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Research Article

Effect of hemp and basalt fiber on fracture energy of cement-based composites: a comparative study

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ABSTRACT

Fiber-reinforced composites are one of the most used construction materials. Nowadays, some types of fibers like steel, carbon, glass and basalt are commonly used in these composites. However, the production of these fibers consumes natural resources and a high amount of energy. Researchers have started working on natural fibers to reduce commonly used fibers productions' drawbacks for more sustainable composites. However, the effect of natural fibers on the properties of cement-based composites -especially fracture energy- still needs further research and comparing with the behavior of commonly used fibers. In this study the effect of hemp fiber on the mechanical properties and fracture energy of cement-based fiber-reinforced mortar mixtures was investigated. The results were compared with those of the basalt fiber-reinforced mixtures. The results showed that the flexural strength and fracture energy improved with the use of hemp and basalt fiber compared to the fiber-free mixture. The flexural strength increased up to 10.7% and 19.6% with the inclusion of hemp and basalt fibers, respectively. The mean peak load and fracture energy of hemp fiber-reinforced mortar was higher than those of the fiber-free mixture by 32.2% and 17.9%, respectively. The corresponding values for basalt fiber addition 60.8% and 146.4%.

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1. Introduction

Concrete is the most commonly used construction material in the world (Jianbing et al. 2022). Despite providing much superiority, concrete has several disadvantages, such as low tensile strength and brittleness (El-Abbasy 2022). Fibers can be used to overcome these issues and improve properties such as ductility, toughness, and durability in cement-based building materials (Vairagade and Dhale 2023). To enhance properties of concrete, it is possible to use various types of fibers like steel, glass, polypropylene (Li et al. 2022), PVA, basalt, etc. (Zhao et al. 2016). However, it is known that the production of these types of fibers results in various drawbacks, like carbon emission, and the consumption of different types of resources (Chen et al. 2023).

Nowadays, various types of natural fibers are being used to enhance some properties of concrete due to their characteristics such as low cost, sustainability, renewability (Abdalla et al. 2022), unlimited availability, biodegradability, recyclability (Suardana et al. 2011) as well as low density, high acoustic damping and reduced industrial fuel expense (Ahmad and Zhou 2022). Interest in natural fibers is expected to increase in the coming years (Sullins et al. 2017).

Hemp is a well-known plant species and industrial hemp is used in different sectors like textile, food, automobile, biofuel and construction (Grubesa et al. 2018). The main components of hemp fiber are cellulose, hemicellulose and lignin (Stevulova et al. 2022). Studies are carried out on the use of fibers obtained from the hemp plant in the production of fiber concrete. Although there are limited studies in the literature, the findings revealed that using hemp fiber in fiber-reinforced concrete is possible. Li et al. (2006) investigated the effect of aggregate size, mixing method, length and amount of hemp fiber on

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some physical and mechanical properties of hemp fiber-reinforced concrete. For this purpose, 10, 20 and 30 mm long fibers were used in different dosages and a total of 30 concrete mixtures were produced. Researchers reported that it is possible to increase the flexural toughness up to 143.6%, 30.3% and 57.4%, respectively, by using hemp fiber in concretes with 20, 14 and 7 mm maximum size aggregates.

Çomak et al. (2018) examined the effect of hemp fiber dosage and length on the mechanical properties of cement mortar mixtures. 6, 12, 18 mm long fibers were utilized at three dosages of 1, 2, and 3% by volume. It was determined that the flexural strength increased in the range of 1.2-16.9% with fiber inclusion. Another finding of the study was that, in mortars containing 6 mm and 12 mm long fibers, the flexural strength improved as the fiber content increased, while the opposite situation was observed when 18 mm long fibers were used. In a similar research Ruano et al. (2020) conducted a study on the flexural behavior of sugarcane bagasse and hemp fiber-reinforced mortars. The load-CMOD relationship of the mixtures was determined and the researchers stated that the flexural toughness increased with the hemp fiber addition. Zhou et al. (2017) explored the effect of the treatment of hemp fiber on some properties of concrete and stated that with the treatment, the 28-day compressive and tensile strength, as well as the critical stress intensity factor, critical strain energy release rate and fracture toughness were affected positively. Kaplan and Bayraktar (2021) reported that the flexural strength of cement mortar increased with the inclusion of hemp fiber of 5, 10 and 20 mm length and 1, 2, 3% by the weight of cement.

Basalt fibers are produced with lower energy consumption than commonly used fiber types such as steel, glass, and carbon. They also have advantages such as high tensile strength, good durability, and corrosion resistance (Al-Rousan et al. 2013). The basalt fibers are widely utilized at different civil engineering applications, and it is known that these fibers improved mechanical properties of concrete (Zhou et al. 2023). Kabay (2014) investigated the effects of 12 and 24 mm long basalt fibers inclusion with 0.07% and 0.14% dosages by volume on the properties of concrete mixtures produced with two different water/cement ratios (0.45 and 0.60). The researcher stated that with the addition of basalt fibers, the fracture energies of concretes prepared with 0.45 and 0.60 water/cement ratios increased up to 112.6% and 140.2%, respectively. In addition, the flexural strengths of concrete were improved up to 10.4% and 15.9% with fiber usage. Arslan (2016) investigated the effect of basalt fiber dosage on fracture energy of notched beam concrete specimens having a water/cement ratio of 0.5. The fibers were used at 0.5, 1, 2, and 3 kg/m^3 dosages, and fracture energies were calculated with crack mouth opening displacements (CMOD). The researcher reported that with basalt fiber addition, flexural strength and fracture energy increased up to 25.4% and 28.6%, respectively, and the optimum fiber dosage for fracture energy was 2 kg/m^3. In a similar study, Kizilkanat et al. (2015) investigated the effects of basalt fiber dosage on the properties of concrete. The fibers were used at 0.25%, 0.50%, 0.75%, and 1% by volume, and the strength and fracture properties were determined. The researchers stated that basalt fiber increased the splitting tensile strength, flexural strength, peak load, and fracture energy. With the increase in fiber dosage, the fracture energies continuously improved and became 51% higher than the fiber-free mixture at 1% dosage.

In spite of several studies, the effect of natural fibers on the fresh properties, sorptivity, strength and fracture energy of cement-based composite still needs to be compared with those of the commonly used fibers like glass, steel, basalt, carbon, etc. This study determined the effect of hemp fiber on flow diameter, unit weight, water absorption, coefficient of sorptivity, compressive and flexural strength as well as fracture energy of the cement mortar mixtures. The experimental work was divided into two different phases. Firstly, the effect of the fiber type (basalt or hemp), fiber dosage (0.125, 0.25, 0.5, or 1% by volume), and fiber length (6 or 18 mm) on fresh properties and mechanical strength were investigated. After that, the selected hemp-fiber and basalt-fiber reinforced mixtures were subjected to 3-point bending test, and the fracture energies of samples were determined using the force-crack mount opening displacement relationship. The results showed that the mechanical properties and fracture energies improved with the use of hemp fiber compared to those of the plain (fiber-free) mixture. However, basalt fibers were much more effective on these properties.

2. Materials and Method

2.1. Materials

CEM I 42.5 R type Portland cement, tap water and CEN standard sand conformed to TS EN 196-1 standard were used in the production of mixtures. Besides, to achieve acceptable workability, a commercial polycarboxylate-based plasticizer was utilized. The chemical composition and some properties of cement are given in Table 1. In the preparation of fiber-reinforced mortar mixtures, commercial basalt fiber 13-20 µm in diameter, 4000-4500 MPa in tensile strength, 88 GPa in modulus of elasticity, and natural hemp fiber was used. The specific gravities of basalt and hemp fiber were 2.80 and 0.85, respectively.

The preparation process of the hemp fibers and the image of the fibers are shown in Figs. 1 and 2, respectively. The dried hemp bundles were provided (Fig. 1a and 1b), the hurds were manually separated from the bulk (Fig. 1c), and bundle of fiber were obtained (Fig. 1-d). Then hemp fibers were cut to 6 and 18 mm by hand (Fig. 2).

SEM micrographs of fibers with different magnifications are given in Fig. 3. The diameter of basalt fibers was around 20 µm. On the contrary, the geometry of hemp fiber was irregular and generally extended in two directions. The widths of hemp fibers were more than their thicknesses, and the width of fibers varied from fiber to fiber from 10 µm up to 1000-1500 µm. Moreover, the surface of hemp fiber was significantly rougher than that of the basalt fiber.

Table 1. Chemical composition and some properties of cement.

Compound	% (by weight)	Mechanical properties	
CaO	63.06	Compressive strength	
SiO_2	18.53	7 days	38.4 MPa
Al_2O_3	5.21	28 days	47.2 MPa
Fe_2O_3	3.65		
MgO	1.01	Physical properties	
Na_2O	0.48	Specific gravity	3.11
K_2O	0.64	Initial setting time	210 mins.
SO_3	3.20	Final setting time	315 mins.
Free CaO	0.91	Blaine specific surface area	3420 cm^2/g
Loss on ignition	2.94		
Insoluble residue	0.10		

Fig. 1. Preparation of hemp fibers:
(a),(b) Hemp fibers with hurds; (c) Cleaning fibers from hurds; (d) Hemp fibers before cutting.

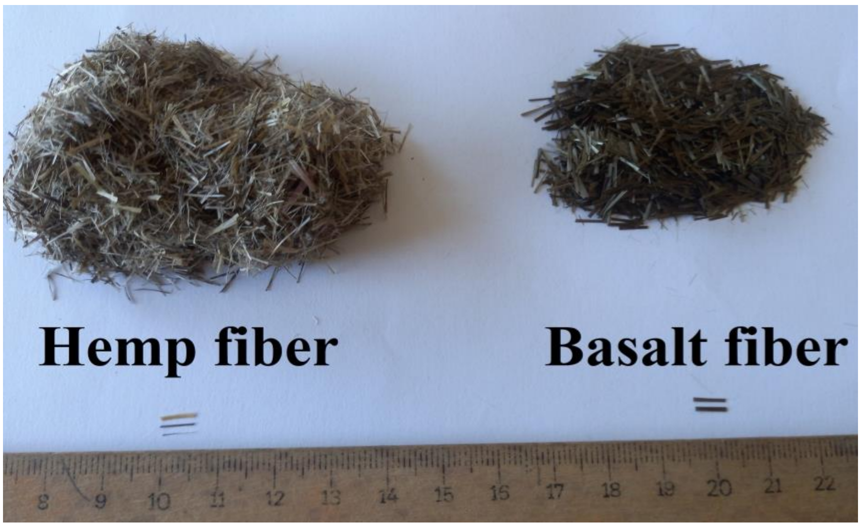

Fig. 2. Photos of fibers.

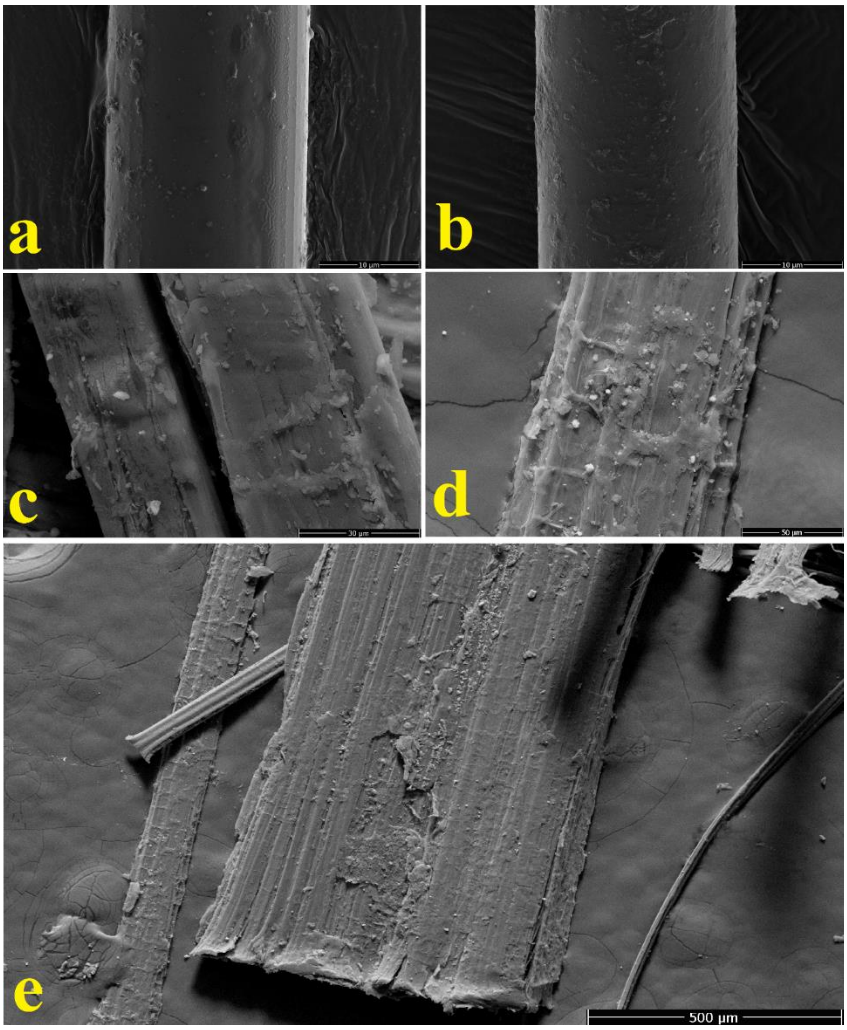

Fig. 3. SEM images of fibers: (a),(b) Basalt fiber; (c),(d),(e) Hemp fiber.

2.2. Method

Mixtures were prepared with an automatic mortar mixer. Firstly, sand, cement and fibers were dry mixed at 62.5 rpm for 60 seconds. Water and plasticizer were combined and added to the bowl. The mixer was operated for 90 seconds at 62.5 rpm. The material adhered to the wall of the bowl was scraped within approximately 15 seconds, then the mixer was run for another 90 seconds at 125 rpm. The fresh mixtures were poured into the molds in two layers, and each layer was compacted by a jolting table with 25 jolts. Samples were stored in laboratory conditions for 24 hours, demolded after this time, and cured for 27 days at the curing pool. All hardened mortar tests were performed at the age of 28 days.

40 mm x 40 mm x 160 mm prismatic specimens were used to determine the coefficient of sorptivity, water absorption and unit weight. Besides, notched specimens (50 mm x 50 mm x 240 mm), with a 10 mm notch height and 3 mm notch width, were prepared for the fracture energy tests. The compressive strength tests were carried out on the broken portions of the specimens after flexural strength tests. Three specimens were used for all tests carried out in the study (except compressive strength which was done on six specimens), and the average values were reported. The flow diameter, coefficient of sorptivity, compressive and flexural strengths were determined in accordance with ASTM C1437, ASTM C1585, ASTM C349 and ASTM C348 standards, respectively. Fracture energy tests were carried out using a 3-point bending test setup with a displacement-controlled device. The rate of loading was 0.01 mm/minute, and the crack mouth opening displacements (CMOD) were measured with a clip-on gage. A strong adhesive was used to connect metal blades to the samples' bottom surfaces, and clip-on gage was attached to the sharp edges of knifes. The experimental setup and sample geometry are shown in Fig. 4. When the peak load dropped by 95%, the test was ended. The graphs of the force-CMOD relationship were drawn, and the fracture energy was calculated using Eq. (1) with the suggestion of Rilem (1985). However, instead of force-deformation curves, force-CMOD curves were used.

$$G_F = \frac{W_0 + mg\delta_0}{A} \quad (1)$$

In this equation, W_0, mg, δ_0 and A represent the area under force-CMOD curve (N·mm), the weight of the specimen between the supports (N), the maximum crack opening (mm) and area of the midspan cross-section of the specimens without notch (mm^2), respectively.

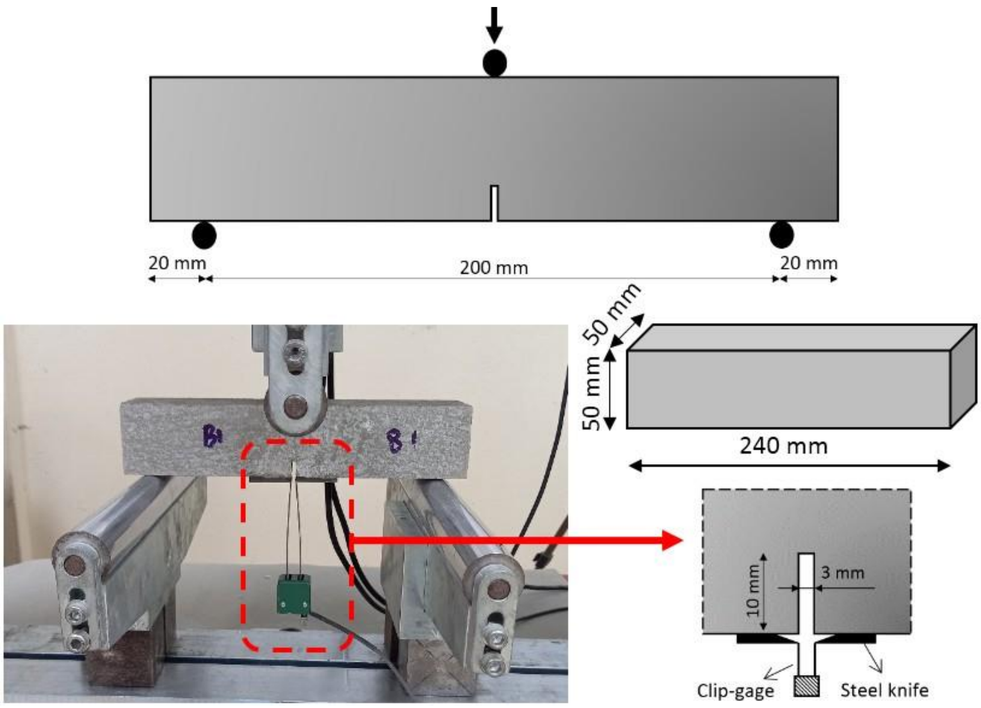

Fig. 4. Fracture energy test setup, geometry of specimen and detail of notch.

2.3. Mixtures

The experimental study is divided into two different phases. The compressive and flexural strengths of the fiber-free mixture and fiber-reinforced mixtures were determined at the first stage. The length and dosage of fibers were the selected variable parameters. In this regard, a total of 16 fiber-reinforced mortar mixtures were prepared with two fiber types (basalt and hemp), two fiber lengths (6 and 18 mm) and four fiber dosages (0.125, 0.25, 0.50 and 1% by volume). In addition to the reference mixture, two mixtures were selected for each fiber type regarding the flexural strength test results for the next phase.

In the second stage, the fracture energy, coefficient of sorptivity and water absorption capacity values of the selected mixtures were determined, and the effect of fiber inclusion on these properties was evaluated comparatively. The proportions and some properties of mixtures are given in Table 2, and the designation of the mixtures is explained in Fig. 5.

Table 2. Ingredients and some properties of mixtures.

Mixture	Ingredients (g)					
	Cement	Sand	Water	Plasticizer	Hemp fiber	Basalt fiber
Control	450	1350.0	225	2	-	-
HS-0.125	450	1348.3	225	2	0.96	-
HS-0.25	450	1346.6	225	2	1.92	-
HS-0.50	450	1343.3	225	2	3.83	-
HS-1.0	450	1336.5	225	2	7.67	-
HL-0.125	450	1348.3	225	2	0.96	-
HL-0.25	450	1346.6	225	2	1.92	-
HL-0.50	450	1343.3	225	2	3.83	-
HL-1.0	450	1336.5	225	2	7.67	-
BS-0.125	450	1348.3	225	2	-	3.12
BS-0.25	450	1346.6	225	2	-	6.24
BS-0.50	450	1343.3	225	2	-	12.48
BS-1.0	450	1336.5	225	2	-	24.96
BL-0.125	450	1348.3	225	2	-	3.12
BL-0.25	450	1346.6	225	2	-	6.24
BL-0.50	450	1343.3	225	2	-	12.48
BL-1.0	450	1336.5	225	2	-	24.96

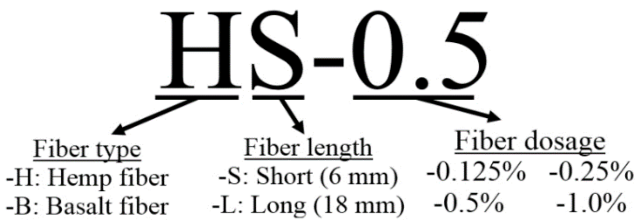

Fig. 5. Designation of mixtures.

3. Results and Discussion

3.1. Flow diameter and unit weight

Figs. 6 and 7 illustrate the flow diameter and unit weight values of mixtures. As seen from the figures, the flow diameter and unit weight of the fiber-free mixture was the highest, as expected. Irrespective of fiber type and length, raising the dosage of fiber from 0.125% to 1% resulted in a gradual decrease in flow diameter. The reductions due to basalt fiber addition were higher than that of hemp fiber addition. This phenomenon is probably due to basalt fiber's high surface area/volume ratio. The mixtures with 1% fiber inclusion had the lowest flow diameter in each series. Increasing the fiber dosage also decreased the fiber-reinforced mixtures' unit volume weight. This situation was more considerable in the mixtures including 1% fiber.

3.2. Compressive and flexural strength

The flexural and compressive strength values of mixtures are given in Figs. 8 and 9, respectively. As seen from the figure, irrespective of the fiber type and length, 0.125% fiber inclusion did not have a meaningful effect on the flexural strength due to insufficient fiber dosage. The results were similar with the addition of 0.25% hemp fiber. 1% fiber-reinforced mixtures in all series had the lowest flexural strength values due to their low workability. Hemp and basalt fiber reinforced mortars containing 0.5% long and 0.5% short fibers have the highest flexural strengths in their series, with 6.2 and 6.7 MPa, respectively. These mixtures were selected for the water absorption, sorptivity and fracture energy tests.

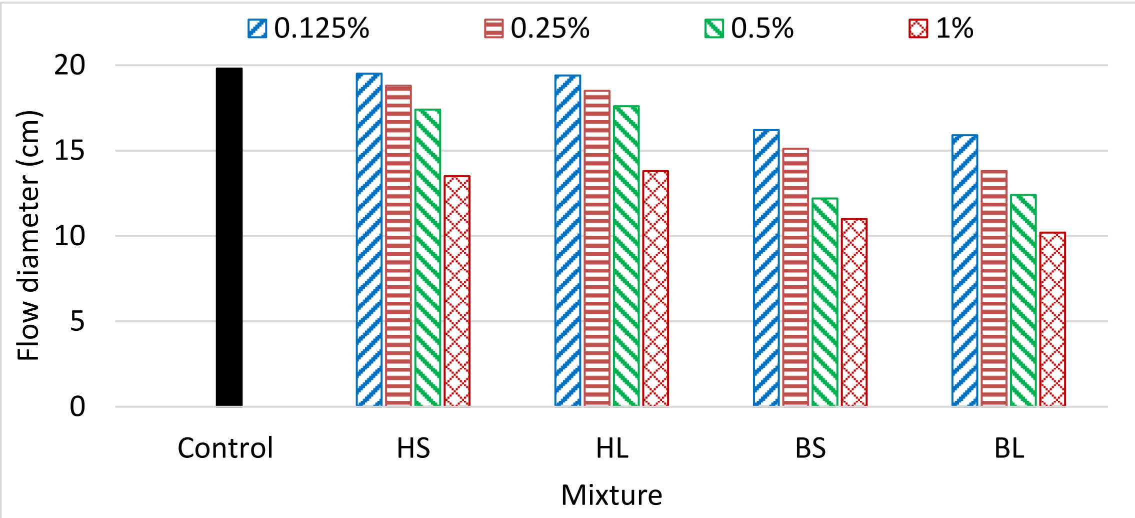

Fig. 6. Flow diameters of the mixtures.

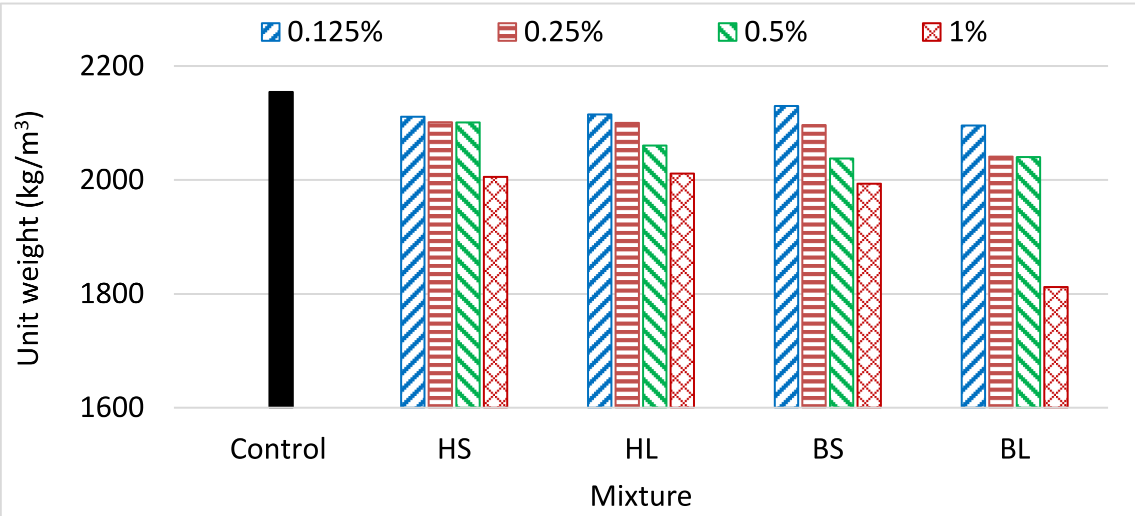

Fig. 7. Unit weights of the mixtures.

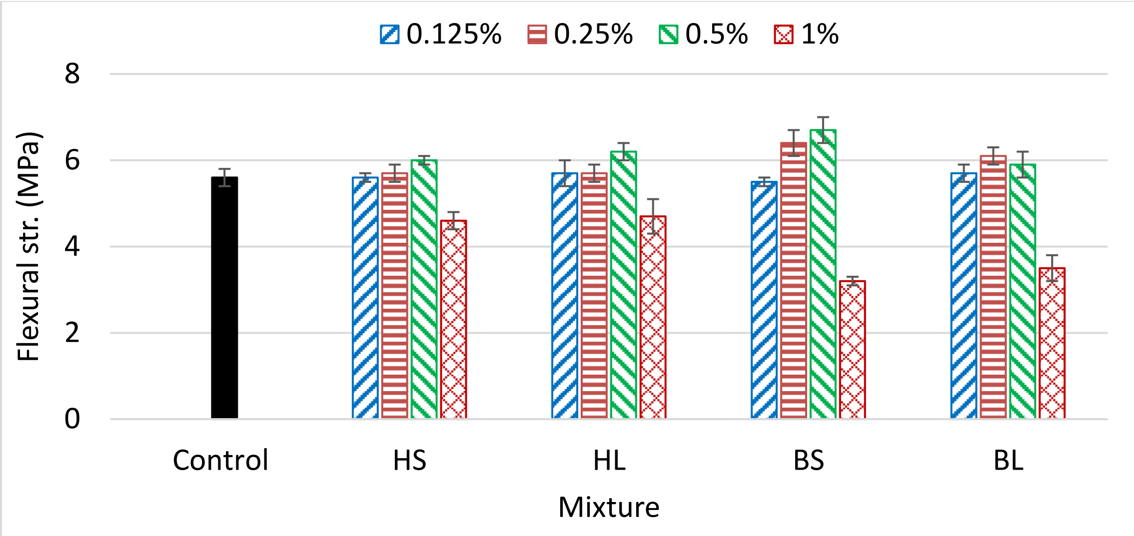

Fig. 8. Flexural strengths of the mortar mixtures.

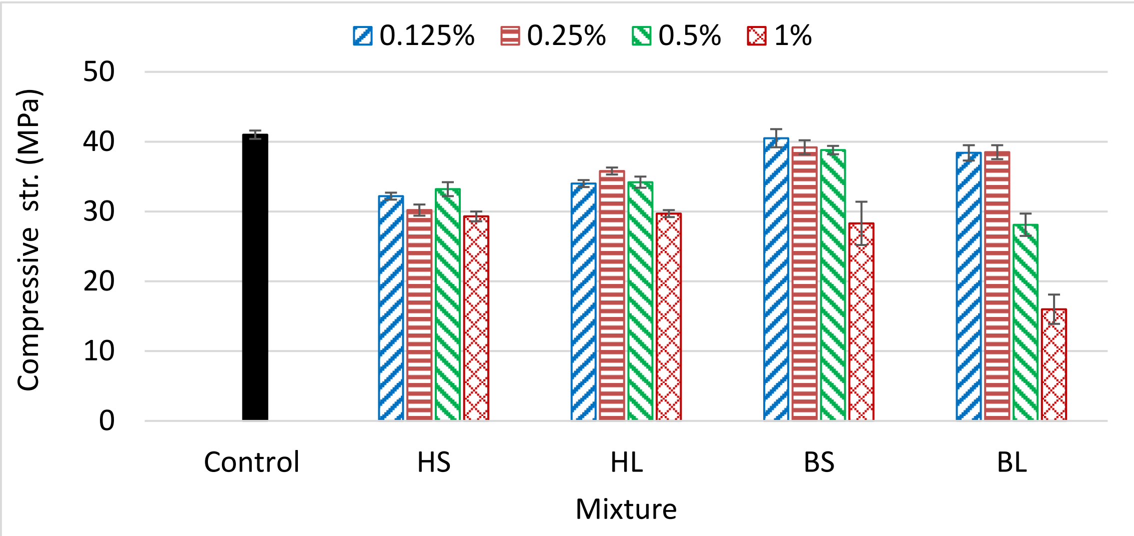

Fig. 9. Compressive strengths of the mortar mixtures.

On the other hand, test results revealed that fiber inclusion had a negative effect on the compressive strength. The compressive strength of hemp fiber-reinforced mortars was 12.7-28.5% lower than that of the reference mortar. Besides, at lower dosages, the basalt fiber inclusion did not significantly affect the compressive strength. However, with the increase in fiber dosage, both flow diameter and strength decreased progressively probably due to the effect of basalt fiber's high surface area/volume on workability and consequently on compactibility of the mixtures. Uygunoğlu et al. (2022) investigated the effect of PVA fiber content on the properties of cement-based mortar. The researchers reported that the compressive and flexural strengths increased with the addition of 2% fiber but at higher dosages it had a negative impact on the mechanical properties. The fact was attributed to the workability and placement issues caused by the increasing fiber dosage. In a similar study, Şahan et al. (2021) examined some properties of polypropylene fiber-reinforced concretes. The researchers reported that the flexural and compressive strengths increased compared to those of the control sample at the optimum fiber dosage of 0.22%; beyond this dosage, the strength decreased.

3.3. Fracture energy

The force-deflection and force-CMOD curves of three specimens of each mixture are given in Figs. 10 and 11, respectively. The peak load, maximum deflection, maximum CMOD values and the area under the curves increased with fiber inclusion. In this respect, the inclusion of basalt fiber had a higher positive effect than that of the hemp fiber.

The peak load, deflection corresponding to the peak load and fracture energy values are given in Fig. 12. With the addition of hemp and basalt fiber, the mean peak load increased by 32.2% and 60.8%, respectively. Although the hemp fibers enhanced the peak load and fracture energy, the amount of increase was considerably lower than that of the basalt fibers.

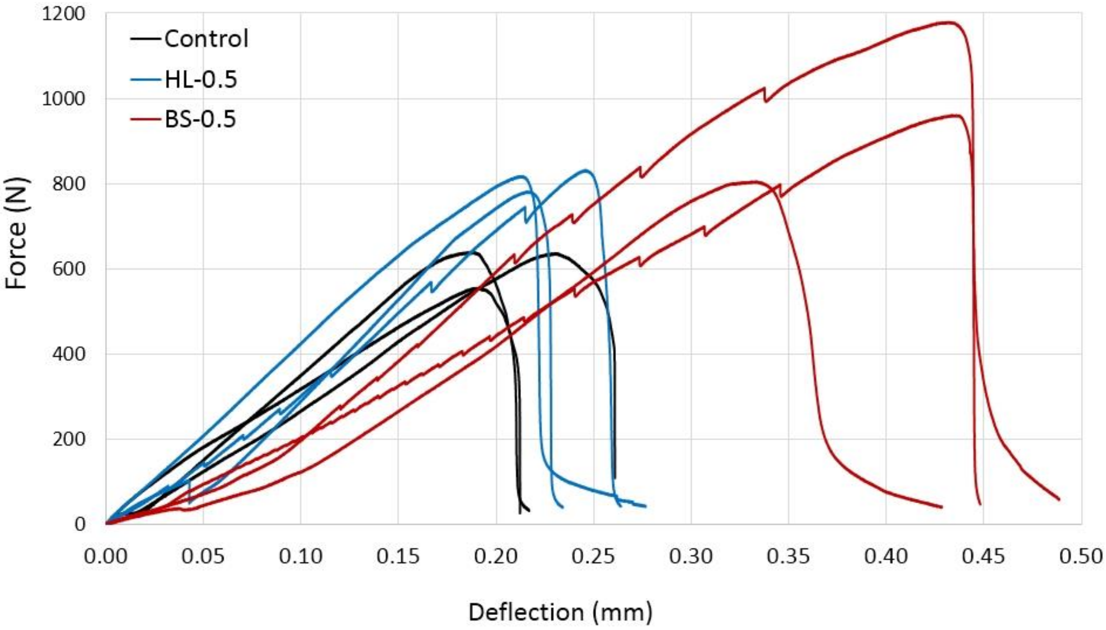

Fig. 10. Force-deflection relationships of the samples.

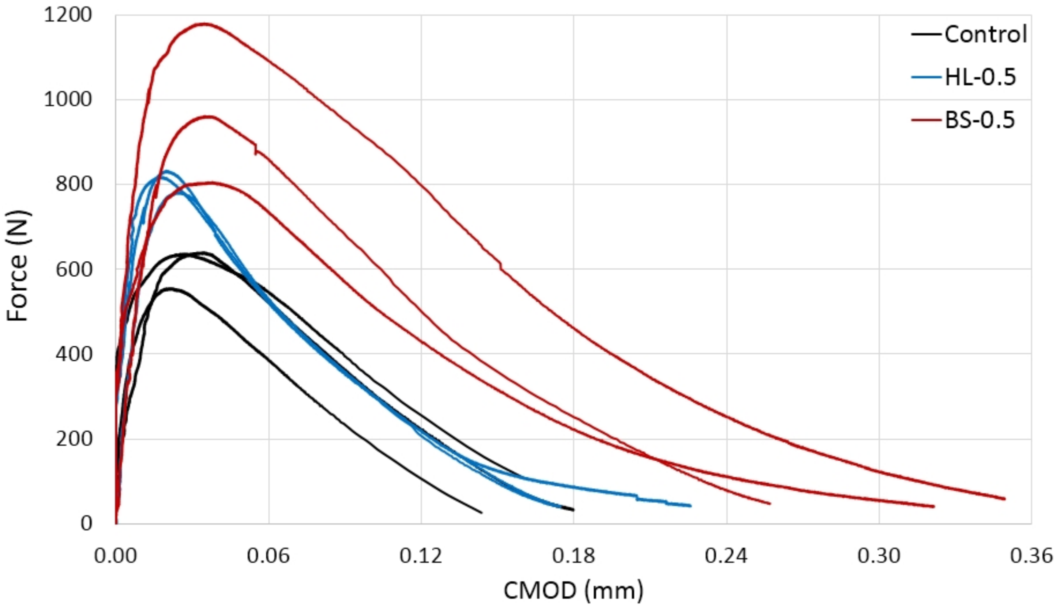

Fig. 11. Force-CMOD relationships of the samples.

Similarly, mean deflection values corresponding to the peak load of hemp and basalt fiber-reinforced mortars were 10.9% and 97.5% higher than that of the control sample, respectively. Compared to that of the reference mixture, the deflection corresponding to the peak load of the fiber-reinforced mixes was greater. The role of fibers in increasing the first cracking point and their bridging effect upon crack propagation is obvious. Fiber inclusion increased the fracture energy too, and the fact was more pronounced with basalt fiber addition. The increment rates were 17.9% and 146.4% for hemp and basalt fiber addition, respectively. Ruano et al. (2020) also reported that the flexural toughness of concrete improves with hemp fiber addition. It is known that fibers transfer the load and show a bridging effect on the fracture surface, resulting in delaying the connection of the cracks (Bencardino et al. 2010) with the mechanisms of debonding, bridging, pull-out and failure (Abbas and Khan 2016). During the fracture energy test, the bridging effect delaying the crack propagation was obvious. At the end of the test, visual observation on the fracture surfaces of specimens revealed the debonding of the fibers and probably fracture of some of them. Arslan (2016) reported that with the use of basalt fiber, the fracture energies of fiber-reinforced concrete increased by 6.8-28.6% depending on the fiber dosage. In a similar study, the increment rate of the fracture energy with basalt fiber inclusion was stated to be in between 3-51% (Kizilkanat et al. 2015). According to a study on fiber-reinforced self-compacting concretes, Gultekin et al. (2022) stated that it is possible to increase the fracture energy with basalt fiber addition up to 30.4%.

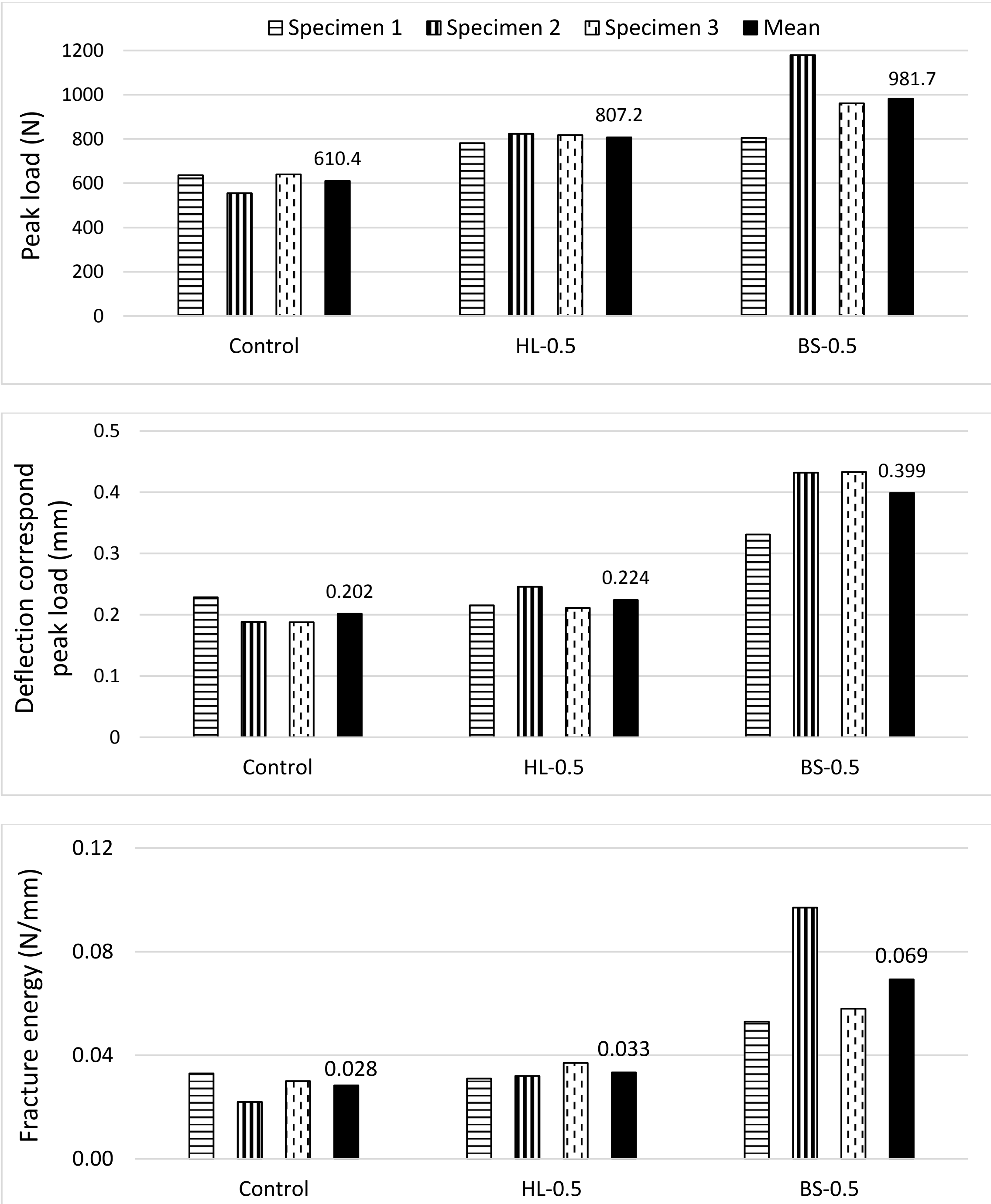

Fig. 12. Peak loads, deflections corresponding to peak loads and fracture energy of the mixtures.

3.4. Water absorption and sorptivity

Water absorption and coefficient of sorptivity of the mixtures are given in Figs. 13 and 14, respectively. Water absorption increased by 12% and 4.8% with the inclusion of hemp and basalt fibers, respectively. The fact is probably due to the reduced workability with the addition of fibers. In addition, hemp fiber also absorbs water due to its porous structure. The addition of basalt fiber did not have a significant effect on the water absorption capacity. Nevertheless, hemp fiber-reinforced specimens had the highest water absorption capacity. However, fiber inclusion reduced the coefficient of sorptivity by 20% and 55% for hemp and basalt fiber, respectively. Wang et al. (2021) marked that the addition of fiber to face slab concrete increased the total porosity and fraction of larger pores, but reduced the fraction of smaller pores. In this study the effect of basalt and hemp fibers on the capillary water absorption was clearly seen. The increase in water absorption and decrease in coefficient of sorptivity suggested that the addition of fiber changed the pore structure of the cement mortar. It is thought that with the inclusion of fibers, the fraction of larger pores (arisen from insufficient compactibility and responsible for water absorption) increased, however, the amount of smaller pores (arisen from crack treatment effect of fibers and responsible for sorptivity) reduced.

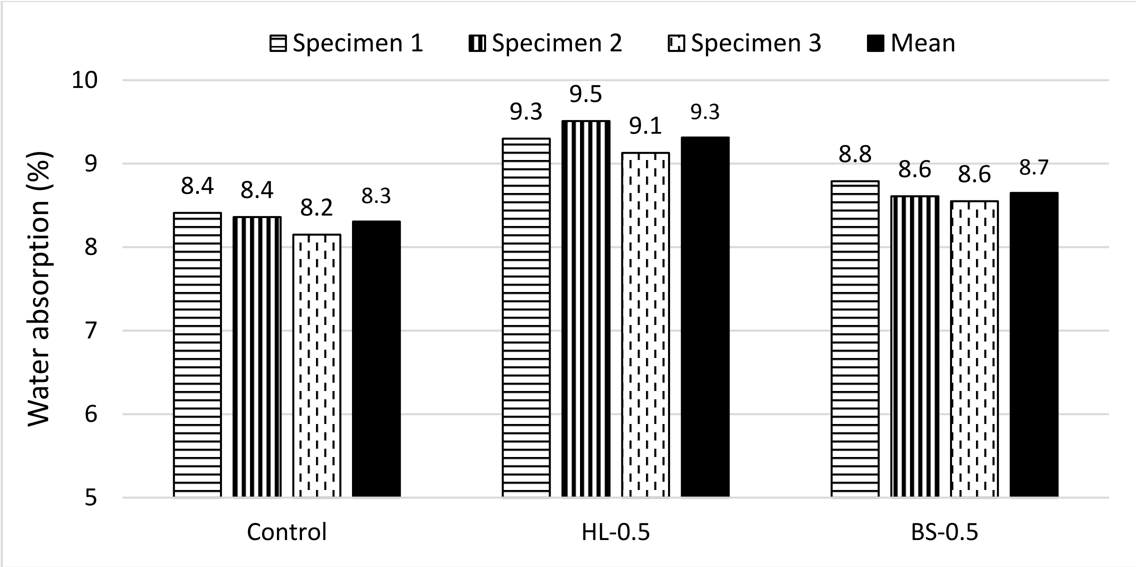

Fig. 13. Water absorption values.

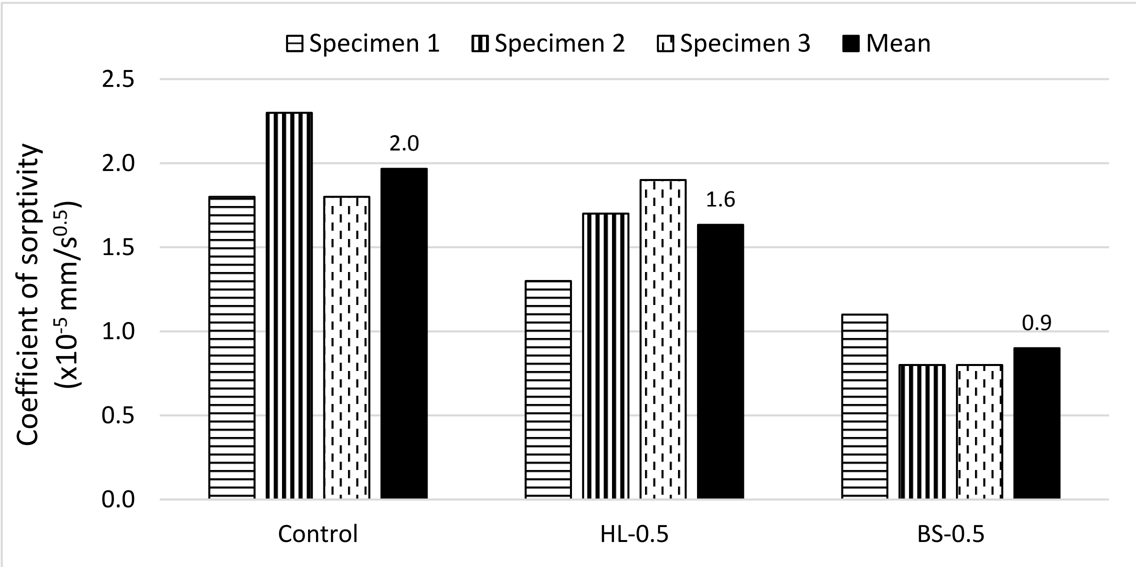

Fig. 14. Coefficient of sorptivity values.

4. Conclusions

This study investigated the effects of inclusion of hemp and basalt fibers on the fresh properties, mechanical strength and fracture energy of fiber-reinforced cement-based composites. For the materials used and tests applied, the following conclusions may be drawn:

- With the inclusion of fiber, mortar flow diameters decreased, and the fact became clearer at higher fiber dosages. As a result of the decreased workability (compactibility) with fiber inclusion, the unit weight of composites decreased progressively. In this regard, the negative effect of basalt fiber addition on flow diameter was higher than that of the hemp fiber.
- The effect of fibers on flexural strength was negligible at lower dosages (0.125 and 0.25%). In terms of flexural strength, the optimum fiber dosage was 0.5%. It was possible to increase flexural strength up to 10.7% and 19.6% with hemp and basalt fiber addition, respectively. Unlike flexural strength, fibers decreased the compressive strength. However, the reduction in compressive strength was negligible in the low dosage basalt fiber-bearing mixtures.
- Fibers enhanced the peak load, the deflections corresponding to the peak loads and fracture energy of the mixtures. From fracture energy viewpoint, positive effect of the basalt fiber was more than that of the hemp fiber. The fracture energy of hemp and basalt fiber-reinforced composites was higher than that of fiber-free mixture by 17.9% and 146.4%, respectively.
- Hemp and basalt fiber inclusion reduced the coefficient of sorptivity by 20% and 55%, respectively. However, the water absorption of fiber-reinforced composites was higher than that of the plain mixture. This probably occurred due to the change in the pore structure.

Author Contributions

The sole author made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; was involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

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Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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