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Comparison of the Corrosion Resistance of Fiber-Reinforced Concrete with Steel and Polypropylene Fibers in an Acidic Environment

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Abstract: Rigid road pavements and industrial floors are not only subjected to moving traffic loads, but can also be exposed to environmental influences such as acid attack. The strength and corrosion resistance of fiber-reinforced concrete with steel fibers (15–25 kg/m^3) and polypropylene fibers (2–3 kg/m^3) in an acidic environment were compared. The influence of the amount and type of dispersed reinforcement on water absorption and the volume of permeable voids, which in turn characterizes the durability of fiber-reinforced concrete under the action of acids, was determined. The change in the compressive strength of the studied fiber-reinforced concrete after 12 months of exposure in an acidic environment was studied. At low dosages of fibers (15 kg/m^3 for steel and 2 kg/m^3 for polypropylene fibers), dispersed reinforcement has little effect on the corrosion resistance of concrete. In turn, the decrease in the compressive strength of concrete without fibers after 12 months of aging in acid medium led to a reduction in the design class of the concrete from C25/30 to C20/25. At a higher consumption of dispersed reinforcement (25–30 kg/m^3 of steel fiber and 2.5–3.0 kg/m^3 of polypropylene fiber), fiber-reinforced concrete had a higher corrosion resistance while maintaining the design compressive strength class C25/30. Structural changes in fiber-reinforced concrete after aging in an acidic environment were determined by X-ray diffraction analysis and compared with samples aged in water. It has been experimentally confirmed that the efficiency of polypropylene fibers in an acidic environment is not lower than that of steel fibers. However, the use of polypropylene fibers is economically advantageous.

Keywords: fiber-reinforced concrete; steel fiber; polypropylene fiber; corrosion resistance; acid resistance; strength; durability; microstructure

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Received: 14 December 2024
Revised: 21 January 2025
Accepted: 22 January 2025
Published: 1 February 2025

Citation: Kroviakov, S.; Kryzhanovskyi, V.; Hedulian, D. Comparison of the Corrosion Resistance of Fiber-Reinforced Concrete with Steel and Polypropylene Fibers in an Acidic Environment. *Constr. Mater.* **2025**, *5*, 6. https://doi.org/10.3390/constrmater5010006

1. Introduction

Highways and industrial floors are an integral part of industrial construction. They are critical structures that contribute to the uniform distribution of moving and static loads on the subgrade soils. According to the principle of mechanical operation, they represent a beam on an elastic base. Fiber concrete is widely used to ensure the high-performance characteristics of road pavements and industrial floors [1–9].

Such materials are a family of concrete composites, which can contain dispersed fibers from different materials (steel, polypropylene, basalt, glass, carbon, kevlar, etc.) that form a spatial reinforcing framework across the entire cross-section of the structure. Fiber concretes have high tensile and flexural strength [10–15], crack resistance [16,17], frost resistance [18–21] and low abrasion resistance [22,23], which is very important for floor structures and road pavements.

An additional problem in the operation of industrial floors is the exposure to various chemicals at the respective industry facilities, in particular acids. In the case of road rigid pavements, subgrade soils with high amounts of SO_4^{2-} sulfates and their presence in the infiltration water of the surrounding area can pose such a hazard [24–28].

In the study of corrosion resistance of ultra-high-performance concrete based on ordinary cement, with steel fibers of 13 mm length and 0.2 mm diameter, there was no negative effect of increasing the amount of fiber up to 2% by the volume of concrete. The compressive strength remained at 130 MPa after 1 year of curing in an acidic environment [29]. The authors of [30] noted an increase in the corrosion resistance of fiber concrete when using 0.15% polypropylene fibers with a length of 12 mm and a diameter of 0.03 mm. Increasing the fiber consumption to 0.3% did not improve the resistance of the concrete in an aggressive environment. The investigated dispersion-reinforced concretes were produced on the basis of ordinary cement; the compressive strength at the age of 28 days was 60 MPa. Fiber-reinforced concretes produced using ordinary cement and propylene fibers with a length of 19 mm and diameters of 0.03 mm and 0.1 mm, as well as a length of 50 mm and a diameter of 0.8 mm were moistened and dried in a 10% sodium sulfate solution. The holding period was 5 months (3 days of humidification and 4 days of drying—1 cycle). The positive influence of polypropylene fiber on corrosion resistance was found, and the greater efficiency of the combined fiber reinforcement of different lengths was also noted. The compressive strength of dispersion-reinforced concretes at the age of 28 days was not less than 40 MPa [31]. In [32], the effectiveness of dispersed reinforcement with different types of fibers on the fracture behavior of fiber concretes in aggressive environment is indicated. This was achieved by increasing the crack resistance and, as a consequence, increasing the time of further failure compared to control concrete samples without fibers. Certain modifications of fiber concrete with a steel filament consumption of 2% (with a length of 50 mm and a diameter of 2 mm) kept for one month in a 1% sulfuric acid solution shows a loss of the concrete's compressive strength not more than 0.32%, with a weight loss not more than 0.2%. The same fiber concrete composition after exposure to a 1% hydrochloric acid solution had a compressive strength loss of 0.7% and a weight loss of 0.23% [33]. Using experimental and statistical modeling techniques, the optimum amount of steel and polypropylene fiber for acid resistance (to H_2SO_4 and Na_2SO_4 solutions) was determined. In order to maintain the balance of compressive strength with minimum mass loss, it is recommended to use 0.04% of steel fibers of a 30 mm length and a 0.9 mm diameter in combination with 0.23% of polypropylene fibers of a 40 mm length and a 0.75 mm diameter [34]. Meanwhile, one study [35] reported the effectiveness of 0.25% of polypropylene fibers and 1% of steel fibers. Researchers [36] have emphasized the effectiveness of the fiber reinforcement of concrete in terms of increasing the resistance of airfield pavements after exposure to defrosting agents up to 70%. The authors of [37] point out the necessity of observing the technological process of fiber concrete preparation to resist the effects of chlorides. The clumping of the fibers used leads to an increase in the pore space in the concrete body, which leads to a decrease in strength and durability characteristics. The use of 12 mm long polypropylene fibers in the amount of 1 kg/m^3 contributed to increasing the resistance of fiber concrete under acid attack [38]. Researchers [39] have emphasized the positive effect of introducing steel fibers into the concrete mixture to resist acid corrosion. Microstructural analysis confirms the densification of the microstructure of the investigated concretes, based on which the pore structure of fiber concretes is improved and their resistance to acid attack is increased. The use of 1% of polypropylene fibers with a length of 30 mm contributed to an increase in resistance to sulfate corrosion of fiber concrete up to 54% with a compressive strength increase from 25 to 35 MPa. In a study of the flexural characteristics of steel fiber concrete, there was a negative effect of increasing the amount of steel fibers of a length of 35 mm up to 40 kg/m^3 of concrete. A decrease in the flexural strength of up to 65% was observed [40].

As can be seen from the analysis of the literature sources, only the geometric characteristics of the applied fibers were varied in the conducted experiments. There is no comparative analysis of polypropylene and steel fibers in terms of obtaining concrete of the same strength class based on the basic composition. It is notable that in all of the processed sources, fiber concretes were produced using Type I cement.

Accordingly, the aim of the authors was to compare the effect of steel and polypropylene fibers on the strength and structural changes in fiber-reinforced concrete based on Type II cement after 1 year of exposure to an acidic environment (pH = 3). This study is a continuation of the experiment [41] and provides a more complete picture in terms of the durability of dispersion-reinforced concretes for rigid road pavements and industrial floors. Such a direct comparison of the resistance to aggressive environments of similar concrete compositions with competing types of fiber reinforcement is of economic and environmental significance, as well as being important from a practical application point of view.

2. Materials and Methods

The following components were used in the production of fiber-reinforced concrete: Portland cement CEM II/A-S 42.5 R [42,43] produced by CRH Ukraine (Podilsky Cement PJSC, Podilsk, Ukraine), crushed granite breakstone of a 5–20 mm fraction [44,45], natural quartz sand of a 0–2 mm fraction [44,46], the water-reducing admixture MC-PowerFlow 3200 manufactured by MC-Bauchemie, Bottrop, Germany [47,48], steel hooked-end fibers (SFs) [49,50] produced by Stalkanat-Silur, Odessa, Ukraine, and polypropylene fibers (PFs) "Baumesh" [51,52] produced by Bautech-Ukraine, Odessa, Ukraine. The appearance of the fibers is shown in Figure 1, the characteristics of the fibers are given in Table 1.

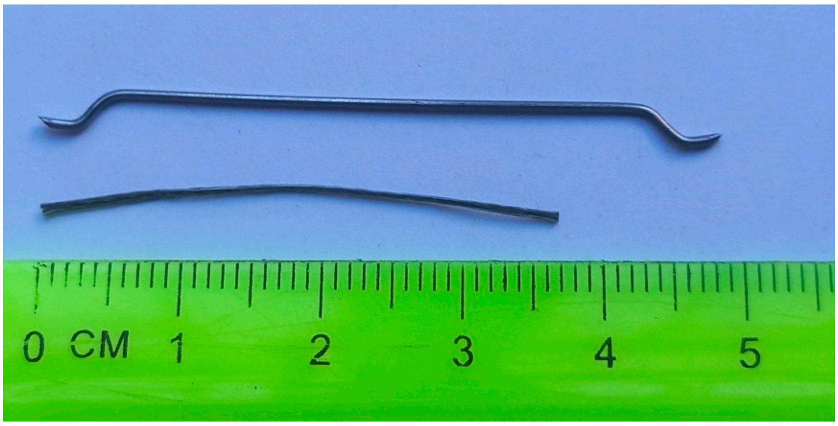

Figure 1. Steel hooked-end fiber (**above**) and polypropylene fiber (**below**).

Table 1. Characteristics of fibers used.

Fiber Type	Length, mm	Diameter, mm	Ultimate Tensile Strength, MPa	E-Modul, GPa
SF	50	1	1150	210
PF	36	0.68	530	2

Table 2 shows the compositions of the investigated disperse fiber-reinforced concretes according to [41].

Table 2. Compositions of the investigated concrete and fiber concretes with different fiber types [41].

No. of Mixture	Marking	Compositions, kg/m^3						
		Cement	Crushed Stone	Sand	SF	PF	MC-Power Flow 3200	Water
1	Control concrete (CC)	360	1110	780	–	–	3.40	180
2	Fiber concrete with steel fibers at 15 kg/m^3 (SF 15)			779	15	–	3.64	
3	Fiber concrete with steel fibers at 20 kg/m^3 (SF 20)			778	20	–		
4	Fiber concrete with steel fibers at 25 kg/m^3 (SF 25)			777	25	–		
5	Fiber concrete with polypropylene fibers at 2.0 kg/m^3 (PF 2)		1105	770	–	2.0	4.08	
6	Fiber concrete with polypropylene fibers at 2.5 kg/m^3 (PF 2.5)		1103	767	–	2.5		
7	Fiber concrete with polypropylene fibers at 3.0 kg/m^3 (PF 3)		1102	763	–	3.0		

Since a constant W/C = 0.5 was chosen for all the compositions under study within the framework of the experiment, the design workability S4 (slump 16–21 cm) [53,54] was achieved by changing the amount of plasticizer. As can be seen from Table 2, when using SFs, it is necessary to increase the dosage of plasticizer by 7% compared to the CC composition. In turn, the compositions of fiber concretes with PFs require an increase in the amount of plasticizer up to 20% in relation to the CC composition. This is explained by the large amount of PFs despite the lower dosage compared to SFs.

At a design age of 28 days, all the tested concretes conformed to compressive strength class C25/30 [55]. It is worth noting the equal effect of PFs and SFs on the flexural strength of concrete. Therefore, despite the lower dosage of PFs in the studied compositions, in the range of 2–3 kg/m^3, in comparison with the consumption of SFs at 15–25 kg/m^3, the flexural strength at the age of 28 days was in the range from 4.45 to 4.75 MPa [41]. It should be noted that flexural strength is an important quality indicator for concrete structures that are being operated in an acidic environment, as it largely determines the crack resistance of the material [56,57]. Under the influence of an aggressive acidic environment, the destruction of concrete as a composite material occurs mainly due to the development of cracks [58].

2.1. Water Adsorption and Volume of Permeable Voids

The permeability of concretes and fiber concretes plays an important role in their durability. Low permeability increases the resistance of concretes to moisture migration, which increases the protection against sulfate attack [59–61]. The test was carried out according to the methodology of [62]. For each studied composition from Table 2, six cubes of 10 × 10 × 10 cm were produced. The samples were cured in a climatic chamber (t = 20 ± 2 °C, relative humidity 65 ± 5%) for 28 days [63,64]. The specimens were then dried to a constant mass (A) for 24 h at 105 °C. The next step was to saturate the samples in 21 °C water for 48 h with the fixation of their weight (B), followed by boiling for 5 h. Subsequently, the specimens were cooled for 14 h to a temperature of 25 °C. After removing the moisture with a cloth, the mass of the sample was recorded (C). Then, the apparent mass of the samples suspended on a wire in water was measured (D). At the end, the water absorption was calculated according to Formula (1) and the volume of permeable voids was calculated according to Formula (2):

$$\text{Water adsorption, \%} = [(B - A)/A] \times 100 \quad (1)$$

$$\text{Volume of permeable pore space, \%} = (C - A)/(C - D) \times 100 \quad (2)$$

2.2. Corrosion Resistance

The determination of the corrosion resistance of dispersion-reinforced concretes was carried out after 12 months of acid exposure (pH = 3), which was obtained by mixing sulfuric acid and distilled water. Twelve 10 × 10 × 10 cm cube specimens were manufactured for each batch of fiber concretes under study. For the first 28 days of hardening, the specimens were stored in a normal curing chamber (t = 20 ± 2 °C, relative humidity 65 ± 5%) [63,64]. Then, the samples were divided into two series (6 specimens in each). The first series was cured in water and the second series in an acidic environment (pH = 3) [65]. Throughout the tests, visual evaluation of the specimens for defects was performed. After 6 and 12 months of exposure, the change in mass of the samples and their compressive strength were determined. Figures of the samples aged in water and in an acidic environment are shown in [41].

2.3. X-Ray Analysis

To determine the microstructural changes in the studied dispersion-reinforced concretes after exposure to an acidic medium, X-ray diffraction analysis was carried out. Diffractograms of the cement–sand matrix samples were recorded using an ElvaX Light SDD spectrometer (range 10–105° 2θ, using CuKα1 radiation (λ = 1.5406 Å) and operating at 40 kV and 15 mA).

The general flowchart of the conducted research is shown in Figure 2.

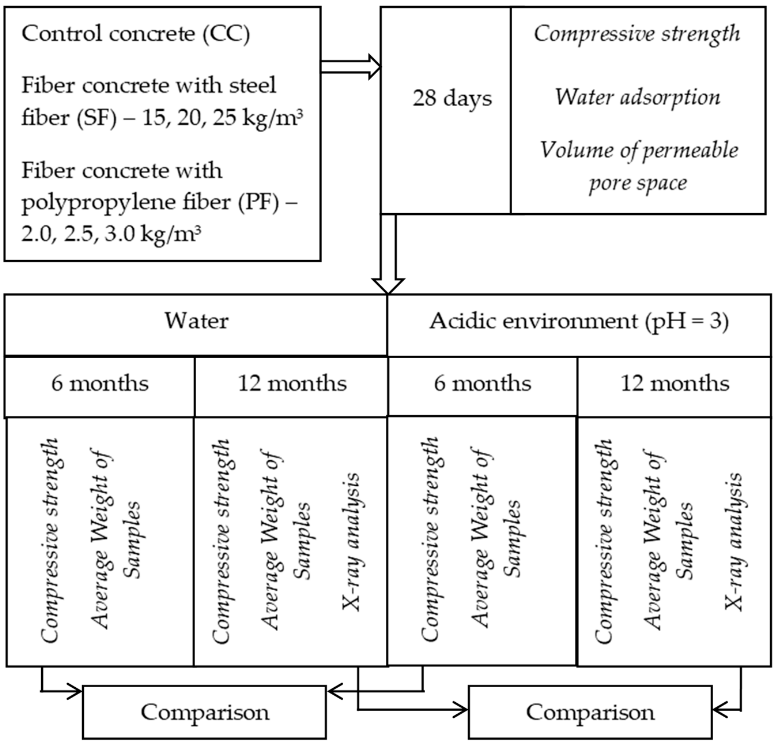

Figure 2. Flowchart of investigated concretes and fiber concretes.

3. Research Results and Analysis

3.1. Water Adsorption and Volume of Permeable Voids

Figure 3 reflects the data on the water absorption and volume of the permeable voids of the investigated fiber concretes.

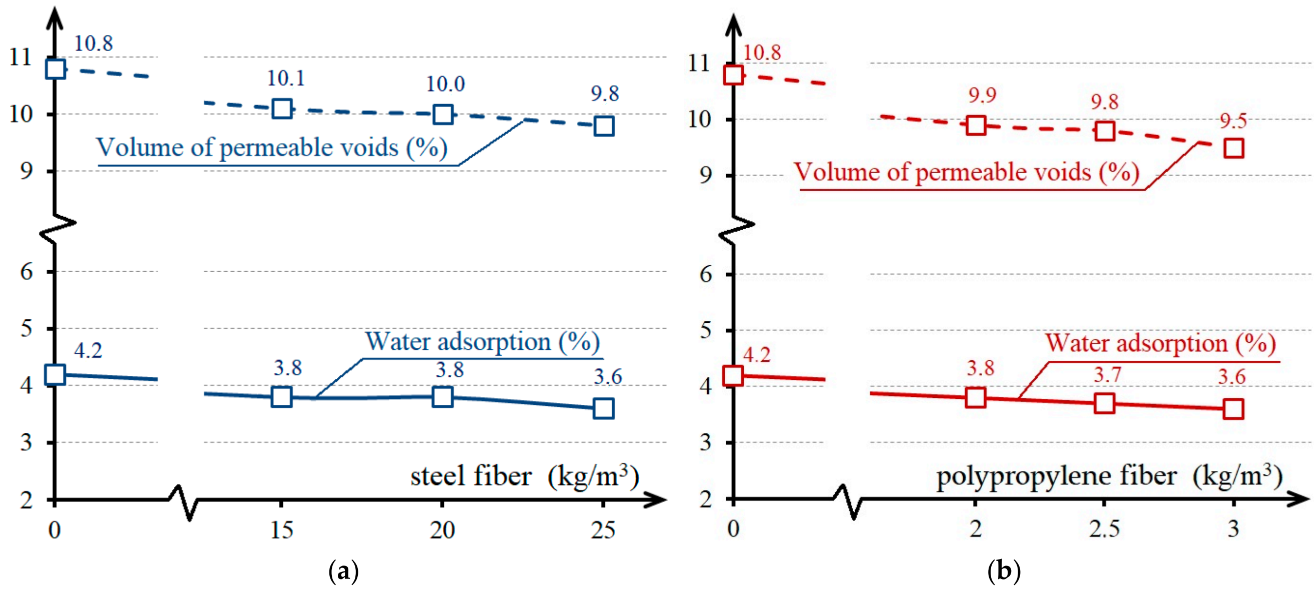

Figure 3. The influence of the SF (**a**) and PF (**b**) amounts on the water adsorption and volume of the permeable voids of the investigated fiber-reinforced concretes.

The data in Figure 3 show the positive effect of the introduction of dispersed reinforcing fibers of both types on the reduction in water absorption and the volume of permeable voids. The decreased water absorption of the fiber concretes ensures their lower open porosity, which is in agreement with previous studies [66,67]. Also, from the diagram in Figure 3b, the better effect of PFs in terms of reducing the volume of permeable voids can be seen. This can be explained by the higher quantitative content of PFs compared SFs, which prevents moisture migration into the body of the fiber concrete.

3.2. Corrosion Resistance

As noted above, the corrosion resistance of fiber-reinforced concrete in an acidic environment was determined by comparing the properties of samples kept in water or in an acidic environment of pH = 3 [65]. The compressive strength of the studied fiber concrete and the CC composition after 6 months [41] and 12 months of exposure, as well as the amount of reduction in the concrete's compressive strength in an acidic environment, are shown in Table 3.

After 12 months of exposure to an acidic environment, individual corrosion-induced surface defects were observed on the samples, as shown in Figure 4. However, the overall geometric dimensions of the samples with both fiber types did not change.

The diagrams shown in Figure 5 were drawn using the data from Table 3. The analysis of the data allows us to conclude that, after 6 and 12 months of water curing, the effect of dispersed steel and polypropylene fiber reinforcement on the compressive strength of the concrete is similar to the effect of the fibers on its strength at the standard age.

Under the influence of an acidic environment, the nature of the fibers' effect on changes to the concrete's compressive strength. Based on this, in a non-aggressive water environment, SFs showed a slightly higher efficiency, while after aging in an acidic environment, the degree of influence of different fiber types on the concrete's compressive strength actually leveled out. It is also notable that, in an acidic environment, at low dosages of fibers (15 kg/m^3 for SFs and 2 kg/m^3 for PFs), dispersed reinforcement has a small impact on compressive strength and does not increase the corrosion resistance of the concrete. At higher amounts of fibers (20–25 kg/m^3 for SFs, and 2.5–3.0 kg/m^3 for PFs), the studied fiber-reinforced concrete has a higher corrosion resistance. It is also remarkable that the loss of compressive strength after the first 6 months of exposure to aggressive environments is more sensitive than in the next 6 months for the CC composition and the compositions with dispersed reinforcement.

Table 3. The compressive strength of the studied fiber concrete after 6 and 12 months of exposure to water and an acidic environment.

Mixture	6 Months of Exposure			12 Months of Exposure		
	Strength After Soaking in Water, MPa	Strength After Aging in an Acidic Environment, MPa	Strength Reduction	Strength After Soaking in Water, MPa	Strength After Aging in an Acidic Environment, MPa	Strength Reduction
CC	45.4	34.4	24%	52.9	33.7	36%
SF 15	49.5	36.4	26%	55.2	36.0	35%
SF 20	52.6	40.4	23%	56.5	38.4	32%
SF 25	53.8	41.6	23%	56.8	40.3	29%
PF 2	48.2	36.2	25%	53.6	35.3	34%
PF 2.5	50.1	39.4	21%	54.8	37.9	31%
PF 3	52.4	42.0	20%	56.6	41.1	27%

(a)

(b)

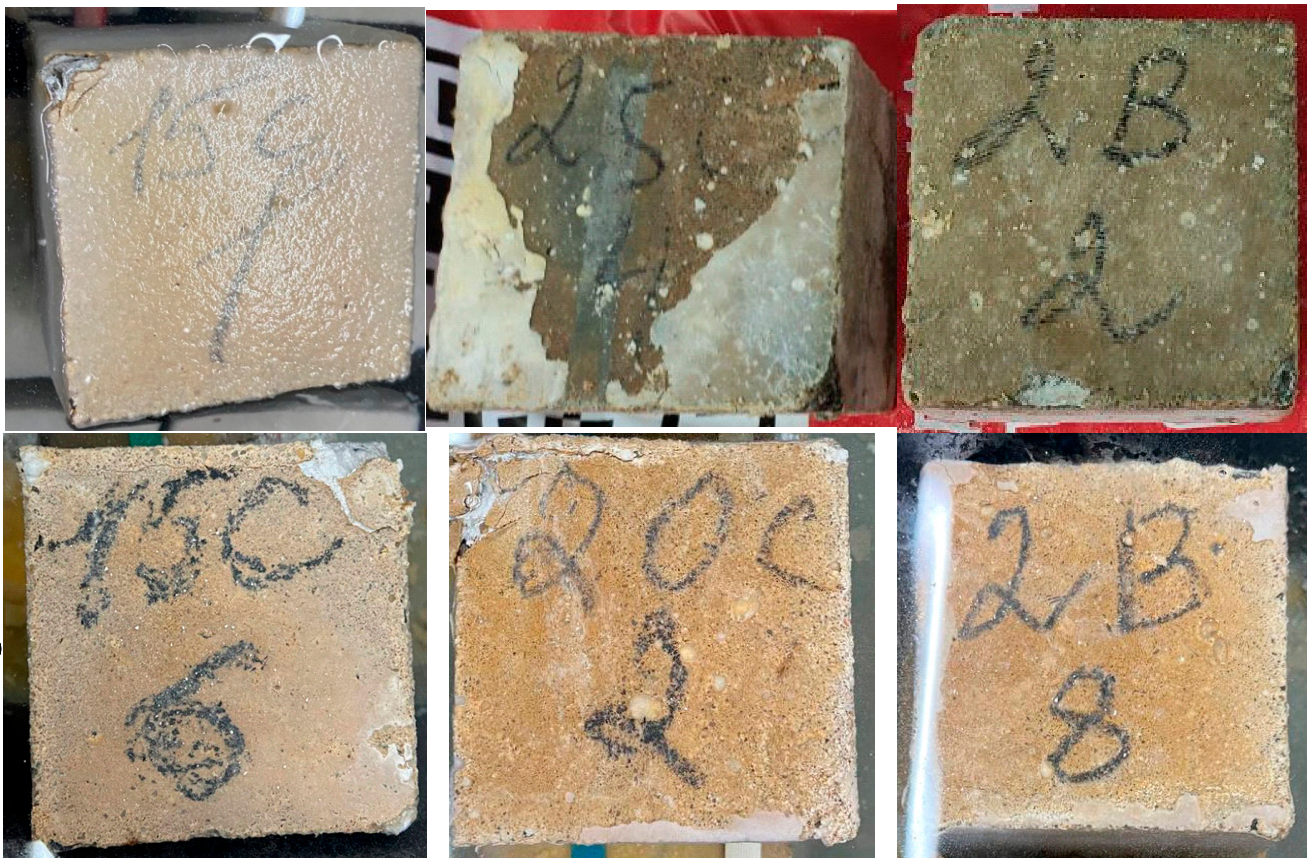

Figure 4. The appearance of the tested fiber concrete samples after 6 months (**a**) and 12 months (**b**) of aging in an acidic environment of pH = 3.

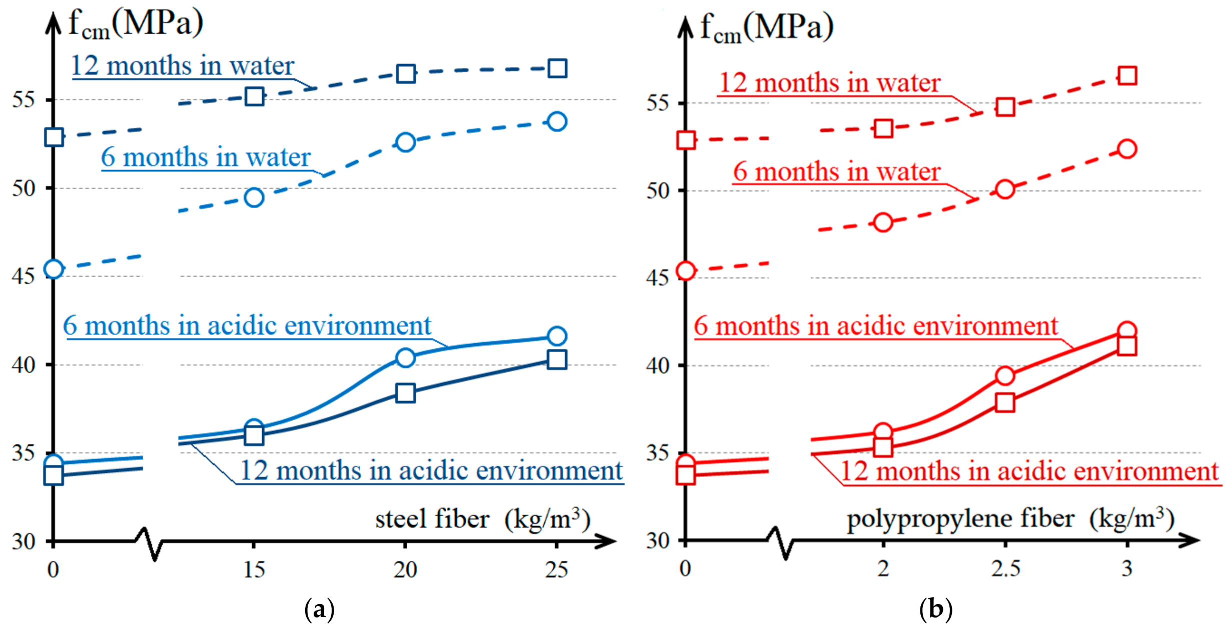

Figure 5. The influence of the SF (**a**) and PF (**b**) dosage on the change in compressive strength of the concretes after 6 and 12 months of exposure to water and an acidic environment.

The positive impact of dispersed reinforcement on corrosion resistance in an acidic environment is explained by the fact that, as a result of the reaction of concrete components with acids, calcium carbonate $CaCO_3$ is formed, which is insoluble in water. Over time, some of the calcium carbonate can turn into ettringite (a highly insoluble calcium hydrosulfoaluminate) [68]. Accordingly, the accumulation of calcium carbonate in pores and microcracks leads to concrete cracking [56,68,69]. Such processes are confirmed, in particular, by the fact that after 6 months of exposure to an acidic environment, the mass of specimens differed from the mass of similar specimens aged in water by no more than 1.9% (Table 4) [41]. However, after 12 months of aging, the mass of the samples in an acidic environment due to the appearance of individual defects was less than the mass of similar samples aged in water by up to 2.3% for dispersion-reinforced concrete and 7.5% for the CC composition.

The above-described main mechanism of the corrosion failure of concrete in an acidic environment was also confirmed by a comparative X-ray diffraction analysis of the cement–sand matrix of concrete samples with a CC composition after 12 months of aging in water and an acidic environment (Figure 6).

It was found that the main hydrate phases in the matrix are portlandite and calcite. Aggregates are represented by quartz and albite (feldspar). In the samples aged in an acidic environment, the formation of ettringite was established (Figure 6b). The most probable reaction is the interaction of acid with calcium carbonate, a product of the carbonization of calcium hydroxide: $CaCO_3 + H_2SO_4 = CaSO_4{\cdot}2H_2O + H_2CO_3$ ($H_2O + CO_2$). The next reaction is the formation of ettringite: $C3AH6 + 3(CaSO_4{\cdot}2H_2O) + 20H_2O = C3A$ $3CaSO_4{\cdot}32H_2O$.

Table 4. Changes in the weight of the investigated fiber-reinforced concretes after 6 and 12 months of aging in water and an acidic environment.

Mixture	Average Weight of Samples Before Aging, g	6 Months of Exposure			12 Months of Exposure		
		Average Weight of Samples After Aging in Water, g	Average Weight of Samples After Aging in Acidic Medium, g	Difference	Average Weight of Samples After Aging in Water, g	Average Weight of Samples After Aging in Acidic Medium, g	Difference
CC	2420	2422	2437	+0.6%	2431	2248	−7.5%
SF 15	2440	2442	2404	−1.6%	2452	2407	−1.8%
SF 20	2437	2449	2404	−1.8%	2463	2407	−2.3%
SF 25	2446	2438	2402	−1.5%	2451	2408	−1.8%
PF 2	2423	2422	2402	−0.8%	2426	2399	−1.1%
PF 2.5	2425	2423	2376	−1.9%	2425	2369	−2.3%
PF 3	2426	2425	2419	−0.2%	2428	2413	−0.6%

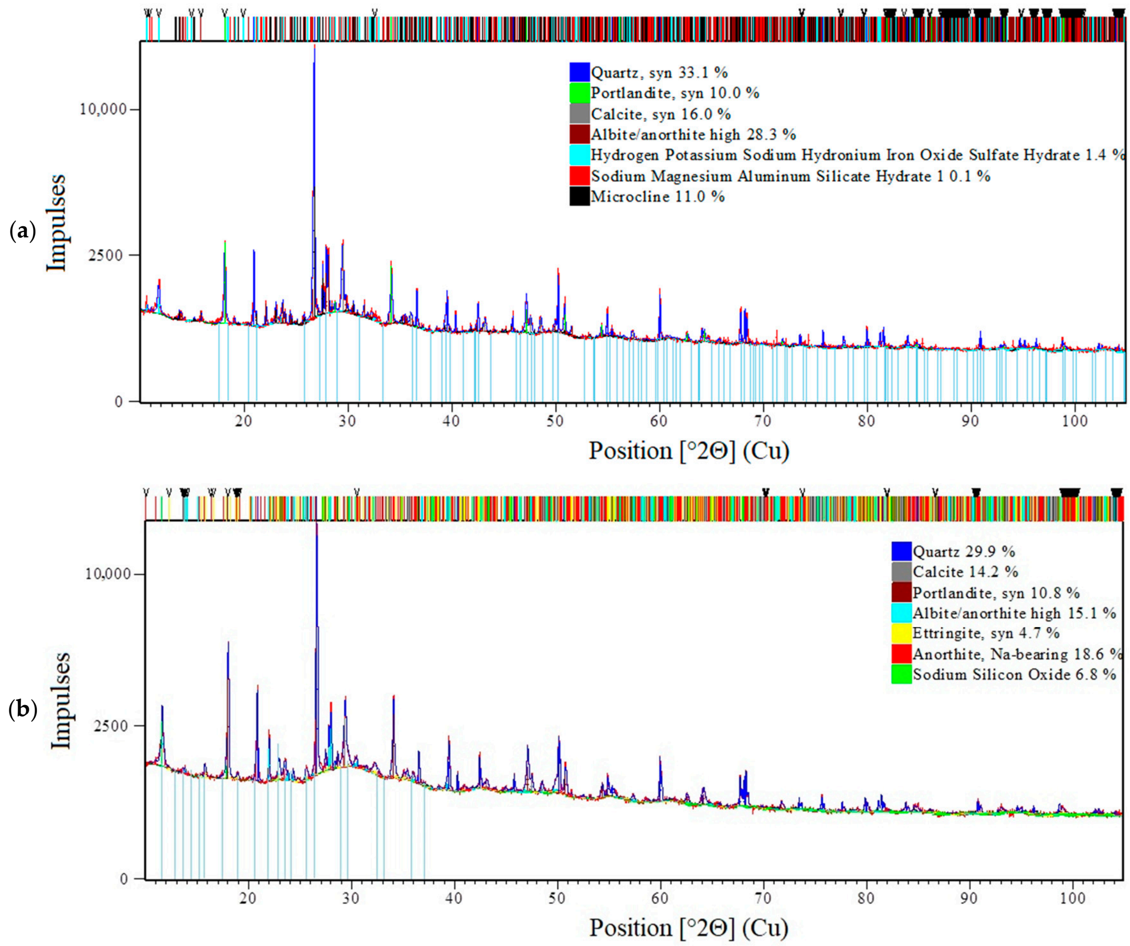

Figure 6. The results of the X-ray analysis of the cement–sand matrix of concrete samples with a CC composition after 12 months of aging in water (**a**) and an acidic environment (**b**).

In other words, dispersed reinforcement with SFs and PFs contributes to increasing the corrosion resistance of concrete under conditions of the accumulation of hardly soluble compounds in its pores and microcracks, which cause internal stresses. Fiber helps redistribute these stresses, which inhibits the destruction of concrete as a composite material. A similar positive result from the use of dispersed reinforcement in aggressive environments was obtained, for example, in [58,68]. At the same time, the effectiveness of dispersed reinforcement significantly depends on the number of filaments, which should be rational for each type of fiber [68,69].

4. Conclusions

The paper analyses the changes in physical, mechanical and structural properties of fiber concrete for road pavements and industrial floors after 12 months of exposure in an aggressive acidic environment. The obtained experimental data make it possible to draw the following conclusions:

- The use of dispersed reinforcement with both types of fibers reduces the water absorption of concrete by up to 30% and the volume of permeable voids by up to 11% in comparison with control concrete without dispersed reinforcement;
- A low dosage of steel and polypropylene fibers (15 kg/m^3 and 2 kg/m^3) does not lead to an increase in the corrosion resistance of fiber concretes. For the effective operation of industrial floors and rigid road pavements, it is recommended to use steel fibers in the amount of 20–25 kg/m^3 and polypropylene fibers from 2.5 to 3 kg/m^3. At the same time, visual inspection showed the absence of geometrical changes in the specimens after sulfate exposure, and the obtained results of compressive strength confirmed the effectiveness of dispersed reinforcement in terms of maintaining the design class of the concrete as C20/25 even after 12 months of exposure to an aggressive environment;
- The possible mechanism of resistance of the fiber concretes in an acid medium on the basis of strength indicators and X-ray phase analysis is described, and the scenario of microstructural changes in the investigated composites is proposed.

In general, regardless of the lower consumption of polypropylene fibers, their efficiency is not lower than that of steel fibers. This makes the use of polypropylene fibers cost-effective. In addition, the production of 2.5–3 kg of polypropylene fiber produces a smaller carbon footprint than the production of 20–25 kg of steel fiber.

A high corrosion resistance makes it possible to recommend fiber concretes with polypropylene fibers for industrial floors, road pavements and warehouses at enterprises associated with the use or production of substances creating an acidic environment, for example, at mineral fertilizer factories.

Further research is planned in order to study the corrosion resistance of road pavements and industrial floors with hybrid reinforcement using steel and polypropylene fibers. The aim will be to study not only compressive strength, but also flexural strength and abrasion resistance after acid attack, as these parameters determine the quality and operational reliability of these types of structures.

Author Contributions: Conceptualization, V.K. and S.K.; methodology, S.K., V.K. and D.H.; formal analysis, V.K. and S.K.; resources, V.K. and D.H.; data curation, D.H. and S.K.; writing—original draft preparation, S.K. and V.K.; writing—review and editing, S.K. and D.H.; visualization, S.K. and V.K.; supervision, S.K. and V.K.; project administration, D.H. and S.K.; funding acquisition, V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting this study are available from the author on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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