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Enhanced Performance of Concrete Dispersedly Reinforced with Sisal Fibers

Alexey N. Beskopylny [1,*], Sergey A. Stel'makh [2], Evgenii M. Shcherban' [3], Levon R. Mailyan [4], Besarion Meskhi [5], Alexandr A. Shilov [2], Nikita Beskopylny [6] and Andrei Chernil'nik [2]

1 Department of Transport Systems, Faculty of Roads and Transport Systems, Don State Technical University, 344003 Rostov-on-Don, Russia
2 Department of Unique Buildings and Constructions Engineering, Don State Technical University, Gagarin Sq. 1, 344003 Rostov-on-Don, Russia
3 Department of Engineering Geology, Bases, and Foundations, Don State Technical University, 344003 Rostov-on-Don, Russia
4 Department of Roads, Don State Technical University, 344003 Rostov-on-Don, Russia
5 Department of Life Safety and Environmental Protection, Faculty of Life Safety and Environmental Engineering, Don State Technical University, 344003 Rostov-on-Don, Russia
6 Department of Hardware and Software Engineering, Don State Technical University, Gagarin Sq. 1, 344003 Rostov-on-Don, Russia
* Correspondence: besk-an@yandex.ru; Tel.: +7-8632738454

Abstract: The fibers used in concrete are mainly materials that require additional production, which negatively affects their cost and environmental friendliness. Therefore, the issue of the effectiveness of the use of natural fibers, the extraction of which does not require mechanized production, becomes relevant. One of these materials is sisal fiber. The main purpose of this work was to study the effect of adding sisal fibers on the structure and properties of environmentally friendly concretes with improved characteristics. The tests were carried out in strict accordance with technological recommendations and normative and technical documents. Laboratory samples were made in the form of cubes and prisms of concrete with a compressive strength of 48 MPa and sisal fiber content of 0.25%, 0.5%, 0.75%, 1.0%, 1.25% and 1.5%. The tests were carried out at a concrete age of 15 days. The compressive strength and tensile strength of concrete samples were studied using the method of optical microscopy. The optimal content of fiber reinforcement with sisal fiber was determined as equal to 1%. The increases in the strength characteristics of the obtained fiber-reinforced concrete samples at the optimal dosage of sisal fiber in an amount of 1% by weight of cement were 22% for compressive strength, 27% for axial compressive strength, 33% for tensile strength in bending and 29% for axial strength stretching. The increases in deformation characteristics were 25% for strains in axial compression, 42% for strains in axial tension and 15% for the elastic modulus.

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

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1. Introduction

1.1. Background

Compared to ordinary concrete, fiber-reinforced concretes have significantly higher tensile strength, deformability, increased compressive strength and durability, as well as the ability to perceive alternating loads and dynamic impact without destruction [1–3]. Ordinary concrete initially has in its structure many microcracks formed during concrete hardening, which develop when a load is applied, causing its low tensile strength [3–5]. The addition of even small fibers to concrete, which would be evenly distributed in the concrete matrix and chaotically oriented, significantly reduces the formation of microcracks during concrete hardening and reduces shrinkage, with a general increase in the strength of the material. Fibers inhibit the development of cracks and hold the concrete matrix even after cracking. Traditionally, steel, basalt, polypropylene and cellulose fibers are used as fiber-dispersed reinforcement of concrete. Fiber reinforcement of concrete with glass and carbon fibers is also quite popular. Despite the outstanding tensile strength characteristics of steel, basalt and synthetic fibers, most of them require separate production and processing, often requiring high energy costs and significantly increasing the cost of construction, which, in the end, does not always justify the obtained characteristics of concrete, and they also have a negative impact on the environment due to massive emissions of greenhouse gases. It can be confidently stated that construction requires significant amounts of non-renewable materials. Thus, the actual problem of modern construction is the search for natural alternatives to steel and synthetic fibers currently used as fiber reinforcement [6–11].

Natural fibers are a topical environmentally friendly and economical material for improving the properties of fiber-reinforced concrete, while at the same time improving the environmental situation through the disposal of waste of natural origin. The advantages of such fibers are low cost, no need for mechanized production and synthesis, renewability, lack of waste, absence of environmental pollutants, safety for humans and animals, as well as strength characteristics sufficient to cover the needs of modern construction [12–17]. The main "components of such fibers are cellulose, hemicellulose, lignin, pectin, wax and water-soluble substances" [18–20]. Several studies [12,13,21,22] were aimed at studying the properties of ordinary concrete with the addition of various types of natural fibers, namely, jute, hemp, pineapple and banana fibers. The results of these studies showed that the addition of natural fibers up to 1% of the volume of concrete improved its compressive strength. A restraining effect on failure was also noted, whereby the failure itself became less brittle as the percentage of fiber reinforcement was increased. The compressive strength of the samples increased with an increase in the amount of fibers up to 2%; however, a decrease in strength was noted at higher reinforcement percentages. Sisal fiber attracts a lot of attention among natural fibers. "It is a coarse natural fiber obtained from the leaves of the Agave sisalana plant" [23–31]. The structure of sisal fiber is shown in Figure 1.

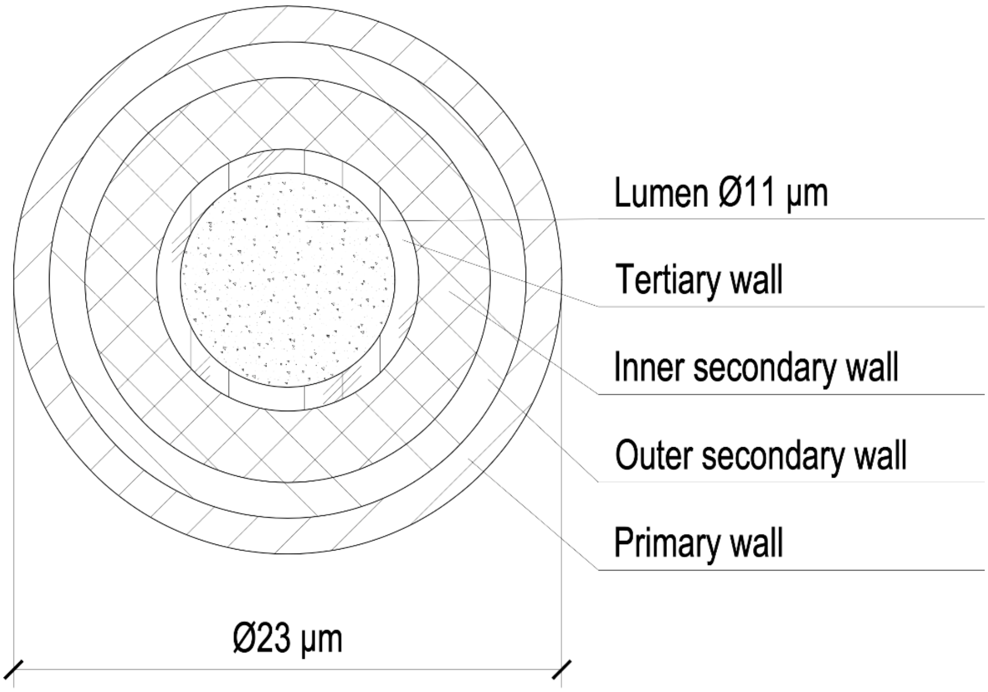

Figure 1. Sisal fiber structure.

The fibers are extracted from the leaves of Agave sisalana through a process of decortication, which involves the mechanical grinding of the leaves until only the coarse fibers remain. Next, the fibers are thoroughly washed and separated, after which the fiber is dried, undergoes a final brushing and is packed for sale. The microstructure of the sisal fiber consists of separate rings with a diameter of 6–30 µm. The fiber consists of cellulose (55–66%), hemicellulose (12–17%), lignin (7–14%), pectin (1%) and ash (1–7%).

In works [32,33], a study was carried out on the properties of sisal fiber for use in fiber-reinforced concrete. Water absorption, chloride ion permeation resistance and impact strength of samples were studied. It has been established that fiber-reinforced concrete with dispersed reinforcement in the form of sisal fibers has improved characteristics compared to conventional concrete, which determines the relevance of using sisal fiber in fiber-reinforced concrete. Studies have shown [34–37] that the use of sisal fibers as a fiber reinforcement of concrete is a suitable alternative, from the point of view of economy and environmental friendliness, to the materials traditionally used as dispersed reinforcement. When compared with conventional concrete, a significant increase in strength characteristics was noted. The relevance of the use of sisal fiber for use in cement composites of finishing materials and decorative elements of buildings and structures is emphasized. The use of sisal fiber in high-strength concretes [38] did not give a significant increase in strength characteristics but changed the form of fracture from brittle to smooth. Fibrous dispersed reinforcement with sisal fibers can provide the same level of increase in strength characteristics as polypropylene fiber, but only when taking into account the equivalence of dosages of each type of fiber [39]. Sisal fibers have greater water absorption than polypropylene fibers, which can lead to the formation of microcracks and a decrease in strength over the area of contact of the cement slurry with sisal fiber. Moreover, the addition of sisal fibers to concrete reduces the fluidity of the latter due to the additional surface area of the fibers, which takes water from the concrete for wetting [40–46].

To predict the assessment of the mechanical properties of fiber-reinforced concrete with cellulose fibers, several micromechanical models are used [47–49]. They are mainly used to predict the effective mechanical properties of fiber-reinforced concrete as a composite material with a well-defined arrangement of fibers. These models can be divided into phenomenological models, which are based on the rule of mixtures: semi-empirical models that use as a basis the mixture rule modified by correcting factors (the Halpin–Tsai model [50] and the Chamis model [51]), the elastic approximation model (the Hashin–Rosen model [52], the Christensen model [53]) and homogenization models (Mori–Tanaka model [54], double inclusion model [55], bridge model [56–59]).

1.2. Rationale

Our research develops the concept of sustainable fiber concrete, which involves replacing the fiber reinforcement of artificial fibers with natural, completely renewable sisal fiber, which does not require mechanized production and does not lead to an increase in CO_2 emissions into the atmosphere, but only requires high water usage. The main purpose of this work was to study the effect of adding sisal fibers on the structure and properties of environmentally friendly concretes with improved characteristics. The scientific novelty of the work lies in obtaining new dependencies for fiber-reinforced concrete with dispersed reinforcement with natural fiber of specific strength classes of concrete used in mass construction. Previously, such dependencies were studied for concretes of a more specific, narrow purpose, so it was important to create an empirical base for the most common types of concretes, which include concretes with a strength of 40–50 MPa. For this, a theoretical and experimental verification of the compatibility of fiber-dispersed reinforcement of plant origin from sisal fibers with the mineral components of concrete (Portland cement, crushed stone, sand) was carried out. The main factors influencing the strength properties of the resulting composite materials were identified, and rational quantitative indicators were established to ensure their best characteristics. Their analytical, mathematical and structural–physical analysis and substantiation were carried out, necessary for understanding the processes occurring at the macro level in the contact zone of concrete and natural fibers of such composite materials. The dependences of the strength and deformation properties of fiber-reinforced concrete on their dispersed reinforcement with sisal fibers were revealed.

2. Materials and Methods

2.1. Materials

The main characteristics of the raw materials used for the manufacture of concrete mixtures in this study are presented in Table 1.

Table 1. Characteristics of raw materials.

Raw Materials' Characteristics	Real Value
Portland cement grade "PC 500 D0" (Novoroscement, Novorossiysk, Russia)	
Specific surface, m^2/kg	330
Normal density cement paste gotten after adding water, %	25
Fineness of grinding, passage through a sieve No. 008, %	95.7
Setting time, min - start - end	 165 230
Tensile strength in bending, MPa: - 2 days - 28 days	 4.6 7.6
Compressive strength, MPa: - 2 days - 28 days	 24.5 55.2
C_3S, %	67
C_2S, %	15
C_3A, %	7
C_4AF, %	11
Quartz sand (Arkhipovsky quarry, Arkhipovskoe, Russia)	
Size modulus	1.73
Bulk density, kg/m^3	1578
True density, kg/m^3	2675
Content of dust and clay particles, %	1.1
Clay content in lumps, %	0.15
Content of organic and contaminants	absent
Granite crushed stone (Pavlovsknerud, Pavlovsk, Russia) according to GOST 8269.0, "Mountainous rock road-metal and gravel, industrial waste products for construction works methods of physical and mechanical tests"	
Fraction size, mm	5–10
Bulk density, kg/m^3	1487
True density, g/cm^3	2.65
Crushability, % by weight	11.6
The content of grains of lamellar (flaky) and acicular forms, % by weight	9.1
Voidness, %	44

Sisal fiber (Fujian Dehua Baihe Arts Co. Ltd., Quanzhou, Fujian, China) was used as the fiber. The fiber was delivered in a ready-to-use form and did not require additional processing. The fibers were cut with a length of 30 ± 2 mm. The fiber was stored in a dry, ventilated room at an air temperature of +25 °C and a humidity of 65% for at least 48 h before use. The characteristics of the sisal fiber used in the study are presented in Table 2, and the appearance is in Figure 2.

Table 2. Characteristics of sisal fiber.

Indicator	Real Value
Fiber diameter (μm)	20 ± 1.2
Fiber titer (Tex, g/km)	21 ± 1.2
Fiber length (mm)	30 ± 2
Fiber length to diameter ratio	200–400
Fiber density (g/cm^3)	1.5
Porosity after cutting (%)	12–14
Cellulose content (%)	66–78
Lignin content (%)	8–11
Crystallinity (%)	68–70
Tensile strength (MPa)	381 ± 23.6
Ultimate strain at break (%)	2.45 ± 0.1
Modulus of elasticity (GPa)	28.5 ± 1.8
Relative fiber strength (cN/Tex)	17.7 ± 0.9
Orientation angle (°)	10–25

(a) (b) (c)

Figure 2. Appearance of the sisal fiber used: (**a**) in the package; (**b**) after cutting; (**c**) dry mix.

2.2. Methods

Samples were made in laboratory conditions from normal weight concrete with a strength of 40–50 MPa with a workability grade of P1 (cone draft 1–4 cm), which was determined according to GOST 10181, "Concrete mixtures. Methods of testing". The parameters of the composition of "the concrete mixture obtained as a result of the calculations" are shown in Table 3.

Table 3. Dosages of concrete mix components.

Parameter	PC, kg/m^3	Water, L/m^3	Crashed Stone, kg/m^3	Sand, kg/m^3	ρ_{cm}, kg/m^3
Parameter value	375	210	1028	701	2314

For the preparation and testing of concrete samples, the same equipment and measuring instruments were used as in [60–69].

The study of the structure of the samples reinforced with sisal fiber was performed using an MBS-10 microscope (Izmeritelnaya Tekhnika OOO, Moscow, Russia).

Heat and moisture treatment during the hardening of samples and the formation of the structure of the cement stone were carried out in the steaming chamber "KUP-1" (OOO "RNPO RusPribor", Chelyabinsk, Russia), with an isothermal holding temperature of 80 °C, according to the following mode:

- Rise in temperature—3 h;
- Isothermal exposure—6 h;
- Cooling in a closed chamber—15 h.

After heat and moisture treatment, the samples hardened in natural conditions for 14 days.

Samples were prepared as follows:

- Batching of concrete components was carried out on a "VLTE-2100" scale ("NPP Gosmetr", St. Petersburg, Russia) with an accuracy of 0.05 g;
- Then, the concrete components were loaded sequentially into the concrete mixer: first water, then Portland cement, sand and crushed stone, and then fiber;
- After loading the components into the concrete mixer, mixing was carried out until a homogenized mixture was obtained;
- After the preparation of the mixture, it was unloaded into metal molds of standard sizes (Figure 3) and then compacted on a laboratory vibration platform;
- Then, the samples in the molds for 1 day were placed in a chamber for heat and moisture treatment, after which they were removed from the molds and continued to gain strength in natural conditions for 14 days;
- Fifteen days after manufacture, the samples were destroyed on the "IP-1000" press (OOO "NPK TEKHMASH", Neftekamsk, Republic of Bashkortostan, Russia) and a tensile testing machine ("IMASH LLC", Armavir, Russia) in accordance with the requirements of GOST 10180, "Concretes. Methods for strength determination using reference specimens" [70], and GOST 24452, "Concretes. Methods of prismatic, compressive strength, modulus of elasticity and Poisson's ratio determination" [71].
- Control and evaluation of the strength of concrete were carried out in accordance with GOST 18105-2018, "Concretes. Rules for control and assessment of strength" [72].

In total, 6 series of samples were made and tested with different values of the percentage of fiber reinforcement with sisal fiber. The experimental research program is shown in Figure 3.

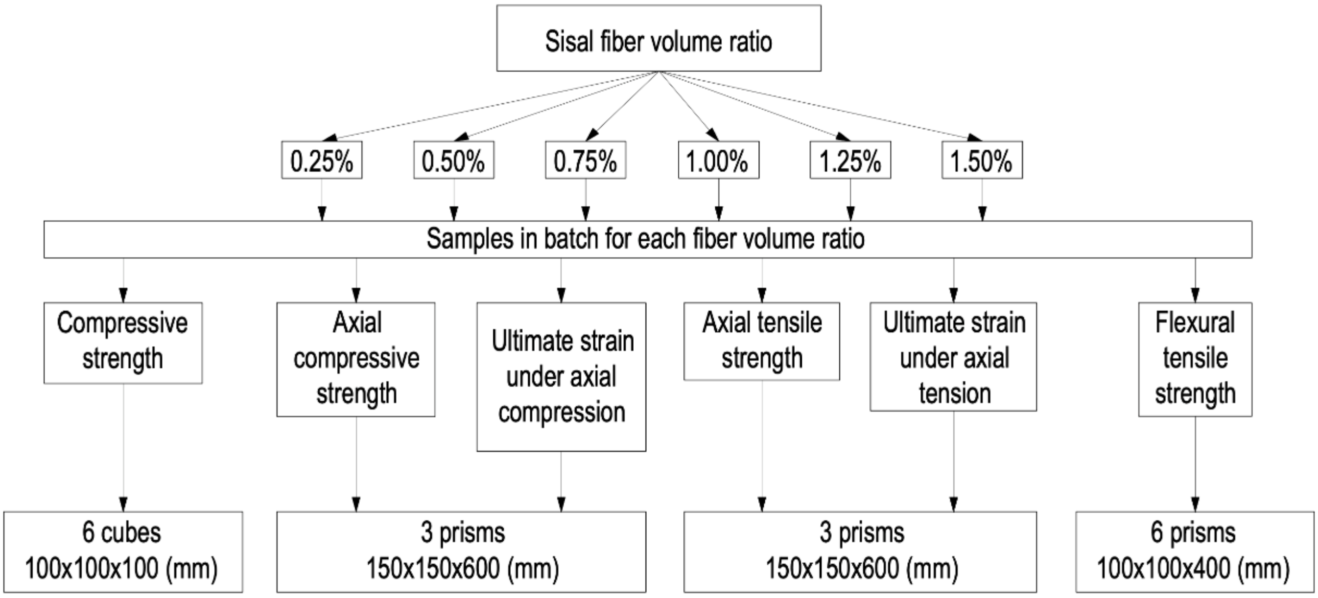

Figure 3. The program of experimental studies of the effect of dispersed fiber reinforcement with sisal fibers on the properties of concrete.

The axial tensile strength was determined as follows. The sample is fixed in a tensile machine according to one of the schemes given in Appendix K to GOST 10180 [70] and loaded to failure at a constant rate of load increase (0.05 ± 0.01) MPa/s. The test result is not taken into account if the destruction of the sample did not occur in the working area or the plane of destruction of the sample is inclined to its horizontal axis by more than 15°. The axial tensile strength of concrete R_t is calculated with an accuracy of 0.01 MPa according to the formula:

$$R_t = \beta \frac{F}{A} \quad (1)$$

where F is the breaking load, N; A is the area of the working section of the sample, mm^2; β is a scaling factor for converting the strength of concrete to the strength of concrete in samples of basic size and shape. The scale factor values were determined according to GOST 10180 [70]. The strength of concrete was determined as the arithmetic mean of the strength of the two samples with the highest strength tested in a series of three samples. The scheme of testing a sample to determine the axial tensile strength is shown in Figure 4.

Deformations under axial compression and axial tension were determined as follows. Strain gauges were used to measure strains with an accuracy of at least 1×10^{-5}. Tensiometers and indicators for strain measurement were installed on the sample using clamping devices in accordance with the fixed strain measurement base. On the side surfaces of the samples, central lines were placed for installing devices for testing deformations and centering the samples along the axis of the press. The bases for measuring the longitudinal and transverse deformations of the samples were marked along the central lines. The strain measurement base was 100 mm. The measurement base was located at the same distance from the ends of the samples. Instruments for measuring strains of specimens were installed along four of its faces. Devices for measuring transverse strains were installed in the middle of the height of the sample normally to the bases for measuring longitudinal strains. To fasten the indicators, fixtures in the form of steel frames were used, fixed on the sample with four stop screws, two on opposite sides of the sample. Preparation for testing was carried out, among other things, according to the scheme for installing devices for mounting indicators when measuring longitudinal and transverse deformations of the sample, presented in GOST 24452 [71].

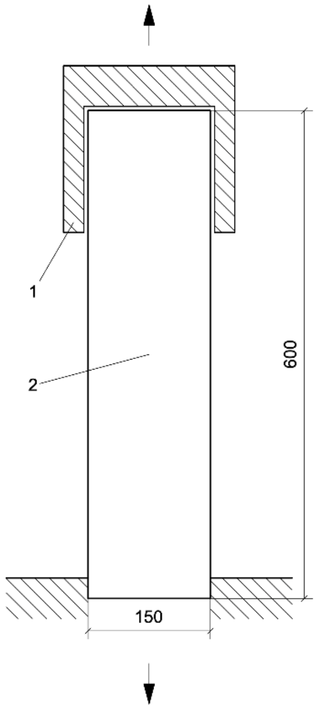

Figure 4. Scheme of testing a sample for determining the axial tensile strength: (1) active capture, (2) sample.

Before testing, the sample with the instruments was installed centrally according to the marking of the press plate, and the alignment of the initial reading with the scale division of the instrument was checked. The initial compression force of the sample, which was subsequently taken as conditional zero, should be no more than 2% of the expected ultimate load. The value of the expected ultimate load (P_{ult}) when testing the samples was set according to the data on the strength of concrete made from the same batch of sample cubes, determined in accordance with GOST 10180 [70]. Its value for the same sections of cubes and prisms should be taken from 80% to 90% of the average ultimate load of sample cubes. When centering the samples, it is necessary that at the beginning of the test from conditional zero to a load equal to (40 + 5%) P_{ult}, the deviations of deformations along each face (generating) do not exceed 15% of their arithmetic mean value. Loading of the sample to a load level equal to (40 + 5%) P_{ult} was carried out in steps equal to 10% of the expected ultimate load, maintaining the loading rate (0.6 ± 0.2) MPa/s during each step. At each stage, the load was held for 4 to 5 min and readings were recorded on the instruments at the beginning and the end of the stage holding. At a load level equal to (40 ± 5)% P_{ult}, the instruments were removed from the sample. After removing the instruments, further loading of the sample was carried out continuously at a constant rate in accordance with the requirement of GOST 10180 [70].

3. Results and Discussion

3.1. Study of the Effect of Dispersed Fiber Reinforcement with Sisal Fibers on the Physical, Mechanical and Deformation Characteristics of Normal Weight Concrete at Different Percentages of Fiber Reinforcement

To predict the mechanical properties of fiber-reinforced concrete with sisal fibers, the Halpin–Tsai model was used. The equations for this model are as follows:

$$K_c = K_m\left[\frac{1+\xi\,\zeta\,V_f}{1+\eta\,V_f}\right],\ \text{here}\ \eta = \left[\frac{\left(K_f/K_m\right)-1}{\left(K_f/K_m\right)+\zeta}\right] \quad (2)$$

where K_c represents effective mechanical properties of fiber-reinforced concrete; K_f and K_m are the mechanical properties of fiber and concrete, respectively; V_f is the volume of the fiber fraction; ζ is a geometric coefficient taking into account the loading conditions (uniaxial, biaxial, multiaxial).

The results of experimental studies of the effect of the percentage of fiber reinforcement with sisal fibers on the strength characteristics of concrete are shown in Figures 5–8.

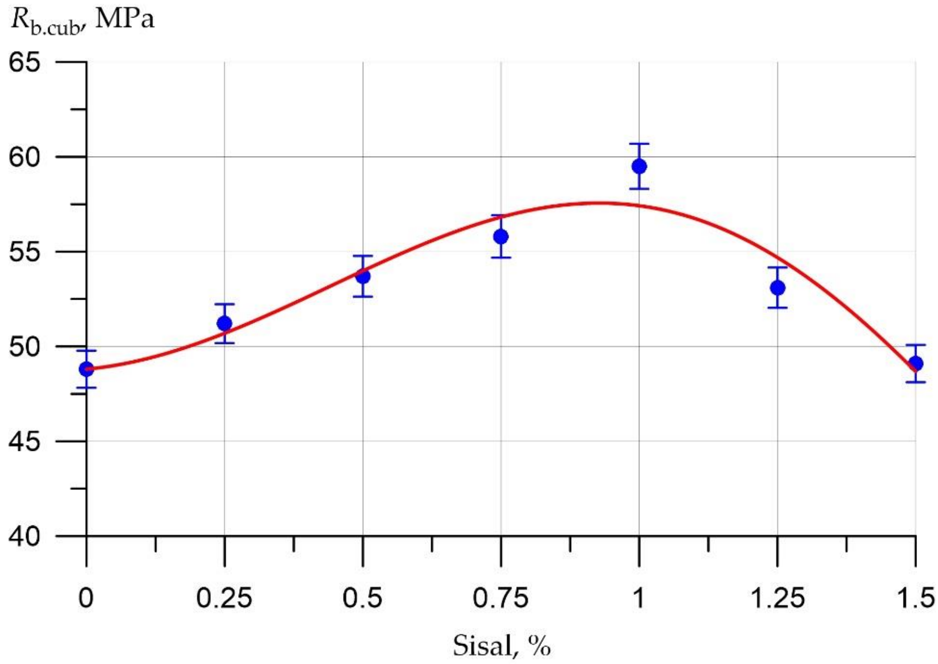

Figure 5. Results of experimental studies of the compressive strength $R_{b.cub}$ of concrete samples in the form of cubes with different percentages of reinforcement with sisal fibers.

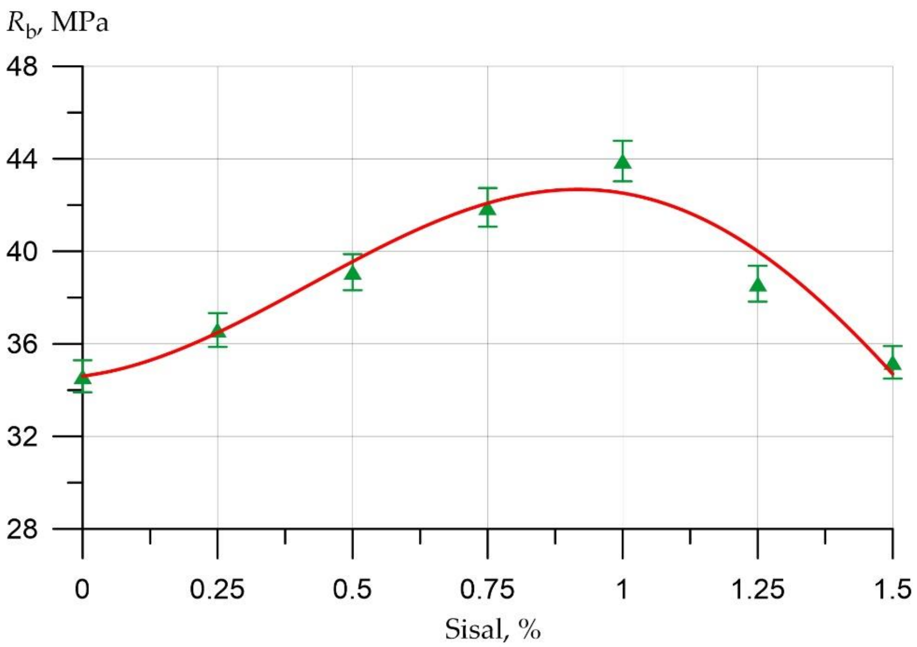

Figure 6. Results of experimental studies of the axial compressive strength R_b of concrete samples in the form of prisms with various percentages of reinforcement with sisal fibers.

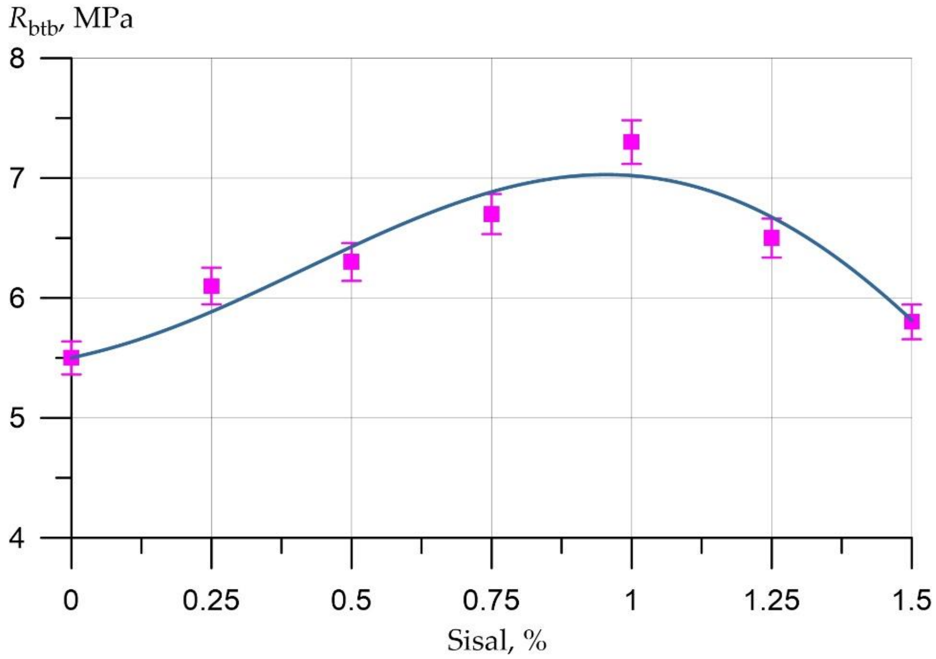

Figure 7. Results of experimental studies of tensile strength in bending R_{btb} of concrete samples in the form of prisms with various percentages of reinforcement with sisal fibers.

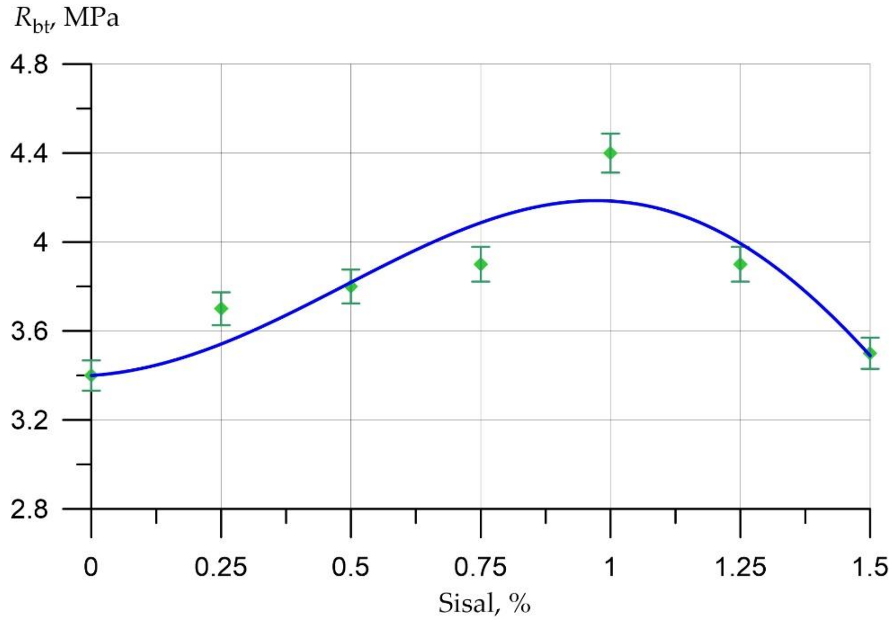

Figure 8. Results of experimental studies of the axial tensile strength R_{bt} of concrete samples in the form of prisms with various percentages of reinforcement with sisal fibers.

The graph in Figure 5 shows the compressive strength (R_b) of a sisal fiber-reinforced concrete as a function of the percentage of fiber reinforcement.

The effect of a sisal additive on the strength and deformation properties of concrete is described by the saturation function, which is suitable for assessing the effect of nano-modifying additives and demonstrates the best results in terms of the coefficient of determination, and also expresses the best physical meaning. Cubic strength is approximated by a formula with a coefficient of determination of 0.917.

$$R_{b.cube} = 48.8 + 10.302 \times x^{0.858} \times \sin(2.0\,x + 0.15),\ R^2 = 0.917 \quad (3)$$

where x is the amount of sisal, %.

Figure 6 shows the axial compressive strength R_b of concrete as a function of the percentage of sisal fiber reinforcement.

The axial compressive strength of test samples of concrete with different amounts of sisal fibers is described by a formula with a coefficient of determination of 0.966.

$$R_b = 34.6 + 9.335 \times x^{0.764} \times \sin(2.01\,x + 0.119), \quad R^2 = 0.966 \tag{4}$$

It can be seen that Equations (3) and (4) adequately reflect the ascending branch of the increase in strength and the descending branch of the decrease in strength from an excessively large number of sisal fibers.

Figures 5 and 6 show that samples with 1% sisal fibers by weight of cement showed the highest compressive strength. A further increase in the percentage of reinforcement led to the formation of voids in concrete, which reduced its compressive strength, which is consistent with the works of other researchers [11,16,19,22–28,30,31,33,35,39,41–43,45]. The results of the study of the compressive strength of samples showed that the compressive strength of samples with fiber dispersion reinforcement with sisal fibers at an optimal dosage of 1% compared with conventional concrete was 22% higher, and the axial compressive strength increased by 27%. The increase in compressive strength with an increase in the number of sisal fibers was followed by a decrease in performance with a further increase in sisal fibers due to the following reasons. Firstly, the introduction of additional fibers leads to a greater water demand of the concrete mixture. Accordingly, in order to close the specified mixture, a larger amount of water is required, and this, in turn, negatively affects the strength characteristics. In addition, the introduction of additional fibrous materials requires a larger amount of cement lubricant and binder matrix materials, while the dosage of cement, sand and water did not change. Therefore, excess fiber leads to the expected reduction in strength characteristics.

Figure 7 shows the flexural tensile strength R_{btb} of test concrete samples as a function of the percentage of sisal fiber reinforcement.

The results of experimental dependences of tensile strength in the bending of concrete samples in the form of prisms on a different amount of sisal fibers are described by a formula with a coefficient of determination of 0.948.

$$R_{btb} = 5.5 + 1.82 \times x^{0.912} \times \sin(1.74\,x + 0.412), \quad R^2 = 0.948 \tag{5}$$

Figure 8 shows the effect of the percentage of sisal fiber reinforcement on the axial tensile strength R_{bt} of test concrete samples.

The results of experimental relations of the axial tensile strength of concrete samples with various percentages of reinforcement with sisal fibers are described by a formula with a coefficient of determination of 0.901.

$$R_{bt} = 3.4 + 0.911 \times x^{0.978} \times \sin(1.943\,x + 0.161), \quad R^2 = 0.901 \tag{6}$$

The results of experimental studies of the tensile strength of samples showed that the maximum gains were recorded at a dosage of sisal fibers of 1%. Compared to conventional concrete, the flexural tensile strength of sisal fiber-reinforced concrete increased by 33% and the axial tensile strength increased by 29%.

Figures 9 and 10 show the effect of the percentage of sisal fiber reinforcement on ultimate strains in axial compression and tension of concrete.

The results of experimental relations of ultimate strains in axial compression of concrete samples at various percentages of reinforcement with sisal fibers are described by a formula with a coefficient of determination of 0.985.

$$\varepsilon_b = 2.07 + 0.559 \times x^{1.178} \times \sin(1.9\,x + 0.2), \quad R^2 = 0.985 \tag{7}$$

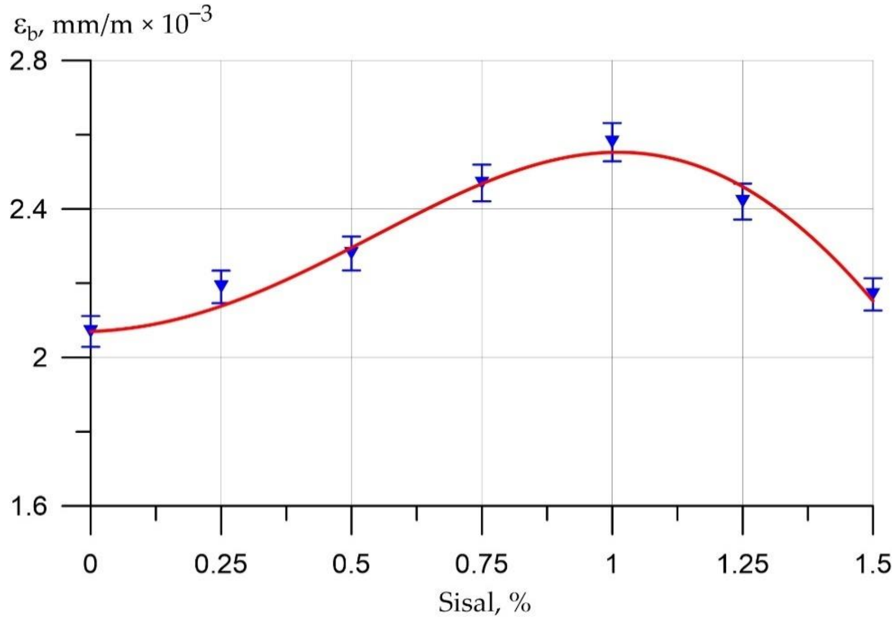

Figure 9. Results of experimental studies of ultimate strains in axial compression ε_b of test concrete samples in the form of prisms at various percentages of reinforcement with sisal fibers.

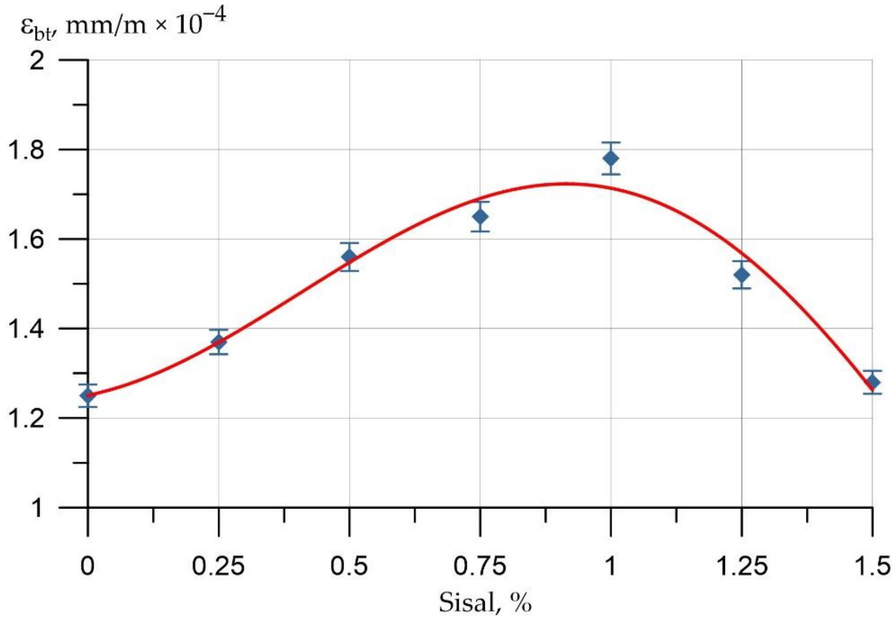

Figure 10. Results of experimental studies of ultimate strains in axial tension ε_{bt} of concrete samples in the form of prisms at various percentages of reinforcement with sisal fibers.

The results of experimental studies of ultimate strains in axial tension of concrete samples at various percentages of reinforcement with sisal fibers are described by a formula with a coefficient of determination of 0.979.

$$\varepsilon_{bt} = 1.25 + 0.554 \times x^{0.78} \times \sin(1.95\,x + 0.2), \qquad R^2 = 0.979 \tag{8}$$

Figure 11 shows the effect of the percentage of sisal fiber reinforcement on the modulus of elasticity of concrete test specimens.

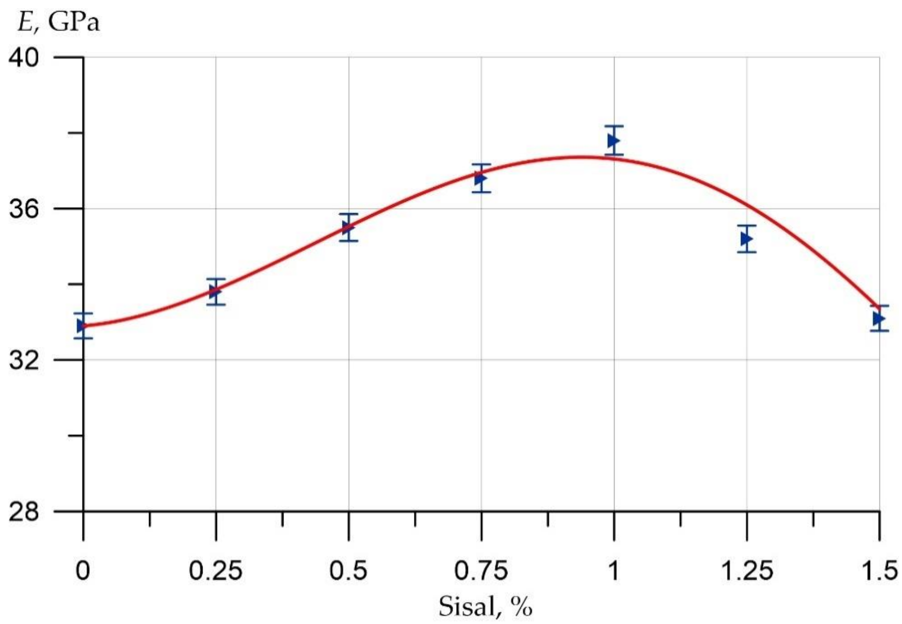

Figure 11. Results of experimental studies of the modulus of elasticity E of concrete samples in the form of prisms with various percentages of reinforcement with sisal fibers.

The results of experimental relations of the modulus of elasticity of concrete samples at various percentages of reinforcement with sisal fibers are described by a formula with a coefficient of determination of 0.979.

$$E = 32.9 + 5.04 \times x^{0.755} \times \sin(2.0x + 0.0755), \qquad R^2 = 0.979 \tag{9}$$

From Figures 9–11, it follows that the best values of deformation characteristics are observed in compositions with a dosage of sisal fiber in an amount of 1% by weight of cement. The increase in ultimate strains under axial compression and tension in comparison with the control composition without fiber was 25% and 42%, respectively, and the value of the elastic modulus increased by 15%.

The effect of the percentage of dispersed sisal fiber reinforcement on the strength and deformation characteristics of the test samples of normal weight concrete is shown in Table 4 and is presented as a percentage difference compared to conventional concrete without fiber reinforcement.

Table 4. Influence of the percentage of reinforcement with sisal fibers on the strength and deformation characteristics of samples from normal weight concrete.

Concrete Characteristics	Change in % (Δ) with the Content of Dispersed Reinforcement with Sisal Fibers, % of the Mass of Cement						
	0	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**
$R_{b.cub}$, MPa	0	+5.8	+10.0	+14.3	+21.9	+8.8	+0.6
R_b, MPa	0	+6.0	+13.0	+21.1	+26.9	+11.6	+1.7
R_{btb}, MPa	0	+10.9	+14.5	+21.8	+32.7	+18.2	+5.4
R_{bt}, MPa	0	+8.8	+11.8	+14.7	+29.4	+14.7	+2.9
ε_{bR}, mm/m × 10^{-3}	0	+5.8	+10.1	+19.3	+24.6	+16.9	+4.8
ε_{btR}, mm/m × 10^{-4}	0	+9.6	+24.8	+32.0	+42.4	+21.6	+2.4
$E_b = E_{bt}$, GPa	0	+2.7	+7.9	+11.9	+14.9	+7.0	+0.6

An analysis of the results of experimental studies of the strength characteristics of samples with dispersed reinforcement with sisal fibers, as well as an analysis of graphical dependencies and data on the effect of the percentage of fiber reinforcement on concrete characteristics (Figures 5–8 and Table 4), show that dispersed fiber reinforcement with sisal fiber has a significant effect on the strength characteristics of concrete. It has been established that the optimal fiber content is 1% by weight of cement. Such a percentage of fiber reinforcement allows achieving maximum strength characteristics of fiber-reinforced concrete. The value of the compressive strength in this case was 59.5 MPa, the axial compressive strength was 43.9 MPa, the tensile strength in bending was 7.3 MPa and the axial tensile strength was 4.4 MPa. It is noted that fiber reinforcement with sisal fibers increases the strength characteristics of concrete even at lower percentages of reinforcement (0.25%, 0.5% and 0.75%); however, compositions with a fiber reinforcement percentage of more than 1.25% showed a decrease in strength indicators up to values close to those of ordinary concrete.

Dispersed reinforcement with sisal fibers with a dosage of 0.25% to 1.5% provides an increase in the deformation characteristics of concrete. The highest values of ultimate strains under axial compression and tension were observed in concretes reinforced with sisal fiber in an amount of 1% of the mass of cement, and their values are 2.58 mm/m × 10^{-3} and 1.78 mm/m × 10^{-4}. In general, the trend of change in deformation properties is similar to the nature of change in strength characteristics. The maximum value of the modulus of elasticity of concrete, 37.8 GPa, was observed for samples reinforced with 1% fiber.

The stress–strain curves constructed based on the results of experimental studies under compression "$\varepsilon_b - \sigma_b$" and under tension "$\varepsilon_{bt} - \sigma_{bt}$" are shown in Figures 12 and 13.

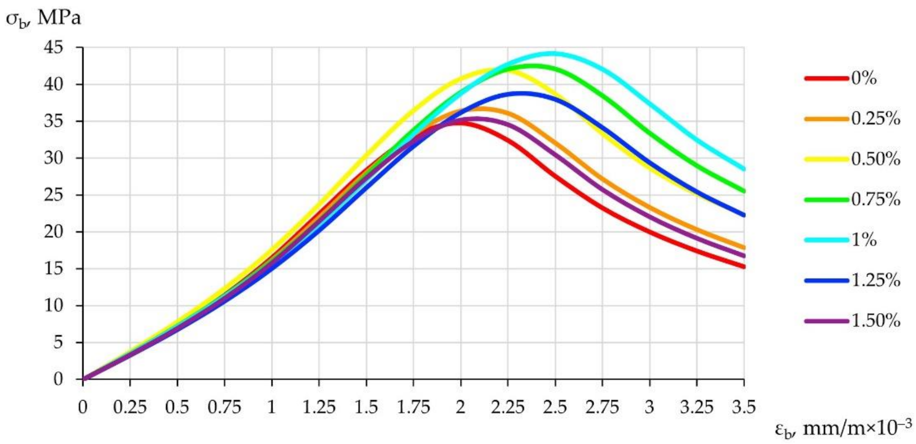

Figure 12. Stress–strain curves in compression.

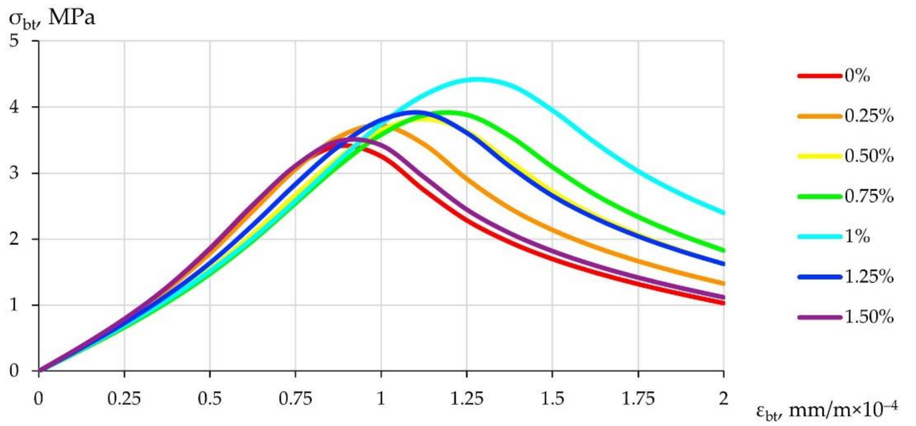

Figure 13. Tensile stress–strain curves.

Analyzing the obtained deformation curves of concrete with dispersed fiber reinforcement with sisal fibers, it can be concluded that dispersed reinforcement with sisal fibers significantly affects the concrete deformation curves. The peak of the stress–strain curves of concretes with a fiber reinforcement content of 0.25–1.25% by weight of cement shifts up and to the right relative to the diagram of ordinary concrete, and the peak of the deformation curve of concretes with a content of sisal fibers of 1.5% approximately coincides with the peak of the diagram of ordinary concrete, being only slightly above and to the right.

3.2. Analysis of the Structure of Normal Weight Concrete, Dispersed Reinforced with Sisal Fibers

This analysis was carried out to establish the relationship between the structure of the material and the strength characteristics of concrete. For the study, concrete samples with a sisal fiber content of 1% were selected, which were previously tested for compression.

Figure 14 shows a photo of the structure of concrete samples reinforced with sisal fibers.

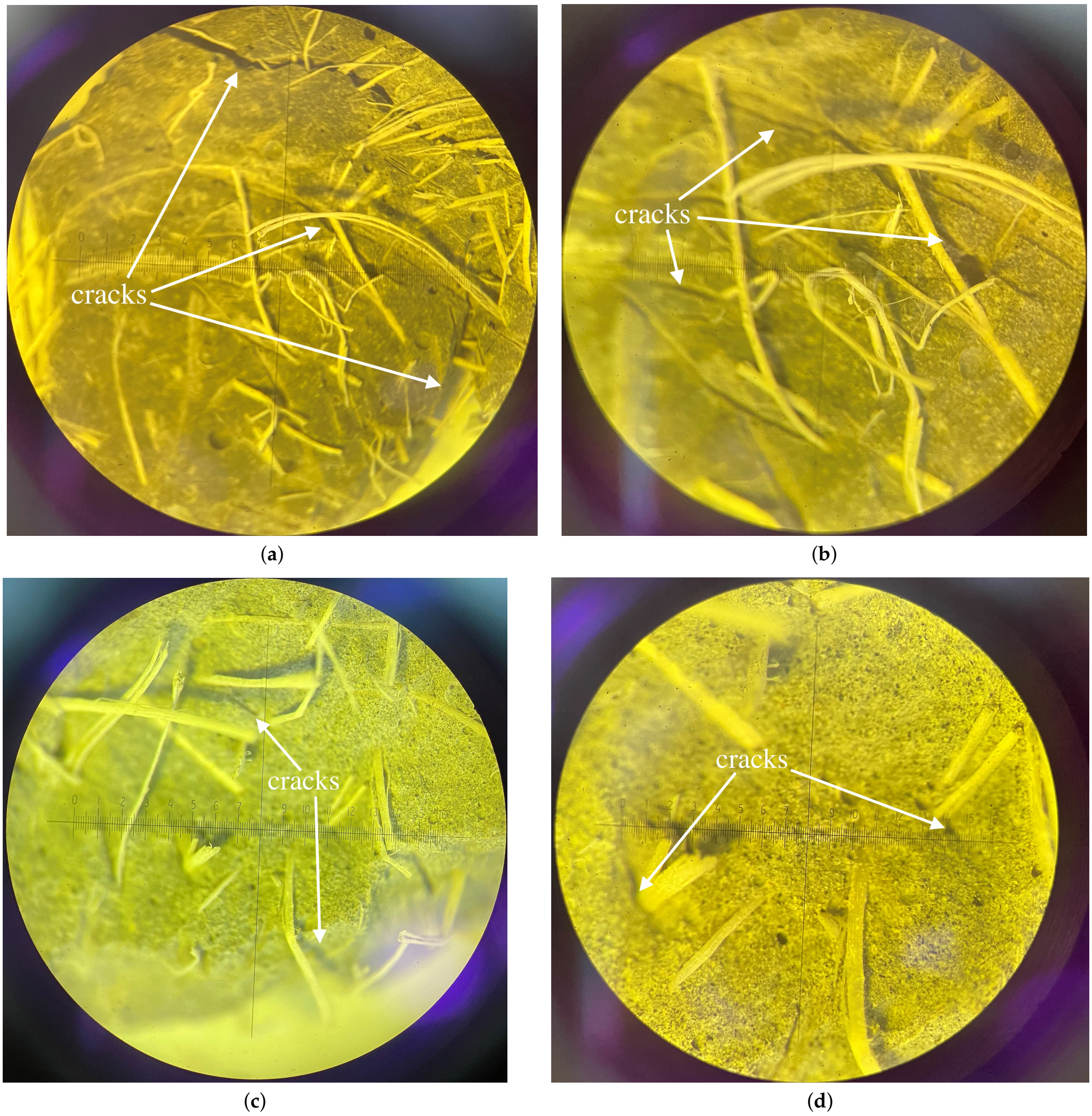

Figure 14. Photographs of the structure of concrete samples with a content of sisal fibers 1%: (**a**) with 4× magnification; (**b**) with 6× magnification; (**c**) with 8× magnification; (**d**) with 10× magnification.

Figure 14 shows that the structure of the samples reinforced with dispersed sisal fibers is loose after destruction and has many cracks; however, unruptured fibers restrain the concrete matrix due to the bridging effect. The obtained images indicate that the dispersed fiber reinforcement with sisal fiber reduces the number of cracks in the structure of the cement stone, restrains their propagation and, due to the bridging effect of sisal fibers, binds the concrete matrix. However, due to the high water absorption of sisal fibers, the formation of cracks is observed along the area of contact of the cement paste and fiber, which reduces the anchoring of fibers in concrete.

Conducting a comparative analysis of the results obtained in this study with the data of other authors, we can conclude that we have achieved an improvement in the increase in the strength characteristics of the resulting fiber-reinforced concrete. The authors of studies [11,16,19,22–28,30,31,33,35,39,41–43,45] obtained increases in the strength characteristics of concrete aged 28 days from 5% to 30% due to fiber-dispersed reinforcement of concrete with sisal fibers. The technology and recipe recommendations used by the authors of the presented study gave an increase in the strength characteristics of concrete at the age of 28 days from 22% to 33%. Moreover, with the help of the stress–strain curves built based on experimental studies of the obtained fiber-reinforced concrete compositions, improvements in the deformation characteristics were also revealed.

Considering the above, we can confidently say that this study has both an applied technological nature and offers significant prospects in the field of economic and environmental efficiency. Further work is planned in the field of research development in the ecological and economic mainstream.

The first task of the study was to prove the possibility of full utilization of agricultural waste, namely sisal fibers, in the construction industry. The fundamental possibility of using sisal fibers as a fiber-reinforcing element for concrete was proved. Rational dosages of such fibers were determined, and their compatibility with cement stone and other components that create a phase boundary with sisal fibers was studied. In this regard, it was important not only to prove the possibility of fiber reinforcement, but also to substantiate its technical, economic and environmental efficiency. In particular, it was determined that the demonstrated results of environmentally friendly concretes based on sisal fiber are not inferior to analogues of concretes reinforced with expensive artificial types of fibers, such as polypropylene, basalt fibers and, to some extent, steel and glass fibers [63–68]. The performed literature review, as well as the analysis of the obtained results provide a basis for the development of a laboratory method and factory technology for the production of concretes with sisal fibers. Its increases in strength characteristics, as well as positive trends in the change in deformation characteristics, suggest that it is necessary to focus in more detail on finding the maximum compatibility of the fiber and the concrete matrix. When studying the structure, we found that sisal fibers at the phase boundary have a fairly low percentage of cracking, there are no defects characteristic of various types of stress–strain state between the fiber and the concrete matrix and, in general, taking into account the suitable chemical properties previously established by other authors, and precisely the resistance to various corrosive influences, such a fiber has broad prospects in the construction industry. Further research should also be deepened in terms of basic science as well as chemical compatibility of fiber sisal fibers after determining its compatibility in terms of joint mechanics.

4. Conclusions

(1) Based on the results of the analysis of literary sources, the possibility of mass use of natural fibers as a fiber-dispersed reinforcement of concrete and reinforced concrete structures of buildings and structures, as well as finishing and landscaping elements, has been established.

(2) A technology was developed for the use of such materials in concretes, dispersed-reinforced with sisal fibers.

(3) The main parameters and characteristics of the sisal fiber used for fiber reinforcement of concrete and other components of the fiber-reinforced concrete mixture are determined.
(4) The optimal dosage of sisal fibers in concrete was determined, equal to 1% by weight of cement.
(5) The increases in the strength characteristics of the obtained fiber-reinforced concrete samples at the optimal dosage of fiber in an amount of 1% by weight of cement were 22% for compressive strength, 27% for axial compressive strength, 33% for tensile strength in bending and 29% for axial tensile strength.
(6) The increases in deformation characteristics were 25% for deformations under axial compression, 42% for deformations under axial tension and 15% for the elastic modulus.
(7) Dependences between the composition, structure and properties of concretes, dispersed-reinforced with sisal fibers, were determined.

A study of the resulting composition using the optical microscopy method was carried out, which shows that the resulting fiber-reinforced concrete composition is not only a new material, but also opens up broad prospects for further research and practical applications.

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