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Recovery and Use of Recycled Carbon Fibers from Composites Based on Phenol-Formaldehyde Resins

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Abstract: The technical feasibility of the recycling of specific polymeric composite materials was evaluated. Two types of carbon composites, both with phenol-formaldehyde resin but with different reinforcement, were studied. It was discovered that the solvolysis with the oxidizing agents used in an acidic environment allowed for the achievement of a high-efficiency fiber extraction. The extracted secondary carbon fibers had a high degree of purity (95–99.5% of resin was removed). Fiber thickness slightly decreased during the process (on average, by 20%). The use of chopped secondary fibers (3–9 mm fiber length) for concrete reinforcement produced a positive effect. Hence, the compressive and bending strength of the concrete blocks were accordingly 1.5% and 16% higher in comparison with the control sample. The use of secondary carbon fabric for the production of composite materials a good result: the effective tensile strength of CFRP samples reinforced with recovered fabric is only lower by 4.5% in comparison with virgin fabric.

Keywords: polymeric composite materials; phenol-formaldehyde resins; solvolysis; pyrolysis; recycling; carbon fibers; fine-grained concrete

Citation: Kulikova, Y.; Sliusar, N.; Korotaev, V.; Babich, O.; Larina, V.; Ivanova, S. Recovery and Use of Recycled Carbon Fibers from Composites Based on Phenol-Formaldehyde Resins. *Recycling* **2022**, *7*, 22. https://doi.org/10.3390/recycling7020022

Academic Editors: Michele John and Wan-Ting (Grace) Chen

Received: 1 March 2022
Accepted: 30 March 2022
Published: 2 April 2022

1. Introduction

The number of products that include composite materials is constantly increasing. A significant growth in the manufacture of products made of reinforced polymers can be observed in the aerospace, automotive, and construction industries. According to some estimates, the demand for polymer composite materials will reach 150 thousand tons by 2020, which is 52% more than in 2014 [1,2]. Considering the life cycle of products, the volume of to-be-disposed reinforced composite materials could reach 1–3% of their annual production [3–6].

The vast majority of polymer composite materials consist of carbon fiber and thermosetting resins (usually epoxy and formaldehyde-based), which provide chemical, thermal, and mechanical stability to the material. CFRP stability from a chemical point of view is explained by the irreversible cross-linking process that occurs during curing and which in turn poses the complexity of their processing [7].

As the use of composite materials is expected to increase [8], it is important to find a solution to cope with the growing volume of CFRP waste. Currently, most polymer composite materials based on phenol-formaldehyde resins are sent to landfills [9]. However, in the future, with tightening landfill regulations and end-of-life directives in European

countries [8], the lack of CFRP processing technologies can complicate the process of their production and use.

There is practically no data on the development of CFRP recycling technologies in Russia [1,10]. However, this issue is being quite actively addressed in the EU and Japan. In these countries, the most popular CFRP recovery technologies are based on physical (mechanical and radiation) and thermal destruction (combustion, gasification, and pyrolysis). The mechanical method includes crushing and grinding, the main product of which is a mixture of resin and fibers of different grinding sizes [11].

The advantage of the mechanical treatment is the simplicity of the equipment, its versatility, and the absence of harmful emissions into the air. The technology also has a number of disadvantages. It involves a high degree of damage and a small amount of carbon fibers, which limits its application.

The general principle of radiation methods is based on the destruction of polymer resin by high-energy radiation. The main drawbacks of this method are the excessive radiation load for the environment and mankind as well as the possibility of recycling only reinforced polymer thin-layer plates (less than several millimeters) [12].

Among the listed thermal methods, the most promising is supposed to be pyrolysis at temperatures from 400 to 800 °C [10,12]. The group of thermal methods is characterized by high-energy consumption, a high level of environmental impact, and the production of low-quality carbon fiber [10,12]. Initially, pyrolysis was considered a viable technology, but it later appeared to be ineffective due to the incomplete removal of pyrolytic carbon from the surface of fibers, which leads to the reduction of their strength and the narrowed field of their secondary use.

Recently, special attention has been paid to the development of CFRP chemical recovery methods. Solvolysis is a special case of exchanging decomposition reactions when an appropriate solvent (supercritical water, alcohols) with alkali metal salts is used as a medium to depolymerize resin in order to release fibers [10]. This approach, as a rule, requires moderate temperatures (from room temperature to 400 °C), which makes it possible to recycle monomers and high-quality fibers [3,10,13].

The advantages of chemical methods are low energy consumption, high effectiveness in removing polymer resins (90–98%), and the preservation of reinforced fiber properties [10]. The level of solvolysis' environmental impact (global warming potential, ozone depletion potential, ecotoxicity, etc.) is lower in comparison to other CFRP recycling technologies [1].

Solvolysis can be implemented by using a wide range of solvents, temperatures, pressures, and catalysts. Its benefit, in comparison with pyrolysis, is that lower temperatures are usually required to break down polymers. A review of scientific data revealed a wide range of reagents used for the destruction of the polymer resin; most often, the process of solvolysis is carried out using water (under subcritical conditions at a pressure of 20–50 bar and a temperature of 300–650 °C) [7,8,14–17], alcohols (ethyl, methyl), phenols, and amines (tetralin, ethanolamine, octylamine, indoline, dihydroanthracene) [3,18]. The possibility of using strong acid solutions (nitric and sulfuric) [19] and oxidants [20] is of interest.

Oliveux et al. [21] studied the extraction of carbon fibers from a composite material based on epoxy resin. In this study, secondary fiber was extracted by solvolysis at a temperature of 320 °C and a pressure of 18 MPa; water and acetone at a 20:80 volume ratio were used as solvents. Recycled fiber was used to produce CFRP with different types of fiber distribution. The mechanical properties of the produced CFRP were found to be comparable to those of virgin fiber materials.

There is a significant amount of research devoted to the successful experience of using recycled carbon fiber for the reinforcement of composite materials [14,22–24]. However, these papers describe the experience of using a secondary fiber extracted from materials based on epoxy and not phenol-formaldehyde resins.

Oudheusden et al. [7] showed that recycled fibers can be used to reinforce new composite materials and concretes [18]. Fiber-reinforced concrete with dispersed reinforcement

is characterized by improved mechanical characteristics (40–60% increase in compressive strength, 100–200% bending, 500% impact strength increase), increased adhesion of concrete to reinforcement, improved ductility, reduced early shrinkage, lower mass, and frost resistance [25].

The aim of this work was to study the processing of polymer composite materials based on phenol-formaldehyde resins by the solvolysis method and to find ways of using recycled fibers to reinforce concrete and produce CFRP. The novelty of this work lies in the extraction and use of carbon fibers from CFRP based on a phenol-formaldehyde resin, whereas most existing research focuses on recovering fibers from epoxy resins [2,5,7–9,14,21–24].

2. Materials and Methods

2.1. Materials

All studies were carried out on CFRP samples with phenol-formaldehyde resin, but reinforced with two different types of carbon fabrics: Ural-Tr knitted fabric (SvetlogorskKhimvolokno, Svetlogorsk, Russia) and Porsher 2/2 6K-300 twill fabric (Porsher Inc., Eclose Badinieres, France). The choice of the material was determined by their accessibility, significant volumes of their production in Russia, and the lack of scientific data on their recycling.

Ural-TR carbon fabric is produced through the heat treatment of viscose yarn at a temperature of 1000–2200 °C. Porsher fabric is made from polyacrylonitrile fiber using the process of multi-stage heat treatment at a temperature of 200–3000 °C. The main technical characteristics of carbon fabric are presented in Table 1.

Table 1. The main technical characteristics of the carbon fabrics used.

Parameter	Ural Fabric	Porsher Fabric
Carbon content	90–99.9%	95–99.9%
Density	1.4 g/cm^3	Surface density 300 g/m^2
Heat resistance	Inert env. up to 3000 °C In oxidizing env. up to 400–450 °C	n/a n/a
Chemical resistance	Resistance to acids, alkalis, solvents at any temperature	Resistance to acids, alkalis, solvents at any temperature
Mechanical properties	Thread strength 1.2–1.5 GPa Modulus of elasticity 60 GPa	Fiber tensile strength 4.3 ± 0.2 GPa Fiber tensile modulus 245 ± 6 GPa
Characteristics of fabric weaving	Knitted weaving	Twill weave type 2/2, fiber orientation 0°/90°, filament 6 K (6000 fibers per filament)

In this work, we studied CFRP made with the use of the phenol-formaldehyde resin SFZh-323 (Scientific and Production Company Astat, Dzerzhinsk, Russia) in a liquid alcohol solution before curing. After preparation of the samples, the resin was in thermosetting form (resol) [26].

2.2. Extraction of Fiber

The solvolysis method was chosen to extract the carbon fiber as it ensures the maximum preservation of a fiber structure, and it is more energy-efficient in comparison to the thermal methods. A scientific data review revealed that there are two main approaches to the implementation of the solvolysis process:

- Solvolysis with organic resin destruction by using strong oxidants in an aggressive environment or critical/subcritical conditions (pressure of 100 bar, temperature above 300 °C) [18];
- Solvolysis using organic solvents, with the dissolution of resin components that provide fiber extraction [27].

A glass reactor (shown in Figure 1) with a stirrer and external heating was used for solvolysis (Büchi AG, Uster, Switzerland). The temperature ranged from room temperature to 220 °C, the duration of the process varied from 1 to 24 h, and the pressure used was from atmospheric to 4 bar.

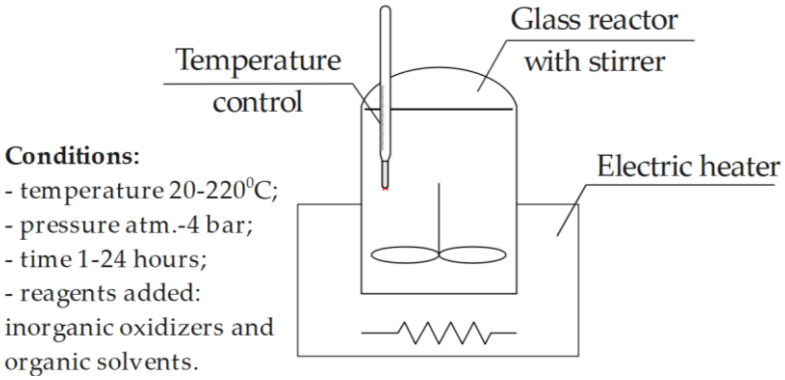


Figure 1. Experiment scheme of carbon fiber extraction in the process of solvolysis.

Samples were cut with a hand saw before loading into the reactor:

- Samples with Ural fabric were cut into 40 × 20 × 20 mm rectangular blocks;
- Samples with Porsher fabric were cut into 3 × 60 × 60 mm square plates.

Stirring in the reactor was disabled during the process. Due to the specific technological characteristics of the reactor, it was cooled by air after the process was completed.

The research was carried out in 2 stages. The optimal conditions of solvolysis were examined at the first stage of the experiments. All the experiments of the first stage were carried out on a composite material reinforced with Ural fabric.

The influence of carbon fabric weaving on the efficiency of phenol-formaldehyde resin removal was checked at the second stage. The change in fiber thickness and the purity of its surface (the degree of removal of the polymer resin) were assessed using electron microscopy. For this, a scanning electron microscope Hitachi S-3400N (Hitachi, Japan) was used.

2.3. The Use of Secondary Fiber for Reinforcing Concrete

In order to evaluate possible prospective directions for the use of secondary carbon fiber, studies were carried out in two directions: reinforcement of concrete and polymer composite materials [28].

The possibility of using secondary carbon fiber for the reinforcement of concrete was evaluated through the production and testing of experimental beams. Portland cement M-400 (LafargeHolcim Russia, Moscow, Russia) and river sand (grain size of 2.5–3 mm) were used for the production of standard experimental beams. The cement:sand:water components were mixed manually at a ratio of 1:3:0.4. The samples were hardened in a steaming chamber for over 24 h. Two key parameters—flexural strength and compression—were tested. During the production of the beams, the mobility of the concrete mix was continuously monitored by a cone spread molded from the concrete mix; deviation from the standard values was not observed (mixture formula correction was not required).

Fibers obtained during solvolysis were manually chopped to a predetermined size. The size of added fiber varied from 3 to 9 mm, the fiber dose was 0.2% and 0.6% of the cement mass. The size and amount of fiber were selected based on scientific data analysis [29].

Determining the strength of the concrete was in accordance with Russian Standard methodology (GOST 10180-2012) [30]. The main idea behind the method was to measure the minimum forces that destroy specially made control concrete samples when they are statically loaded (load increased constantly), and then to calculate the stress under these

efforts. The "Universal tensile testing machine R-50" (GOST, Neftekamsk, Russia) was used for testing (measurement range: −0–500 KN).

In order to assess the uniformity of carbon fiber distribution in concrete, scanning electron microscope Hitachi S-3400N (Hitachi, Japan) was used.

2.4. Production of Composites Reinforced with Secondary Carbon Fiber

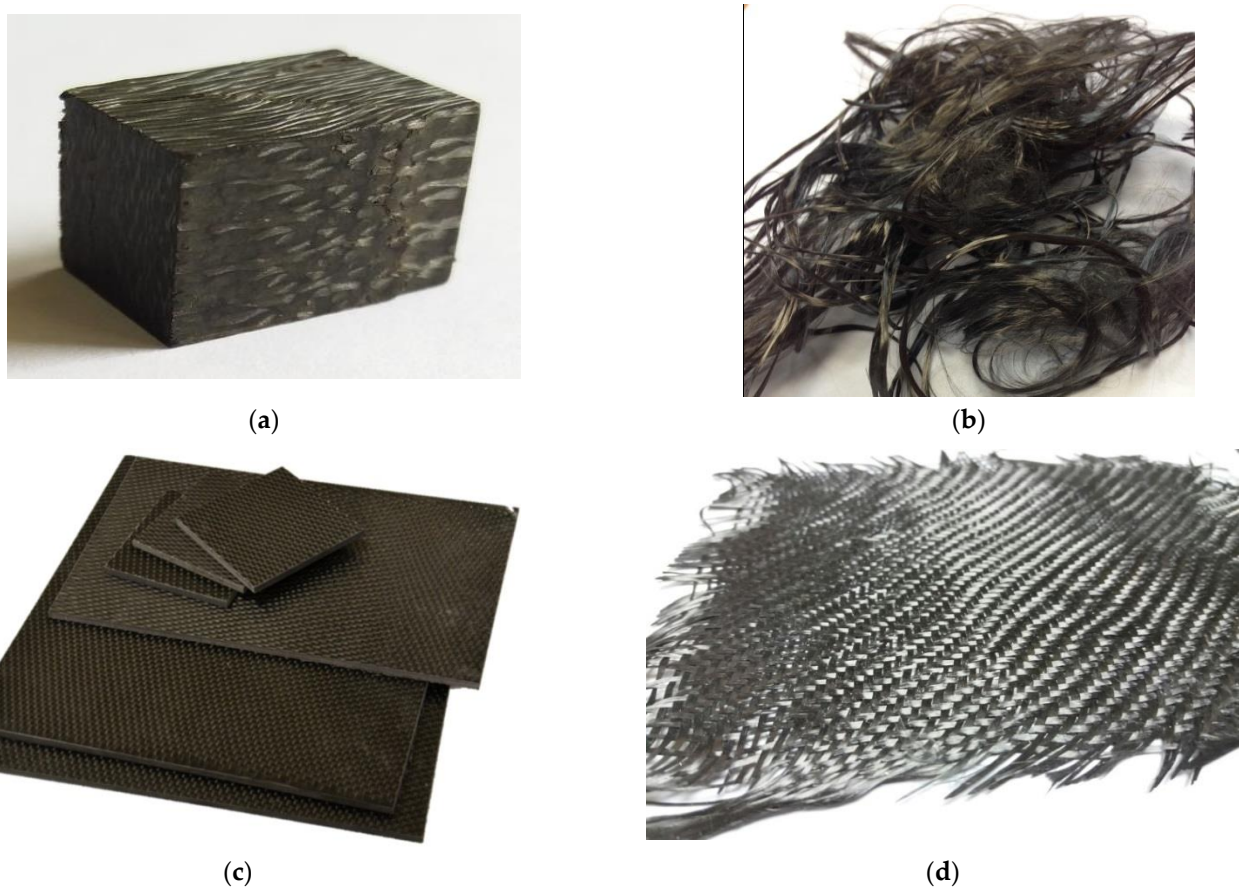
Composites were produced from primary and secondary Porsher fabric (twill 2/2 6K-1200–300) with epoxy resin. The samples were molded by vacuum. They underwent tensile testing according to the ASTM D 3039 method [31] as it is the main parameter for secondary rolled products that is subjected to changes during molding [32]. The samples were tested in a Zwick Z100 test machine (Zwick Roell Group, Ulm, Germany) with a maximum compressive force of 100 kn.

The main idea behind the method was to monotonically load thin flat rectangular CFRP strips and to record the load. The ultimate strength of the material can be determined from the maximum load carried before failure. Based on the results of coupon strain monitoring, the stress–strain response of the material was determined, from which the ultimate tensile strain, the tensile modulus of elasticity, Poisson's ratio, and the transition strain could be derived.

3. Results and Discussion

3.1. Fiber Extraction by Solvolysis

The results of the implementation of the solvolysis method for fiber extraction are presented in Tables 2 and 3, and Figures 2–4.



(**a**) (**b**) (**c**) (**d**)

Figure 2. The result of processing CFRP by the solvolysis method: CFRP before the process (**a**) with Ural fabric and (**c**) with Porsher fabric; (**b**,**d**) recovered fibers after solvolysis at the second stage.

Table 2. Results of fiber extraction by solvolysis (Stage 1: Selection of optimal conditions of solvolysis).

Reagent	Experem. Cod	Boiling Time, min	Temperature, Degrees C	Pressure, Bar	Results	Change in Mass, %
Solvolysis using strong oxidants (all results were obtained in experiments using CFRP with the textile Ural-Tr)						
H_2SO_4 (50%)	A1	120	120–130	2	Almost absent	-2 ± 0.5
HNO_3 (50%)	A2	60	90	2	None	-0.3 ± 0.1
$K_2Cr_2O_7$ (pure)	A3	120	110	4	Negligible fiber release	-6 ± 0.7
CrO_3 + H_2SO_4 (50%)	A4	480	120–130	4	Fibers are completely released	-21 ± 2.6
CrO_3 + HNO_3 (50%)	A5	480	90–95	4	Fibers are completely released	-20 ± 1.3
HNO_3 (50%) + H_3PO4 (50%) + K_2CrO_4	A6	480	90–100	4	Fibers are completely released	-22 ± 2.4
H_2SO_4 (30%) + H_2O_2 (30%)	A7	60	110	Atm.	Fibers are completely released	-23 ± 1.1
Solvolysis using organic solvent (all results were obtained in experiments using CFRP with the textile Ural-Tr)						
$(C_2H_4)_3N$ (pure)	A8	120	90	Atm.	None	-
C_2H_5OH (92%)	A9	120	80–85	2	Swelling	$+2 \pm 0.3$
C_3H_7NO (pure)	A10	120	213–220	2	None	-
$C_6H_5CH_3$ (pure)	A11	120	110–112	Atm.	None	$+0.8 \pm 0.1$
CH_3—C(O)—CH_3 (pure)	A12	1440	20–24	Atm.	None	$+1.2 \pm 0.1$

Table 3. Results of fiber extraction by solvolysis (Stage 2: The influence of carbon fabric weaving and the duration of the process on solvolysis effectiveness).

Reagent	Experem. Cod	Material	Boiling Time, min	Results	Change in Mass, % of Initial Sample Mass	Degree of Resin Degradation, % from Initial Content in CFRP
H_2SO_4 (30%) + H_2O_2 (30%)	B1	CFRP with Porsher textile	30	The fibers contained polymer resin residues	-22.1 ± 0.9	68.0 ± 2.8
H_2SO_4 (30%) + H_2O_2 (30%)	B2	CFRP with Porsher textile	60	Fibers were released, but there were foci containing resin residues	-29.2 ± 1.6	89.8 ± 4.9
H_2SO_4 (30%) + H_2O_2 (30%)	B3	CFRP with Porsher textile	90	Fibers were completely released	-31.4 ± 1.8	96.6 ± 5.5
H_2SO_4 (30%) + H_2O_2 (30%)	C1	CFRP with Ural textile	30	Fibers were released, but there were foci containing resin	21.4 ± 0.8	89.2 ± 3.3
H_2SO_4 (30%) + H_2O_2 (30%)	C2(=A7)	CFRP with Ural textile	60	Fibers were completely released	23.0 ± 1.1	95.8 ± 4.6
H_2SO_4 (30%) + H_2O_2 (30%)	C3	CFRP with Ural textile	90	Fibers were completely released	23.4 ± 0.7	97.5 ± 2.9

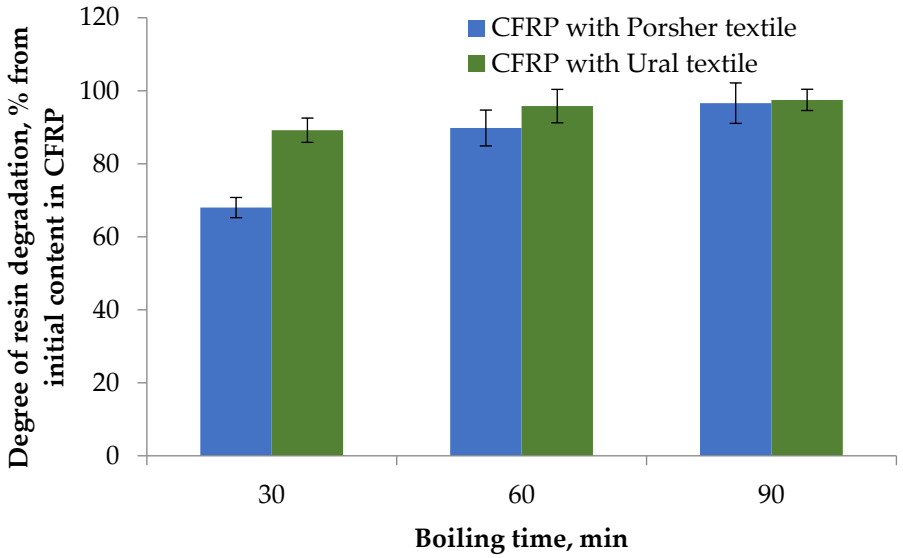
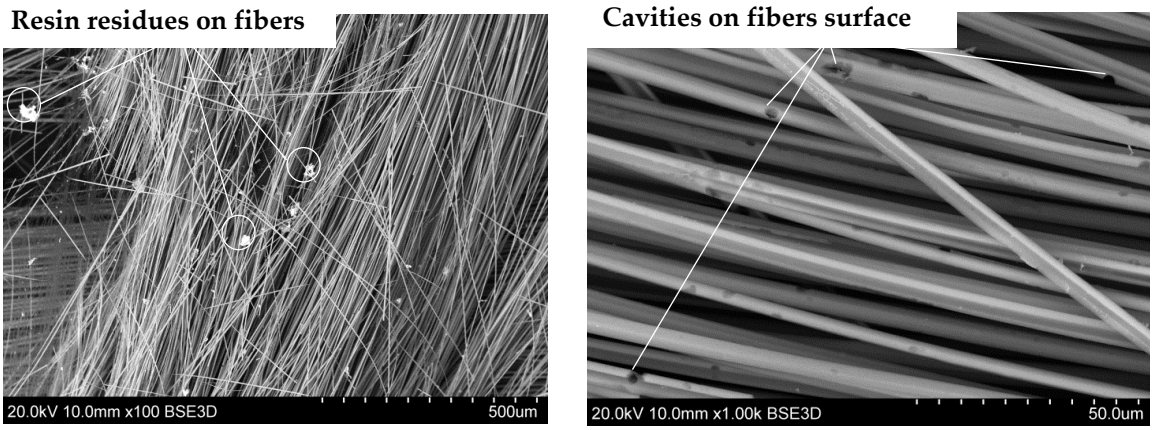


Figure 3. Resin breakdown efficiency vs. duration of the process.



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

Figure 4. ESEM images of fiber surface (**a**) with resin residues, (**b**) with traces of damage.

During the experiments, the samples of composite materials absorbed the solvent and swelled, which led to the increase of their mass, which is why we can see, in some cases, an increase in the mass of the sample in comparison with the initial weight.

The best results in carbon fiber release were obtained when using a mixture of hydrogen peroxide, sulfuric acid, and water (at a ratio of 1:1:1.3 by volume) (A7). Sample weight loss was 23% of the initial weight, which is 95.8% of the polymer resin content (24%). This is most likely due to the formation of the maximum amount of active oxygen in the form of radicals attacking hydrogen and carbon bonds in a phenol-formaldehyde resin.

Moreover, good results were achieved using a mixture of nitric and orthophosphoric acids at a ratio of 1:1 by volume and with the addition of potassium chromate at a dose of 10 g per 100 mL of acid mixture (A6). Sample weight loss was 22% of the initial weight, which is 91.7% of the polymer resin content (24%). Nitric acid is a strong acid and a powerful oxidizing agent (one that acts as an electron acceptor in oxidation-reduction reactions). Furthermore, the presence of potassium chromate and chromium oxide initiated the formation of peroxides, which in turn dissociated to form active oxygen and water. The destruction mechanism is similar when using sulfuric acid and nitric acid in the presence of chromium oxide, the use of which also provided good results in the extraction of carbon fiber: sample weight loss was 20% with the use nitric acid (A5) and 21% with the use of sulfuric acid (A4). Chromates, bichromates, and oxides of chromium in an acidic

environment led to the formation of chromic acid. Under the influence of chromic acid, the phenol-formaldehyde resin was oxidized [33].

The use of organic solvents did not produce a noticeable result in the release of the fiber; therefore, their application under mild conditions (low heat and pressure) was meaningless.

In view of the environmental hazard potential of reagents containing chromium, a reaction mixture based on hydrogen peroxide and sulfuric acid (A7) was chosen for further development. At the second stage of the research, an assessment of the influence of process duration on the dynamics of fiber extraction was made, as well as an assessment of the influence of weaving/type of fabric on the efficiency of the solvolysis (Table 3).

A high efficiency of fiber extraction was achieved in all variants of the experiment at the second stage (Figure 2). At the same time, reducing the process duration to 30 min led to the significant decrease in the efficiency of the process, especially in the case of CFRP reinforced with Porsher fabric. Hence, the process duration significantly affects the efficiency of the process; this fact is associated with the difficulty of diffusion inside the composite materials (Figure 3). It has been demonstrated that under identical conditions, the extraction efficiency of the Porsher fabric is lower than that of Ural. This fact highlights the importance of customizing the process duration based on the product's configuration and the thickness of the processed polymeric materials because the speed of diffusion processes is a limiting factor.

A visual analysis of fibers and fabric purity showed that using a mixture of sulfuric acid and hydrogen peroxide (C3 and B3, Table 3) provides almost a complete removal of phenol-formaldehyde resin. Analysis of fiber microstructure using an electronic microscope revealed a small amount of inclusions on fiber surface (Figure 4a). The inclusions were sporadic and had low adhesion with the fiber (can easily be removed by washing with distilled water). It was discovered that the thickness of secondary fibers was significantly reduced—on average by 20% (from 9.49 μm in the primary fiber to 7.36 μm in the secondary fiber). Additionally, it was determined that the roughness that emerged on the surface of fibers (see Figure 4b) could ultimately affect the mechanical properties of products reinforced with secondary carbon fiber.

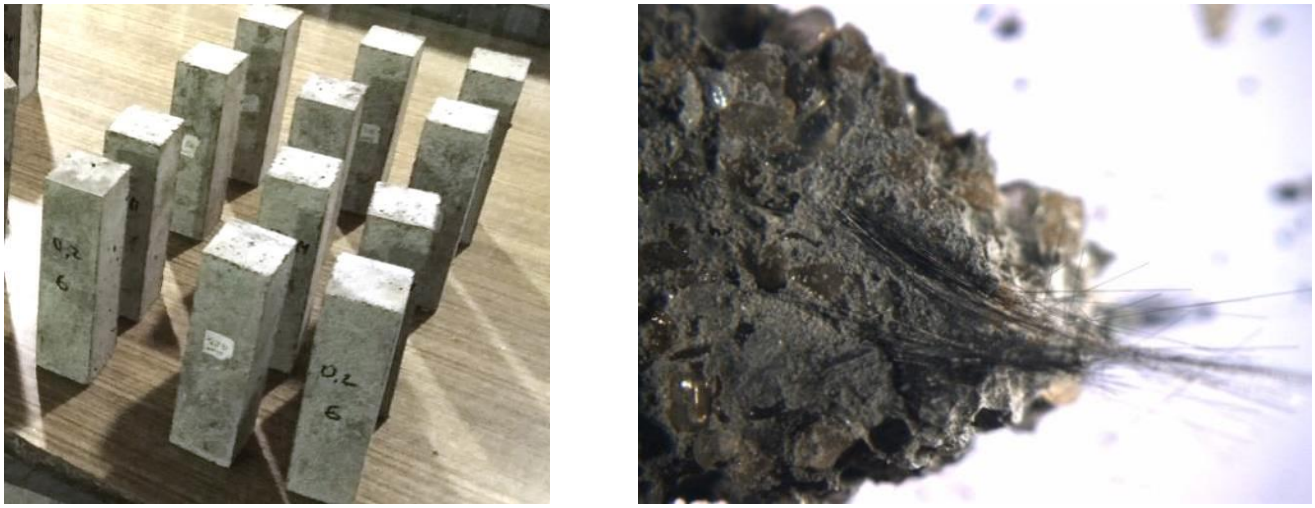
3.2. Using Secondary Fibers for Reinforcing Fine-Grained Concrete

The prepared samples of concrete test blocks were sent for bending and compression tests after curing. These parameters were chosen to evaluate the effectiveness of concrete reinforcement because they are the ones that undergo changes during reinforcement. A block was produced according to an identical formula, and a sample without the addition of carbon fibers was used as a comparison standard.

Visual control of distribution uniformity was carried out using microscopy (Figure 5b). Test results of the samples reinforced with carbon fiber are presented in Table 4 and on the Figure 6. It was found that the addition of fibers with a size of 3 mm increases the mechanical bending strength of concrete blocks by 8.1 and 16.6%, and 0.2 and 0.6%, respectively, for the dose of fiber. Simultaneously, the compressive strength of the concrete test blocks containing fibers decreased by 6.6–10.5% with the addition of 9 mm fibers, by 2.0–2.3% with 6 mm fibers, and remained almost unchanged or increased slightly with the addition of 2 mm fibers.

Table 4. Test results of the samples reinforced with carbon fiber.

Fiber Size	Fiber Amount, % Mass	Bending Strength, MPa	Compressive Strength, MPa
Control (no fiber)	-	5.113 ± 0.276	36.206 ± 2.865
3 mm	0.2	5.528 ± 0.211	36.760 ± 2.793
	0.6	5.962 ± 0.185	36.382 ± 1.963
6 mm	0.2	5.279 ± 0.395	35.480 ± 1.145
	0.6	5.430 ± 0.224	35.380 ± 0.475
9 mm	0.2	5.302 ± 0.138	32.400 ± 1.450
	0.6	5.279 ± 0.604	33.820 ± 2.442



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

Figure 5. Samples of standard fine-grained concrete beams reinforced with carbon fiber: (**a**) general view of a beam; (**b**) fracture after tests.

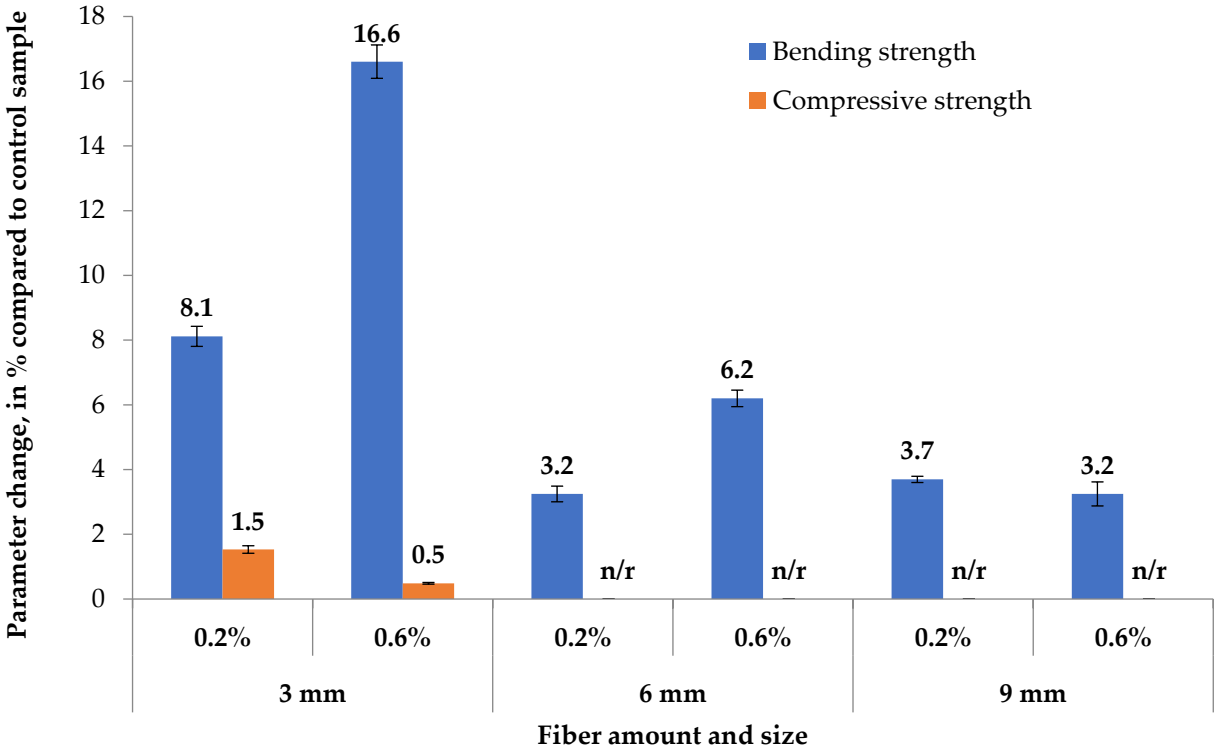


Figure 6. Changes in fracture size and bending strength of concrete blocks in comparison with the control sample (without the addition of fibers); n/r—negative results.

Based on the study of the reinforcement of concrete blocks, it was established that the compressive strength did not change significantly since four of six samples presented an average decrease of 6.6–2.0%, while two other samples demonstrated a 1.5–0.5% increase.

At the same time, a considerable increase of 3.2–16.6% in bending strength was noted. Samples reinforced with 3 mm fibers presented the best mechanical properties. At this stage, it is too early to make any conclusions about the effect of fiber dose on the mechanical properties due to significant variability in the results.

An analysis of the test beam microstructure showed the presence of well-distributed carbon fibers and carbon fiber bundles (Figure 5a). Such uneven distribution of fibers

reduces reinforcement efficiency and leads to instability in the samples' mechanical strength. An even distribution of fibers is difficult to achieve due to the accumulation of static stress on the surface of fibers and their cohesion when sand and cement are introduced into the mixture.

Fibers that were 9 mm long were especially difficult to disperse, which indicates the need to expand research in the direction of fine-grained reinforcement of concrete with 3–6 mm carbon fiber. In general, the research on using secondary fibers for reinforcing concrete products has been recognized as promising, given that the addition of fiber increases the bending (3.2–16.6%) and compressive (1.5–0.5%) strength.

3.3. Use of Secondary Fibers for Producing Composite Materials

Studies have been carried out to assess changes in the properties of secondary carbon fabrics. They included the production of two types of samples: one reinforced with secondary fabric and the other with the primary fabric Porsher. The mechanical characteristics of the "recycled" and primary fabrics were compared with the use of a stretching test. The samples were made of two layers of carbon fabric and epoxy resin by the vacuum infusion technology. The general appearance of fabrics and panels is presented in Figure 7a–d. Samples were cut from each panel for testing.

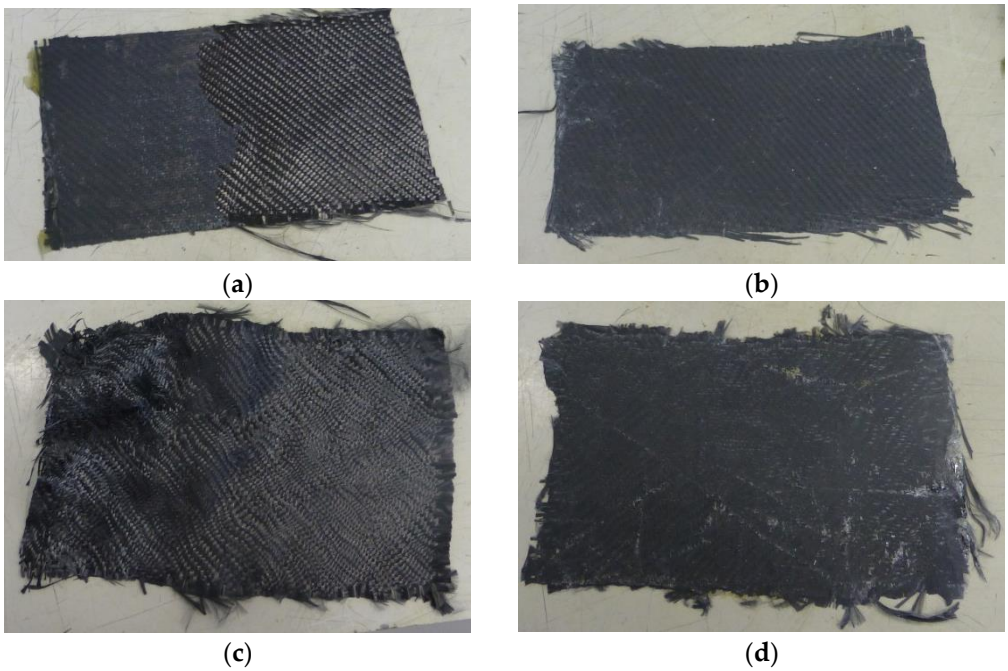


Figure 7. General view of the panel fabrics: (**a**) primary carbon fiber fabric; (**b**) recycled carbon fiber fabric; (**c**) primary carbon fiber reinforced plastic panel; (**d**) recycled carbon fiber reinforced plastic panel.

Mechanical tests determined the effective tensile elastic modulus (Ec), the maximum test load (Fmax), and the effective tensile strength (σMc) for each sample. Table 5 and Figure 8 show the effective mechanical characteristics of the samples. It was shown that the effective tensile elastic modulus decreases by 27%, the maximum test load by 34.8%, and the effective tensile strength by 4.5%.

Table 5. Effective mechanical characteristics of carbon fiber samples.

Sample Type	Ec, GPa	Fmax, kN	σMc, MPa
Carbon plastic reinforced with carbon fabric	27.4 ± 0.3 [a]	1.15 ± 0.09 [a]	130.02 ± 8.13 [a]
Carbon plastic reinforced with recovered carbon fabric	20.0 ± 0.9	0.75 ± 0.067 [a]	124.18 ± 12.01

Data presented as a mean ± SD (n = 3). [a]—Values do not differ significantly ($p > 0.05$) as assessed by a post hoc test (Tukey test).

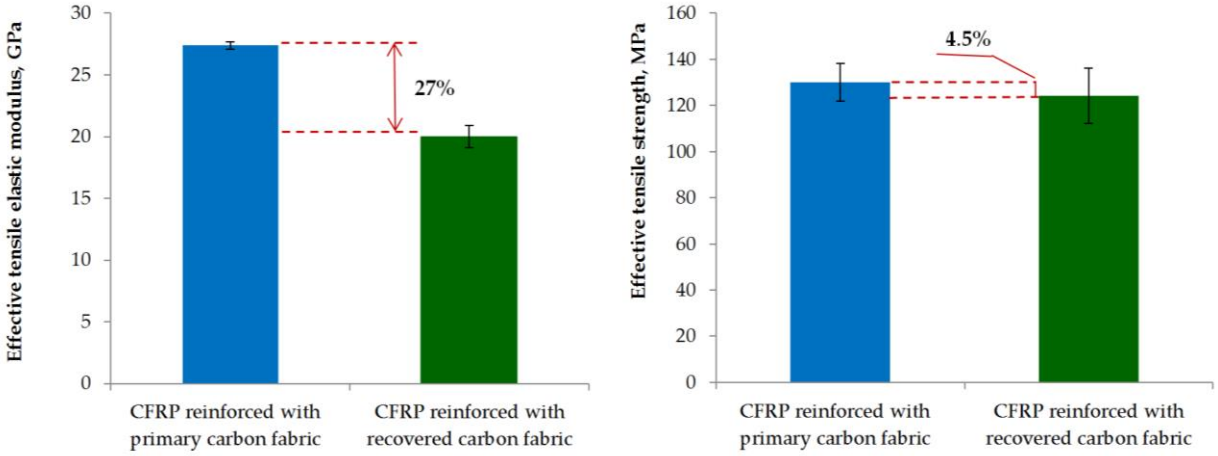


Figure 8. Mechanical characteristics of CFRP with primary and recycled carbon fiber textile.

The tensile strength parameter was used to assess the mechanical properties of the carbon fiber-reinforced plastics reinforced with secondary carbon fabric, taking into account the relationship between the geometric dimensions of the samples and the breaking load [34]. The stresses were then calculated as the ratio of the effective load to the sample cross-sectional area. The obtained stress values were used in calculating the effective mechanical characteristics of the aggregate. The deformations were determined by the traversing movement of the testing machine.

An analysis of the test results proves that the quality of the recovered fabric is quite high. The effective rigidity and the effective strength of the carbon fiber plastic samples reinforced with recovered fabric is lower by 27.01% and 4.62%, respectively, as compared to samples of CFRP reinforced with primary fabric. This reduced rigidity of the carbon fiber samples reinforced with recovered fabric is caused, first of all, by damage to the weaving of the fabric during the release of the binding elements and not by the properties of the fiber. After testing on destroyed samples reinforced with recycled carbon fabric, a significant resin-fatigued area is observed due to insufficient density of the fiber weaving. Nonetheless, the results show that the obtained fibers are of high quality as the mechanical properties of the samples deteriorated within acceptable limits.

4. Conclusions

This study demonstrated the feasibility of using solvolysis (developed for processing CFRP based on epoxy resins) to extract fibers from composite materials based on phenol-formaldehyde resin. The high quality and prospects for returning the obtained secondary fibers to the resource cycle, including those for reinforcing concrete and producing composite materials, were revealed. The research results have high practical importance in solving the problem of processing CFRP based on phenol-formaldehyde resins, which are widely produced and used in machinery in Russia. The use of strong acids and oxidizing agents for the extraction of fibers is associated with significant economic costs and resource consumption. It is clear that there is currently room for improvement in terms of optimizing

the technical and technological parameters, which ensures an increase in the resource and energy efficiency of the process.

Author Contributions: Conceptualization, N.S., V.K. and O.B.; data curation, Y.K.; funding acquisition, N.S.; investigation, V.L.; project administration, V.K.; resources, Y.K., N.S. and V.K.; validation, S.I.; writing—original draft, Y.K.; writing—review and editing, O.B. and S.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Higher Education of the Russian Federation (Project № FSNM-2020-0024).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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