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Normal-Weight Concrete with Improved Stress–Strain Characteristics Reinforced with Dispersed Coconut Fibers

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Abstract: According to the sustainable development concept, it is necessary to solve the issue of replacing fiber from synthetic materials with natural, environmentally friendly, and cheap-to-manufacture renewable resources and agricultural waste. Concrete is the primary material for which fibers are intended. Therefore, the use of vegetable waste in concrete is an essential and urgent task. Coconut fiber has attracted attention in this matter, which is a by-product of the processing of coconuts and makes it relevant. This work aims to investigate the experimental base for the strength properties of dispersed fiber-reinforced concrete with coconut fibers, as well as the influence of the fiber percentage on the mechanical, physical, and deformation characteristics. The samples were made of concrete with a compressive strength at 28 days from 40 to 50 MPa. The main mechanical characteristics such as strength in compression (cubic and prismatic) and tension (axial and bending), as well as the material's compressive and tensile strains, were investigated. The percentage of reinforcement with coconut fibers was taken in the range of 0% to 2.5% with an increment of 0.25 wt.%. Tests were carried out 28 days after the manufacture. The microstructure of the resulting compositions was investigating using the electron microscopy method. The most rational percentage of coconut fibers was obtained at 1.75%. The increase in mechanical indicators was 24% and 26% for compression and axial compression, respectively, and 42% and 43% for tensile bending and axial tension, respectively. The ultimate strains in compression were raised by 46% and in tension by 51%. The elastic modulus was increased by 16%.

Keywords: concrete; fiber-reinforced concrete; sustainable concrete; natural fibers; coconut fiber

1. Introduction

Current construction is rapidly developing the world economy, but at the same time it carries several problems that engineers and scientists must solve. One of these problems is the environmental pollution that occurs in the world from the construction process and construction production. One of the concrete features, as well as its main disadvantage, is its low tensile strength compared to its high compressive strength. To compensate for this shortcoming, building structures are provided with bar reinforcement, which perceives the main tensile loads and prevents the reinforced concrete structure from collapsing. However, bar reinforcement does not practically influence the microstructure of the concrete matrix, in which many microcracks are formed already at the stage of hardening and shrinkage, which inevitably begin to develop during load application. Restraining the development of microcracks significantly increases the strength characteristics (SC) of the concrete itself as a material [1,2].

Traditionally, fiber-reinforced concrete (FRC) structures contain steel, polypropylene, cellulose fibers [3–11], and others. The use of fiber reinforcement made of coarse basalt fibers has a certain popularity [10]. Recently, the popularity of the use of glass and carbon fiber dispersed reinforcement of concrete (FDRC) has been growing [12]. The above materials have high tensile strength and other properties that have rightfully made them traditionally used materials for FDRC. However, their significant common disadvantages are their high cost and the need for production processes associated with high emissions of greenhouse gases into the atmosphere. Additionally, the obtained SC of FRC with fiber reinforcement from classic materials are often much higher than required for the normal operation of a particular FRC structure, and the cost of FRC in this case may not correspond to the required characteristics [1,2,8,10]. The above reveals the environmental and economic problem of FRC, which can be solved by using fibers that do not require separate production, which are a rapidly renewable natural material, or that are waste from the agricultural industry [13,14]. Thus, primary attention for the creation of environmentally friendly and relatively inexpensive FRC is attracted by natural fibers that do not require energy-intensive and environmentally unsafe production. The raw materials for such fibers are obtained by mechanical processing of plant parts, their cleaning, and drying. At the same time, plant fibers are often a by-product or waste of agriculture, and their use as a FDRC is one of the ways to obtain relatively waste-free agricultural processes, which corresponds to the concept of sustainable development [15–24]. The advantages of such fibers for dispersed fiber reinforcement of concrete are high tensile strength that meets the requirements of modern construction, low cost, no need for energy-intensive production with high CO_2 emissions into the atmosphere, renewability, low waste production, and relative safety for humans and animals. Several studies were carried out [18,22], during which it was found that the addition of various types of plant fibers to concrete improved its strength properties and affected its deformation properties, making the destruction "smooth" instead of brittle such as ordinary concrete. It was revealed that the addition of the listed types of plant fibers in an amount up to 2 % *vol.* of concrete increased the SC in direct proportion to the percentage of fiber reinforcement, and when this value was exceeded, an inverse relationship was observed [18,22].

Coconut fiber, which is a by-product of coconut processing, has attracted special attention in this regard. The structure of the coconut palm fruit is shown in Figure 1.

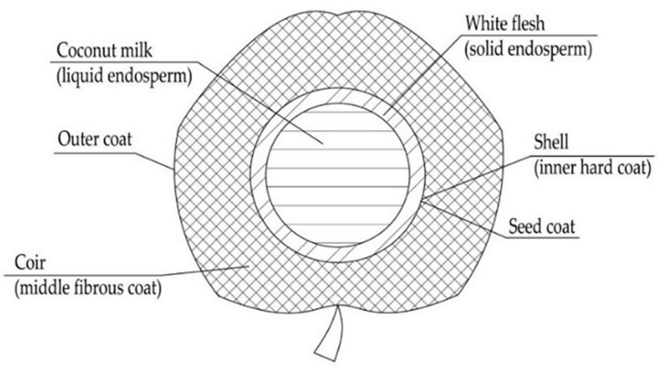


Figure 1. Schematic of the fruit of the coconut palm.

Coconut fiber (coir) is originally a part of the fruit of the coconut palm, namely, the fibrous shell surrounding the endocarp (the so-called coconut), which protects the seed from overheating and provides buoyancy to the fruit [25–27]. Coir is obtained from mature fruits of the coconut palm and contains a large amount of lignin, due to which it does not rot and has high strength and elasticity [28–30]. It consists of lignin (45.77%), cellulose (43.24%), water-soluble components (5.22%), pectin (3.30%), ash elements (2.22%), and hemicellulose (0.25%) [31–33]. The schematic of coconut fiber is shown in Figure 2.

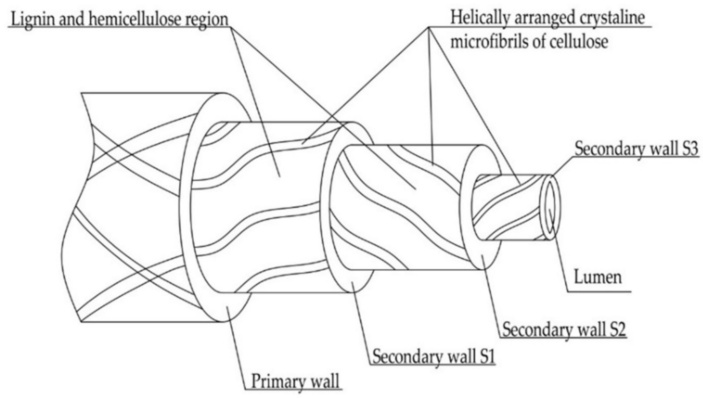


Figure 2. Schematic of coconut fiber.

Coconut fiber consists of four layers: the main and three inner walls surrounding the cavity in the center. The wall mainly consists of lignin and cellulose, which are the main components of coconut fiber, which are arranged in a helical pattern with different angles of inclination to the fiber axis [34–37]. The study [38] investigated the properties of concrete with the inclusion of coconut shells and coconut fibers. The water absorption of concrete, the volume of permeable pore voids, the permeability of chloride ions, and the sorption capacity and resistance at elevated temperature were studied. The samples were cured under three different conditions: full immersion in water, curing under normal conditions, and curing at low humidity. The samples tested for temperature resistance hardened only under conditions of immersion in water. The study showed that the SC of conventional concrete with dispersed coconut fiber reinforcement were better when cured under water immersion conditions, and the performance of concrete with the addition of coconut shell was higher when cured under normal conditions. Temperature resistance tests have shown that all the studied compositions have the required minimum characteristics and are safe for construction [38,39]. The study [40] considered the impact of the length of coconut fibers and the percentage of their content in concrete on high-strength concrete properties. Coconut fibers had a positive effect on the strength in compression and tension, flexural strength, and deformability of high-strength concrete compared to a similar composition without coconut fibers. The optimal values for the length of coconut fibers and the percentage of fiber reinforcement for high-strength concretes, namely, 50 mm and 1.5% by weight of cement, respectively, have been identified. In [41], the possibilities of recycling industrial and agricultural wastes as additives in asphalt concrete and bitumen were studied. Additives in the form of coconut and sisal fibers substantially enhanced the mechanical properties of asphalt concrete and increased the elasticity modulus of the material. The study [29] is also part of the data on the efficient use of natural fibers in the form of coir and waste in construction. The addition of 1% and 1.5% coconut fiber, as well as 1.5% mineral wool to the mortar, led to an improvement in its flexural strength and an increase in durability [29]. Research [42] in the field of fiber-reinforced concrete with experiments, numerical modeling, and microstructure study once again confirmed that a high dosage of fiber can adversely affect the compressive strength, which can also lead to a change in the microstructure, an increase in pore volume, or non-large increases or decreases in bulk density. A very positive effect of the use of fiber was confirmed by experiments with reinforced concrete beams without transverse reinforcement, with tests performed for various spans and sections [42]. In some studies [43–49], the properties of concretes with coconut fiber as a dispersed reinforcement and various production wastes as coarse aggregates and additives were studied. According to the results of the research, it was revealed that construction waste in the form of crushed concrete can act as a partial substitution for coarse aggregate without losing the quality of concrete, and additives in the form of fly ash, coconut fibers, and other materials improve the deformation and strength properties [43–48] as well as the fresh and long-term properties [47] of such concrete. In [50], coconut fiber was added to the composite as a replacement for sand in the amount of 3%, 6%, 9%, and 12% by weight during mixing and curing. It was found that the composite reinforced with 9% coconut fiber showed the highest tensile strength and compressive strength [50]. In general, based on the studied literature and [51], the following disadvantages of using coconut fibers in concrete can be distinguished: susceptibility to shrinkage during drying or volume changes due to alternating wetting and drying of concrete, deterioration in the workability of concretes of normal strength, a decrease in density, and an increase in water absorption. The advantages of using coir are as follows: increasing the strength of concrete of normal strength at a fiber dosage of 0.5–1.5% and a length of 50 mm, increasing tensile and bending strength at a dosage of up to 2% coir, and improving the impact strength of concrete. In addition, the use of coconut chips increases the permeability of concrete, as well as the carbonization and permeability to chloride ions; the treatment of coconut fiber with alkali increases the roughness of the coir; and the protective coatings of latex and pozzolana help to preserve the properties of coconut fiber in the cement matrix [51].

The principal differences between coconut fibers and other types of fibers are:

(1) Their plant origin, that is, their classification as renewable resources;
(2) The low cost of concrete based on them, in view of their classification as plant and agricultural waste;
(3) The environmental friendliness of their production, in contrast to glass, basalt, and polymer fibers;
(4) The relatively high physical and mechanical characteristics in comparison with other types of fibers of plant origin;
(5) The sufficient prevalence and hence the wide geography of potential application;
(6) Good compatibility with other concrete components.

This article examines and develops the idea of environmentally friendly FRC. Accordingly, it is necessary to develop methods that make it possible to use their natural, cheap, environmentally friendly, and renewable counterparts as fiber dispersed reinforcement instead of artificial fibers [52–59].

This study aims for scientific novelty as follows: A rational dosage of fibrous coconut fiber was firstly determined as a component of a new material—FRC with improved characteristics. In terms of technological aspects, the parameters of the processes of introducing and mixing the components of fiber-reinforced concrete mixtures for improved concretes were first set. During the microstructure investigation, the fundamental processes of its formation, both controlled and uncontrolled, occurring during physical and chemical interactions, were first revealed.

For construction elements, the effective joint work of the cement matrix and coconut fiber as a composite system with improved structure and properties was first proven.

The main goal of this article was experimental research of the strength properties of FRC with coconut fibers, and the impact of fiber reinforced percentage on the SC and deformation characteristics of concrete. The main task was to obtain material with improved SC and lower cost, and in addition, more environmentally friendly and safe for humans and animals.

The scientific result was to obtain new dependencies for FRC with coconut fibers. The analysis was carried out, and the justification of the processes occurring at the microlevels at phase boundaries was given.

2. Materials and Methods

2.1. Materials

For purity of the experimental study, a careful approach to the choice of the initial components was formed. To establish the effect of the addition of coconut fibers most correctly, Portland cement grade CEM I 42.5N (CEM 42.5N – Portland cement type CEM I, strength class 42.5, normally hardening) (Novoroscement, Novorossiysk, Russia) was used as a binder in the manufacture of samples with the following main physical and mechanical characteristics (without additives): 335 m^2/kg; fineness of grinding (passage through a sieve No. 008)—25%; the beginning of setting—165 min; end of setting—230 min; tensile strength in bending at the age of 28 days—7.6 MPa; compressive strength at the age of 28 days—55.7 MPa. The mineralogical composition of Portland cement is presented in Table 1.

Table 1. Mineralogical composition of Portland cement.

Mineral	Content (%)
C_3S	67
C_2S	15
C_3A	7
C_4AF	11

The applied quartz sand (Arkhipovsky quarry, Arkhipovskoye village, Russia) had the following main characteristics: bulk density—1478 kg/m^3; true density—2675 kg/m^3; content of dust and clay particles—1.1%; clay content in lumps—0.11%; organic impurities were absent. The characteristics of the grain composition of sand are presented in Table 2.

Table 2. Grain composition and modulus of sand size.

Residues on Sieves (%)	Sieves Diameter (mm)						Size Modulus
	2.5	1.25	0.63	0.315	0.16	<0.16	
Partial	1.28	1.28	10.51	45.04	39.74	2.15	1.73
Full	1.28	2.56	13.07	58.11	97.85		

Coarse aggregate in the form of crushed granite ("Pavlovsknerud", Pavlovsk, Russia) had the following properties: size—5–10 mm; bulk density—1487 kg/m^3; true density—2650 kg/m^3; crushability—11.6 % *wt*.; the presence of lamellar and acicular grains—9.1%.

Coconut fiber (Auriki Gardens, Yaroslavl, Russia) was used as a fiber-dispersed reinforcement. The characteristics of coconut fiber and its appearance are presented in Table 3 and Figure 3, respectively.

(**a**) (**b**)

Figure 3. Appearance of coconut fiber: (**a**) ready for use; (**b**) dry mix.

Table 3. Characteristics of coconut fiber.

Name of Indicator	Actual Value
Diameter (µm)	21 ± 1.1
Titer (Tex, g/km)	30 ± 1.3
Length of fiber (mm)	30 ± 2
Density (kg/m^3)	1200
Porosity (%)	32–35
Cellulose content (%)	32–43
Lignin content (%)	41–45
Crystallinity (%)	27–33
Tensile strength (MPa)	175 ± 8.2
Ultimate strain (%)	3.6 ± 0.2
Elasticity modulus (GPa)	22.0 ± 0.2
Relative fiber strength (cN/Tex)	15.3 ± 0.6
Angle of orientation (°)	30–49

2.2. Methods

When conducting scientific research, relying on the existing regulatory and technical base containing testing and research methods was crucial. As a concrete sample, concrete of the Russian class B30 was chosen, corresponding to SC in the range from 40 to 50 MPa. The workability grade was P1 (cone draft 1–4 cm, determined according to GOST 10181 "Concrete mixtures. Methods of testing"). A metal cone for determining the flowability of concrete was "filled with a concrete mixture through a funnel in three layers of the same height on a smooth sheet" [59]. The concrete mix was rodded 25 times, tightly pressing the cone to the sheet. Next, the loading funnel was removed, the excess mixture was cut off, and the surface was smoothed. The time for filling and removing the cone was no more than 3 min. The rise of the cone lasted 5–7 s. The draft of the cone was determined twice. The error was no more than 0.5 cm. The total test time did not exceed 10 min [60]. The process of determining the workability of a concrete mixture is shown in Figure 4.

(**a**) (**b**)

Figure 4. Testing the concrete mix for workability: (**a**) filling and bayoneting the mix in a cone; (**b**) slump measurement.

The calculations of the concrete composition parameter were based on GOST 27006 "Concretes. Rules for mix proposing". The selection of the concrete composition was carried out according to the following steps:

- Selection and characterization of raw materials for concrete;
- Calculation of the initial basic composition;
- Calculation of initial additional compositions of concrete;
- Production of experimental batches from the initial and additional compositions:
  (a) Taking samples for testing the concrete mixture and making control samples;
  (b) Concrete testing to determine standardized quality parameters;
  (c) Processing of the results obtained with the establishment of dependencies reflecting the influence of the parameters of the concrete composition on the standardized quality indicators;
  (d) Designation of the nominal composition of concrete, ensuring the receipt of a concrete mixture and concrete of the required quality [61].

The parameters of the concrete composition obtained in this way, the method of preparing the concrete mixture, the curing of the samples, and subsequent tests were carried out based on verified methods, confirmed by a large amount of experimental and regulatory data. The parameters of the composition are presented in Table 4.

Table 4. Composition of the concrete mixture.

Name	Cement (kg/m^3)	Water (L/m^3)	Crushed Stone (kg/m^3)	Sand (kg/m^3)	ρ_{cm} (kg/m^3)
Value	375	210	1028	701	2314

The composition of the concrete mixture is the following ratio of components: C:W:S:CS = 1:0.56:1.87:2.74.

The concrete components were mixed using a BL-10 laboratory concrete mixer (ZZBO, Zlatoust, Russia). The components were loaded in this order: fine aggregate, then Portland cement, then water. Coconut fiber was introduced into a homogenized mixture of binder solution and fine aggregate. The resulting mixture was stirred for 3 min, and then the coarse aggregate was loaded. The resulting concrete mixture was mixed until homogeneous. The mixture was vibrated on an SMZh-539-220A unit (IMash, Armavir, Russia). Vibration was carried out for 60 s. Samples were tested by the following test equipment:

- Hydraulic press IP-1000 (TEKHMASH, Neftekamsk, Russia);
- R-50 tensile testing machine (IMash, Armavir, Russia);
- Metal measuring ruler 500 mm (Stavropol Tool Plant, Stavropol, Russia);
- Laboratory scales HT-5000 (Gosmetr, St. Petersburg, Russia);
- Caliper ShTs-I-250-0.05 (Chelyabinsk Tool Plant, Chelyabinsk, Russia);
- A device for measuring deviations from the plane NPL-1 and a device for measuring deviations from perpendicularity NPR-1 ("RNPO "RusPribor", St. Petersburg, Russia).

Sample manufacture consisted of the following steps:

(1) Dosing of the initial components of concrete using VLTE-2100 scales (NPP Gosmetr, St. Petersburg, Russia) with an accuracy of 0.05 g;
(2) Loading of the components into a concrete mixer in the following sequence: water, cement, sand, crushed stone, coconut fibers;
(3) Mixing of the components until a mixture of a homogeneous consistency was obtained;
(4) Molding of FRC samples—The homogenized mixture was poured into molds, compacted by vibration, and then its surface was leveled in the molds;
(5) Hardening of the samples—The samples were in the molds for 1 day in a hardening chamber (RNPO RusPribor, St. Petersburg, Russia), then demolding was carried out. The samples were removed from the molds, and then they were again placed in the chamber and hardened there again for 27 days;
(6) Testing of samples: for compression, for flexural strength by GOST 10180 "Concretes. Methods for strength determination using reference specimens" [62], for axial com-

pression according to GOST 24452 "Concretes. Methods of prismatic, compressive strength, modulus of elasticity, and Poisson's ratio determination" [63].

(7) Concrete strength estimating following GOST 18105-2018 "Concretes. Rules for control and assessment of strength" [64]

Detailed test procedures from these standards are described in [59].

Electron microscopy was used to study the dispersity and morphology of the samples. "The structure of samples with coconut fiber was studied using a ZEISS CrossBeam 340 electron microscope (Carl Zeiss Microscopy GmbH (Factory), Jena, Germany)" [58].

The experimental program scheme is presented in Figure 5. A photo of test samples is shown in Figure 6.

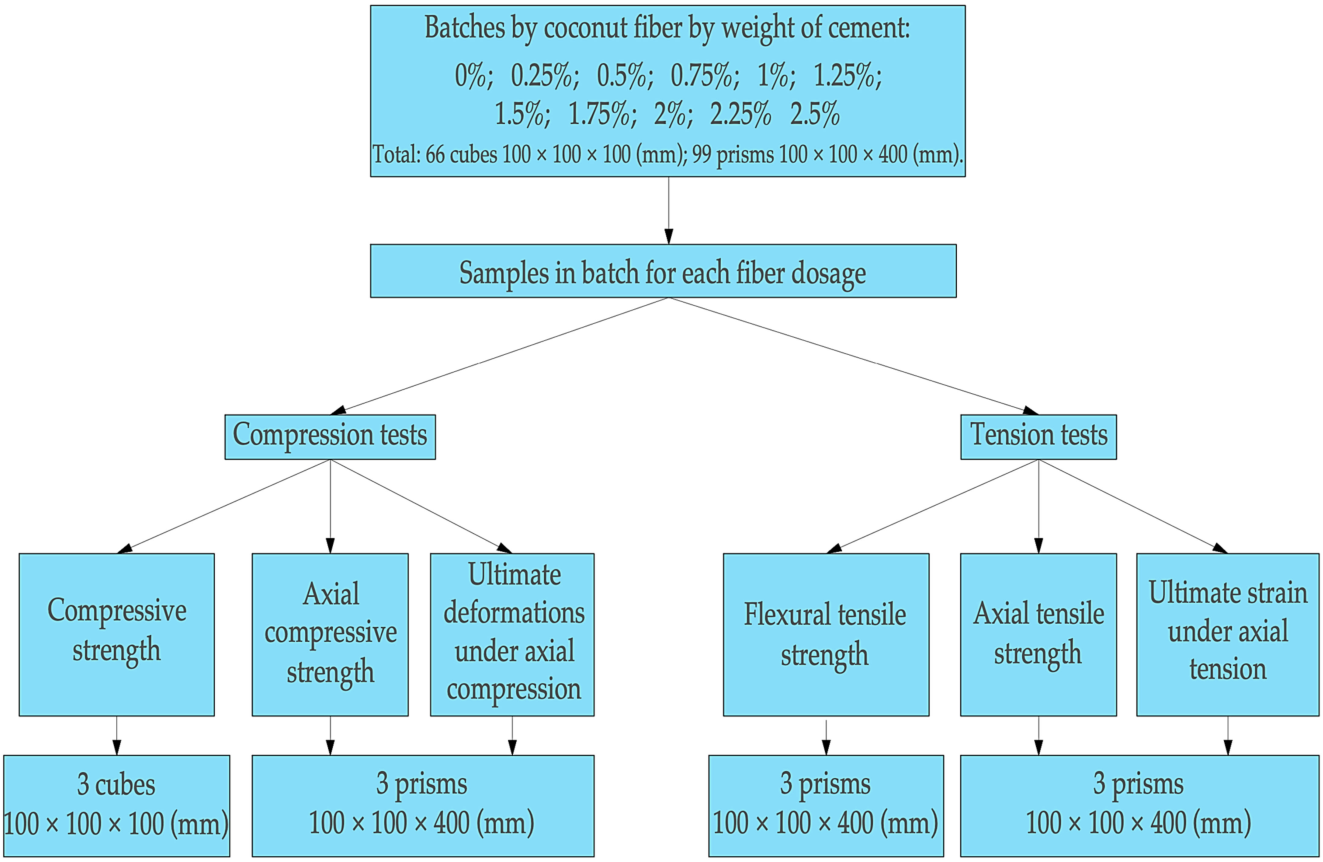


Figure 5. The scheme of the experiment for the effect of dispersed reinforcement with coconut fibers on the strength and deformation properties of concrete.

(**a**) (**b**)

Figure 6. Test specimens: (**a**) cubes; (**b**) prisms.

3. Results and Discussion

3.1. The Influence of Various Percentages of FDRC with Coconut Fibers on the Strength and Strain Characteristics

Figures 7–10 illustrate the influence of the percentage of FDRC with coconut fibers on the SC.

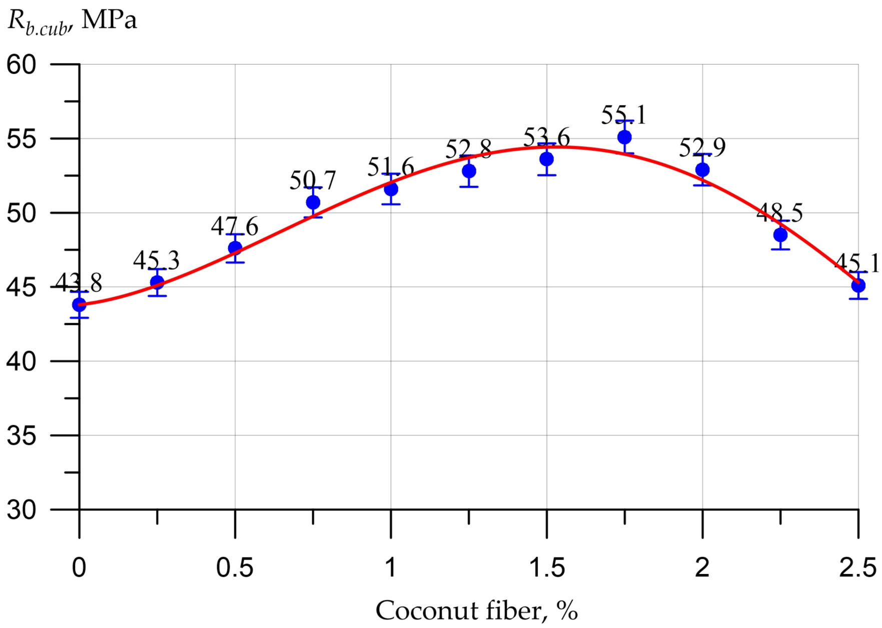


Figure 7. Dependence of the compressive strength ($R_{b.cub}$) of cube concrete samples with a face of 100 mm on the percentage of dispersed reinforcement with coconut fibers.

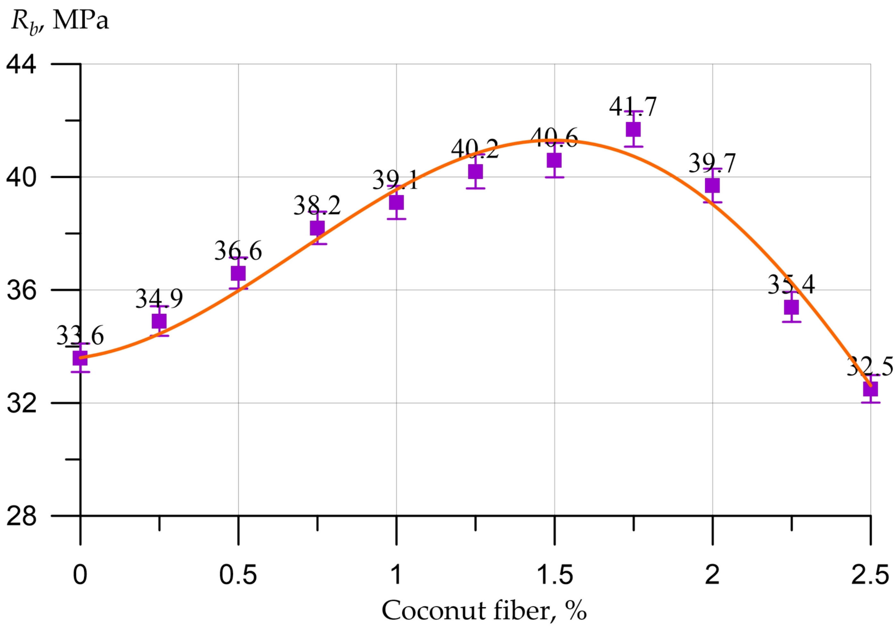


Figure 8. Dependence of the axial compressive strength (R_b) of prism concrete samples with dimensions of 100 × 100 × 400 (mm) on the percentage of coconut fibers.

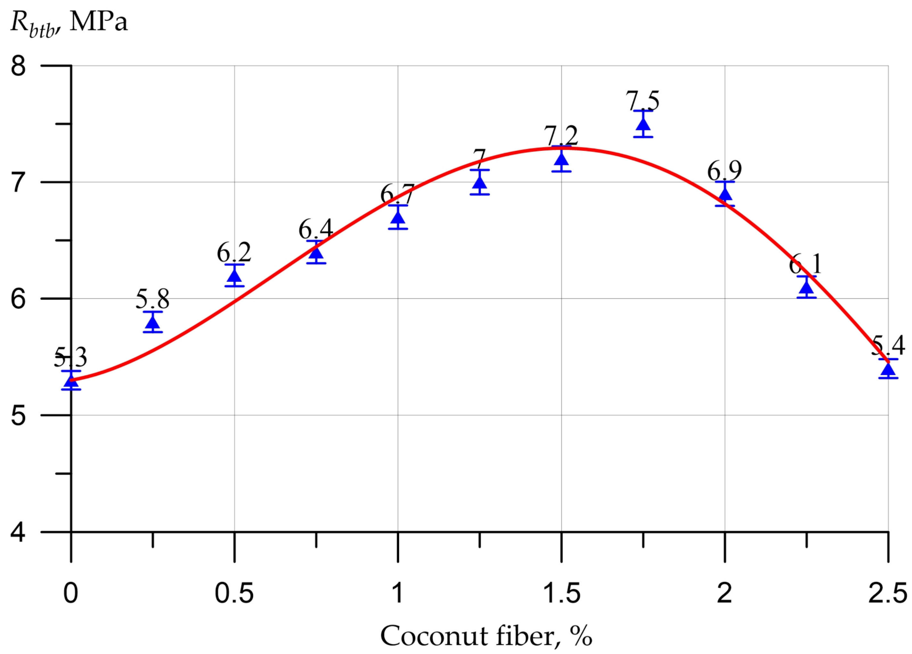


Figure 9. Dependence of tensile strength in bending (R_{btb}) of prism concrete samples with dimensions of 100 × 100 × 400 (mm) on the percentage of coconut fibers.

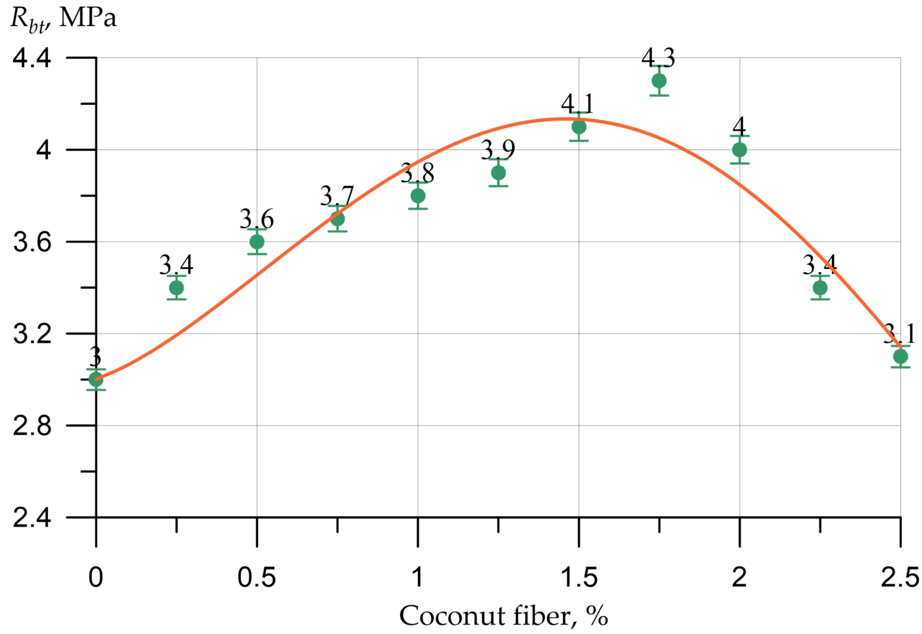


Figure 10. Dependence of the axial tensile strength (R_{bt}) of prism concrete samples with dimensions of 100 × 100 × 400 (mm) on the percentage of dispersed reinforcement with coconut fibers.

Figure 5 shows that at a dosage of coconut fibers from 0.25% to 1%, a gradual increase in compressive strength from 43.8 MPa to 51.6 MPa was observed, in the range from 1% to 1.5%, and the increase in compressive strength was already less intense, namely, from 51.5 MPa up to 53.6 MPa. At a dosage of coconut fibers of 1.75% by weight of cement, a peak was observed—the maximum value of compressive strength, equal to 55.1 MPa. However, with a further increase in the percentage of fibers from 2% to 2.5%, the strength began to decrease up to a value approximately equal to the strength of the control composition (without fibers).

Figure 8 shows the most intense increase in axial compressive strength at a dosage of coconut fibers from 0% to 0.75% and then continues slightly less intensively with a peak at around 1.75%; at dosages from 2% to 2.5%, axial compressive strength was similar to compressive strength decreases.

Figures 9 and 10 demonstrate that the flexible strength and axial tensile strength curves were similar, and the maximum values, as in the case axial compression, were fixed at a dosage of coconut fibers of 1.75% by weight of cement.

Figures 11–13 show the results of a study of dispersed coconut fibers on the concrete strain characteristics.

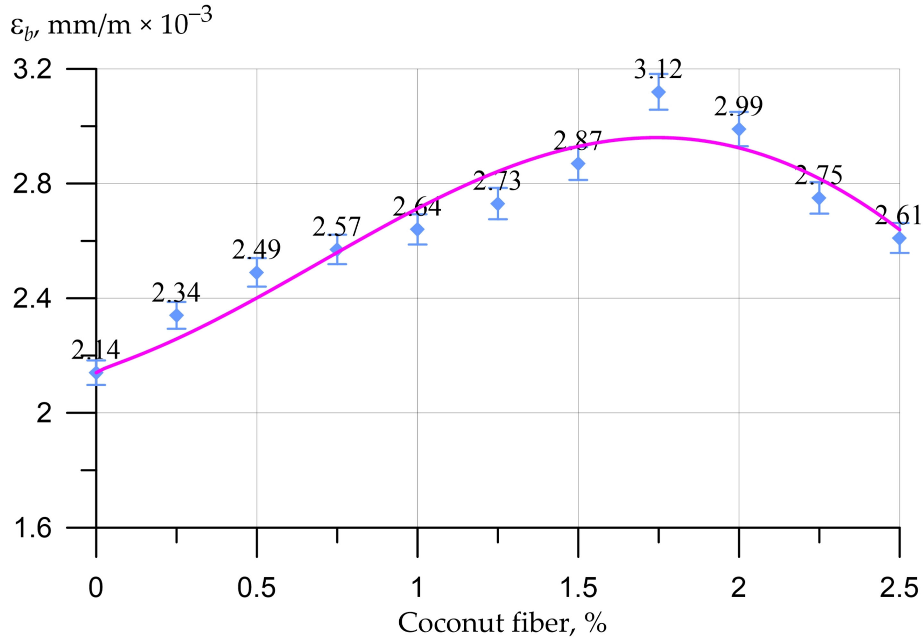


Figure 11. Dependence of the limiting deformations in axial compression (ε_b) of prism concrete samples with dimensions of 100 × 100 × 400 (mm) on the percentage of dispersed reinforcement with coconut fibers.

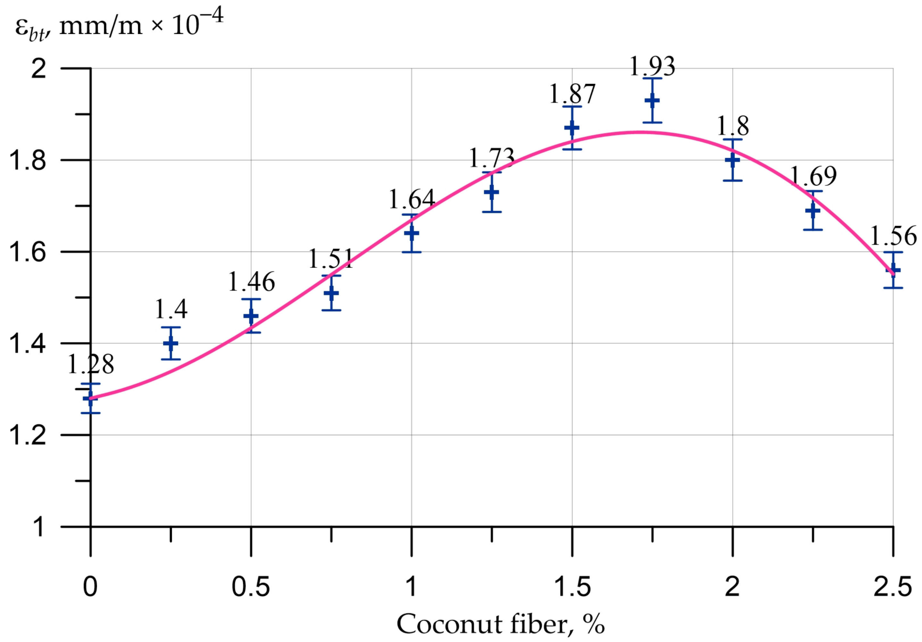


Figure 12. Dependence of the limiting deformations in axial tension (ε_{bt}) of prism concrete samples with dimensions of 100 × 100 × 400 (mm) on the percentage of dispersed reinforcement with coconut fibers.

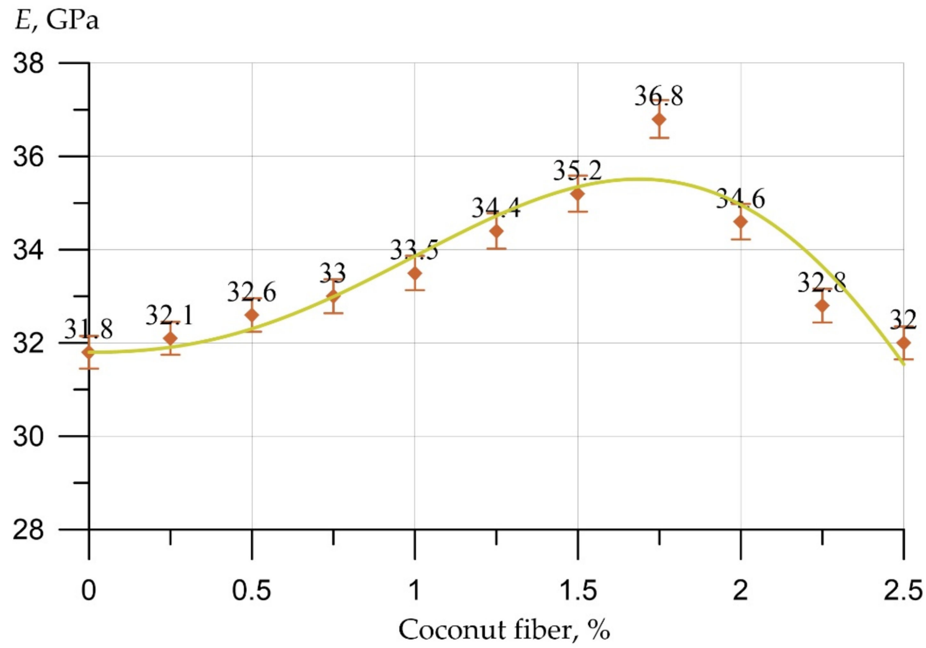


Figure 13. Dependence of the modulus of elasticity of concrete samples (E) on the percentage of dispersed reinforcement with coconut fibers.

Figures 11 and 12 show that the nature of the change in breaking strains in axial compression and axial tension depending on the percentage of fiber reinforcement was similar to the behavior of SC. The maximum values of compressive and tensile strains were observed with coconut fiber of 1.75 % *wt*.

Figure 13 illustrates that a more significant increase in the elastic modulus was observed at a percentage of dispersed reinforcement with coconut fiber from 1.25% to 1.75%; the maximum value of the elastic modulus was recorded at a dosage of 1.75% and amounted to 36.8 GPa, and at a fiber dosage of 2% it dropped to 34.6. In general, in the range from 0% to 1.75%, a stable increase in the elastic modulus was observed, the values of which, respectively, ranged from 31.8 GPa to 35.2 GPa.

The relations of SC of concrete on the content of coconut fiber were approximated by the "saturation" function (1), which has shown itself well [59] in problems of analyzing the properties of concrete in the structural modification of mortar with additives of various types [53,58]

$$Y = C_0 + Ax^b(\sin \omega x + \varphi) \tag{1}$$

Here Y is the mechanical property, C_0, A, b, ω, φ are constants, and x is coconut content.

The saturation function (1) has specific physical meaning as follows: Coefficient C_0 shows the value of the corresponding characteristic without an additive. The second component consists of two factors. The first, the power function, is responsible for the growth of properties regarding the content of the additive x. The second factor shows the degradation of properties when the additive becomes too much, and it begins to play a negative role.

Figures 7–13 show that the mechanical characteristics of concrete are well described by function (1) with high coefficients of determination.

$$R_{b.cube} = 43.8 + 8.72 \times x^{0.577} \times \sin(1.2x + 0.04),\ R^2 = 0.969 \tag{2}$$

$$R_b = 33.6 + 6.095 \times x^{0.79} \times \sin(1.24x + 0.12),\ R^2 = 0.962 \tag{3}$$

$$R_{btb} = 5.3 + 1.655 \times x^{0.567} \times \sin(1.218x + 0.04),\ R^2 = 0.945 \tag{4}$$

$$R_{bt} = 3.0 + 1.0 \times x^{0.40} \times \sin(1.20x + 0.044),\ R^2 = 0.876 \tag{5}$$

$$\varepsilon_b = 2.14 + 0.60 \times x^{0.715} \times \sin(0.95x + 0.32),\ R^2 = 0.918 \quad (6)$$

$$\varepsilon_{bt} = 1.28 + 0.41 \times x^{0.822} \times \sin(1.05x + 0.20),\ R^2 = 0.965 \quad (7)$$

$$E = 31.8 + 2.14 \times x^{1.405} \times \sin(1.25x + 0.05),\ R^2 = 0.883 \quad (8)$$

From Figures 7–13 and Equations (2)–(8), it can be seen that the concrete strength in compression with the optimal percentage of coconut fiber of 1.75% compared to ordinary concrete was 26% higher. The axial compressive strength became larger by 24%, tensile strength and flexible strength increased by 42%, and axial tensile strength increased by 43%.

Thus, samples with a reinforcement percentage of 1.75% demonstrated the highest SC. An increase in the reinforcement proportion more than 1.75% up to 2.5% led to the opposite trend, that is, to a decrease in strength indicators. This may occur due to the formation of voids in concrete due to an excessive amount of fibers, "an increase in the water demand of the concrete mixture, which is consistent with studies" [5,36].

The effect of the proportion of FDRC with coconut fibers on SC and strain characteristics of concrete prototypes are shown in Table 5 and are presented as proportions compared to the control composition, that is, ordinary concrete without fibers.

Table 5. Influence of the percentage of FDRC with coconut fibers on the strength and deformation characteristics of concrete samples (Δ).

Concrete Characteristics	**Δ (%), Depending on the Content of Coconut Fibers (%)**										
	0	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2**	**2.25**	**2.5**
$R_{b.cub}$ (MPa)	0	3.4	8.7	15.8	17.8	20.5	22.4	25.8	20.8	10.7	3.0
R_b (MPa)	0	3.9	8.9	13.7	16.4	19.6	20.8	24.1	18.2	5.4	−3.3
R_{btb} (MPa)	0	9.4	17.0	20.8	26.4	32.1	35.8	41.5	30.2	15.1	1.9
R_{bt} (MPa)	0	13.3	20.0	23.3	26.7	30.0	33.3	43.3	33.3	13.3	3.3
ε_{bR} (mm/m × 10^{-3})	0	9.3	16.4	20.1	23.4	27.6	34.1	45.8	39.7	28.5	22.0
ε_{btR} (mm/m × 10^{-4})	0	9.4	14.1	18.0	28.1	35.2	46.1	50.8	40.6	32.0	21.9
E_b (GPa)	0	0.9	2.5	3.8	5.3	8.2	10.7	15.7	8.8	3.1	0.6

During the analysis of the concrete mechanical characteristics, dispersed reinforcement with coconut fiber constructed several dependencies on the impact of the amount of FDRC on its strength properties, the results were compared with those obtained on the control composition, which had a significant influence on the concrete SC, not only of the fiber reinforcement itself with coconut fibers, but also of its quantity in relation to the mass of cement. It was found that an increase in the SC of concrete along with the higher percentage of fiber reinforcement was observed until the point of 1.75% fiber amount. Thus, it was determined that dispersed reinforcement with coconut fibers in an amount of 1.75% by weight of the binder made it possible to obtain a higher SC of FRC and was optimal.

The "stress–strain" curves in compression "ε_b-σ_b" and in tension "ε_{bt}-σ_{bt}", constructed from the results of determining the strength and deformation characteristics of the test concrete, are shown in Figures 14 and 15.

The stress–strain curves of concrete obtained by dispersed reinforcement with coconut fibers demonstrated that coconut fibers significantly affected the deformability. The maximum of the "stress–strain" curves of FDRC in the amount of 1.75 % *wt*. of cement is above and to the right in the diagrams of concrete with other considered dosages of coconut fiber, and the peak of the curve of concrete deformation with the amount of fiber 2.5 % *wt*. almost coincides with the peak diagrams of concrete with the amount of fiber 0.25% and 0.5%, or slightly below and to the right of them.

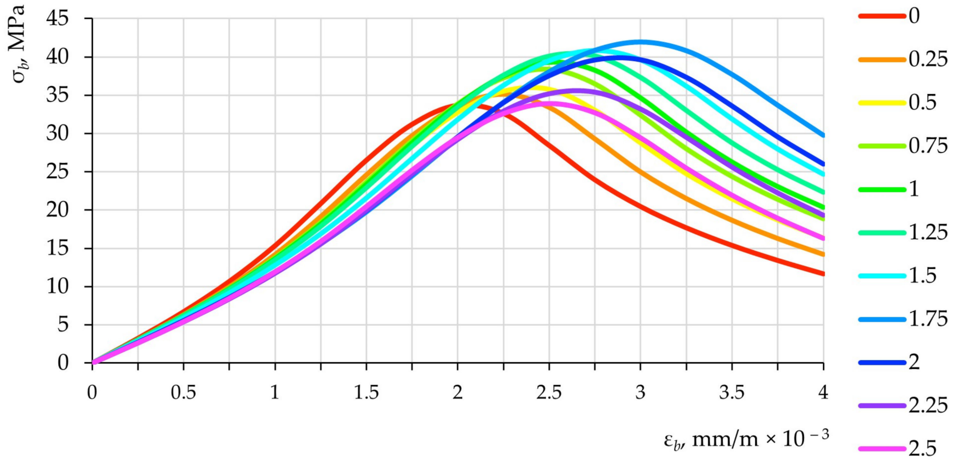


Figure 14. Stress–strain curves in compression.

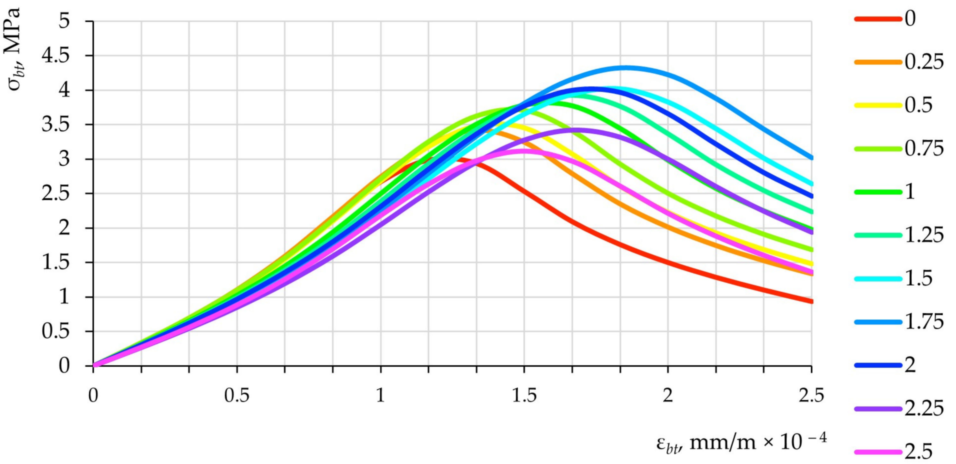
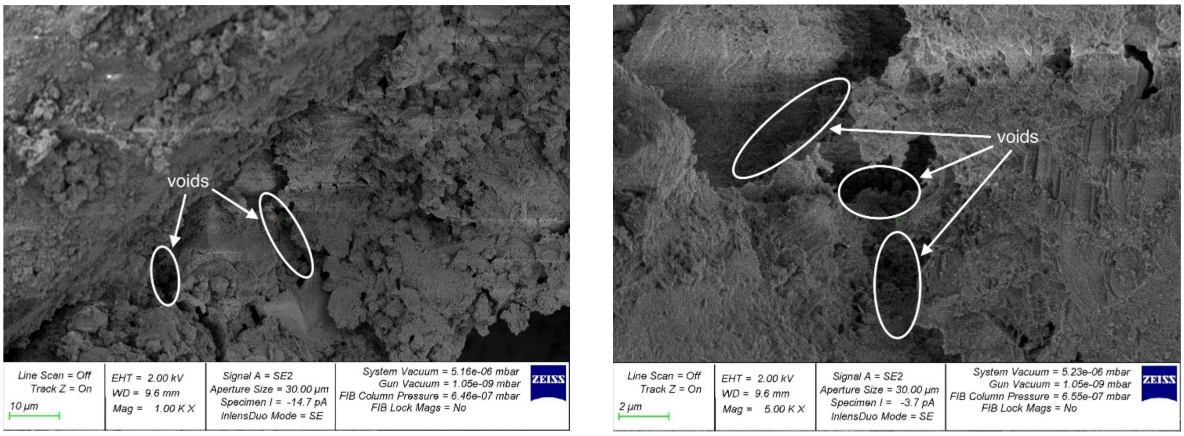


Figure 15. Stress–strain curves in tension.

The established dependencies and identified characteristic relationships between the initial factors and output parameters proved the high efficiency of dispersed coconut fibers in the composition of concrete. The next task was to analyze the microstructure of the hardened cement paste of concrete, dispersedly reinforced with coconut fibers, to analyze it at the micro level after evaluating the effectiveness of such reinforcement at the macro level.

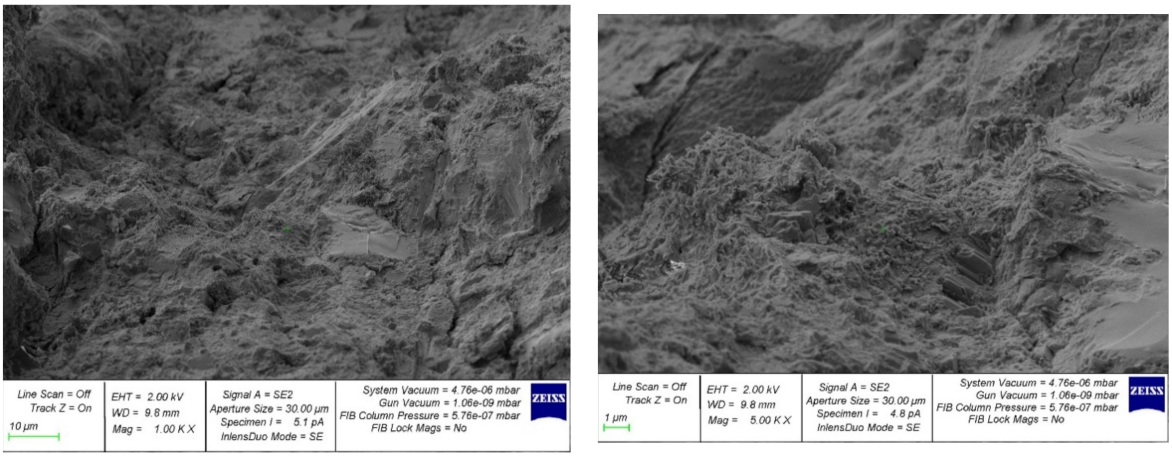
3.2. Study of the Microstructure of Hardened Cement Paste, Dispersion-Reinforced with Coconut Fibers

Microstructural changes in cement paste, dispersion-reinforced with coconut fibers, were investigated to find the relationship between the concrete structure and its SC. Figures 16–18 show the microstructure photos of the hardened cement paste of the control composition and with coconut fibers in amounts of 1.75 % *wt*. and 2 % *wt*.



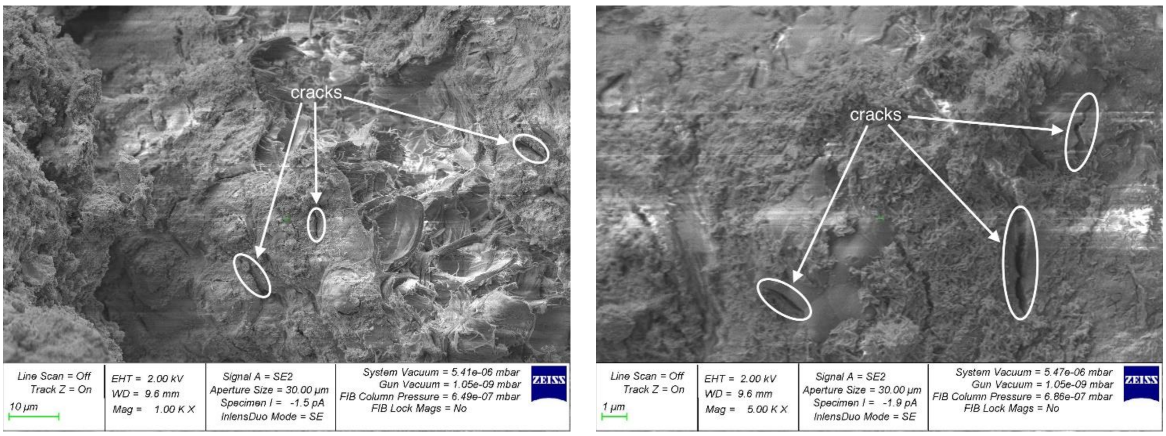
(**a**) (**b**)

Figure 16. Photographs of the microstructure of a sample of the hardened cement paste of the control composition: (**a**) 1000×; (**b**) 5000×.



(**a**) (**b**)

Figure 17. Photographs of the microstructure of a sample of hardened cement paste with dispersed reinforcement with coconut fibers in an amount of 1.75% by weight of cement: (**a**) 1000×; (**b**) 5000×.



(**a**) (**b**)

Figure 18. Photographs of the microstructure of a sample of hardened cement paste with dispersed reinforcement with coconut fibers in an amount of 2%: (**a**) 1000×; (**b**) 5000×.

Figure 16 demonstrates the microstructural changes in the control composition after collapse. The structure was loose and had many voids. Figures 17 and 18 demonstrate that coir particulate reinforcement shortened the number of microcracks in the microstructure of the hardened cement paste. They restrained the stack propagation and, thanks to the bridging effect created by the fiber, bound the concrete matrix. The microstructure of hardened cement paste samples with a percentage of fiber reinforcement of 1.75% was the densest, practically not containing structural defects in the form of voids and cracks (Figure 17). However, at a dosage of coconut fiber in an amount of 2%, due to their high water absorption, cracking was observed at the phase boundaries, which reduced the anchoring of the fiber in concrete (Figure 18). Figure 18 deserves special attention, since this area illustrates the nature of microcracking at the interfaces of the phases "coconut fiber—cement–sand matrix". By the nature of this microcracking, good compatibility of coconut fiber with the mineral matrix was visible. SEM analysis thus proved the expediency of dispersed reinforcement of cement systems with coconut fiber at the microstructural level.

Thus, at the micro level, in the course of studying the structure formation of concretes reinforced with coconut fiber, it was established that the proper quality of the structure was maintained, the degree of cracking at the interface was low, and the fibers were well compatible with cement paste and other concrete components. Microstructural studies also confirmed the effectiveness of concrete reinforcement with dispersed fibers.

In view of the formation of the concrete structure at the micro and macro levels, under the condition of a uniform distribution of coconut fibers in the mixture, a rational concentration of crystallization centers occurred throughout the entire volume of the composite. Good chemical compatibility of coconut fibers with hydration products and a high degree of mechanical anchoring of the fibers in the cement–sand matrix contributed to the high final strength characteristics of concrete and the expansion of its serviceability.

Compared with the results of other authors, we achieved high values of the SC of concrete reinforced with coconut fibers. In [5], the authors achieved an increase in the axial tensile strength of concrete up to 30.63% due to the FDRC with coconut fibers. The technology we used and composition recommendations gave an increase in the axial tensile strength of concrete up to 43%. In [43], the authors managed to obtain an increase in tensile strength in bending up to 45% by adding coconut fibers and recycled filler from 16% to 45%. In our study, by using only coconut fibers, it was possible to achieve an increase in the tensile strength in bending of concrete up to 42%, which approximately corresponded to the increase achieved in [43]. The augmentation of compressive strength up to 26% exceeded the gains achieved in [45], namely, 12%. The effective dosage of coconut fibers obtained in the current study was in good agreement with the work, systematizing many similar investigations [51]. At the same time, it was possible to achieve the maximum improvement not only in the compressive strength of concrete but also in tensile strength. In a study [65], coconut fiber was used in foam concrete to improve its compressive strength, flexural strength, and splitting tensile strength. The test results showed that all three studied types of foam concrete strengths increased as the volume percentage of coconut coir fibers in the concrete mixture increased from 0% to 0.4%, while the best performance was observed at a fiber dosage of 0.4% [65]. In [29], a dosage of coconut fiber of the order of 1.5% turned out to be effective, which is consistent with the rational dosages selected in the current study. Thus, this comparative analysis also confirms the effectiveness of the study.

From the point of view of analytics, we worked out all the dependencies on the components of the FRC mixture. The study was evaluated from the point of view of chemical, physical, and mathematical aspects. Thus, the research work, described in this article, is a study aimed at obtaining new fundamentals and, at the same time, at the development of existing ideas about FRC, dispersed-reinforced with coconut fibers. With all this, the study allows us to solve a significant task, not only for the construction industry, but also for the agricultural sector, which is directly interested in the disposal of production waste, which determines the practical significance of the work.

4. Conclusions

The main achievements of the study are as follows.

(1) The optimal percentage of fiber reinforcement of concrete with coconut fibers was determined, which was 1.75%.
(2) The enhancement in the concrete properties due to its dispersed reinforcement with coconut fibers was expressed as an augmentation in its SC. The increase in the strength parameters of the obtained FRC samples was for compressive strength—26%, for axial compressive strength—24%, for tensile strength in bending—42%, and for axial tensile strength—43%.
(3) The increase in strain characteristics was 46% for deformation under axial compression, 51% for deformation under axial tension, and 16% for the modulus of elasticity.
(4) The microstructure of hardened cement paste samples with a percentage of fiber reinforcement of 1.75% was the densest, practically not containing structural defects in the form of voids and cracks. At a dosage of coconut fiber in an amount of 2%, due to their high water absorption, cracking was observed at the phase boundaries, which reduced the anchoring of the fiber in concrete.
(5) A significant advantage of the proposed recipe method and the material produced for the economy and ecology was noted, with a general increase in its SC compared to ordinary concrete.
(6) Recommendations for future research are to study the effect of coconut fiber on the physical properties of concrete, including the properties of long-term strength, as well as the co-inclusion of coir fiber and other industrial and agricultural waste in composites.
(7) The resulting material should be used in individual and cottage housing construction. The high mechanical characteristics of concrete give rise to good predictions for the durability of such buildings.

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Abbreviations

C	cement
CS	crushed stone
FDRC	fiber dispersed reinforcement of concrete
FRC	fiber-reinforced concrete
S	sand
SC	strength characteristics
W	water

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