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Flexural properties of hogweed chips reinforced cement composites

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Abstract. Application of natural plant additives allows improving thermal and mechanical properties of concrete composites. Environmentally friendly wood waste is gaining particular popularity. One of the promising filler types for concrete is hogweed chips. In this study, the flexural properties of two types of concrete composites reinforced with plant additive samples, including a large additive of hogweed 50 mm long and a medium additive of hogweed 25 mm long were examined. In addition, a composite sample reinforced with short polypropylene fiber was produced. Each series of concrete composite consists of three samples. A three-point bending test was conducted to determine the reinforcement efficiency of the manufactured composites. Instron 5965 (USA) unit helped determine maximum load and normal stress. The results showed that the flexural strength of composites with long additive pieces is greater than that of the other samples. The increase in flexural strength was 5% and 25% for composite made of short and long pieces, respectively. The interaction mechanism between wood additives and cement matrix in the composite was analyzed by means of optical microscopy. The surface formations were found to significantly affect the bonding properties of the concrete and the hogweed.

1. Introduction

Concrete has been a conventional material in construction for the last 150 years and its composition is permanently improved by various additives that affect its thermal and mechanical properties [1–9]. Concrete admixtures (additives) enhance the properties of concrete for applications in construction with special requirements. Concrete additives are used to achieve desired workability in case of low water-cement ratio, and to enhance setting time of concrete for long distance transportation of concrete [10–13].

Today, there are many wood additives in the market of construction and building materials. Many of available materials are environmentally friendly. Wood additives may be used in the following form: wood chips, sawdust, shavings, wood dust, ash. In addition to low density, wood materials have high strength performance. Wood is also characterized by unique physical and chemical characteristics, including low heat and sound conductivity, corrosion resistance in aggressive environments, the ability to quench vibrations, easy workability and shaping.

Using more efficient materials, an ecological approach to design is aimed at developing a comfortable building environment with lower environmental costs. The production of cement wood fiber panels contributes to the re-evaluation of industrial by-products, such as the use of waste from the wood industry [14–16]. Cheap wood fuel in the form of briquettes without the use of binding substances are widely used in the Russian market. In addition, soft waste in small quantities is used in hydrolysis production, for the manufacture of albolite (wood concrete). In albolite, cement occupies on average 10–22% and in

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sawdust concrete up to half. This does not affect strength performance, but significantly reduces thermal protection of concrete. Wood-based concrete cannot absorb water due to lack of pores. The place of pores is occupied by wood filler. In most cases, wood is well impregnated with lime, and also tightly captured with cement, so that water cannot penetrate inside the material.

Sawdust-based concrete (structural and thermal insulation concrete), in which sawdust and sand are used as a filler, while cement and lime as a binder, also found some appropriate applications. For the production of sawdust concrete blocks, small sawdust wood without adding wood chips is used. Mixtures can be used for manufacturing unit blocks of various sizes for subsequent erection of walls of buildings, as well as for direct laying in formwork during erection of monolithic walls. There is gypsum-sawn concrete used for the construction of walls in residential, public and industrial buildings (single-story buildings of III and IV category of durability) with a relative humidity not exceeding 60% [17]. In works [18, 19], wood waste (sawdust and wood shaving) ash (WWA) of pretreated timber was added as a supplement to a concrete from 0 to 30% by weight of cement with step of 5%, while the strengths and the water absorption of the matrix were evaluated. The compressive and the flexural strengths of WWA concrete investigated ranged from 3.65 to 28.66 N/mm^2, with the lowest values obtained at 30% additive level of ash. When compared with the strength of reference concrete sample, the compressive and flexural strengths of WWA concrete were between 62 and 91% and 65 and 98%, respectively. It was concluded that WWA could be blended with cement without adversely affecting the strength properties of concrete.

Some researchers have conducted tests which showed promising results that wood ash can be suitably used to partially replace cement in concrete production [20, 21]. Another main advantage of wood filler addition to cementitious materials is that they are inexpensive, available in large quantities, environmentally friendly, and easy to process. Hence, incorporating the usage of wood ash as replacement for cement in blended cement is beneficial for the environmental point of view as well as producing low cost construction entity thus leading to a sustainable relationship.

To build for tomorrow, the two building methods are being combined. Hybrid structures containing both wood and concrete elements are becoming increasingly popular in contemporary architecture. In the context of the National Resource Programme “Resource Wood” (NRP 66), Swiss researchers have now developed an even more radical approach to combine wood and concrete. They are fabricating a load-bearing concrete which itself consists largely of wood. In many blends, the volume fraction of the wood is over 50 percent. Cement-bonded wood products have been around for more than a hundred years. However, previously they were used only for non-load-bearing purposes, such as insulation [22].

Cement-bonded wood composite panels are not novel products used in construction. They are available on the market since the early 1960s [23]. The results indicate that fibers reduces permeability and the infiltration rate, while reducing surface abrasion and improving freeze-thaw durability. It is also shown that the ratio between flexural and compressive strength is around 47%. For the numerical simulation [24], an eXtended Finite Element Method (XFEM) has been used to simulate the fracture process of the three-point bending panel using Abaqus software. The results of study [25] showed that increasing the amount of wood waste reduces density and slightly decreases thermal conductivity. In 1934, an innovative technology in low-rise construction – the use of wood-concrete blocks of permanent formwork in the Netherlands developed [26]. Durisol has been manufactured since the 30s by the Swiss company of the same name on special industrial production lines from machine chips, M500 Portland cement and chemical additives. The company produces wall panels, coating plates, hollow blocks (50×25×30 cm). In the construction of residential buildings up to 14 stories high in Switzerland, durisol hollow blocks are used, while the voids located vertically and horizontally are filled with concrete, which forms a concrete grid that carries a vertical load, and the durisol itself serves as thermal insulation.

A series of experiments were carried out to study the effect of wood extractives, chamotte and $CaCl_2$ on hydration and hardening of cement paste [27–29]. It also allowed study of the effects of these additives on mechanical and physical properties of Cement-bonded Particle Board (CBPB). The CBPB was tested for Modulus of Rupture (MOR), Internal Bond (IB), Thickness Swelling (TS) and Water Absorption (WA). The results showed that water-soluble wood extractive increases the hydration time of cement. It was observed that different amounts of chamotte and $CaCl_2$ in neat cement could significantly affect the setting and hardening time. Replacement of cement with 10% of $CaCl_2$ and 10% chamotte in boards increased the MOR and IB. It was determined that alder and poplar wood extractives increase the hydration time of cement paste and decrease the amount of compression strength of cement stone compared to control samples.

The study [30] investigates the influence of maple-wood sawdust addition on the mechanical and microstructural properties of cemented paste backfill (CPB). Mechanical properties of CPB were determined by uniaxial compressive strength (UCS) tests and microstructural changes were evaluated by mercury intrusion porosimetry (MIP), and scanning electron microscopy (SEM) analysis. Results indicate that the addition of 12.5% maple-wood sawdust (by dry mass of binder) improves the strength development of CPB specimens at later hydration age (91 curing days). However, the UCS showed lower improvement at a higher maple-wood sawdust content of 14.5%. Furthermore, the incompatibility of some wood species with cementitious materials means that the compatibility of each wood species must be assessed individually [31].

This experimental study aims to evaluate the contribution of the High-Performance Fiber-Reinforced Cementitious Composite (HPFRCC) laminate with steel and GFRP bars to the flexural behavior of RC slabs. The experimental results were suggestive of the effect of the properties of the HPFRCC laminate, including its application procedure, steel fiber volume fraction, incorporation of longitudinal reinforcement, and the type of reinforcement (steel or GFRP bars), on the increase in the load-bearing capacity of the slab [32]. The effect of replacing aggregate with waste glass particles on the compressive strength and weight of concrete is investigated in [33]. Results indicated that replacing aggregate with glass particles of more than 30% lead to an increment in the compressive strength of concrete. The weight of concrete remains almost the same in all of the specimens. Briefly, based on the results it could be concluded that the optimum percentage for replacing aggregate with glass particles is 50%. Concrete-containing wood aggregate in percentages of 0, 15, 20, and 25 in place of crushed stone was developed with characteristic compressive strength of 25 MPa, with a mix proportion of 1:1.26:2.76 and with a water/cement ratio of .45. The compressive strength of control concrete was 31.40 MPa and that of wood aggregate concrete with 15% replacement level was 32.36 MPa that is 3.06% above the control concrete. Therefore, wood aggregate can be used in the production of concrete, and the optimum replacement was found to be 15% from all considerations [34]. In this study [35], the wood waste, wood shavings, and sawdust were tested in ratios of 2.5, 5, 10, and 20% by the weight of sand. The results showed that increasing the amount of waste hinders the workability of the sample and prolongs setting times. Furthermore, compounds with larger-sized particles, those based on wood shavings, showed a more pronounced decrease in density and produced the best thermal results. Finally, contrary to what one might expect, the wood-shavings compounds also presented better mechanical properties.

In this regard, for Russia, it is worth considering hogweed (Heracleum mantegazzianum) as a plant additive to concrete: it is ubiquitous and is considered a big problem. Hogweed Sosnowski is a large, herbaceous plant in the umbrella family (Apiaceae). The natural range is within the boundaries of the forest belt of the mountains of the Caucasus. I.P. Mandenova was first to describe this plant in 1944. In the middle of the 20th century, it was widely introduced in the fields of the European part of the USSR and Eastern Europe as a fodder culture. Due to the ability to self-sow in the late 20th century, it began to spread intensively beyond the land on which it was cultivated. All parts of the plant contain furocoumarins: substances that dramatically increase sensitivity of human or animal skin exposed to them to ultraviolet light. The toxic sap and pollen lesions of the plant can cause burns not only on contact with unprotected skin, but through clothing as well [36]. The plants of hogweed can reach heights of around 3–5 m with 1 m long leaves. People can spread the seeds by transporting the soil containing them stuck to car tires [37].

Despite all the shortcomings, there are positive examples of the use of hogweed. Scientists have proposed the use of hogweed in the manufacturing of batteries. Supercapacitors, which were used in the production of fibers from the stems of hogweed, are a kind of storage devices for energy. They are distinguished from conventional batteries by high power, long energy storage life and long service life. Researchers from NUST “MISiS” suggested that the optimal electrodes for supercapacitors are the fibers contained in the dry stems of the plant. The stems consist of a hard bark and a soft inner core, similar to a sponge, which forms a diverse porous structure. Such a design is suitable for use in carbon materials as the basis for a storage device [38, 39].

A literature review showed that dry hogweed was not used as a wood and plant additive in the world practice. Therefore, the research topic is relevant and it should be considered from the point of view of the mechanical properties of the new concrete composite. Hogweed is advisable to use as a plant additive, as in our country large areas of fields and roadsides are occupied by this plant. In dry form, it is safe (it does not emit any harmful substances) and, given the structure of the stem, it is of interest as a cheap additive. To do this, research focuses on the use of hogweed in construction as an additive to concrete.

The purpose of this work is to determine the flexural properties of concrete reinforced with various additives. To achieve this purpose, the following objectives must be achieved:

1. Manufacturing samples of concrete with various additives
2. Determination of the flexural properties of concrete composites.
3. Analysis of wood aggregate-concrete matrix interaction.

2. Methods

2.1. Manufacture of the concrete samples

In this work, four types of concrete samples were manufactured, including a reference unreinforced sample; sample of concrete composite with short polypropylene (PP) fibers, and two types of composite samples reinforced with hogweed chips of different length.

Hogweed was collected in a dry form during the wintertime (when hogweed stops blooming). At this time of the year, hogweed has an empty stem, like bamboo, and it is not poisonous. After that, the stem was cut into additives for concrete composite with a length of 25 mm and 50 mm.

Short PP fiber was selected for comparative analysis specifically, since this type of filler is most often used for the manufacture of fiber-reinforced concrete. The characteristics of the samples are listed in Table 1. The reinforcing fillers are shown in Fig. 1.

Table 1. Samples specification.

№	Reinforcement	Abbreviation	Length, mm
1	non-reinforced	Ref.	–
2	PP short fiber	PP short fiber	54
3	Hogweed chips	B-1	50
4	Hogweed chips	B-2	25

Fine-grained concrete with sand grains 2.5 mm in size was used. Plasticizer was added to concrete mixtures in order to improve workability. The amount of each constituent of the concrete is listed in Table 2. The compressive strength at the age of 28 days is at least 30 MPa. The aggregate volume fraction in the manufactured samples was approximately 2%. Composite samples were made by using the mold of 77×200×20 mm. Prior to testing, the test samples were cured for 28 d at 23°C and 95% RH. No fewer than three samples were tested for each series. Table 3 summarizes the experimental results of three-point bending tests for all specimens.

Table 2. The constituents of fine-grained concrete (kg/m^3).

Cement	Sand (0–2.5 mm)	Plasticizer	Water
500	1000	10	285

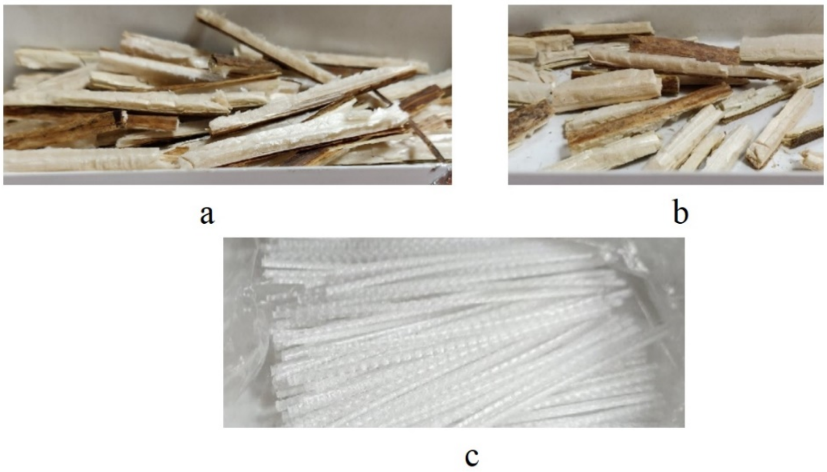

Figure 1. Types of additives: (a) large (50 mm), (b) medium (25 mm), and (c) PP short fiber (54 mm).

2.2. Flexural testing of the concrete samples

Samples of composites were subjected to a three-point bending test as shown in Fig. 2. The flexural tests were performed on an Instron 5965 universal testing machine at a span of 150 mm. The specimens were tested at a constant loading rate of 1 mm/min in a standard climate at 20°C and 65% RH. The concrete specimen is subjected to a load at its center. Specimen deflection is measured by movement of the crosshead displacement of the testing machine.

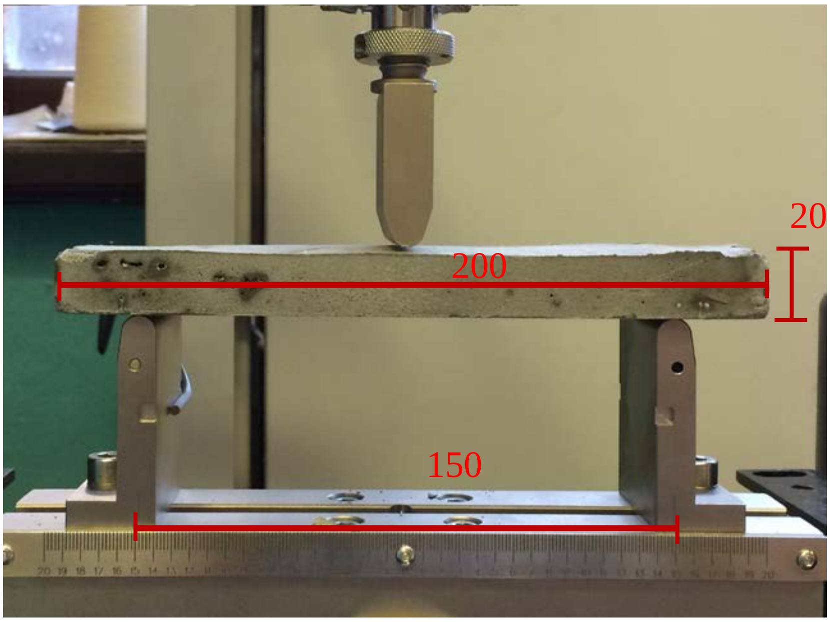

Figure 2. Three-point bending test.

From the results of the tests, the value of the flexural strength was determined as the ratio of the maximum bending moment at sample failure to the axial moment of inertia by the following equation:

$$\sigma = \frac{M_{bend}^{\max}}{W_z}, \tag{1}$$

where $M_{bend}^{\max}$ is the maximum bending moment, kNm; W_z is moment of inertia, m^3 [40].

3. Results and Discussion

3.1. Flexural behavior

The results of the tests showed that the fillers used have a significant effect on the flexural performance of the concrete composites. Fig. 3 shows the flexural stress-deflection curves of the concrete composites developed in this study. The flexural behavior of the samples is very similar and does not depend on the type of reinforcing aggregates. The initial part of the stress-deflection curve is characterized by linear properties. There is a first transverse crack corresponding to the maximum peak in the curve.

There is a certain difference in both the strength and plasticity characteristics. Analyzing these results shows that the sample of cement composites reinforced with long chip pieces (B-1) has the highest flexural strength. For the other samples, this difference is less noticeable. The value of the deflection demonstrates that the additives improve the plasticity characteristics (approx. 1/3) compared to the non-reinforced sample. Further, with increasing deflection, flexural stress and the slope of the curves decrease. In other words, the reinforcing component significantly contributes to increasing the elastic modulus of the sample.

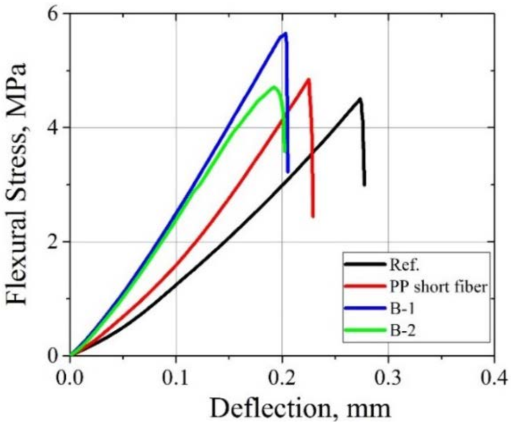

Figure 3. Stress-deflection curves of cement composites with different aggregate types.

Table 3. Test results.

	Sample	b, m	h, m	l	F, N	M, Nm	Wz, m^4	σ, MPa	σ_{avr}, MPa
1	B-1	0.077	0.018	0.150	592.7	22.3	3.96E-06	5.6	5.6
2	B-2	0.077	0.018	0.150	522.2	19.6	3.98E-06	4.9	4.4
3	PP	0.077	0.021	0.150	630.1	23.7	5.39E-06	4.4	4.8
4	Ref	0.077	0.024	0.150	859.7	32.4	7.19E-06	4.5	4.6
5	B-1	0.077	0.019	0.150	631.0	23.7	4.65E-06	5.1	
6	B-2	0.077	0.021	0.150	540.5	20.3	5.52E-06	3.7	
7	PP	0.077	0.020	0.150	708.4	26.6	5.15E-06	5.2	
8	Ref	0.077	0.020	0.150	600.1	22.6	5.11E-06	4.4	
9	B-1	0.077	0.016	0.150	537.6	20.2	3.29E-06	6.1	
10	B-2	0.077	0.022	0.150	719.4	27.0	5.99E-06	4.5	
11	PP	0.077	0.020	0.150	688.4	25.8	5.34E-06	4.8	
12	Ref	0.077	0.017	0.150	446.4	16.7	3.53E-06	4.8	

Another point to note when comparing the developed samples is that the flexural strength calculated according to equation (1) was selected. Fig. 4 shows the maximal flexural strength (MFS) of the developed samples. The flexural strength of the reference sample is 4.6 MPa, which is minimal among all the results obtained. The highest MFS value, 5.6 MPa, was obtained in the case of sample B-1, reinforced with 50 mm long hogweed chips. Sample with 25 mm long hogweed chips (B-2) has a bending strength of 4.4 MPa. The flexural strength of the PP short fiber sample is 4.8 MPa.

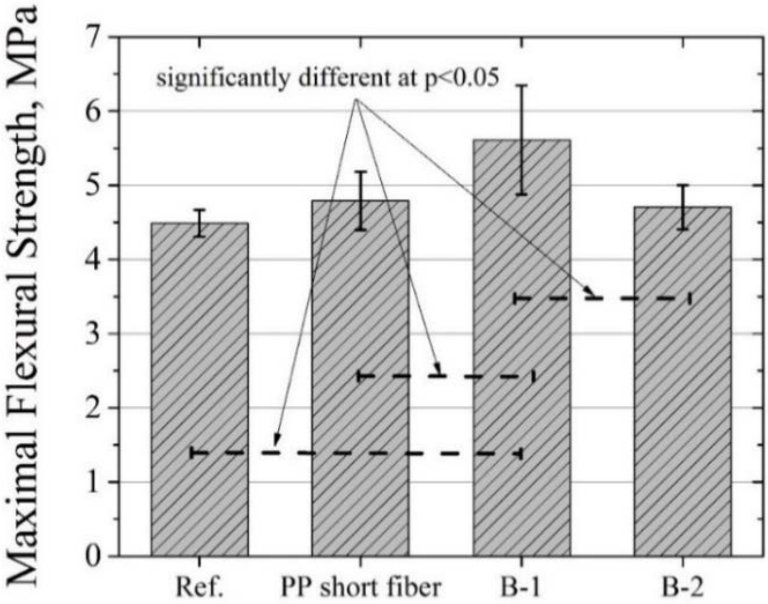

Figure 4. Effect of the concrete filler on the flexural strength of the concrete samples.

3.2. Reinforcement efficiency

In order to determine the reinforcement efficiency, we calculated an efficiency factor as the ratio of the MFS value to the value of the non-reinforced sample. Fig. 5 shows the reinforcement efficiency of the developed samples. The results show that a maximum increase of 25% is observed in the case of the B-1 sample. This is because the additives themselves have a large dimension and absorb a certain percentage of moisture from the mixture on contact with water. In the other two samples, the increase is not more than 5 to 7%.

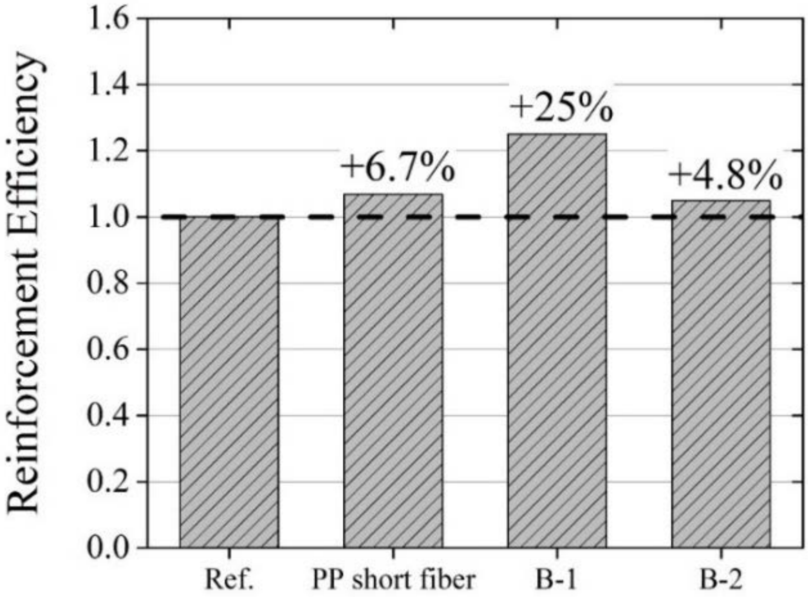

Figure 5. The percentage of effectiveness of reinforcement.

However, as shown above, this difference may not always be statistically significant. In other words, it is impossible to confirm the effect of using a particular reinforcing component. To confirm these results, it is necessary to perform a statistical analysis of pair comparison of individual samples among the series.

3.3. Statistical analysis

A series of three samples were tested for each type of concrete composite. The amount of experimental data is sufficient to identify statistics and confirm the results.

The effect of the concrete filler on the flexural properties of the concrete samples was revealed via statistical analyses. These analyses were performed by using one-way ANOVA (analysis of variance) at a significance level of 0.05. Fisher's Least Significant Difference (LSD) post hoc test was applied to determine which specific groups were significantly different from others. Table 4 summarizes the ANOVA results for the Maximal Flexural Strength analyzed in this work. For investigated characteristic, the p values are equal to 0.064, which are greater than 0.05. From these results, it can be concluded that the difference in flexural strength among the four specimens is not significantly different.

Table 4. One-way ANOVA test results.

Source	DF	Sum of squares	Mean square	F Value	P Value
Dependent variable: Maximal Flexural Strength					
Model	3	1.71913	0.57304	3.86548	0.064
Error	7	1.03773	0.14825		
Total	10	2.75685			

Fisher's (LSD) post hoc test was applied to examine the significance of the differences between average values of Maximal Flexural Strength of concrete samples. Table 5 shows the Fisher's (LSD) post hoc test results between groups of mean. Different letters indicate significant differences among groups ($p < 0.05$). The results showed that the effect of the filler type on the maximal flexural strength was significant for B-1 sample.

Table 5. Fisher's (LSD) post hoc test results.

Sample	Maximal Flexural Strength	p-value			
		Reference	PP short fiber	B-1	B-2
Reference	A		0.338	**0.012**	0.535
PP short fiber	A			**0.049**	0.816
B-1	B				**0.047**
B-2	A				

The same letter indicates that the difference of the means is not significantly different at the 0.05 level.

3.4. *The mechanism of interaction of the hogweed chips and concrete matrix*

The results obtained above indicate that the reinforcement effect when using hogweed additive is achieved only when using long pieces (50 mm). This length of the reinforcing chip may introduce some inaccuracies in the determination of flexural strength. In addition, the mechanism of interaction between the chip and the matrix in a concrete composite is unclear. One of the determining factors is the bonding of the reinforcement to the matrix in the composite. Weak adhesion may lead to a significant decrease in the mechanical properties of concrete composites. Optical microscopy analysis was performed to determine the interaction mechanism of chips and matrix in the composite. Fig. 6 shows micrographs of the surface of hogweed chips taken with a 50x magnification. As it can be seen, spherical growths like crystals form on the chip surface. This can be explained by the capillarity effect. In this case, the spherical drops on the surface are formed because the worse wetting, the closer the shape of the particles will be to the spherical one. In the optimal case, the crystals should grow inside the aggregates, for example, in the case of alkali-resistant glass-roving, which is well wetted; or at least cover the surface evenly for better adhesion to the matrix. In this case, such formations on the surface worsen the adhesion of the concrete mixture and hogweed.

Figure 6. Sediment on the surface of hogweed.

The research in this paper differs from others in that previously dry hogweed was not used in concrete composites as wood and plant additives. But at the same time, this material also has increased mechanical properties. The flexural strengths of WWA concrete investigated ranged from 3.65 to 5.57 MPa, with the lowest values obtained at 30% additive level of ash [18]. The highest flexural strengths value, 5.6 MPa, was obtained in the case of sample B-1, reinforced with 50 mm long hogweed chips. Comparing the results with other works we can note the following: the developed samples of composites are similar in structure to those presented in [18, 19, 24, 26]; their main difference is the cheapness and availability of the filler material. It should also be noted that similar strength indicators of the developed composites were obtained by various authors in [20, 21, 25].

Table 6 shows the properties of a conventional concrete composite and a new material. The last column shows the difference between the composites

Table 6. Properties of concrete.

Properties	Unit	Values for typical concrete	Values for the new material	Difference
Density	Kg/m^3	2400	1754	–27%
Normal stress	MPa	4.6	5.6	+22%

4. *Conclusions*

In this paper, experimental studies have shown that the type of reinforcing aggregate has an effect on the flexural properties of concrete composites. Four types of samples were developed, including reference non-reinforced sample; concrete composite reinforced with PP short fibers; two types of concrete composites reinforced with plant additive samples, including a large additive of hogweed 50 mm long and a medium additive of hogweed 25 mm long were examined. In addition, a series of composite samples were made from a composite sample reinforced with short polypropylene fiber of 54 mm length. Manufactured samples were tested for flexural strength at the age of 28 days. The results showed that a 50 mm long hogweed sample has the highest maximum flexural strength. However, a large-scale factor that requires larger beams to be tested may have an impact here. For the other samples, no statistically significant reinforcement effect was found. However, it should be noted that the determining factor in the application of such short reinforcement is not only the reinforcing efficiency, but also the increase in crack resistance and ductility characteristics of the concrete composite. In addition, the analysis has shown that at least the mechanical characteristics of the original concrete are preserved if another function of using the composite is assumed, for example, increased thermal conductivity.

During the experiment, the greatest increase in strength was revealed in samples with an additive of 50 mm; with the additive of hogweed 25 mm, a high increase in strength was not observed. As for recommendations: in construction, when creating a concrete composite, it is better to use a 50 mm long hogweed additive.

The research of this topic is in high demand for the following reason: the additive will not only have a positive effect on the environment (reducing the weed), but can also improve the mechanical properties of concrete and reduce the amount of cement used in the concrete composite production. Due to the reduction in density, the weight of the structure is reduced, which leads to a reduction in the load from its own weight.

In prospect, concrete composites reinforced with a dry plant additive will be studied and calculated for thermal properties.

5. *Acknowledgments*

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