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PAPER

Sustainability and economic evaluation of non-metallic fiber and reed fiber concrete materials in Belarus

Xianpeng Wang,[1,2] Fanmiao Gao,[1,3] Yifan Wang, Junshu Wang[1,4] and Xiaohong Guo[5*]

[1] International Institute of Management and Business, 220086, Minsk, PR Belarus, [2] Belarusian National Technical University, Republic of Belarus, 220013, Minsk, PR Belarus, [3] Guangzhou Institute of Science and Technology, 510540, Guangzhou, China, [4]AnYang University, 455000, Anyang, China, [5] Inner, Mongolia Agricultural University, Inner Mongolia, 010018, Hohhot, China
Correspondence:Xiaohong Guo

Abstract

To address the issues of weak tensile strength, susceptibility to nanocracks, and insufficient durability in ordinary cement-based concrete, carbon nanofiber concrete and alkali-modified reed fiber concrete were prepared based on local Belarusian building material resources. The fiber content ranged from 0% to 6%. 28-day compressive and tensile mechanical tests were conducted. The environmental load of the two types of fiber-reinforced concrete was quantified using the ISO 14040/14044 Life Cycle Assessment (LCA) system. Durability performance was compared using data from dry-wet cycles, carbonation, and sulfate attack. Mechanical test results show that both types of fibers can improve the mechanical properties of concrete. At the optimal nanofiber content of 4%, the compressive failure load was 52.1 kN and the tensile failure load was 5.3 kN, representing increases of approximately 15% and 25% respectively compared to the baseline concrete. At the optimal reed fiber content of 4%, the compressive strength was 50.7 kN and the tensile strength was 5.9 kN, representing increases of approximately 10% and 17.5% respectively. Using 1 m^3 of concrete as a functional unit, LCA (Limited Carbon Concrete) calculated the Global Warming Potential (GWP), Primary Energy Consumption (PED), and Acidification Potential (AP). Reed fiber significantly reduces life-cycle carbon emissions due to its plant carbon sequestration effect; nanofibers offer more prominent reinforcement, but their raw material preparation consumes more energy and has a higher environmental impact. Durability analysis shows that carbon nanofiber concrete exhibits superior fatigue resistance, erosion resistance, and carbonation resistance compared to reed fiber concrete. Reed fiber is a natural and renewable material with significant advantages in thermal insulation, energy saving, and low carbon emissions. Considering overall mechanical, durability, and environmental benefits, carbon nanofiber modified concrete is the preferred choice for high-durability, high-load-bearing projects; reed fiber concrete is suitable for low-carbon green civil buildings and thermal insulation projects, providing data support for the development and engineering application of sustainable fiber concrete in Belarus.

Key words: nonmetallic fibers, nanofibers, reed fibers, concrete, LCA assessment, sustainable development

Introduction

Ordinary cement composites have low tensile strength and limited strain capacity. They are prone to nanocracks under relatively low tensile loads, which seriously affect the long-term service durability of cement matrix. In the context of green and low-carbon transformation of the construction industry and implementation of sustainable development goals, green reinforcement technologies such as nano-modification and natural fiber modification have become research hotspots for cement-based composites. The application of nanomaterials and natural plant fibers in the field of building materials is becoming more and more widespread. Studies by Konstantin-Gedutos et al. have shown that adding carbon nanotubes (CNTs) as reinforcement materials can effectively regulate the propagation of nanoscale cracks in cement-based materials and improve matrix stability [4]. Among them, carbon nanofibers (CNFs) are functional reinforcing fillers with great advantages in cement composites. With high stiffness, high tensile strength, excellent electrical and thermal conductivity and corrosion resistance, they can significantly improve the comprehensive mechanical properties of nano-modified cement composites [5, 7]. At the same time, CNFs have a large number of exposed edges on their surface, which can form an interface with cement hydration products to form a special interface transition zone, effectively improve the nanoscale mechanical properties of the material, and greatly improve the matrix strength, fracture resistance and durability.

Reed fiber concrete is a green composite building material with natural reed fiber as the reinforcing phase, which has both excellent mechanical properties and outstanding environmental benefits. Reed fiber has natural advantages such as light weight, high strength, low thermal conductivity, renewability and low cost, which makes reed fiber concrete have broad application prospects in the fields of green building and energy-saving engineering [3]. Meheddene Machaka et al. systematically studied the effects of different reed fiber dosages on concrete performance. Concrete samples were prepared with a water-cement ratio of 0.5 and a reed fiber dosage of 0%~1.5%. The reed fibers with a size of 40 mm×2 mm were modified with 4% NaOH solution, and a series of performance tests such as compressive strength, density and water absorption were carried out. The results showed that reed fiber modified concrete can reduce the total immersion water absorption and capillary water absorption by up to 45%, and the concrete

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density and compressive strength have no significant decrease. 1.5% is the optimal fiber dosage, which confirms that reed fiber modified concrete is a sustainable building material with both mechanical stability and environmental protection [6]. Cardinale and Arleo's research further confirmed that the incorporation of reed fiber can significantly improve the tensile strength and crack resistance of concrete, optimize the seismic, wind and frost resistance of the structure, effectively alleviate the problem of concrete shrinkage cracking, and extend the service life of building structures [1]. Shon and Mukashev's research also pointed out that reed fiber can optimize the thermal insulation performance of concrete, reduce building operating energy consumption, and help the energy-saving and low-carbon development of buildings [13].

In the research system of green building materials, it is no longer possible to fully evaluate the engineering application value of fiber-reinforced concrete by only exploring its mechanical and durability properties. Life cycle assessment (LCA) is a core method for quantifying the environmental benefits of building materials and assessing the low carbon content of the entire life cycle. It has been widely used in the sustainability research of fiber-reinforced concrete and has become an important research tool for balancing the mechanical properties and environmental benefits of materials [9]. Existing research shows that the modification technology of natural plant fibers and nanofibers can effectively reduce the carbon emissions, energy consumption and environmental load of concrete throughout its entire life cycle, avoid the drawbacks of high energy consumption and high pollution of traditional concrete, and meet the carbon neutrality and development needs of the construction industry [10]. Schultz et al. confirmed through quantitative analysis of the entire life cycle that fiber modification can significantly reduce the environmental impact of building materials in the production, service and disposal stages while ensuring the mechanical service performance of concrete. The renewable characteristics of natural plant fibers can further enhance the recycling value of building materials [12]. Another study pointed out that compared with traditional modified concrete, reed fiber and carbon nanofiber composite modified concrete has a lower global warming potential and resource consumption rate, and stronger material adaptability. It can effectively balance engineering performance and ecological benefits and is a green building material with great promotion value [2]. Meanwhile, LCA technology can accurately identify environmental shortcomings in the entire process of fiber concrete preparation, construction and service, providing data support for fiber content optimization, modification process upgrading and low-carbon formula design, and promoting the two-way upgrade of fiber concrete from "performance meeting standards" to "green, low-carbon, high-efficiency and durable" [17].

Therefore, this paper systematically analyzes the mechanical properties and durability characteristics of carbon nanofiber modified concrete and reed fiber concrete, and explores the green application value and engineering practicality of the two types of fiber concrete by combining life cycle assessment methods, clarifying their performance advantages and low-carbon development potential, and providing reference and guidance for the engineering application and subsequent research of green fiber concrete.

Materials and Methods

Experimental Materials

R42.5 ordinary Portland cement was used; the natural coarse aggregate was ordinary crushed stone (0/5 particle size 5-10mm, 1/2 particle size 10-20mm) , continuously graded; the fine aggregate was natural river sand from the Minsk Sea; the mixing water was laboratory tap water; and reed fibers (40mm long, 3-5mm wide, 0.45mm in diameter, density 1.7g/cm^3) treated with 4% NaOH solution were used , with a purity >99.9%.

Nanofibers with an outer diameter of 200–600 nm , a length of 5–50 μm , a specific surface area of 18 m^2/g , and an electrical conductivity >100 s/cm were used. The mixing design was based on a substitution rate of 0–6 % , with a target design strength of C25 and a design standard slump of 180–220 mm. The material mixing proportions are shown in Table 1.

Experimental Design

According to the above material design ratio, the material ratio of 100mm*100mm*100mm mold is calculated as follows: cement, sand, water, 1-6% nano-reed fiber = 0.4kg:0.6kg:0.18L:0.004kg; 0.4kg:0.6kg:0.18L:0.008kg;0.4kg:0.6kg:0.1 0.4kg:0.6kg:0.18L:0.024kg.

According to the above material design ratio, the material ratio of 150mm*150mm*650mm mold is calculated as follows: cement, sand, water, 1-6% nano-reed fiber =3.71kg:5.58kg:1.67L:0.037kg;=3.71kg:5.58kg:1.67L:0.074kg; =3.71kg:5.58kg:1.67L:0.11kg: =3.71kg:5.58kg:1.67L:0.14kg: =3.71kg:5.58kg:1.67L:0.18kg:=3.71kg:5.58kg:1.67L:0.22kg.

Each layer is compacted with a shaker for 30 seconds. After the casting operation is completed, the samples are demolded for 24 hours and then stored at 95% relative humidity and 23.0 ± 2.0 C temperature for 28 days.

Life Cycle Assessment Materials and Methods

This paper conducts a life cycle assessment of fiber-reinforced concrete based on ISO 14040 and ISO 14044 standards. It adopts a "cradle-to-gate" system boundary, takes 1 m^3 of concrete as a unified functional unit, and completes the bill of quantities calculation and environmental impact assessment by combining core quantitative formulas. The specific assessment formulas and calculation methods are as follows.

Lifecycle Inventory Calculation Method

The environmental load throughout the entire life cycle is calculated using an inventory-based cumulative calculation method. The formula for calculating the total consumption of various resources and the total emissions of pollutants is as follows:

$$E_{total}=\sum_{i=1}^{n}(Q_i\times EF_i)$$

In the formula: E_{total}represents the total environmental load (carbon emissions, energy consumption, pollutant emissions, etc.); $Q_i$represents ithe consumption/workload of the type of raw material or process; EF_irepresents the environmental factors of the corresponding material or process, with data taken from the Ecoinvent database and the domestic building materials life cycle database.

Based on the natural carbon sequestration properties of reed fiber, a carbon sequestration correction formula was used to adjust the carbon emission results:

$$GWP_{corrected}=GWP_{raw}-C_{sequestration}$$

In the formula: $GWP_{corrected}$represents the corrected global warming potential; GWP_{raw}represents the initial calculated total carbon emissions; $C_{sequestration}$and represents the amount of carbon sequestrated during the growth stage of reed fiber.

Environmental Impact Characterization Calculation

Global warming potential (GWP), primary energy consumption (PED), acidification potential (AP), and eutrophication potential (EP) are selected as the core evaluation indicators, and the characteristic calculation formulas are unified as follows:

$$EI_k=\sum_{j=1}^{m}(E_j\times CF_{kj})$$

In the formula: EI_krepresents kthe characteristic result of the i-th type of environmental impact indicator; $E_j$represents jthe total amount of the i-th pollutant/energy consumption; $CF_{kj}$and represents the characteristic factor of the corresponding impact type.

Table 1. Material Proportions

r/%	water-cement ratio	Concrete material usage (kg / m³)							
		cement	water	sand	natural coarse aggregate		reed fiber	Nanofibers	Water reducing agent
					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	twenty four	twenty four	4.0

Table 2. ensile failure load of the specimen

serial number	substitution parameter r /%.	Ordinary concrete 28d /(kN)	Reed fiber 28d /(kN)	Nanofibers 28d /(kN)
C1	1	4.1	5.0	5.8
C2	2	3.9	4.9	4.6
C3	3	4.5	5.8	5.2
C4	4	4.2	5.9	5.3
C5	5	4.2	5.4	5.6
C6	6	4.0	4.9	4.7

Table 3. ompressive failure load of the specimen

serial number	substitution parameter r /%.	Ordinary concrete 28d /(kN)	Reed fiber 28d /(kN)	Nanofibers 28d /(kN)
C1	1	44.1	44.1	47.4
C2	2	42.3	45.6	49.5
C3	3	42.8	43.8	46.4
C4	4	41.5	50.7	52.1
C5	5	40.2	48.3	48.5
C6	6	42.5	43.9	46.5

Sensitivity Analysis Methods

Single-factor sensitivity analysis was used to quantify the magnitude of index changes through parameter fluctuations. The calculation formula is as follows:

$$S=\frac{\Delta EI/EI}{\Delta X/X}$$

In the formula: Sis the sensitivity coefficient; ΔEIis the change in environmental indicator; EIis the initial value of the indicator; ΔXis the fluctuation change of the parameter; Xis the initial value of the parameter. This formula is used to determine the degree of influence of parameters such as fiber content and cement carbon emission factor on the LCA evaluation results.

Results and Discussion

Results and Analysis

Compressive strength results

This study prepared specimens of ordinary concrete, non-metallic nanofiber concrete, and reed fiber concrete, and conducted 28-day compressive strength tests. The average compressive failure load of ordinary concrete was 42.23 kN, while the compressive load of non-metallic nanofiber concrete with the optimal admixture reached 48.4 kN, representing an improvement of approximately 15% in compressive strength. The compressive load of reed fiber concrete with the same optimal admixture was 46.06 kN, representing an improvement of approximately 10% in compressive strength. The micro-reinforcing effect of nanofiber filling the matrix pores and bridging microcracks was superior to that of alkali-modified reed fiber. Reed fiber achieved its compressive strength improvement by sharing compressive stress through its excellent mechanical properties and good compatibility with cement hydration products. Both types of fibers can improve the compressive capacity of concrete, but nanofiber has a more prominent application potential in improving the mechanical properties of concrete. The relevant experimental conclusions can provide theoretical and practical support for improving the durability and safety of engineering structures.

Tensile strength results

Tensile loading tests were conducted on three types of concrete specimens for 28 days. The average tensile failure load of the benchmark ordinary concrete was 4.15 kN, while the tensile load of the non-metallic nanofiber concrete with the optimal admixture increased to 5.2 kN, an increase of 25%. The tensile load of the reed fiber concrete with the optimal admixture was 4.85 kN, an increase of 17.5%. Due to its high specific surface area, high strength, and stable chemical properties, the non-metallic nanofiber continuously transmits tensile stress and inhibits crack propagation after the matrix cracks, and its toughening effect is significantly better than that of reed fiber. The alkali-treated reed fiber has good weather resistance and stable interfacial bonding with the cement matrix, which can also effectively improve the crack resistance of concrete. The reed fiber concrete has the advantages of mechanical improvement and green renewability, providing experimental basis for the research and development of new low-carbon building materials.

Durability Results

Based on the existing literature test data, the durability performance of the two types of fiber concrete is compared. Non-metallic nanofiber concrete has a better overall durability performance and can significantly improve the service safety of concrete structures. The test results of the dry-wet cycle test show that the nanofiber modified concrete matrix has higher density. After repeated dry-wet cycles, the specimens did not produce obvious cracks or surface damage, and the structural integrity was well maintained [11]. The fatigue test data confirms that nanofibers can delay the initiation and propagation of fatigue cracks. The fatigue life of the specimens is much better than that of ordinary concrete, and the fatigue resistance is outstanding [15]. At the same time, the test results of carbonation and sulfate attack show that nanofibers refine the pore structure of the matrix and can block the penetration of the corrosive medium. Its resistance to carbonation and sulfate attack has a significant advantage over ordinary concrete and can effectively extend the service life of concrete structures [16].

Based on existing literature data, the durability characteristics of reed fiber concrete were evaluated. The results of the wet-dry cycle test showed that the reed fiber concrete did not have obvious cracking or damage after the cycle, and the structural integrity was good. The fatigue loading test showed that the fatigue life of reed fiber concrete was slightly higher than that of ordinary concrete, and it had a certain fatigue resistance. At the same time, the carbonation and sulfate attack test data can be combined to comprehensively evaluate its long-term service durability [8]. The relevant results proved that the reed fiber concrete has a better ability to resist chemical attack than the reference concrete, and there is room for improvement in durability performance. In summary, reed fiber concrete has reliable durability performance and practical engineering application value, and can provide theoretical and experimental support for the development and engineering application of green building materials [14].

Analysis of the sources of experimental error

For each mix design, six parallel specimens were used to collect mechanical data. The overall compressive strength coefficient of variation ranged from 6.2% to 11.7%, and the tensile strength coefficient of variation ranged from 8.5% to 14.3%, which is within the normal dispersion range of 5% to 15% for concrete mechanical testing. Data deviation was caused by multiple factors, including raw materials, sample preparation and curing, and loading testing. Differences in reed fiber size, alkali modification uniformity, and carbon nanofiber agglomeration caused uneven fiber dispersion. Small fluctuations in manual vibration compaction, curing temperature and humidity (23.0 ± 2.0 °C, 95% RH) altered the internal defects and hydration degree of the matrix. Specimen centering misalignment and fluctuations in the loading rate of the testing machine also contributed to the test dispersion. The test strictly followed the specifications, eliminating abnormal data with a deviation exceeding 15% from the median value before taking the average value. This effectively reduced the interference of various errors on the test conclusions and ensured the reliability of the analysis results.

Comparison of material properties

Performance characteristics of non-metallic nanofibers

First, non-metallic nanofibers have advantages such as high specific surface area and high strength, which can effectively enhance the mechanical properties of concrete. Adding non-metallic nanofibers to concrete can significantly improve the tensile strength, compressive strength and crack resistance of concrete. Second, it also has good heat insulation and thermal insulation properties, which can effectively improve the thermal insulation effect of concrete. In cold regions or buildings that require thermal insulation, the use of concrete containing non-metallic nanofibers can reduce energy consumption and improve the energy efficiency of buildings. Finally, it also has good physical stability and can effectively resist the influence of environmental factors, such as fire resistance, impact resistance and wear resistance [18] . Therefore, the use of non-metallic nanofibers can increase the durability of concrete and extend the service life of concrete. However, non-metallic nanofibers are a synthetic extracted fiber, the production process is relatively complicated and the cost is too high, so it cannot be widely used in engineering.

Performance characteristics of reed fiber

Reed fiber is a natural renewable resource and has a greater environmental advantage than traditional concrete. It also has good heat insulation, heat preservation and sound insulation properties, and 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 has good chemical stability, which can effectively resist the influence of environmental factors, such as oxidation and corrosion. Therefore, adding reed fiber to concrete can significantly improve the tensile strength, compressive strength and crack resistance of concrete.

Comparative Analysis of Material Properties

Both types of fibers can enhance the mechanical properties of concrete, but non-metallic reed fiber has a stronger reinforcing effect. This is because non-metallic reed fiber has a higher specific surface area and strength, allowing it to disperse better in concrete, thereby improving tensile strength, compressive strength, and crack resistance. While both non-metallic nanofibers and reed fiber can improve the durability of concrete , non-metallic nanofibers have better chemical stability and are more resistant to environmental factors such as oxidation and corrosion. Therefore, non-metallic nanofibers may be more suitable for applications requiring long-term durability. Reed fiber is a natural, renewable resource with environmental advantages. However, non-metallic nanofibers are also environmentally friendly materials, made from renewable resources, and have a lower environmental impact over their life cycle. Therefore, both fibers have their advantages in terms of environmental protection. Both fibers have thermal insulation, heat preservation, and sound insulation properties, playing an important role in concrete. In addition, non-metallic nanofibers also have advantages such as high modulus and low density, which can improve the lightweight and high-strength properties of concrete. Therefore , both non-metallic nanofibers and reed fibers can contribute to the reinforcement, durability, and environmental friendliness of concrete . However , there are some differences between them, and the choice should be made based on specific application requirements.

LCA Sustainable Development Assessment

Note: The GWP of reed fiber has deducted the carbon sequestration by plant growth; nanofibers have no carbon sequestration effect, and the values are the original calculation results.

As shown in Table 4, the environmental indicators of nanofiber concrete and reed fiber concrete exhibit completely opposite trends when calculated based on the patterns of GWP, PED, and AP. The baseline concrete's GWP, PED, and AP are 326.4 kg CO_2−eq, 1386.2 MJ, and 1.82 kg, respectively SO_2−eq. As the nanofiber content increases from 1% to 6%, GWP rises from 341.7 kg to 412.8 kg CO_2−eq, PED from 1472.6 MJ to 1853.7 MJ, and AP from 1.91 kg to 2.28 kg SO_2−eq. At the optimal mechanical content of 4%, the environmental loads increase by 16.2%, 21.8%, and 17.0% respectively compared to the baseline. This is due to the high energy and chemical raw material consumption during the purification and dispersion of carbon nanofibers, leading to a significant increase in carbon and pollutant emissions during the production phase. In contrast, reed fiber concrete relies on the carbon fixation effect during the plant growth stage. After correction by formula (2), the environmental load throughout the entire life cycle continues to decrease with the increase of admixture. The GWP of the 4% admixture sample is only 284.6 kg CO_2−eq, PED is 1129.3 MJ, and AP is 1.52 kg SO_2−eq. Compared with the benchmark concrete, the carbon emissions, primary energy consumption, and acidification potential are reduced by 12.8%, 18.5%, and 16.4%, respectively. Reeds only need to be harvested and simply modified with low-concentration NaOH. The processing energy consumption is extremely low. Moreover, the increase of fiber admixture can relatively reduce the amount of cement used, further reducing the core environmental load brought about by cement clinker production.

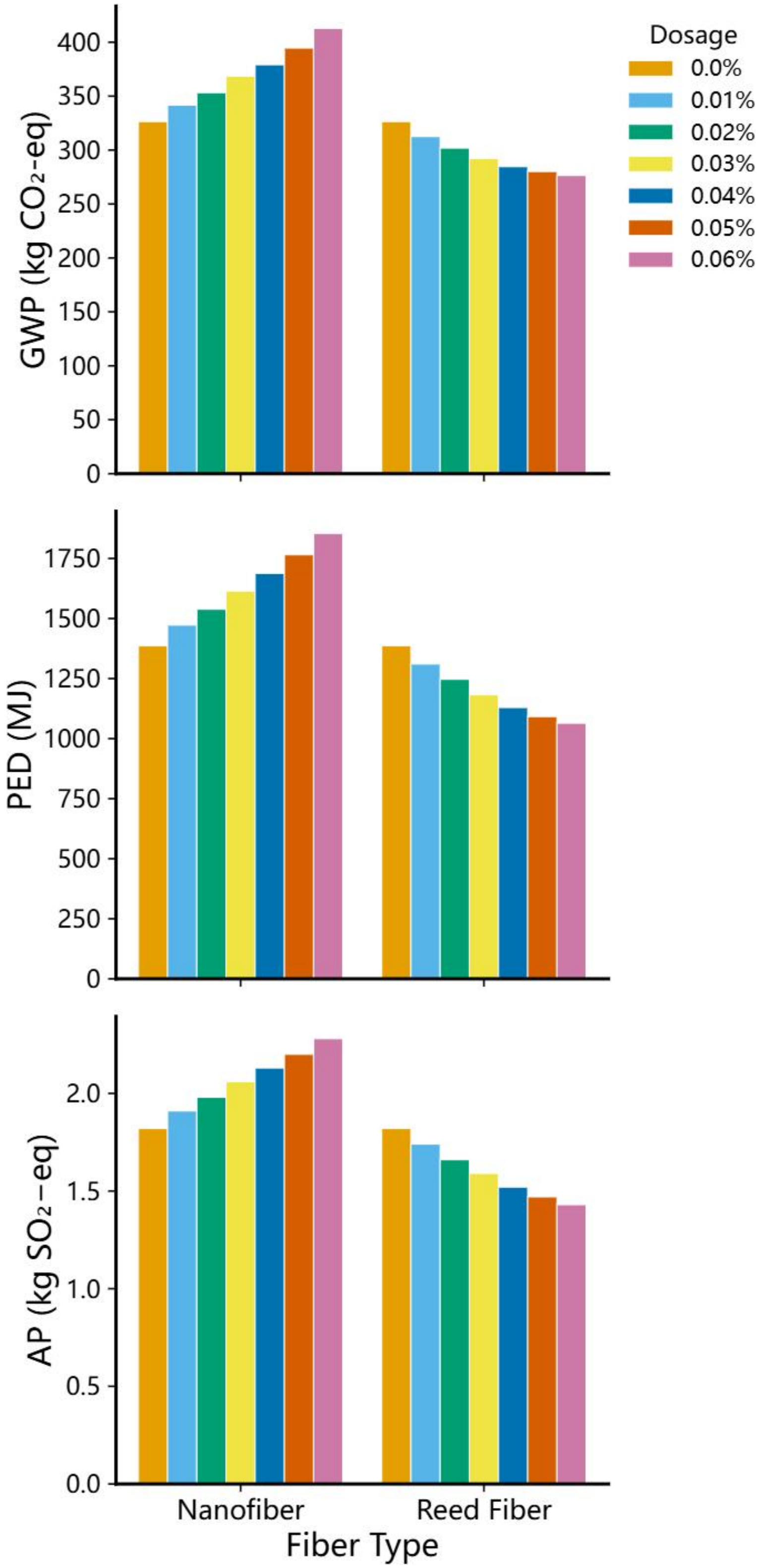

Fig. 1. Figure 1: Carbon Emission Maps for Three Single Environmental Indicators: GWP, PED, and AP

Table 4. Table 4 Environmental Impact Indicators of Concrete LCA with Different Fiber Content

Sample number	Fiber content	Sample type	GWP (kg CO_2-eq)	PED (MJ)	AP(kg SO_2−eq)
Ref	0%	Standard ordinary concrete	326.4	1386.2	1.82
N1/R1	1%	Nanofiber/Reed Fiber Concrete	341.7/312.5	1472.6/1310.4	1.91/1.74
N2/R2	2%	Nanofiber/Reed Fiber Concrete	353.2/301.8	1538.5/1246.7	1.98/1.66
N3/R3	3%	Nanofiber/Reed Fiber Concrete	368.5/292.3	1614.3/1182.5	2.06/1.59
N4/R4	4%	Nanofiber/Reed Fiber Concrete	379.1/284.6	1687.9/1129.3	2.13/1.52
N5/R5	5%	Nanofiber/Reed Fiber Concrete	394.6/280.1	1765.2/1091.6	2.20/1.47
N6/R6	6%	Nanofiber/Reed Fiber Concrete	412.8/276.4	1853.7/1064.2	2.28/1.43

Relying solely on LCA environmental indicators is insufficient to fully assess the comprehensive value of the two types of fiber-reinforced concrete. A combined analysis of mechanical tests and durability data is necessary, as detailed in Figure 1. 4% nanofiber concrete exhibits a greater increase in compressive and tensile strength, and demonstrates superior resistance to carbonation, sulfate attack, and fatigue durability. It is suitable for engineering scenarios with stringent requirements for load-bearing capacity and long-term service stability, such as bridges and underground corrosion structures. However, its high raw material production costs and relatively high carbon emissions and energy consumption throughout its lifecycle present both environmental and economic constraints for large-scale promotion. At the same 4% dosage, reed fiber concrete shows a slightly lower increase in mechanical properties than the nanofiber system, and a minor difference in durability. However, its advantages, including being renewable, readily available locally, having low environmental impact, and providing thermal insulation and energy savings, make it highly suitable for low-carbon green projects such as Belarusian civilian insulation walls and low-rise rural buildings. Although the 6% reed fiber sample exhibits the best environmental indicators, its mechanical strength shows a significant decrease at this dosage. Therefore, 4% is determined to be the optimal ratio balancing mechanical performance and low-carbon benefits. Overall, reed fiber concrete has significant advantages in terms of sustainability and low carbon emissions. The core advantages of nanofiber concrete are concentrated in mechanical and durability properties. Engineering materials can be selected differently based on structural load, service environment, and low carbon construction goals.

CONCLUSION

This paper systematically completed mechanical tests, durability comparisons, and LCA environmental quantitative evaluations of concrete modified with carbon nanofibers and reed fibers at dosages of 0%–6%. The following conclusions were drawn: Both types of fibers effectively improve the tensile and compressive properties of concrete, with carbon nanofibers showing superior overall reinforcement compared to reed fibers. A 4% dosage is the optimal ratio for both types of fibers. In terms of durability, carbon nanofibers, with their high specific surface area optimizing the cement interface transition zone, exhibit stronger resistance to wet-dry cycles, sulfate attack, carbonation, and fatigue, resulting in better long-term service stability. Reed fiber concrete shows limited durability improvement, but its advantages in recyclability, low cost, and thermal insulation are significant. LCA results indicate that reed fibers can fix CO_2 during their growth stage, and the corrected GWP is significantly lower than that of carbon nanofiber concrete, resulting in a substantial reduction in primary energy consumption and greater environmental friendliness. However, the production process of carbon nanofibers is complex, leading to higher raw material energy consumption and carbon emissions. Engineering selection should consider both performance and low-carbon requirements: carbon nanofiber concrete is recommended for heavy-duty, highly corrosive, and long-life structures; alkali-modified reed fiber concrete should be given priority for rural residential buildings, thermal insulation and energy-saving walls, and low-carbon green building material to local resources in Belarus, and can provide theoretical and experimental basis for optimizing green concrete mix proportions and promoting low-carbon buildings.

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