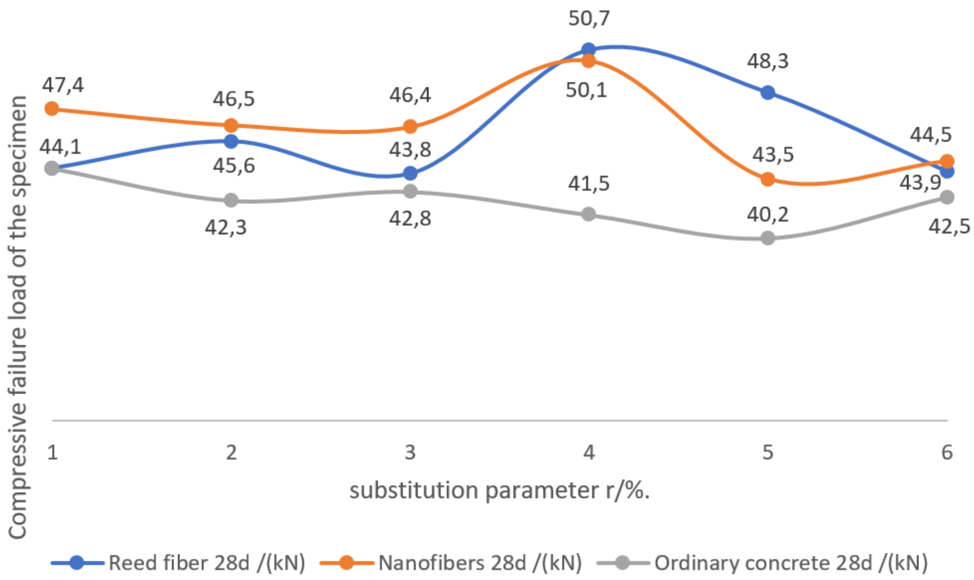

Figure 7. – Compressive failure load of the specimen

2.1.2 Compressive strength of reed fiber reinforced concrete

Through the compressive strength test of specimens made with reed fiber concrete. The results show that the compressive strength of reed fiber concrete is approximately 10% higher than that of ordinary concrete. Specifically, the compressive strength of ordinary concrete is 42,23 kN, while the compressive strength of reed fiber concrete reaches approximately 46,06 kN. This demonstrates that the inclusion of reed fiber effectively enhances the compressive strength of concrete. Reed fiber has excellent mechanical properties and natural weather resistance. Additionally, its chemical properties are highly compatible with cement and other materials used in concrete. These characteristics allow reed fibers to serve as reinforcement in concrete and enhance its compressive strength.

2.2 Tensile strength results

2.2.1 Tensile strength of non-metallic nanofiber reinforced concrete

We conducted tensile tests on specimens of non-metallic nanofiber concrete. Observing figure 8 which show that the tensile strength of non-metallic nanofiber concrete is approximately 25% higher than that of ordinary concrete. The tensile strength of ordinary concrete is 4,15 kN, while the tensile strength of non-metallic nanofiber concrete reaches approximately 5,2 kN. Non-metallic nanofibers possess excellent physical and chemical properties, including a high specific surface area, strong mechanical strength, and chemical stability. Non-metallic nanofibers possess properties that allow them to reinforce concrete and enhance its tensile strength. Therefore, non-metallic nanofibers help to improve the durability and safety of concrete structures.

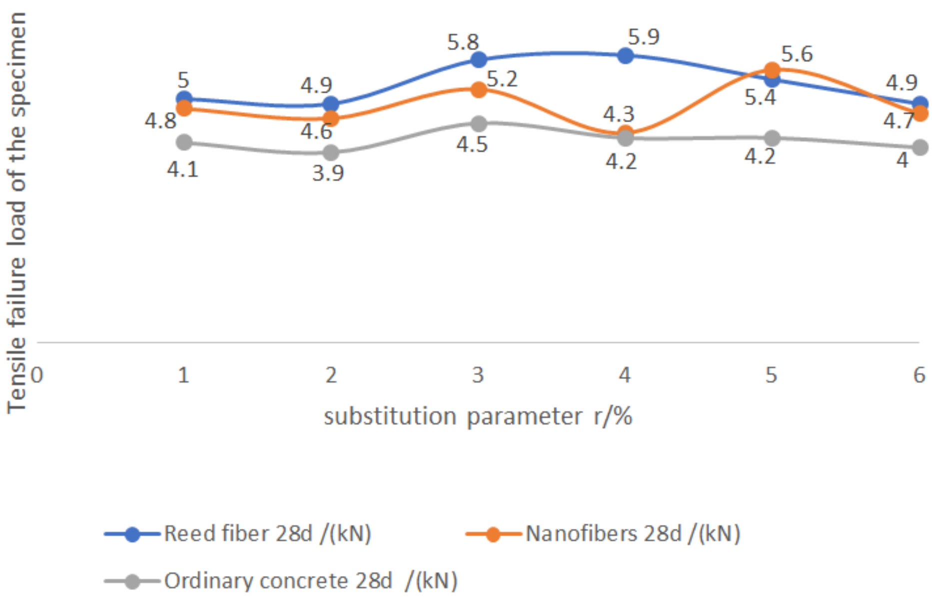

Figure 8. – Tensile failure load of the specimen

2.2.2 Tensile strength of reed fiber reinforced concrete

We prepared specimens of reed fiber concrete and tested their tensile strength. Experimental results show that the tensile strength of reed fiber concrete is approximately 17,5% higher than that of ordinary concrete. The tensile strength of regular concrete is 4,15 kN, whereas the tensile strength of reed fiber concrete reaches approximately 4,85 kN. Reed fiber has excellent mechanical properties and natural weather resistance. Additionally, its chemical properties are highly compatible with cement and other materials used in concrete. These characteristics allow reed fibers to serve as reinforcement in concrete and enhance its tensile strength. In summary, reed fiber concrete also has high tensile strength, indicating that reed fiber has the potential to improve the mechanical properties of concrete. This result provides a theoretical basis and practical guidance for engineering applications, helping to develop new green building materials.

2.3 Durability results

2.3.1 Durability of non-metallic nanofiber concrete

In our study, we compared the durability of non-metallic nanofiber concrete to that of reed fibers in concrete, focusing on their applicability. We conducted a literature review to gather information on the subject. We found that non-metallic nanofiber concrete performs well in terms of durability, thereby enhancing the longevity and safety of concrete structures.

First, we compared the experimental data on dry-wet cycles in the literature. The data showed that non-metallic nano-fiber concrete has a strong ability to maintain performance under dry-wet cycles without any noticeable cracks or damage [7]. Second, we compared fatigue test data from the literature. The results show that the fatigue life of non-metallic nanofiber concrete is significantly higher than that of ordinary concrete, indicating that it has better fatigue resistance [8]. In addition, we also compared the data from the carbonization experiment and the sulfate attack experiment. The data results show that non-metallic nanofiber concrete has a strong ability to maintain performance under these environmental factors and has obvious advantages compared to ordinary concrete [9].

2.3.2 Durability of reed fiber reinforced concrete

First, we compared the experimental data on dry-wet cycles in the literature. The data showed that reed fiber concrete has a strong ability to maintain performance under dry-wet cycles without any noticeable cracks or damage [6]. Second, we compared the fatigue test data. The results show that the fatigue life of reed fiber concrete is slightly higher than that of ordinary concrete, indicating that it has better fatigue resistance. In addition, we compared experimental data on carboni-zation and sulfate attack to evaluate the durability of concrete under specific environmental conditions [10]. The data shows that reinforced fiber concrete has a strong ability to maintain performance under these environmental factors and has certain advantages over regular concrete. To sum up, reinforced fiber concrete also demonstrates good durability and has potential for various applications. This result provides a theoretical basis and practical guidance for engineering applications, helping to develop new green building materials [11].

2.4 SEM electron microscopy image analysis

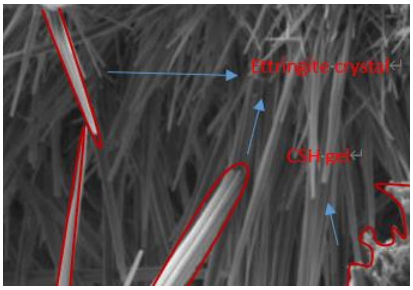

Figure 9. – SEM without fiber added

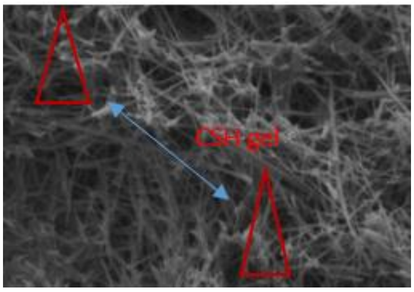

Figure 10. – SEM of nanofiber added

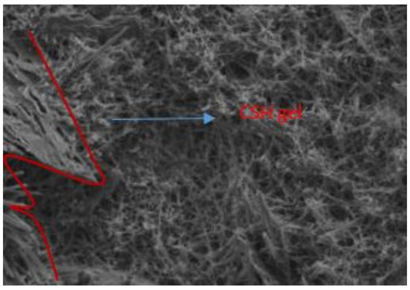

Figure 11. – SEM of reed fiber

Figure 9 shows the microscopic morphology of concrete without fiber. In the figure, needle like ettringite crystals and some lamellar CSH gel can be clearly seen. As can be seen from figure 10, when nanofiber is added, the SEM microstructure of concrete has changed significantly compared with ordinary concrete. The ettringite formed by cement hydration becomes fine and dense, and ettringite crystals are bound together by many films, Create smaller gaps and tighter distribution between structures. In addition, the performance of reed fibers in concrete is more prominent, as they have a tighter structural arrangement, as shown in figure 11.

3. Comparison of material properties

3.1 Performance characteristics of non-metallic nanofibers

Firstly, non-metallic nanofibers offer several advantages such as a high specific surface area and strength, which can effectively enhance the mechanical properties of concrete. Adding non-metallic nanofibers to concrete can significantly enhance its tensile strength, compressive strength, and crack resistance. Secondly, it also has good heat insulation and thermal insulation properties, which can effectively enhance the thermal insulation effect of concrete. In cold areas or buildings that require insulation, the utilization of concrete containing non-metallic nanofibers can decrease energy consumption and enhance the energy efficiency of buildings. Finally, it also exhibits good physical stability and can effectively withstand the influence of environmental factors, such as fire resistance, impact resistance, and wear resistance, among other performance characteristics [12]. Therefore, the use of non-metallic nanofibers can enhance the durability of concrete and prolong its lifespan. Non-metallic nanofibers, however, are a type of fibers that are synthetically extracted. The production process is relatively complicated, and the cost is too high, so they cannot be applied to a large number of projects.

3.2 Performance characteristics of reed fiber

Reed fiber is a natural, renewable resource and has more environmentally friendly advantages than traditional concrete. It also has good thermal insulation, sound insulation, and other performance characteristics, which can play an important role in concrete. Specifically, it has high strength and stiffness, which can effectively enhance the mechanical properties of concrete. It also exhibits good chemical stability and can effectively resist the influence of environmental factors, such as oxidation and corrosion [5]. Therefore, adding reed fiber to concrete can significantly improve its tensile strength, compressive strength, and crack resistance.

3.3 Comparative analysis of material properties

Both fibers can enhance the mechanical properties of concrete, but non-metallic reed fibers have a more pronounced reinforcing effect on concrete. This is because non-metallic reed fibers have a higher specific surface area and strength, allowing them to be more effectively dispersed in concrete. As a result, they enhance the tensile strength, compressive strength, and crack resistance of the concrete. Although both non-metallic nanofibers and reed fibers can improve the durability of concrete. Non-metallic nanofibers, however, exhibit superior chemical stability and are more resistant to environmental factors such as oxidation and corrosion. Therefore, non-metallic nanofibers may be more suitable for applications that require long-term durability. Reed fiber is a natural, renewable resource with environmental advantages. However, non-metallic nanofibers are also environmentally friendly materials that can be made from renewable resources and have a lower environmental impact throughout their life cycle. Therefore, both fibers have their advantages in terms of environmental protection. Both fibers have performance characteristics such as heat insulation, thermal insulation, and sound insulation, and can play an important role in concrete. In addition, non-metallic nanofibers also offer the advantages of a high modulus and low density, which can enhance the lightweight and high-strength characteristics of concrete. Therefore, both non-metallic nanofibers and reed fibers can play a role in reinforcing concrete, improving durability, and enhancing environmental protection. However, there are some differences between them, and the choice needs to be based on specific application needs.

Conclusion. First of all, it is worth confirming that both non-metallic nanofibers and reed fibers can enhance the mechanical properties of concrete. The compressive strengths of non-metallic nanofiber concrete and reed fiber concrete are respectively 6,17 kN and 3,83 kN higher than ordinary concrete, which is an increase of about 15% and 10%. The tensile strength of non-metallic nanofiber concrete and reed fiber concrete are respectively increased by 1,05 kN and 0,7 kN, which is about 25% and 17,5% higher compared to ordinary concrete. This indicates that the reinforcing effect of non-metallic nanofibers is more significant. In addition, an analysis of the microstructure of non-metallic nanofibers and reed fiber concrete under a scanning electron microscope (SEM) reveals that the flexural density of metal nanofiber concrete and reed fiber concrete is higher. This significantly enhances the compactness of the internal structure. Furthermore, the addition of reed fiber results in a denser ettringite structure compared to nanofiber. This indicates that the inclusion of reed fiber leads to improved distribution and workability of the internal structure.

Not only can they improve the durability of concrete, but non-metallic nanofibers also exhibit better chemical stability and resistance to environmental factors. But reed fiber is a natural, renewable resource with environmentally friendly advantages. Additionally, non-metallic nanofiber is also an environmentally friendly material that can be derived from renewable resources and has a lower environmental impact throughout its life cycle. Therefore, non-metallic nanofibers and reed fibers have the advantages of high modulus and low density, which can enhance the lightweight and high-strength characteristics of concrete.

Therefore, we can leverage the performance characteristics of non-metallic nanofibers and reed fibers to enhance the durability and environmental sustainability of concrete. However, there are some differences between them, and the choice needs to be based on specific application needs. In applications that require higher reinforcement and durability, non-metallic nanofibers may be more suitable. On the other hand, in applications that prioritize the utilization of natural renewable resources and environmental friendliness, reed fibers may be more suitable.

REFERENCES

1. Konsta-Gdoutos, M.S., Metaxa, Z.S. & Shah, S.P. (2010). Highly dispersed carbon nanotube reinforced cement based materials. *Cem. Concr. Res., 40(7),* 1052–1059. DOI: 10.1016/j.cemconres.2010.02.015.
2. Lawrence, J.G., Berhan, L.M. & Nadarajah, A. (2008). Elastic properties and morphology of individual carbon nanofibers. *ACS Nano, 2(6),* 1230–1236. DOI: 10.1021/nn7004427.
3. Mordlkovich, V.Z. (2003). Carbon nanofibers: A new ultrahigh-strength material for chemical technology. *Theor. Found. Chem. Eng., 37(5),* 429–438. DOI: 10.1023/A:1026082323244.
4. Machaka, M., Khatib, J., Baydoun, S., Elkordi, A. & Assaad, J.J. (2022). The Effect of Adding Phragmites australis Fibers on the Properties of Concrete. *Buildings, 12(3),* 278. DOI: 10.3390/buildings12030278.
5. Cardinale, T., Arleo, G., Bernardo, F., Feo, A. & De Fazio, P. (2017). Investigations on thermal and mechanical properties of cement mortar with reed and straw fibers. *International Journal of Heat and Technology, 35(1),* 375–382. DOI: 10.18280/ijht.35Sp0151.
6. Shon, C.-S., Mukashev, T., Lee, D., Zhang, D. & Kim, J.R. (2019). Can common reed fiber become an effective construction material? Physical, mechanical, and thermal properties of mortar mixture containing common reed fiber. *Sustainability, 11(3),* 903. DOI: 10.3390/su11030903.

7. Polonina, E.N., Leonovich, S.N., Khroustalev, B.M., Sadovskaya, E.A. & Budrevich, N.A. (2021). Cement-based materials modified with nanoscale additives. *Science and Technique, 20(3),* 189–194. DOI: 10.21122/2227-1031-2021-20-3-189-194.
8. Wang, Y., Zhang, L. & Sun, B. (2020). The use of non-metallic nanofibers in concrete: A review. *Construction and Building Materials, 237,* 117593.
9. Xu, M., Li, Q. & Ma, L. (2021). Performance and Durability of Nanofiber-Reinforced Concrete: A Review and Future Perspective. *Construction and Building Materials, 271,* 122691.
10. Nahhab, A.H. (2009). Some Mechanical Properties of Concrete Reinforced with Reed Fibers. *Al-Qadisiya Journal for Engineering Sciences, 2(1),* 31–37.
11. Van, S., Leonovich, S., Vei, M. & Kovshar, S. (2023). Konstruktsionnyi beton, armirovannyi trostnikovym i kokosovym vidami volokon. *Arkhitektura i stroitel'stvo [Architecture and Construction], (3),* 20–28. (In Russ., abstr. in Engl.). URL: https://smp.by/wp-content/uploads/2023/08/ais_03_2023-20-28.pdf.
12. Wang, T., Xu, J., Meng, B. & Peng, G. (2020). Experimental study on the effect of carbon nanofiber content on the durability of concrete. *Construction and building materials, 250(3),* 118891. DOI: 10.1016/j.conbuildmat.2020.118891.
13. Sadovskaya, E.A., Leonovich, S.N., Zhdanok, S.A. & Polonina, E.N. (2020). Prochnost' nanofibrobetona na rastyazhenie. *Inzhenerno-fizicheskii zhurnal [J. of Engineering Physics and Thermophysics], 93(4),* 1051–1055. (In Russ.).

Поступила 08.12.2023

СРАВНИТЕЛЬНОЕ ИССЛЕДОВАНИЕ ПРИМЕНИМОСТИ НЕМЕТАЛЛИЧЕСКИХ НАНОВОЛОКОН И ТРОСТНИКОВЫХ ВОЛОКОН В БЕТОНЕ

С. ВАН[1], Х. ЮЙ[2], Е.А. САДОВСКАЯ[3], канд. техн. наук, доц. С.Н. КОВШАР[4],
д-р техн. наук, проф. С.Н. ЛЕОНОВИЧ[5]
([1)-5)] Белорусский национальный технический университет, Минск)

В данной статье в основном проводятся механические и механохимические эксперименты по изучению неметаллического нановолокнистого бетона и неметаллического бетона из тростникового волокна. На основе соответствующих механических экспериментальных данных подробно сравниваются механические свойства этих двух волокон и определяются их структуры в бетоне. Долговечность, экологическая безопасность, химическая стабильность и физико-механические свойства позволяют надеяться, что они послужат основой для разработки бетонных материалов на основе неметаллических волокон.

Ключевые слова: *неметаллическое волокно, нановолокно, тростниковое волокно, бетон.*