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Optimization of the Properties of Eco-Concrete Dispersedly Reinforced with Hemp and Flax Natural Fibers

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Abstract: Dispersed reinforcement of concrete with various types of plant fibers is currently a fairly popular area in the field of construction materials science. The relevance of this topic is determined by the fact that the issue has not been studied on a large scale in comparison with concrete reinforced with artificial fibers, and the fact that these types of concrete meet the requirements of the Sustainable Development Goals. The purpose of this work was to evaluate the efficiency of using hemp fiber (HF) and flax fiber (FF) for the dispersed reinforcement of concrete, and to compare their efficiency and practical applicability in the construction industry. Before use, HF and FF were treated with a NaOH solution and stearic acid to increase their resistance to the aggressive alkaline environment of concrete. A total of 15 concrete compositions were made. The percentage of dispersed reinforcement for both types of fibers varied from 0.2% to 1.4%, with a step of 0.2%. The standard methods of mechanical testing and microscopy for investigation the properties of fresh and hardened concrete were applied. The optimum amount of HF in concrete was 0.6%, which provided an increase in compressive and flexural strength of 7.46% and 28.68%, respectively, and a decrease in water absorption of 13.58%. The optimum percentage of FF concrete reinforcement was 0.8%, which allowed an increase in compressive and flexural strength of 4.90% and 15.99%, respectively, and a decrease in water absorption of 10.23%. The results obtained during the experiment prove the possibility and effectiveness of the practical application of hemp and flax fibers in concrete composite technology.

Keywords: plant fibers; hemp fiber (HF); flax fiber (FF); concrete; bending strength; optimization

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1. Introduction

The building materials market grows rapidly every year, primarily because of the accelerated construction of infrastructure in developing countries [1,2]. Intensive construction undoubtedly has a powerful impact on the environment by emitting large amounts of greenhouse gasses and generating waste [3–5]. Concrete is the most popular building material, and is the basis of the global construction industry. Currently, research on the use of industrial waste and renewable components in cement composite technology is booming [6–8]. The most common industrial wastes are fly ash and slag, which is confirmed by several studies [9–11]. Renewable components of concrete include various plant wastes, such as nut shells, which are used as part of fine or coarse aggregate [12,13]; or plant fibers, which can be used in concrete as dispersed reinforcing fibers [14–17]. Concrete and mortars often utilize coconut, sisal, jute, and banana fibers as plant-based reinforcement materials [1,18]. The inclusion of coconut fibers and coconut shells in the composition of concrete improves the performance properties of concrete and increases its compressive strength by 30% [19,20]. The addition of coconut fiber improves the impact resistance of the cement composite and increases its flexural properties (at 28 days, the impact index increases to 302%, and 28-day flexural strength increases by 42%) [21]. Introducing 0.5% to 1.0% coconut fiber into concrete does not significantly reduce the compressive strength of the cement composite at 14, 28, and 56 days of age [22]. Shear strength increases by up to 70%, and tensile strength at splitting by up to 47%, with the addition of 1.5% coconut fiber [23]. The usage of coconut fibers has shown a beneficial effect on the properties of cement composites in studies [24–26]. Another equally popular type of plant fiber is sisal. Concrete compressive strength is demonstrably improved by the addition of sisal fiber, reaching an increase of up to 14.18% [27]. Introducing 1% sisal fibers increases the compressive strength (up to 6%) and flexural strength (up to 4%) of concrete, compared to its unreinforced counterpart, at 28 days of age [28]. Sisal reinforcement improves the integrity of concrete on secondary aggregate and reduces crack propagation [29]. Foam concrete's strength improves with the inclusion of 0.133% sisal fiber. The introduction of 1% sisal fiber increases flexural strength (up to 50% at 28 days of age) and Young's modulus (up to 20%) [30]. Jute is also used as a reinforcing fiber. Columns reinforced with hybrid jute fiber show increased load-bearing capacity up to 64% [31]. The addition of 10 mm long jute fibers at 0.1% improves compressive and splitting strength by 39% and 37%, respectively, after 28 days [32]. Furthermore, jute fiber at 0.2% increases the splitting and flexural strength of concrete by 11.64% and 10.72%, respectively, after 28 days [33]. The positive effect of dispersed reinforcement with jute fiber is confirmed by other studies [34–36]. A popular trend is also the dispersed reinforcement of concrete with several types of plant fibers simultaneously, and in combination with synthetic fibers [37]. For example, the use of a combination of sisal, banana, and glass fibers with an optimal selection of the recipe makes it possible to obtain concrete with properties improved by up to 12% [38]. The properties of composites used at elevated temperatures are improved by up to 170% by combining sisal and basalt fibers [39]. Sisal and coconut fibers introduced into the composition of lightweight expanded clay concrete increase its compressive strength by up to 10% and its bending strength by up to 18% [40]. Effective combinations of several types of plant fibers for reinforcing concrete are also confirmed by other studies [41,42].

Regarding hemp and flax fibers, their application in the technology of cement composites has not been widely studied, and there is a knowledge gap in this area. Based on research [43–58] using HF and FF in cement composites, the effectiveness of their application remains unclear. For example, the use of hemp fibers improves the compressive strength and ultimate deformation of a concrete composite made using secondary waste [43]. The introduction of hemp fiber into lightweight concrete ensures a significant improvement in its strength properties [44]. At the same time, hemp fiber does not always have any significant effect on changing the properties of the concrete composite [45]. The addition of 1% hemp fiber improves the compressive strength of cement mortar by up to 12% [46]. The inclusion of flax fiber in lightweight concrete increases its strength and thermal properties [47,48]. Flax fibers in the composition of heavy concrete with recycled aggregate improve its deformation properties [49]. Similarly, in works [50,51], the use of flax fibers improved the strength properties of the composite. A study on the use of plant fibers, including hemp and flax, in comparison with synthetic fibers has shown their competitiveness in terms of flexural strength and density, provided that rational fiber dosages are observed [52]. High porosity of cementitious composites with plant fibers (lechuguilla, flax, hemp, wood) reduces compressive strength and density; however, thermal conductivity, hygroscopicity, and vapor resistance show better behavior in most cases than control samples, i.e., without plant fibers [53]. Reviews of cementitious composites containing plant fibers such as abaca, bamboo, banana, coir, jute, kenaf, pineapple leaf, sisal, hemp, flax, and others, covering their chemical, physical, and mechanical properties, as well as various areas of application, highlight these as a promising direction for innovation and progress in various industries, as well as their excellent performance in industrial applications [54–56]. Improving the long-term mechanical properties of plant fiber-reinforced cementitious composites is possible through the use of alternative binders that can slow down fiber degradation and allow the maintenance of significant strength, equivalent to that of conventional Portland cement-based composites, after 90 days of curing [57]. However, there is no unambiguous and clear understanding of the mechanisms of the effects of HF and FF on the structure and properties of cement composites, as well as any comparative analysis of the effectiveness of these types of fibers among themselves and other types of plant fibers. The novelty of the research conducted here comprises several aspects. From the point of view of the systematization of existing scientific knowledge on the modification of concretes with plant fibers, new dependencies of the mechanical properties on the amount of these fibers were obtained. These dependencies demonstrate the connection between the recipe and technological factors in the manufacture of such concretes, and their structure and properties. From the point of view of novelty in engineering practice, a scientifically substantiated principle for obtaining improved environmentally friendly green concretes is proposed, which also meets the concept of the Sustainable Development Goals. The existing knowledge on these types of concrete is developed, and the existing technologies for their production are improved, which is new from the point of view of engineering practice. The purpose of the present study is to investigate the influence of hemp and flax fibers on the structure and properties of concrete, and to assess the effectiveness of this dispersed reinforcement for practical applicability in the construction industry. The objectives of the study are the following:

– The development of an experimental research program to determine the quantitative range of the level of dispersed reinforcement with hemp and flax fiber;
– The selection and calculation of experimental concrete compositions, considering the properties of the raw materials used;
– The production of experimental concrete compositions and evaluation of their fresh properties;
– The production of experimental samples of concrete, dispersion-reinforced with hemp and flax fiber, and the evaluation of their properties, such as density, compressive and flexural strength, and water absorption;
– The study of the structure of dispersion-reinforced concrete;
– The analysis of the obtained results and the determination of optimal dosages of plant fibers, as well as the performance of a comparative analysis of the effectiveness of hemp and flax fiber among themselves within the framework of this study, and a comparison of their effectiveness with other types of plant fibers used for the dispersion-reinforcement of cement composites.

2. Materials

Portland cement CEM I 42.5N (CEMROS, Moscow, Russia) was used as a binder for the production of experimental concrete samples. The characteristics of the Portland cement are presented in Table 1.

Table 1. Properties of Portland cement CEM I 42.5N.

Specific Surface Area (m^2/kg)	Setting Times (min)	Standard Consistency (%)	Compressive Strength at 28 Days (MPa)	Flexural Strength at 28 Days (MPa)
348	- start 180 - end 240	31.4	48.5	5.6
		Mineralogical composition		
C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	CaO_{fr} (%)
71	10.1	5.3	12.5	1.1

Quartz sand (Don Resource, Kagalnik, Russia) was used as a fine aggregate. The properties of the sand are presented in Table 2.

Table 2. Properties of quartz sand.

Bulk Density (kg/m^3)	Apparent Density (kg/m^3)	Content of Dust and Clay Particles (%)	Content of Clay in Lumps (%)
1346	2662	0.07	0

Granite crushed stone Solntsedar-Don (Rostov-on-Don, Russia) was used as a large aggregate. The characteristics of the crushed stone are presented in Table 3.

Table 3. Characteristics of granite crushed stone.

Bulk Density (kg/m^3)	Apparent Density (kg/m^3)	Resistance to Fragmentation (wt %)	Content of Lamellar and Acicular Grains (wt %)
1447	2662	11.0	7.6

The sieving curves of quartz sand and granite crushed stone are shown in Figure 1.

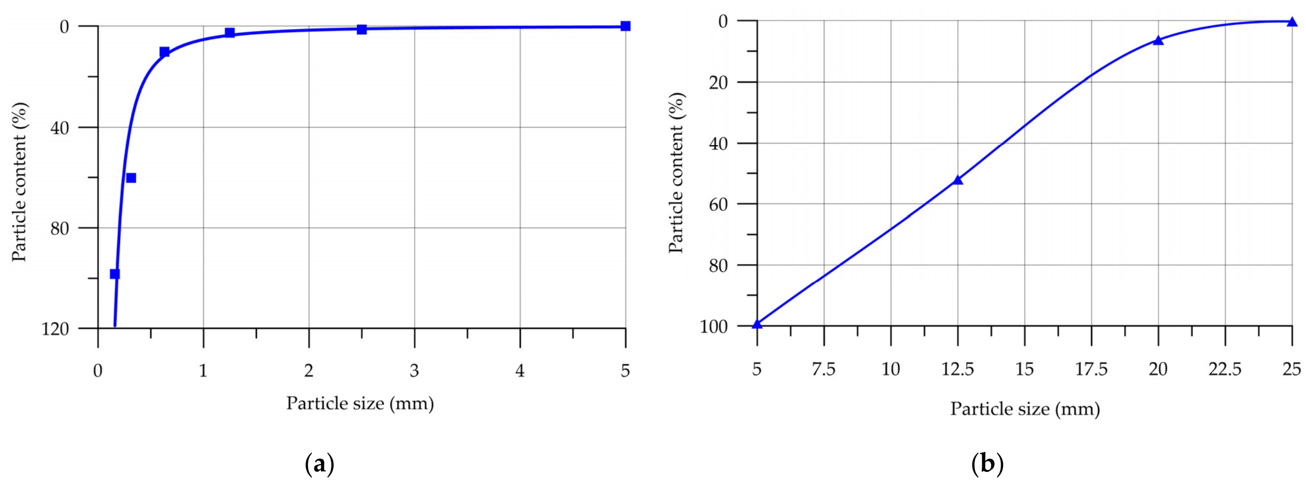


Figure 1. Particle size distribution curves: (**a**) quartz sand; (**b**) crushed granite.

As can be seen in Figure 1a, the sand had a fineness modulus of 1.73, and the grain size of the crushed stone varied from 5 mm to 20 mm (Figure 1b).

Hemp fibers (Adyghe Hemp Company, Ulsky, Russia) and flax fibers (Vyshnevolotsky Flax Mill, Tver, Russia) were used as dispersion-reinforcing fibers. The appearance of the fibers and their properties are presented in Table 4 and Figure 2.

Table 4. Fiber properties.

Fiber Type	Fiber Length (mm)	Breaking Strength of Twisted Tape (N)	Mass Fraction of Bun (%)	Humidity (%)
HF	20–40	245 ± 18	11	6.1
FF		189 ± 14	10	5.5

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

Figure 2. Appearance of fibers: (**a**) flax; (**b**) hemp.

The data presented in Tables 1–4 were obtained from the manufacturers (suppliers) of the materials, with the exception of data on the length of fibers, which was already estimated by the authors.

Before introduction into the cement composite, hemp fibers were treated with 5% NaOH solution for 24 h, and flax fibers were treated with stearic acid (1%) for 4 h. Drying after fiber treatment was carried out in a drying oven at a temperature of 60 ± 3 °C. This solution recipe allowed us to increase the protection and resistance of the plant fibers to an aggressive alkaline environment. The effectiveness of treating hemp and flax fibers with these solutions is confirmed by studies [58,59].

Also, a plasticizing additive PK1 on a polycarboxylate basis (Polyplast, Russia, Moscow) was additionally used. The additive was introduced with the mixing water, not with the dry components of the concrete mix. The following conditions for thorough mixing of the additive in the mass of the mix must be ensured: appearance—homogeneous translucent liquid without foreign inclusions; solution density—1020–1050 kg/m^3; solution pH—6–8. The plasticizer was introduced in an amount of 1% of the cement mass.

3. Experimental Methods

The effects of dispersed reinforcement with hemp fiber (HF) and flax fiber (FF) on the properties of fresh concrete and hardened composite were assessed in accordance with the experimental research program presented in Figure 3.

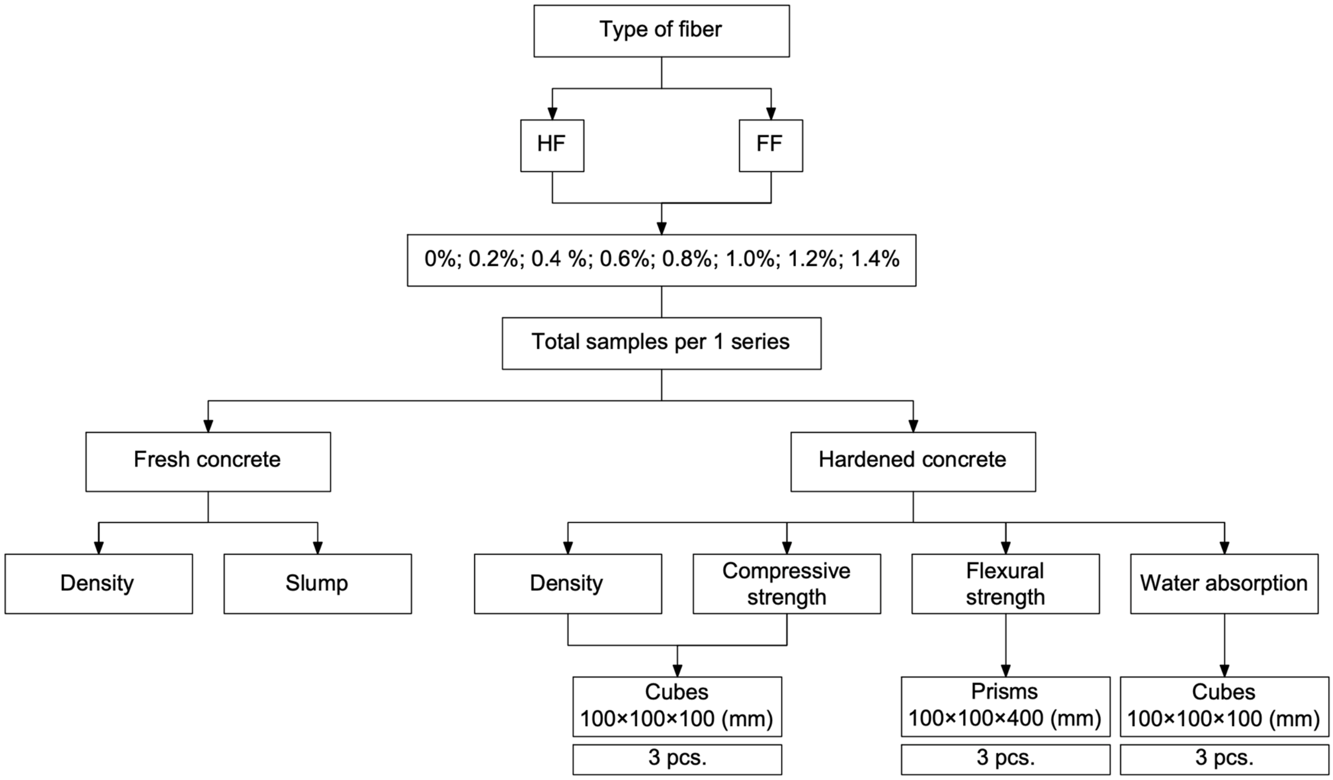


Figure 3. A flowchart of the experimental part of the study: types and dosages of fibers, types of tests, and types and sizes of concrete samples.

To determine the density, compressive strength, and water absorption, 90 cube samples and 45 prism samples were made to determine the flexural strength. For the density test of concrete, 45 cube samples (3 for each type of composition) were taken; the same 45 cube samples, after determining the density of concrete, were subjected to a compressive strength test; another 45 cube samples (3 for each type of composition) were tested for the water absorption of the concrete; and 45 prism samples (3 for each type of composition) were tested for bending strength.

The concrete mix compositions for the control composition and for the mixes with different HF and FF contents are presented in Table 5.

The introduction of fiber into the concrete mixture based on the mass of cement is a generally accepted standard solution, which is also confirmed by a number of other studies [44,46,50,58]. In this study, it was very important to leave the content of the main components of the concrete mixture unchanged, in order to maintain the purity of the experiment and to assess as accurately as possible the effect of hemp and flax fibers on the properties of the concrete composite, because even a small decrease in the cement content can lead to a change in strength. It is also worth noting that when uniformly distributed throughout the volume of the concrete mixture; the fibers are mainly located in the volume of pores and voids, without significantly affecting the change in the total volume [44,46,50,57].

Table 5. Experimental concrete compositions.

Composition	Portland Cement (kg/m^3)	Sand (kg/m^3)	Crushed Stone (kg/m^3)	Water (L/m^3)	PK1 (kg/m^3)	HF (kg/m^3)	FF (kg/m^3)
0F	395	792	1045	189	3.95	0	0
0.2HF	395	792	1045	189	3.95	0.79	-
0.4HF	395	792	1045	189	3.95	1.58	-
0.6HF	395	792	1045	189	3.95	2.37	-
0.8HF	395	792	1045	189	3.95	3.16	-
1.0HF	395	792	1045	189	3.95	3.95	-
1.2HF	395	792	1045	189	3.95	4.74	-
1.4HF	395	792	1045	189	3.95	5.53	-
0.2HL	395	792	1045	189	3.95	-	0.79
0.4HL	395	792	1045	189	3.95	-	1.58
0.6HL	395	792	1045	189	3.95	-	2.37
0.8HL	395	792	1045	189	3.95	-	3.16
1.0HL	395	792	1045	189	3.95	-	3.95
1.2HL	395	792	1045	189	3.95	-	4.74
1.4HL	395	792	1045	189	3.95	-	5.53

The production of concrete mixtures and pouring of cube and prism samples were carried out in a standard manner [59–61], and included the following main technological stages:

- The preparation and dosing of raw components was carried out in accordance with the recipe;
- The production of the concrete mixture was carried out in a laboratory concrete mixer BL-10 (ZZBO, Zlatoust, Russia), by pouring in raw components in the following sequence: cement, sand, vegetable fiber, water with a plasticizing additive, and coarse aggregate. The concrete mixture was stirred until it reached a homogeneous consistency;
- After production, the concrete mixture was poured into metal molds, and then installed on a laboratory vibrating platform and compacted for 1 min;
- The surface of the finished samples was brought to a flat and smooth state. The samples were kept in the molds for 1 day, and then removed from the molds and placed in a normal hardening chamber KNT-1 (Raspribor, St. Petersburg, Russia) for the remaining 27 days. The curing temperature was maintained in the range from 18 °C to 22 °C, and the curing humidity was no less than 90%.

The fresh concrete properties were controlled by measuring density and slump. The density of the mixtures was determined according to the method described in [62], and calculated using the following formula:

$$\rho_{cm} = \frac{m - m_1}{V} \times 1000 \quad (1)$$

Here, m is the mass of the graduated vessel with the concrete mix (g); m_1 is the mass of the graduated vessel without mix (g); and V is the capacity of the graduated vessel (cm^3).

The slump was determined using the method described in [63]. A metal cone, a metal sheet, and a ram were used to determine the slump. Before determining the slump, all tools were wiped with a damp cloth. The concrete mix was loaded into the cone in three stages.

Each of the three layers was compacted with 25 blows of the ram. Before removing the cone, excess mix was removed from its upper part, and the surface was smoothed. Then, the cone was quickly and smoothly raised and placed next to the settled concrete mix. The slump was estimated as the difference between the height of the metal cone and the highest point of the settled concrete mix.

After 28 days of hardening, the experimental samples were tested for density, compressive strength, flexural strength, and water absorption. Before testing, all samples were removed from the normal hardening chamber and kept under laboratory conditions. The density was determined using the method described in [64]. To determine the density, the cube samples were weighed and measured, and the density itself was calculated using the following formula:

$$\rho = \frac{m}{V} \times 1000 \quad (2)$$

Here, m is the mass of the sample (g), and V is the volume of the sample (cm^3).

The compressive and bending strengths were determined in accordance with the requirements of the methods described in [59,61,65–68]. The compressive strength of concrete was calculated using the following formula:

$$R = \alpha \frac{F}{A} \quad (3)$$

Here, F is the breaking load (N); A is the area of the working cross-section of the sample (mm^2); and α is the coefficient, taking into account the dimensions of the samples (for samples with a side of 100 mm, $\alpha = 0.95$).

The bending strength was calculated using the following formula:

$$R_{bt} = \delta \frac{F\,l}{a\,b^2} \quad (4)$$

Here, F is the breaking load (N); a, b, l are the dimensions of the prism cross-section and the distance between the supports; and δ is a coefficient taking into account the dimensions of the samples (for samples with a side of 100 mm $\delta = 0.92$).

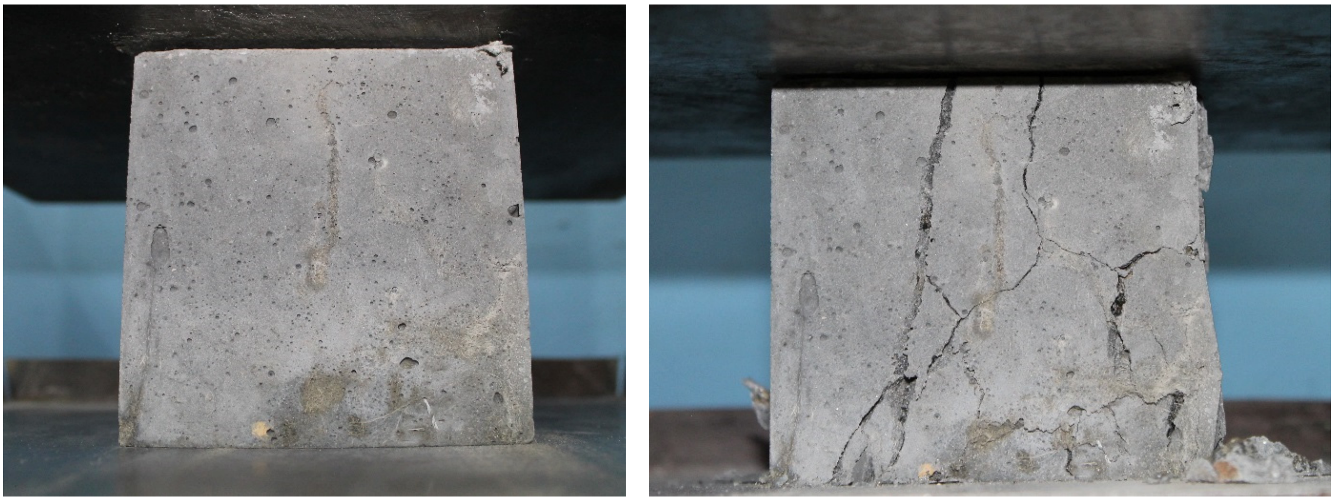
Water absorption was determined using the method described in [69,70]. The samples were placed in a special container, so that the distance between them was at least 50 mm, and filled with water. Saturation was carried out until the difference between two successive weighings was no more than 0.1%. The water absorption value was calculated using the following formula:

$$W = \frac{m_W - m_d}{m_d} \times 100 \quad (5)$$

Here, m_W is the mass of the water-saturated sample (g), and m_d is the mass of the dry sample (g).

The appearances of the experimental samples reinforced with HF and FF are shown in Figures 4 and 5, respectively.

The inclusion of HF and FF made it possible to reduce the brittle nature of the concrete during destruction. During the destruction process, concrete cubes do not break into many fragments, and retain an integral structure with a crack network (Figures 4b and 5b). All of this happens due to the HF and FF, which additionally bind the cement matrix.



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

Figure 4. Cube specimens of concrete with HF during compression testing: (**a**) before failure; (**b**) after failure.

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

Figure 5. Cube specimens of concrete with FF during compression testing: (**a**) before failure; (**b**) after failure.

4. Results and Discussion

The results of determining the density (ρ_{fc}) and slump of fresh concrete, dispersion-reinforced with HF and FF, are presented in Figures 6 and 7, respectively.

The dependences of the density ρ_{fc} of fresh concrete, presented in Figure 6, are well approximated by a linear dependence, as follows:

$$\text{for hemp fiber}: \ \rho_{fc} = 2429 + 13.09\,x, \quad R^2 = 0.96 \tag{6}$$

$$\text{for flax fiber}: \ \rho_{fc} = 2428 + 11.48\,x, \quad R^2 = 0.99 \tag{7}$$

Here, x is the proportion of fiber, %, and R^2 is the coefficient of determination.

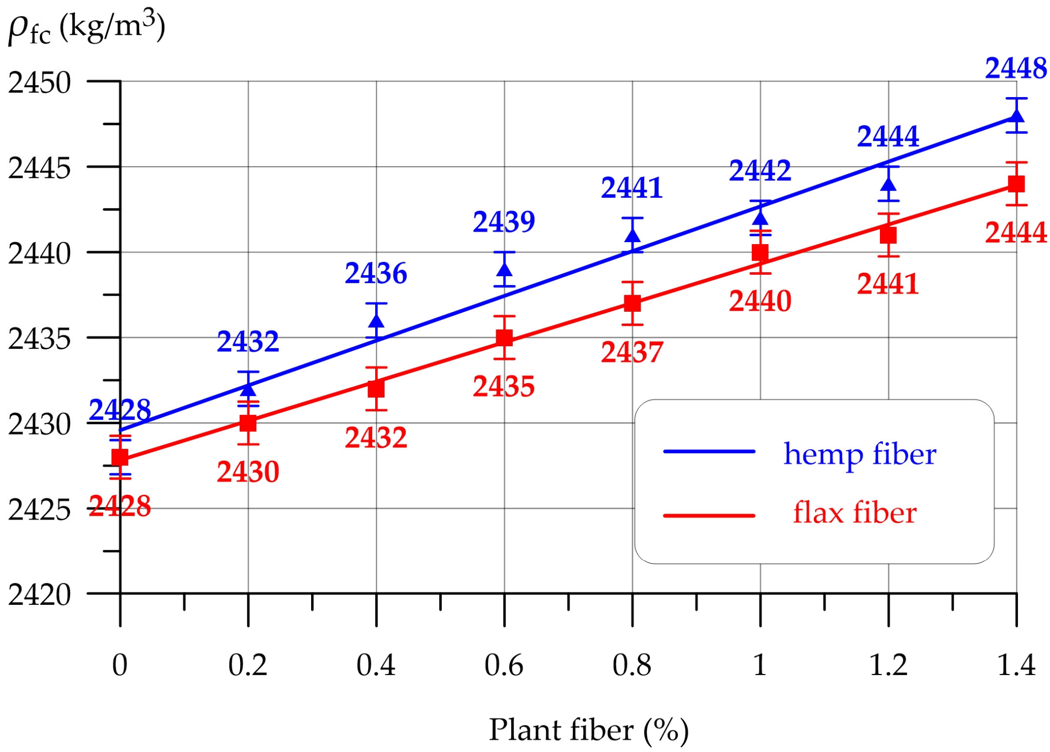


Figure 6. Density of fresh concrete (ρ_{fc}) containing HF and FF in different dosages.

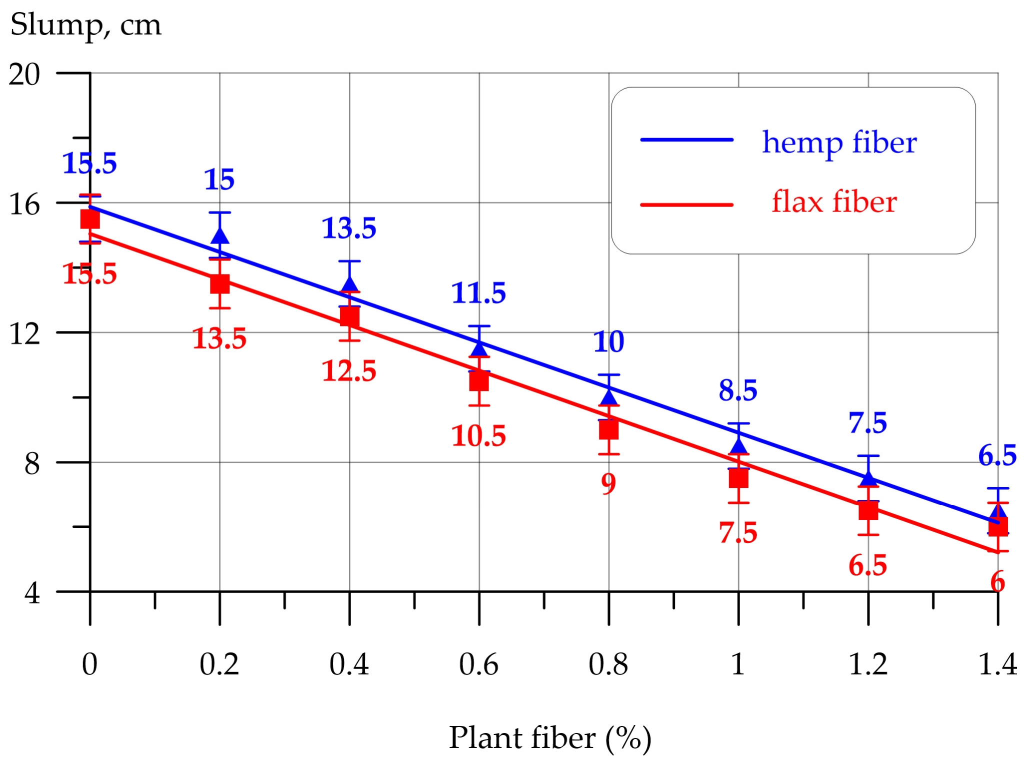


Figure 7. Slump of fresh concrete modified with different amounts of HF and FF.

As can be seen from Figure 6, the introduction of HF and FF into the concrete composition in an amount from 0.2% to 1.4% does not significantly affect the change in its density. The leanness of the mixture with HF changed from 2432 kg/m^3 to 2448 kg/m^3. For the mixtures with FF, the density values varied from 2430 kg/m^3 to 2444 kg/m^3. The deviation in the density of concrete with HF and FF did not exceed 0.82% in the specified range of fiber dosages. Thus, with an increase in the dosage of both types of fibers, the density increases slightly. The difference between fresh concrete without fibers, and with fibers in an amount of 1.4%, was up to 20 kg/m^3. These results are consistent with the results presented in previous studies [44,46,50].

The slump dependencies shown in Figure 7 are well approximated by a linear function on the fiber proportion, as follows:

$$\text{for hemp fiber}: \ Sl = 15.8 - 6.96\,x, \quad R^2 = 0.987 \tag{8}$$

$$\text{for flax fiber}: \ Sl = 15.0 - 7.02\,x, \quad R^2 = 0.982 \tag{9}$$

Here, x is the proportion of fiber, %, and R^2 is the coefficient of determination.

According to the results of determining the slump of fresh concrete, as presented in Figure 7, it is evident that HF and FF reduce the slump of the mixtures. In the case of both HF and FF, as the amount of fiber increases, the slump of the mixture decreases. If HF and FF are compared separately, FF has a greater effect on reducing the slump of the mixtures compared to HF. With a maximum fiber amount of 1.4%, the slump of the mixture with HF decreased by 58.1%, and that of the mixture with FF decreased by 61.3%. This effect of plant dispersion-reinforcing fibers on the workability of concrete mixtures is due to the fact that they have a high water absorption capacity, and absorb part of the water from the mixture [36,71,72]. In addition, the fibers are an obstacle to the movement of concrete particles [73,74]. All of these factors together lead to a decrease in the slump of concrete mixtures.

The amount of plasticizer was selected such that in the given range of plant fiber dosages, the slump was maintained in such an interval that allowed the fibers to be evenly distributed in the mixture, to achieve high mechanical properties in the composite. The plasticizer dosage was also not changed, in order to maintain the purity of the experiment. One of the objectives of this study was to determine how exactly these types of fibers affect the rheological properties. Increasing the amount of plasticizer would not have allowed for the determination of this indicator. The plasticizer also affects the mechanical properties of concrete. After determining the best fiber dosage, if necessary, it is possible to increase the plasticizer dosage and provide the required level of concrete slump for working with it.

Furthermore, in Figures 8–11, the properties of hardened dispersion-reinforced concrete are presented. Figure 8 shows the dependences of concrete density (ρ) on the amount of added fibers.

The dependences of the density ρ of hardened concrete, presented in Figure 6, are well approximated by a linear dependence, as follows:

$$\text{for hemp fiber}: \ \rho = 2338 + 24.8\,x, \quad R^2 = 0.984 \tag{10}$$

$$\text{for flax fiber}: \ \rho = 2336 + 24.0\,x, \quad R^2 = 0.985 \tag{11}$$

Here, x is the proportion of fiber, %, and R^2 is the coefficient of determination.

As in the case of fresh concrete, the density of hardened concrete modified with HF and FF does not change by more than 1.54%. The density values of concrete with HF varied from 2345 kg/m^3 to 2374 kg/m^3, while for concrete with FF, the density varied from 2340 kg/m^3 to 2371 kg/m^3. The density of concrete increased to 36 kg/m^3 with the introduction of fibers in an amount of up to 1.4%.

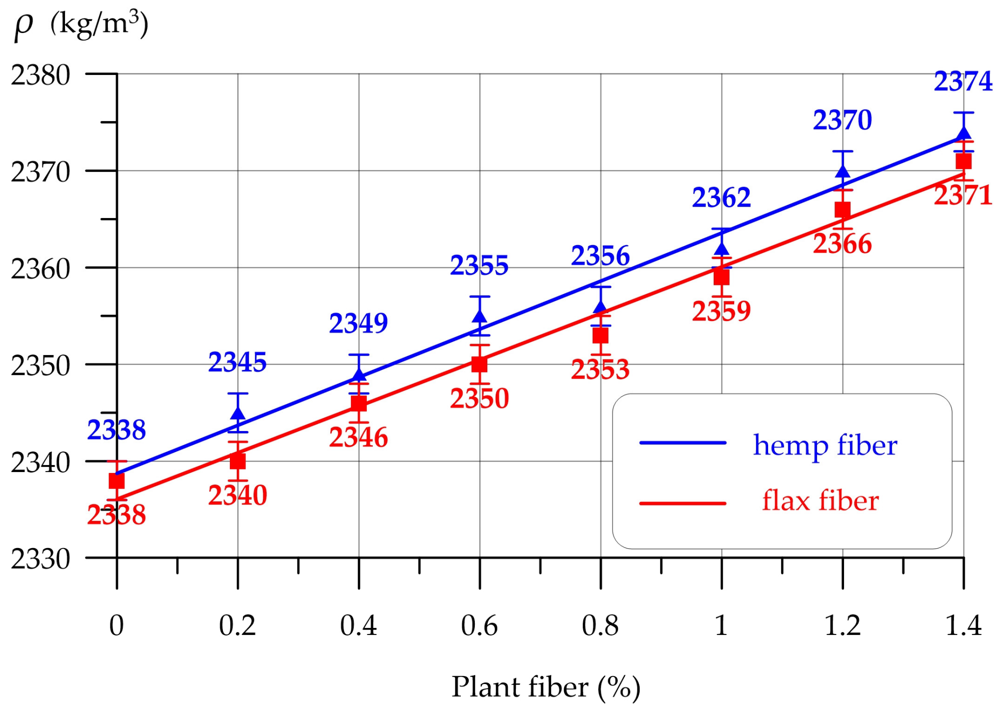


Figure 8. Density of concrete (ρ) dispersion-reinforced with different amounts of HF and FF.

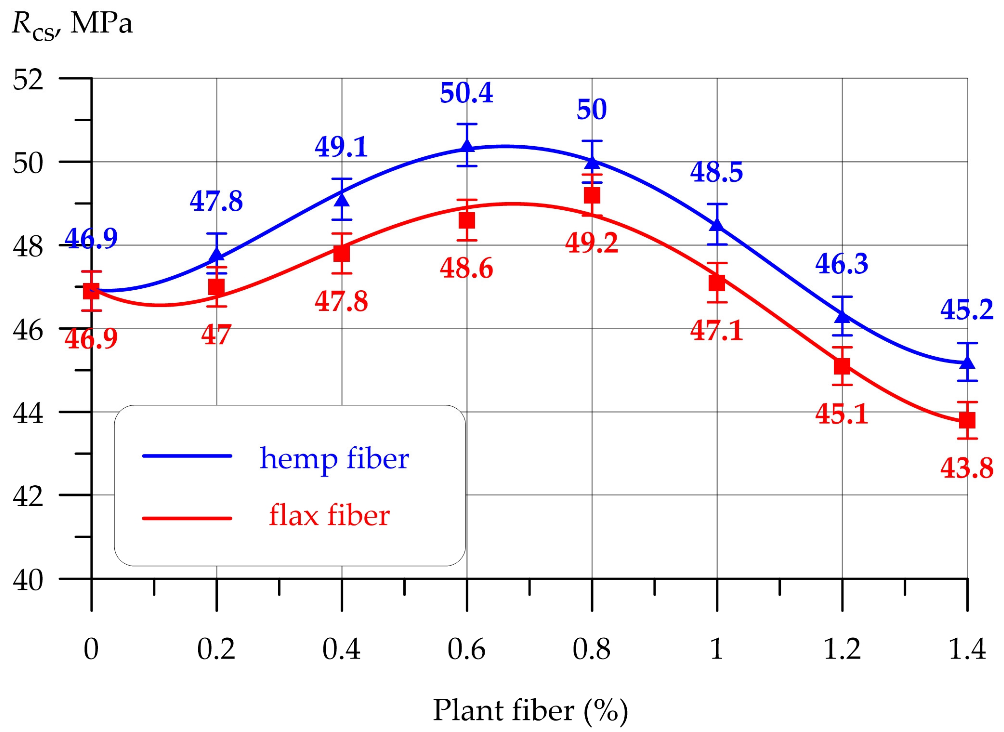


Figure 9. Compressive strength of concrete (R_{cs}) with dispersion-reinforced HF and FF of different dosages.

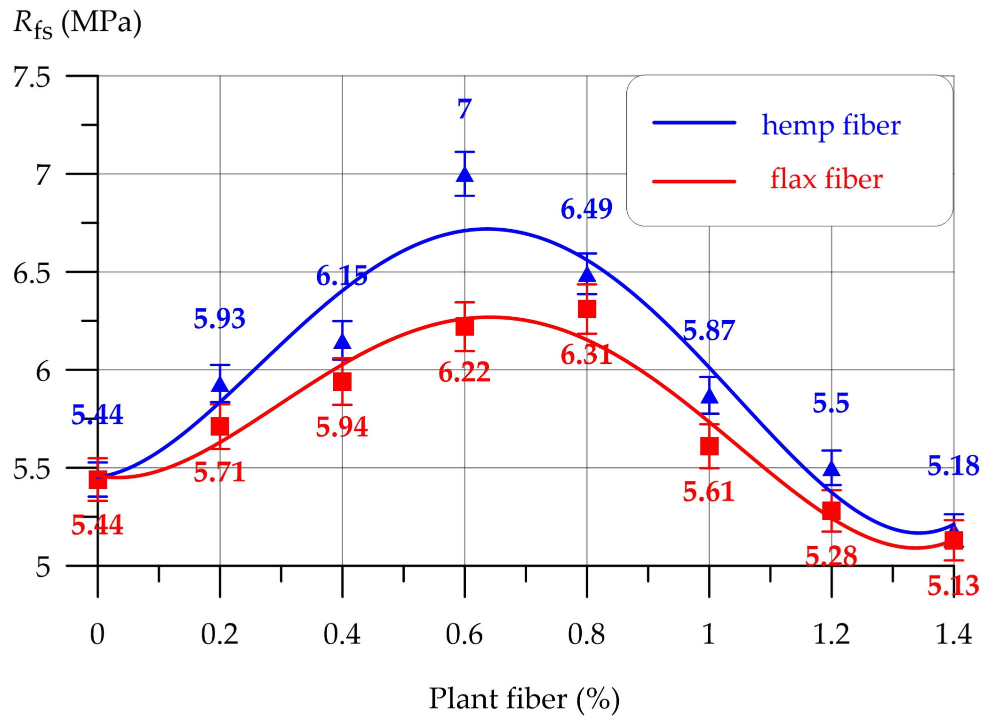


Figure 10. Flexural strength of concrete (R_{fs}) with dispersion-reinforced HF and FF.

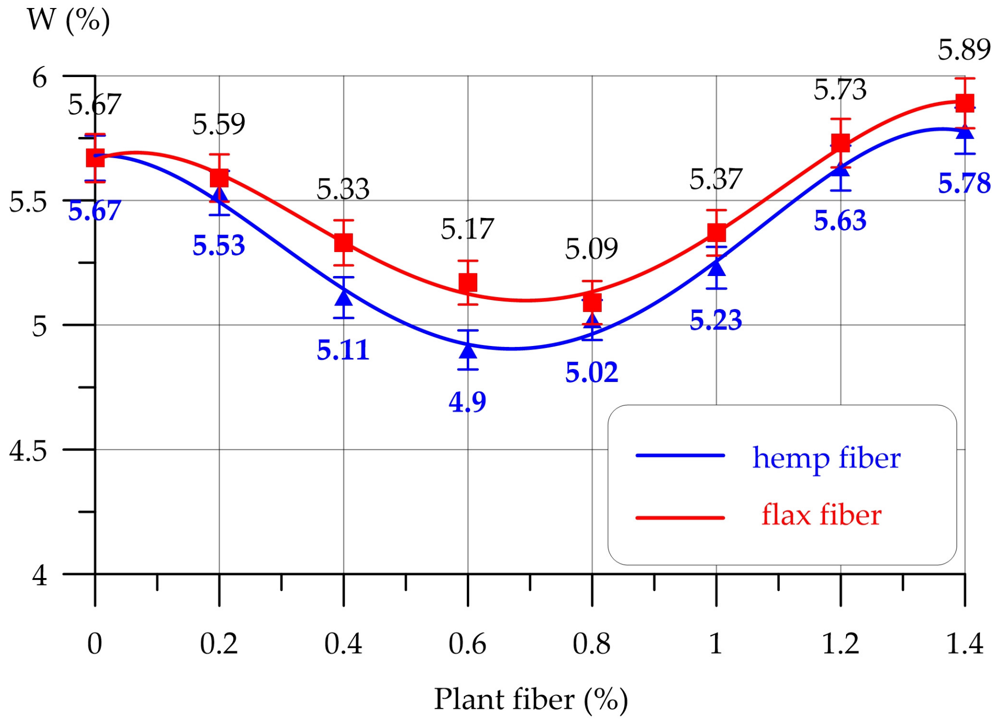


Figure 11. Water absorption of concrete (W) with dispersion-reinforced HF and FF.

Thus, the results of the experimental studies prove that the introduction of HF and FF in an amount from 0.2% to 1.4% does not significantly affect the density of fresh concrete and the density of hardened concrete. This fact is confirmed by other studies [75,76], in which the introduction of small doses of fiber of plant or synthetic origin did not have any significant effect on such a property of concrete as density.

Figure 9 shows the results of the effect of the amount of fibers on the compressive strength of concrete (R_{cs}).

The experimental dependencies of the compressive strength of concrete (R_{cs}), shown in Figure 9, can be approximated by a polynomial of fourth degree on the amount of different dosages HF and FF, as follows:

$$\text{for hemp fiber}: \ R_{cs} = 46.93 - 1.77\,x + 37.3\,x^2 - 53.0\,x^3 + 19.0\,x^4, \quad R^2 = 0.99 \tag{12}$$

$$\text{for flax fiber}: \ R_{cs} = 46.97 - 8.22\,x + 46.7\,x^2 - 57.7\,x^3 + 19.6\,x^4, \quad R^2 = 0.98 \tag{13}$$

Here, x is the proportion of fiber, %, and R^2 is the coefficient of determination.

The dependencies presented in Figure 10 reflect the change in the compressive strength of concrete with dispersion-reinforced HF and FF. Concrete with HF has higher values of compressive strength. Starting from 0.2% to 0.6% HF, the compressive strength tended to increase, with a peak value of 50.4 MPa at 0.6% HF, where the strength increase was 7.46% compared to the control composition. At a fiber content of more than 0.6%, the opposite effect was observed. The introduction of 0.8% and 1.0% HF maintained a positive effect at the level of compressive strength, with increases of 6.61% and 3.41%, respectively. However, at the levels of 1.2% and 1.4% HF, the compressive strength decreased below the level of the control concrete composition by 1.28% and 3.62%, respectively. The dependence of the change in the strength of concrete with FF was as follows. At dosages of 0.2–0.8%, an increase in compressive strength of 4.9% was observed, with a maximum strength value of 49.2 MPa at the level of 0.8%. Starting from 1.0%, the opposite effect was observed. The introduction of 1.0% FF did not provide any significant increase, and the compressive strength value was comparable to the strength of concrete without fibers. In compositions with 1.2% and 1.4%, the compressive strength was lower by 3.84% and 6.61%, respectively, in comparison with concrete without fibers. Thus, it can be concluded that HF is more effective than FF, and, at the optimal dosage, provides a greater increase in compressive strength. This result is explained by the higher strength of hemp fiber compared to flax. In addition, there is a rational range of fiber dosage values. In the specified range, the overall improvement of the concrete structure has a positive picture. This occurs due to the creation of additional structural bonds in concrete with dispersed reinforcement. When the rational range is exceeded, poor hydration occurs. Therefore, it is important to adhere to the rational range of dosage of fiber additives. Figure 10 shows the curves of the dependence of the flexural strength of concrete (R_{fs}) on the type and amount of fibers.

Experimental dependencies of the flexural strength of concrete (R_{fs}), shown in Figure 10, can be approximated by a polynomial of fourth degree on the amount of different dosages of HF and FF, as follows:

$$\text{for hemp fiber}: \ R_{fs} = 5.45 + 0.39\,x + 10.8\,x^2 - 17.2\,x^3 + 6.56\,x^4, \quad R^2 = 0.92 \tag{14}$$

$$\text{for flax fiber}: \ R_{fs} = 5.46 - 0.63\,x + 10.1\,x^2 - 14.7\,x^3 + 5.46\,x^4, \quad R^2 = 0.955 \tag{15}$$

Here, x is the proportion of fiber, %, and R^2 is the coefficient of determination.

The change in flexural strength depending on the amount of introduced fiber can be described as follows. A positive effect was observed for all compositions of concrete with HF. Active growth in flexural strength was recorded at 0.2%, 0.4%, and 0.6% HF. The maximum flexural strength of 7.0 MPa was observed for concrete with 0.6% HF, where the value of the increase in flexural strength was 28.68% compared to concrete without fiber. The introduction of HF in the amounts of 0.8% and 1.0% also provided increases in flexural strength; however, these values were smaller. Higher fiber dosages of 1.2% and 1.4% did not lead to significant improvements or deteriorations in flexural strength, the values of which were approximately comparable to the strength of concrete without fibers. The dependence of the change in the flexural strength of concrete with FF has a slightly different character. The optimal dosage of FF was 0.8%. This composition had a strength value of 6.31 MPa, which was 15.99% higher than the control composition of concrete. At higher FF dosages of 1.2% and 1.4%, a negative effect was observed. The flexural strength decreased in comparison with concrete without FF. The mechanism of action of dispersed reinforcement with plant fibers can be described as follows. With an optimal content and uniform introduction into the concrete mixture, HF and FF are distributed mainly throughout the entire volume of the concrete composite. Also, due to their porous structure, plant fibers have good adhesion to the cement stone, and, when exposed to mechanical loads, they absorb part of the forces and prevent brittle destruction of the concrete composite [77]. When the structure of the concrete composite is oversaturated with HF and FF, a negative effect is observed. Plant fibers are lumped together, and low-strength zones with fiber accumulation and interweaving are formed. When exposed to load, the presence of such zones with fiber accumulation has a negative effect on the strength properties of concrete [78]. According to the obtained experimental results, it was revealed that a further increase in the dosage of hemp and flax fibers will lead to even greater supersaturation of the concrete composite structure with fibers, affecting their adhesion and increasing the formation of low-strength zones with accumulation and interweaving of fibers. When exposed to load, the presence of such zones with fiber accumulation negatively affects the mechanical properties of concrete. Accordingly, an increase in the dosage of fibers by more than 1.4% will lead to the deterioration of other properties, such as durability and resistance to atmospheric influences, since it will negatively affect the structure of the composite and its mechanical strength [25,50,76]. Figure 11 shows the dependencies of concrete water absorption (W) on the amount of introduced fibers.

The experimental dependencies of the water absorption of concrete (W), shown in Figure 11, can be approximated by a polynomial of fourth degree on the amount of different dosages of HF and FF, as follows:

$$\text{for hemp fiber}: \; W = 5.68 + 0.14\,x - 7.38\,x^2 + 10.8\,x^3 - 3.95\,x^4, \quad R^2 = 0.99 \tag{16}$$

$$\text{for flax fiber}: \; W = 5.66 + 0.90\,x - 7.83\,x^2 + 10.2\,x^3 - 3.55\,x^4, \quad R^2 = 0.99 \tag{17}$$

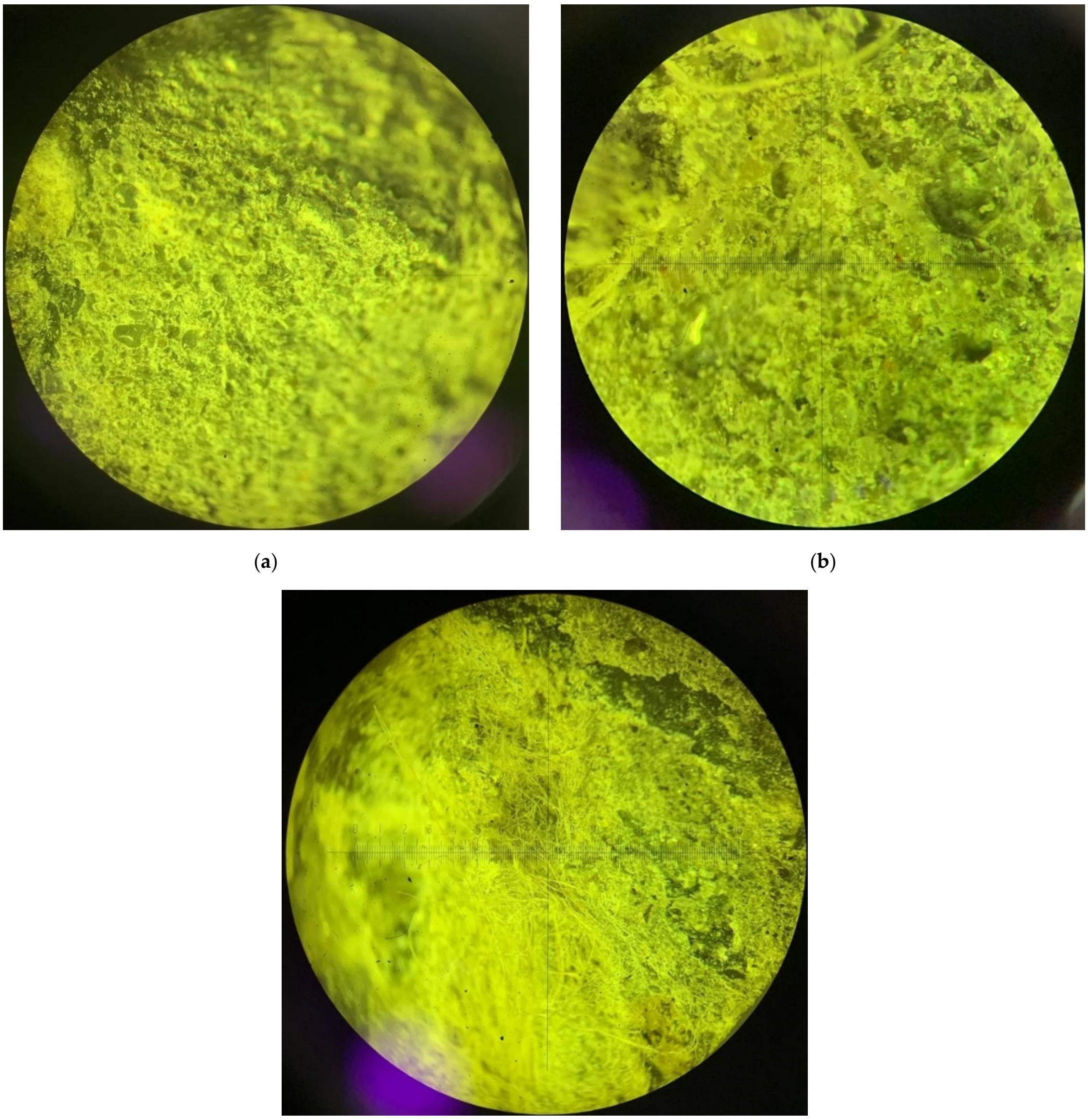
Here, x is the proportion of fiber, %, and R^2 is the coefficient of determination.

According to Figure 11, dispersed reinforcement of HF and FF at optimal dosages helps to reduce the water absorption of concrete. With the introduction of HF, the minimum water absorption value was recorded at 0.6% and amounted to 4.90%, which was 13.58% less than the control composition. Then, with an increase in the HF content, water absorption began to increase, and at the maximum fiber dosage of 1.4%, a negative result was recorded. The water absorption value was 5.78%, which was 2.0% higher than that of the control concrete. In the case of FF, the minimum water absorption value was observed at 0.8% FF, and amounted to 5.09%, which was 10.23% less than that of concrete without FF. The maximum water absorption value was also recorded at the maximum percentage of dispersed reinforcement, and amounted to 5.89%. It is possible to reduce the water absorption of concrete composites by introducing flax and hemp fibers by using the following formulation solutions. For example, the fibers can be treated with special hydrophobic additives. These additives will reduce the water absorption capacity of the fibers, and as a result, the water absorption capacity of the concrete composite itself will decrease. It is also possible to reduce the water absorption of concrete by modifying it with various mineral and plasticizing additives, which will affect the structure of the composite and make it denser and stronger [35,46,74].

The positive effect of dispersed reinforcement is explained by the fact that with the optimal content of HF and FF, the concrete composite has a more organized, more coherent, and slightly denser structure. The fibers are distributed fairly evenly throughout the entire volume of the composite, and have good adhesion to the cement stone [69]. For strong bonds between the composite matrix and the fibers, good adhesion is necessary, which can be improved by surface modification of plant fibers. For this purpose, physical (stretching, heat treatment, clantering, electric discharge, cold plasma treatment and alkalization, etc.) or chemical (copolymerization, silane coupling method, esterification, etc.) methods are usually used [79].

With a rational dosage of the fibrous additive, the quality of the structure and its cohesion are improved, which means that the number of pores is reduced. In this case, water is proportionally spent on wetting and absorption into the structure of the material. However, when the rational range is exceeded, the structure of the material deteriorates, additional porosity occurs, and more water is required.

Photographs of the structure of the concrete of the control composition and compositions with HF and FF are shown in Figure 12.



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

(**c**)

Figure 12. Photographs of the structure of the concrete samples with a 10-fold increase: (**a**) control composition; (**b**) composition with 0.6% HF; (**c**) composition with 0.8% FF.

The performed analysis of the structure proves the function of hemp and flax fibers as additional binding elements in the concrete structure. Figure 12b,c show the structural bonds formed by HF and FF at the phase boundaries. Hemp and flax fibers are inert, and do not enter into a reaction interaction during the cement hydration process. As is known, any fiber, regardless of its origin, is a structural element, and performs additional binding functions due to the bonds formed at the phase boundaries of "cement matrix–fiber" and "cement matrix–fiber–coarse aggregate" [69,70,80,81].

After analyzing the changes in the physical, mechanical, and structural characteristics of concrete, when introducing hemp and flax fibers into them, it is necessary to determine the mechanisms of interaction of the components in the formation of the structure and the properties of modified concrete. In particular, relying on scientific literature and our own data on improving the characteristics and improving the structure of the material, the following should be noted. An increase in strength characteristics is rightly associated with an improvement in the structure of concrete, due to the introduction of additional bonding centers in the form of fibers that act as a micro-reinforcing component. In particular, the use of plant fiber in a rational amount, be it flax or hemp fiber, has a positive effect on the structure and properties of concrete. The structure of concrete becomes more homogeneous, and additional fiber reinforcement allows other properties to be imparted to concrete. In particular, the nature of destruction becomes viscous, in contrast to more brittle unreinforced concrete, and the improvement of the mechanical properties of the material proves the hypothesis of structural improvement of the obtained concrete. In this case, one should rely on the fundamental principle of "composition–structure–properties". In the case of using a rational amount of flax, and especially hemp fibers, a positive effect occurs, leading to an improvement in the structure and properties of concrete. This is in good agreement with studies [15,17,40,48,51–56,78].

Furthermore, Table 6 presents a comparative analysis of the effect of various dosages of HF and FF on the properties of concrete. The effects of dispersed reinforcement are shown in percentages.

Table 6. Values of the influence of different dosages of HF and FF on the properties of concrete.

Amount of Fibers (% by Weight of Cement)	$\Delta\rho_{fc}$ (%)		ΔSlump (%)		$\Delta\rho$		ΔR_{cs} (%)		ΔR_{fs} (%)		ΔW (%)	
	HF	FF	HF	FF	HF	FF	HF	FF	HF	FF	HF	FF
0	0		0		0		0		0		0	
0.2	0.16	0.08	−3.2	−12.9	0.30	0.09	1.92	0.21	9.01	4.96	−2.47	−1.41
0.4	0.33	0.16	−12.9	−19.4	0.47	0.34	4.69	1.92	13.05	9.19	−9.88	−6.00
0.6	0.45	0.29	−25.8	−32.3	0.73	0.51	7.46	3.62	28.68	14.34	−13.58	−8.82
0.8	0.54	0.37	−35.5	−41.9	0.77	0.64	6.61	4.90	19.30	15.99	−11.46	−10.23
1	0.58	0.49	−45.2	−51.6	1.03	0.90	3.41	0.43	7.90	3.12	−7.76	−5.29
1.2	0.66	0.54	−51.6	−58.1	1.37	1.20	−1.28	−3.84	1.10	−2.94	−0.71	1.06
1.4	0.82	0.66	−58.1	−61.3	1.54	1.41	−3.62	−6.61	0.74	−5.70	1.94	3.88

Thus, based on the results of the conducted experimental studies, the following conclusions can be made:

– Hemp fiber in the composition of concrete composite works better in comparison with flax fiber, which is confirmed by higher positive effects (Table 6);
– Having studied the fresh properties of fresh concrete, it can be summarized that HF and FF do not significantly affect the density of mixtures, only slightly increasing it with an increase in the dosage of fibers; however, they do reduce their slump. The dependence of the decrease in the slump of the mixture on the amount of dispersed

reinforcement is direct; namely, as the amount of fiber increases, the slump of the mixture decreases. With a maximum content of HF and FF of 1.4%, the reduction in the slump of the concrete mixtures was 58.1% and 61.3%, respectively;

- The density of hardened concrete with the introduction of HF and FF in the considered ranges also does not change significantly, only increasing to 1.54% with the addition of fibers up to 1.4%;
- The introduction of HF and FF in optimal quantities has a positive effect on the strength properties of concrete. With the introduction of HF, the greatest increases in compressive and flexural strength were recorded at 0.6% HF, and amounted to 7.46% and 28.68%, respectively; in concretes with FF, the highest compressive and flexural strength were observed with a fiber content of 0.8%, and amounted to 4.90% and 15.99%, respectively;
- Dispersed reinforcement also has a positive effect on the water absorption rate of concrete. The lowest water absorption values were recorded in concretes with 0.6% HF and 0.8% FF; in comparison with the control composition, they were less by 13.58% and 10.23%, respectively. For a more complete understanding of the effect of dispersed reinforcement with hemp and flax fiber on concrete, a comparative analysis was performed with the results of other authors [22,23,27,35,44,46,49,82–92], which is presented in Table 7.

Table 7. The effects of different types of plant fibers on the properties of cement composites.

Number	Plant Fiber Type	Proportion of Reinforcement	Effect
[82]	Coconut fiber	0.5% cement wt.	An increase in compressive strength of up to 6% and flexural strength of up to 40% was recorded.
[83]		0.25%	A concrete composition was developed that simultaneously included recycled aggregates, ground blast furnace granulated slag, and coconut fiber. The optimal combination of all formulation solutions provided increased in flexural and tensile strength when splitting by 30.5% and 33% compared to the control composition.
[22,23]		0.5–1.5%	The inclusion of coconut fiber in dosages of 0.5–1.5% provided improved strength properties.
[49]	Flax fiber	Up to 1.0%	The introduction of flax fibers into the composition of the concrete composite improved its deformative properties and reduced brittleness during destruction.
[84]			Mechanical properties were improved and autogenous shrinkage was reduced by up to 26%.
[44]	Coconut fiber	Up to 3%	Hemp fiber-reinforced foam concrete composites had improved compressive and flexural strength values.
[46]		1%	An increase in compressive strength of up to 12% was observed.
[27]	Sisal fiber	1.5%	The strength of concrete was increased by 14.18% compared to the control composition.
[85]		1%	The introduction of sisal fiber into concrete with ceramic waste allows its strength properties to be optimized to the required level.
[86]		1%	Compressive strength was increased by 15.81%, and splitting and bending strength were increased by 22.80% and 21.75%, respectively.
[87–89]	Banana fiber	1–5%	Increases in bending strength and durability characteristics were achieved.
[90]	Jute fiber	0.1%	Compressive, splitting, and bending strengths were increased by 6.77%, 6.91%, and 9.63%, respectively, compared to the control composition.
[34]		1.0%	The increases in compressive, tensile, and bending strength were 11.71%, 14.10%, and 11.04%, respectively.
[35,91,92]		0.05–1.0%	Increases in the strength properties of concrete composites, a decrease in water absorption, and an improvement in deformation properties were recorded.

Thus, based on the results of the analysis in Table 7, the following can be summarized. With regard to the range of optimal dosages of the considered types of plant fibers, namely coconut, flax, hemp, sisal, banana, and jute, this varies on average from 0.05% to 1.5% by weight of cement. With such percentages of dispersed reinforcement, positive effects are observed in most cases, expressed in the improvement of the physical and mechanical properties of concrete composites with an acceptable decrease in the slump of fresh concrete. Dispersed reinforcement of concrete composites with flax and hemp fiber, carried out in the works [22,23,44,45,49,52,53,84], made it possible to improve their strength properties, and the results of experimental studies are well comparable with the results presented in this study. The efficiency of hemp and flax fibers was lower than that of plant fibers such as coconut, sisal, and jute. First of all, this is due to the properties of the plant fiber itself. Coconut, sisal, and jute fibers are inherently stronger; therefore, they provide higher strength under bending and tensile loads. However, reinforcing concrete composite with banana fibers [87–89] leads to an increase in strength properties that is approximately similar to those achieved with dispersed reinforcement with hemp and flax fiber.

Thus, firstly, it is necessary to systematize knowledge on plant fibers in concrete according to the criteria of specific regions in the world, and secondly, it is necessary to indicate a specific place and advantages of the considered hemp and flax fibers. It turns out that in comparison with flax fibers, hemp fibers are superior in terms of concrete tensile strength, which allows us to recommend them, for example, for road surfaces in those regions where such an additive is available.

At the same time, some restrictions should be set, taking into account the fact that the rational dosage of fibers should take into account the features of concrete in each specific region; namely, the composition of the raw material base for concrete and the compatibility of such fibers with other components of concrete should be checked individually in each specific case.

Nevertheless, it is possible to arrange a certain rating of individual types of plant fibers used in concrete as a comparative analysis. In this rating, the leading three places can be taken by coconut, sisal, and jute fibers. Immediately after these, hemp and banana fiber can be placed, according to their characteristics; and finally, flax closes the specified rating [22,23,27,44,46,49,82–92]. Such a comparative analysis is useful for systematizing knowledge about plant fibers in concrete, and also allows one to focus on a specific raw material base in each specific region, and to predict the improvement of concrete properties due to the proposed recipe and technological method—modification of the concrete composition with plant fiber.

The determination of the performance characteristics of concrete reinforced with hemp and flax fibers requires long-term studies. The variability in the nature of these fibers requires careful study of the durability of composites. Certainly, without special treatment of plant fibers, the durability of concrete based on them will be inferior to conventional concrete, due to their degradation [76]. Chemical treatment of fibers [57] contributes to improvements in the durability and wear resistance of the composite, correlating with conventional concrete [88]. In addition, the use of plasticizing additives maintains the slump of concrete at the required level. Currently, plasticizers are quite a popular product. A wide range of such additives is presented on the modern construction market. As an alternative solution for increasing the mobility of concrete mixtures while improving the mechanical properties and maintaining the durability of the composite, an additive obtained from dead jellyfish mass can be used, the effectiveness of which has been studied previously [93].

It is worth noting the environmental aspects associated with the use of plant fibers in concrete. Plant hemp and flax fibers are a renewable raw material components, and do not require a significant degree of industrialization of the process of their processing and production in comparison with synthetic fibers. Concrete with HF and FF has improved strength properties, and can be easily used in the construction industry. There are also limitations associated with the use of hemp and flax fibers, which are determined by insufficient research on the durability of such concrete and its resistance to the effects of aggressive chloride and sulfate environments.

In the case of the modification of building materials by recipe-technological methods, it is necessary to evaluate the carbon footprint, which decreases or increases due to one or another method. In our case, it is proposed to use plant fibers in concrete in order to improve its properties and characteristics. It should be noted that, first of all, this leads to the rational use of natural resources and disposal of accumulated waste. On the other hand, increasing the strength and structural characteristics of concrete can ultimately help to reduce the consumption of cement or other components that are extracted using non-ecological methods and leave a carbon footprint on the atmosphere. Therefore, the desire for green technologies in concrete production, and specifically the use of plant additives, including fibers, has a positive effect on achieving the goal of sustainable development, and helps to reduce the carbon footprint in the modern environmental situation.

5. Conclusions

The properties of concrete dispersion-reinforced with hemp and sisal fibers were studied, and the optimal dosages of these fibers were determined.

(1) Dispersed reinforcement of HF and FF in the range from 0.2% to 1.4% does not significantly affect such a property as concrete density. The maximum increase in density achieved was 1.54%. Plant fiber has a low density and, when introduced in small quantities into the composition of heavy concrete, it cannot significantly affect the composite's density.
(2) HF and FF reduce the fresh concrete slump. The slump of the mixtures decreases as the content of plant fiber increases. At a maximum dosage of 1.4% HF and FF, the slump decreased by 58.1% and 61.3% compared to concrete without fibers.
(3) The optimal amount of HF, at which the maximum values of the strength properties of concrete and the minimum value of water absorption were observed, was 0.6%. The increases in compressive and flexural strength were 7.46% and 28.68%, respectively, water absorption decreased by 13.58%.
(4) The optimum amount of FF, which resulted in maximum values of concrete strength properties and minimum water absorption, was 0.8%. The increases in compressive and flexural strength were 4.90% and 15.99%, respectively, and water absorption decreased by 10.23%.
(5) The study of the concrete composite structure showed that the dispersed reinforcement of HF and FF affects the concrete structure, forming additional strengthening bonds with the cement matrix, giving the concrete a viscous nature of destruction.
(6) Comparison of the experimental results showed that hemp fiber gives a better effect in comparison with flax fiber.

The limitations of this study include the dosage ranges of hemp and flax fibers in concrete, the technology parameters associated with the preparation of plant fibers for use in concrete, and the need to use plasticizing additives to maintain concrete slump.

The new concrete compositions with hemp and flax fibers developed in this study have improved performance properties, and also meet the requirements of sustainable development. The most promising specific applications of hemp and flax fiber-reinforced concrete, especially in environments where strength and resistance to aggressive agents are critical, are in the strengthening and repair of various concrete products and structures, such as columns, beams, walls, and bridges. Concrete with hemp and flax fibers can be fully used in the construction of various buildings and structures, provided that positive conclusions are made on its durability in comparison with conventional concrete.

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