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Image Processing-Based Crack Analysis on Splitting Tensile Strength Test

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Abstract

Nowadays, fiber reinforcement is widely utilized to enhance the performance of concrete and mitigate crack formation. By improving the tensile strength of concrete, fiber reinforcement hinders the initiation and propagation of cracks and emerges as an effective method for increasing long-term durability. In recent years, image processing techniques have also provided innovative approaches for the detection and monitoring of cracks on concrete surfaces. These methods enable the precise identification of cracks, thereby facilitating early detection of potential structural damage. This study aims to examine the influence of basalt fiber reinforcement on the mechanical and physical properties of concrete. Basalt fibers were incorporated into concrete mixtures at four different dosages: 1 kg/m³, 2 kg/m³, 3 kg/m³, and 4 kg/m³. The impact of basalt fiber content on crack initiation and propagation was evaluated using an image processing-based approach. Furthermore, the effects of basalt fiber reinforcement on water absorption, porosity, capillary water absorption, and electrical resistivity were investigated. The findings indicate that basalt fiber reinforcement is notably effective in reducing crack formation and propagation in concrete. However, the optimum fiber dosage should be determined through preliminary testing to ensure balanced performance.

Keywords: Basalt Fiber, Fibrous Concrete, Image-Processing Techniques, Crack Analysis

1. Introduction

Concrete stands out as one of the most widely used construction materials worldwide, while the weak tensile strength and crack formation tendency of traditional concrete can negatively affect the long-term performance of structures. Therefore, the low tensile capacity and poor toughness properties mainly affect the overall concrete performance [1]. The development of high-performance fiber-reinforced cement-based composites has made remarkable progress in the field of concrete technology and is gaining great popularity in modern civil engineering applications [2,3]. Fiber-reinforced concrete technology is a significant development that enhances the mechanical properties of concrete, including tensile strength, impact resistance, and crack control. Numerous studies have demonstrated that the inclusion of discrete fibers effectively restrains crack initiation and propagation in concrete under various loading conditions [4–6]. In recent years, advances in artificial intelligence and image processing technologies have significantly transformed the detection and evaluation of cracks on concrete surfaces. Specifically, image processing methods enable rapid, accurate, and repeatable crack identification, enhancing the reliability of structural assessments [7]. Using high-resolution images, these methods can detect even fine microcracks that the human eye cannot detect, thus enabling early intervention and repair of structures. Image processing techniques are also used to evaluate the performance of concretes reinforced with various additives such as fibers. Discrete fiber elements in the concrete increase the tensile strength by closing the microcracks and change the overall behavior of the composite [8]. Various studies have investigated the positive effect of the addition of basalt, polypropylene, steel fibers and other fibers on the ductility of concrete. The addition of fibers effectively controls the proliferation of microcracks while providing toughness, torsion, bending, split tensile strength and impact resistance [9-12]. Basalt fibers are produced by melting basalt obtained from volcanic rocks at high temperatures and turning it into fibers. The addition of basalt fibers provides many advantages to concrete, such as high tensile strength, resistance to high temperatures, heat resistance, ability to withstand acid and alkali attacks, and corrosion resistance [13,14]. Yang et al. [15] reported that incorporating basalt fiber into concrete reduced transverse deformation and mitigated surface cracking. Furthermore, it improved the overall strength and modulus of elasticity of the basalt fiber-reinforced concrete, while causing only a negligible reduction in maximum strain. In addition, basalt fiber addition aims to reduce crack formation by strengthening the internal structure of concrete and to control the water permeability of structures. However, in order to fully evaluate the effect of fiber addition, parameters such as the size, density and distribution of cracks need to be measured precisely. In this study, the mechanical strength and crack formation behavior of basalt fiber reinforced concrete samples were analyzed in detail using image processing techniques.

Although numerous studies have investigated the mechanical behavior of fiber-reinforced concrete, research that examines crack formation in basalt fiber-reinforced concrete using image processing techniques in conjunction with mechanical testing remains limited in the literature. This study aims to address this gap by analyzing the crack formation behavior of basalt fiber-reinforced concrete through image processing of video recordings captured during the 28-day splitting tensile strength test.

In this study, concrete samples containing 1, 2, 3, and 4 kg/m³ of basalt fiber were evaluated through physical and mechanical tests, and crack development was qualitatively analyzed using image processing during the 28-day splitting tensile strength test. In order to determine the mechanical properties, the compressive and splitting tensile strengths of 7 and 28-day samples were determined. While determining the 28-day splitting tensile strength, a video recording was taken with the camera system installed and crack analysis was performed by image processing method. Water absorption, porosity, electrical resistivity and capillary water absorption coefficients were determined for physical properties. It was observed how the fiber ratio affected the crack formation by image processing analysis. As a result, it is revealed that fiber reinforcement can increase the performance of concrete when used in the right proportions, but excessive fiber usage can lead to undesirable results.

2. Materials and Methods

CEM I 42.5 R type Portland cement was preferred as the binder in concrete production. In accordance with TS 706 EN 12620 standards, crushed sand with a grain size of 0-4 mm and coarse aggregate with a grain size of 4-16 mm were used [16]. The specific gravity of crushed sand is 2.70 g/cm³ and the specific gravity of coarse aggregate is 2.67 g/cm³, and these materials are present in the mixture at 47% and 53%, respectively. In order to increase the shear capacity, 12 mm long basalt fibers, the properties of which are specified in Table 1, were added to the mixture at 1 kg, 2 kg, 3 kg and 4 kg per cubic meter of concrete. The amounts of material required for 1 m³ in concrete production are presented in Table 2.

Table 1. Properties of basalt fiber

Properties	Basalt Fiber
Tensile Strength	4840 MPa
Module of Elasticity	89 GPa
Melting Temperature	1450°C
Specific Gravity	2.60-2.80
Fiber Diameter	9-23 micron

Table 2. Required materials quantities for 1 m³ concrete, kg

Samples Name	REF	1BF	2BF	3BF	4BF
Cement	350	350	350	350	350
Water	150	150	150	150	150
Chemical Additive	4.2	4.2	4.2	4.2	4.2
Crushed Sand	915	915	915	915	915
Coarse Aggregate	1032	1032	1032	1032	1032
Basalt Fiber	0	1	2	3	4

After concrete production, the first slump test was applied to determine the workability in fresh state. Fresh concrete placed in molds was taken from the mold after 24 hours and placed in the curing pool. Mechanical strengths of samples that completed 7 days in the curing pool and both physical and mechanical properties of samples that completed 28 days were determined. Water absorption, porosity, unit volume weight, capillary water absorption, and electrical resistivity tests were conducted to evaluate the physical properties of the samples. The standards for all physical and mechanical tests performed are listed in Table 3. Water absorption, porosity, and unit volume weight values were measured using a scale operating based on Archimedes' principle. Capillary water absorption coefficients were determined in accordance with the standard by impregnating the sample with water by capillary method in 1 min, 4 min, 9 min, 16 min and 25 min in oven dry state. Electrical resistivity measurements were performed on water-saturated samples at frequencies of 0.1, 0.12, 1, and 10 kHz to minimize the influence of humidity conditions on the results. The primary objective of measuring resistivity at varying frequencies was to identify how resistivity values change depending on the measurement frequency. To evaluate the mechanical properties of the concrete samples, compressive strength and splitting tensile strength tests were conducted at curing ages of 7 and 28 days. During the 28-day splitting tensile strength test, crack initiation and propagation were visually monitored, and a qualitative analysis was conducted using an image processing-based approach. For this purpose, a high-resolution camera was fixed laterally to the specimen and used to record the entire loading process. The camera was mounted on a tripod to ensure stability, and appropriate lighting was provided to enhance image quality. The experimental setup, including the specimen placement and camera position, is shown in Figure 1.

Figure 1. Image processing setup

After the test, the recorded video was split into frames, which were processed using ImageJ, an open-source image analysis software. The selected frames were converted to grayscale and processed using thresholding techniques to enhance the visibility of surface cracks.

Table 3. Physical and mechanical properties experiment to be applied to the samples

Experiment Name	Standard
Slump Test	TS EN 12350-2, 2019 [17]
Compressive Strength	TS EN 12390-3, 2019 [18]
Splitting Tensile Strength	TS EN 12390-6, 2024 [19]
Water Absorption and Porosity	TS EN 1170-6, 2010 [20]
Capillary Water Absorption Test	TS EN 772-11, 2012 [21]
Electrical Resistivity	ASTM C 1760-12, 2021 [22]

2. Results and Discussion

Slump Test Results

The slump test results conducted to determine the workability properties of fresh concrete mixtures are presented in Table 4. While REF constitutes the initial level with a slump value of 18 cm, this value was measured as 18.5 cm in the 1BF sample containing 1 kg/m³ basalt fiber and a slight increase was observed. This situation is due to the fact that the low fiber content increases the cohesion of the concrete and creates a more homogeneous mixture structure. However, a decreasing trend was observed in the slump values with the increase in the fiber ratio. Slump values of 17 cm, 16.5 cm and 15 cm were obtained in the 2BF, 3BF and 4BF samples, respectively. This decrease is due to the restriction of free water in the mixture and the decrease in workability due to the increased fiber amount. As a result, in order to maintain workability in fiber concrete designs, it is necessary to control the optimization of the appropriate additive and water/binder ratio.

Table 4. Slump Test Results

Samples Name	Slump, cm
REF	18
1BF	18,5
2BF	17
3BF	16,5
4BF	15

Compressive Strenght Results

The 7 and 28-day compressive strength results of the concrete samples are given in Figure 2. It was observed that the compressive strength of the concrete increased in all series as the concrete age progressed. It was observed that the 1BF samples containing 1 kg of basalt fiber per cubic meter exhibited higher strength values compared to the reference sample. The 2BF, 3BF and 4BF samples, which used higher fiber ratios, exhibited lower compressive strength compared to the reference sample. This situation can be attributed to the deterioration of concrete homogeneity and a decrease in workability at high fiber ratios. Therefore, determining the optimum ratio in basalt fiber reinforcement is important in terms of both workability and strength. It was determined that the optimum fiber ratio was 1 kg per cubic meter as basalt fiber increased, which was effective in increasing the compressive strength of the concrete, but the strength increase decreased after a certain point. In the literature, decreases in strength are observed due to the deterioration of concrete homogeneity and the decrease in workability with the increase in basalt fiber ratios [23,24]. Kizilkanat et al. [25] reported that basalt fibers increase durability by filling microcracks in concrete, but homogeneity deteriorates with increasing fiber ratio. This situation coincides with the decrease in strength observed at high fiber ratios in our study. The decrease in compressive strength can be explained by the irregular distribution of fibers in the concrete at high fiber ratios and the tendency of fibers to tangle.

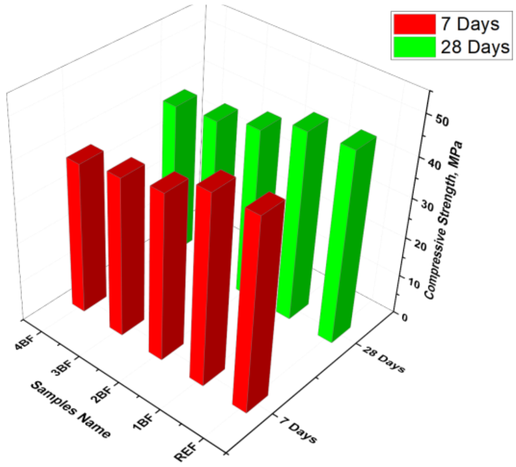

Figure 2. 7 and 28 day compressive strength results

Splitting Tensile Strengths Results

Figure 3 presents the splitting tensile strength results of concrete samples at 7 and 28 days. All mixtures exhibited strength gains over time, indicating a positive correlation between curing age and tensile performance. The splitting tensile strength results indicated that the 1BF and 2BF samples exhibited improved performance compared to the reference. Specifically, the 1BF sample achieved a splitting tensile strength of 3.51 MPa, representing a 17% increase compared to the reference sample, which had a strength of 3.0 MPa. Similarly, the highest splitting tensile strength for the 28-day results was obtained in the 1BF sample (3.7 MPa). These results confirm that basalt fibers are effective in increasing the tensile strength of concrete, as stated in the study of Yan and Shi [26]. However, a decrease in strength was observed with the increase in the amount of fibers (3BF and 4BF samples). In the literature, it has been reported that the splitting tensile strength of concrete increases significantly at low fiber ratios; however, this increase remains limited as the fiber ratio increases [27,28]. Similarly, in this study, while 1BF and 2BF samples showed high splitting tensile strength, the strength tended to decrease in 3BF and 4BF samples. This situation was observed that high fiber ratios negatively affected the homogeneous structure and workability of the concrete and limited the splitting tensile strength.

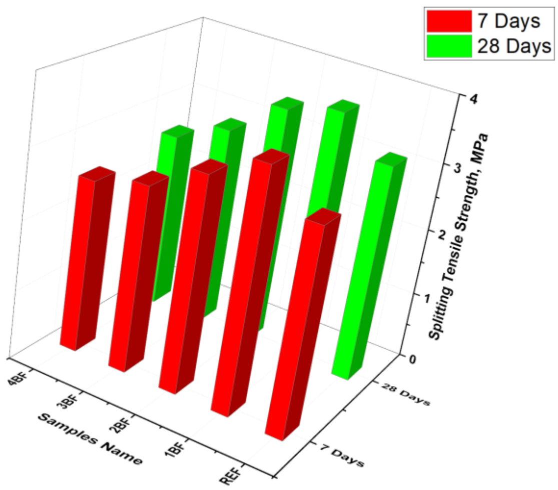

Figure 3. 7 and 28 day splitting tensile strengths results

The Crack Analysis Results

The crack analysis results obtained with the image processing method taken simultaneously while determining the splitting tensile strength of concretes with basalt fiber addition are given in Figure 4. As the basalt fiber ratio increased, the cracks became more confined and finer. Although no pixel-scale width measurement was performed, the pattern reveals that basalt fibers contributed significantly to the formation of a more ductile failure surface, with numerous distributed microcracks rather than large, singular cracks. It is shown that crack widths decrease and crack distributions become more homogeneous with the increase in basalt fiber content. These findings are consistent with studies in the literature, which indicate that fiber concretes control crack formation by increasing tensile strength [29-31]. Especially in samples containing 4% basalt fiber, the thinner and more limited spread of cracks supports the effects of basalt fibers on crack prevention mechanisms. It is stated that basalt fibers slow down crack propagation by increasing the energy absorption capacity of concrete and ensure that cracks remain in a more regular structure [32,33]. In this context, it is understood that although voids increase at higher fiber contents, basalt fibers act as a barrier against crack growth and limit the propagation of microcracks within the matrix. In addition, the positive effects of basalt fibers on the flexural and tensile strength of concrete are also emphasized in the literature [34]. The findings indicate that basalt fibers can serve as an effective reinforcement material, particularly in high-performance concrete applications, and image processing analysis confirmed that they delay and limit crack formation. Incorporating basalt fibers into concrete technology may significantly enhance the durability and safety of structures.

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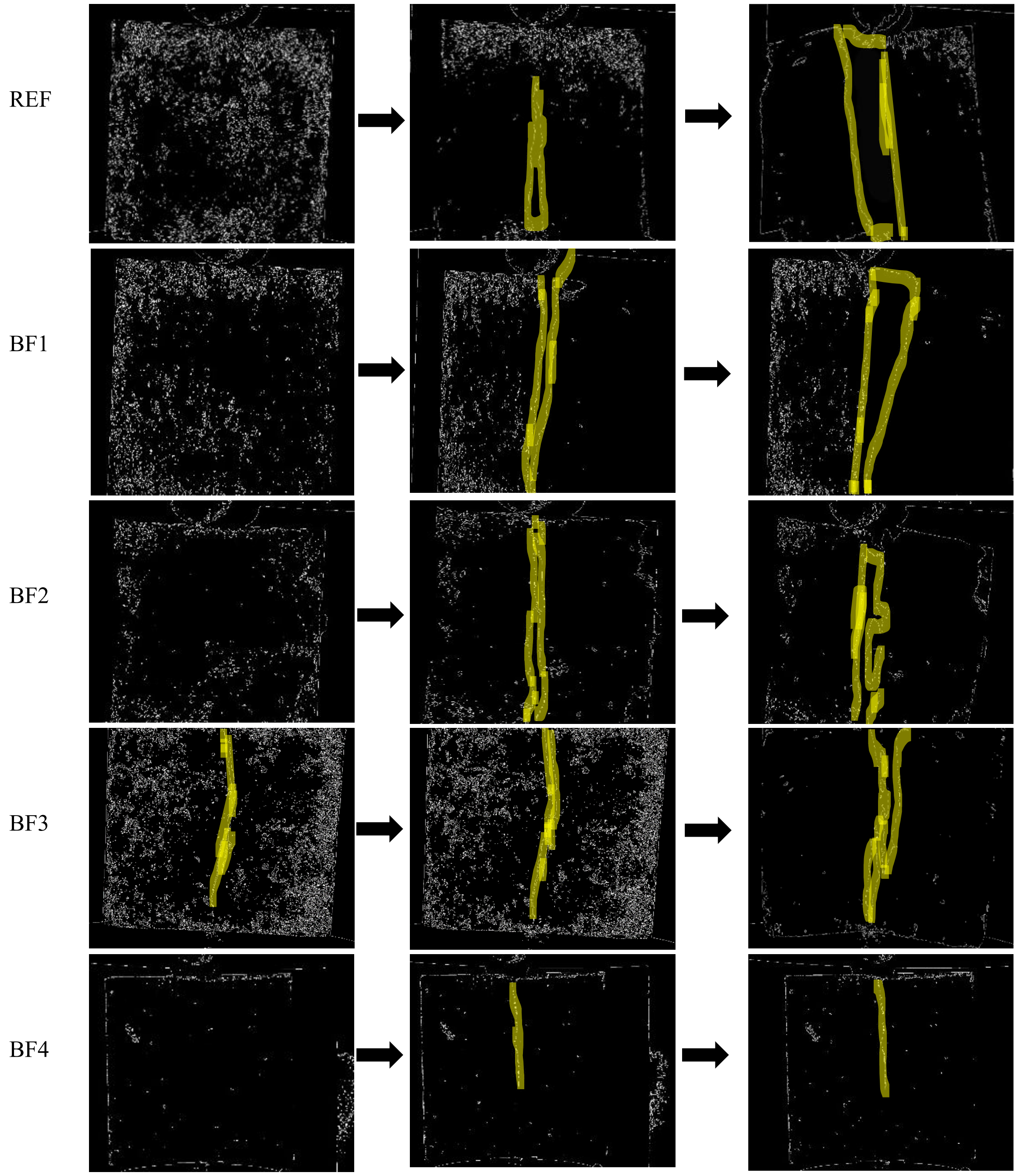

Figure 4. Crack formation in concrete samples by image processing method

Electrical Resistivity Results

Figure 5 presents the electrical resistivity measurement results of basalt fiber-reinforced concrete samples evaluated at different frequencies. Electrical resistivity is an indirect indicator of the electrical conductivity of concrete and is directly related to the porosity and crack density in the internal structure of the concrete. While the electrical resistivity of the REF sample was 0.254 ohm-cm at a frequency of 0.1 Hz, it is observed that the resistivity values in samples with basalt fibers are reduced. A significant decrease in electrical resistivity was observed, especially in 2BF, 3BF and 4BF samples. This situation shows that basalt fibers contribute to the electrical conductivity in the concrete. Nili and Afroughsabet [35] reported that fiber addition increases the electrical conductivity of concrete by lowering its resistivity. In the present study, basalt fibers were found to promote a more homogeneous microstructural distribution, which contributes to enhanced electrical conductivity. Similarly, Gao et al. [36] investigated the effect of varying fiber dosages and observed a decrease in resistivity with increasing basalt fiber content. Zhao et al. [37] also confirmed that basalt fibers enhance conductivity by reducing electrical resistivity. Experimental results of this study revealed a notable decline in resistivity values for 1BF, 2BF, 3BF, and 4BF samples at low frequencies compared to the reference sample. These findings confirm that basalt fiber incorporation improves electrical conductivity by decreasing the resistivity of concrete. In particular, the low resistivity values recorded at lower frequencies suggest the formation of a more conductive network within the concrete's internal structure.

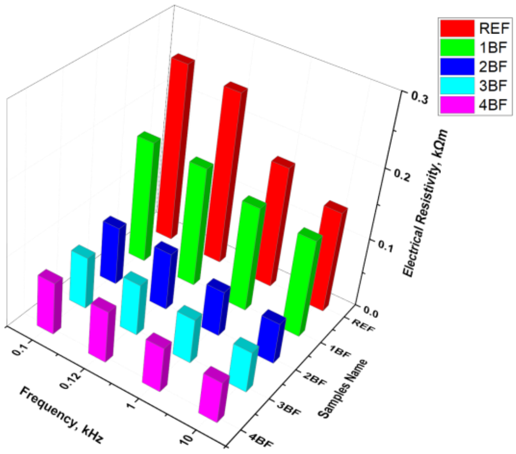

Figure 5. Electrical resistivity results of concrete samples at different frequency values

Capillary Water Absorption Results

The capillary water absorption coefficients of basalt fiber-reinforced concrete samples at varying fiber content rates are presented in Figure 6. The capillary water absorption coefficient is a parameter that measures the rate of water advancement through the pores and microcracks in the internal structure of concrete. In terms of the durability and long-term performance of concrete, low capillary water absorption coefficient plays a critical role in preventing water permeability and durability damage of structures. Compared with the REF sample, the capillary water absorption coefficient of the 1BF sample was found to be lower. The incorporation of a small amount of basalt fiber reduces the water absorption capacity of concrete and contributes to the densification of its internal structure. According to the studies by Kim and Park [38], low basalt fiber rates can reduce the water permeability of concrete. Liu et al. [39] reported that adding basalt fiber at low dosages can improve the capillary water absorption behavior of concrete, while higher dosages may adversely affect the pore structure and increase water absorption. In line with this, the experimental results showed a notable rise in capillary water absorption coefficients as the fiber content increased. Especially, 4BF sample has the highest capillary water absorption coefficient, which shows that the porosity of the concrete increases and water permeability increases.

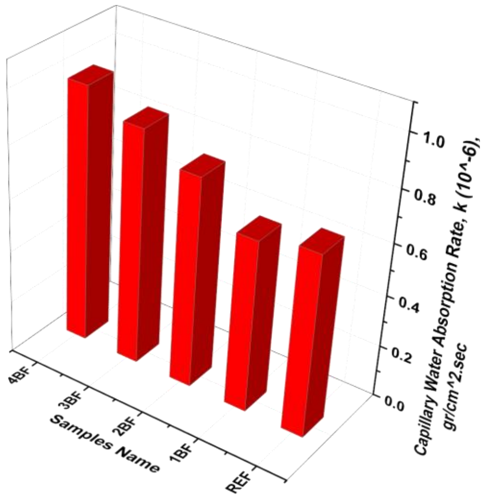

Figure 6. Capillary water absorption rate of concrete samples

Water Absorption And Porosity Results

Figure 7 presents the water absorption values of concrete samples with varying basalt fiber contents, while Figure 8 illustrates their corresponding porosity values. When the water absorption values are examined, the water absorption rate was measured as 3.56% for the REF sample without basalt fibers, while it decreased to 3.04% in the 1BF sample. This indicates that the addition of low-rate basalt fiber reduces the water permeability of the concrete. However, an increase in the water absorption rate was observed with the increase in the fiber ratio. The water absorption rates for the 2BF, 3BF and 4BF samples were determined as 3.92%, 4.42% and 4.46%, respectively. Notably, the highest water absorption rate was observed in the 4BF sample. This result indicates that high fiber ratios enhance the formation of pores within the internal structure of the concrete, thereby facilitating water penetration. As stated in the literature in the study of Al-Hadithi and Hilal [40], it was determined that the low-rate basalt fiber addition reduces the water absorption capacity of the concrete and reduces its permeability. In another study, Chen et al. [41] reported that high fiber ratios can increase the water absorption rate by increasing the formation of microcracks in the internal structure of concrete. In this study, it was observed that water absorption rates increased with the increase in fiber ratio.

The porosity was measured as 8.31% for REF and decreased to 7.20% in the 1BF sample, indicating that a low fiber content reduces porosity by densifying the internal structure of the concrete. However, the porosity values also increased with the increase in the fiber ratio. The porosity rates in the 2BF, 3BF and 4BF samples were measured as 8.98%, 9.95% and 10.26%, respectively. The highest porosity value was determined especially in the 4BF sample. It was concluded that high fiber ratios disrupt the homogeneity of the concrete, increasing porosity and water absorption. Wang et al. [42] states that low fiber ratios reduce the porosity of the concrete and create a tighter internal structure. In general, it was observed that the low-rate basalt fiber additive (1BF) provides a decrease in both water absorption and porosity values, but these values increase when high rates of fiber are used (especially 3BF and 4BF). This shows that high fiber ratios lead to an increase in micro cracks and pore formation in the internal structure of the concrete, facilitating the advancement of water.

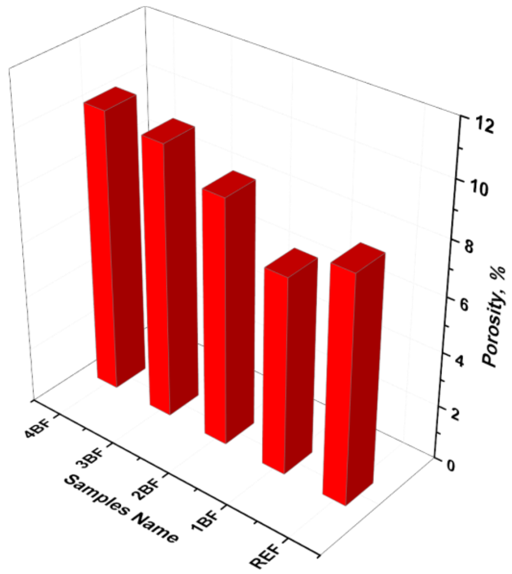

Figure 7. Porosity results of concrete samples

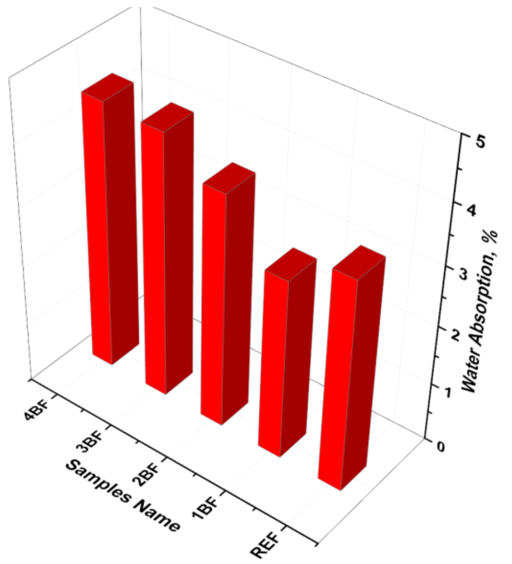

Figure 8. Water absorption results of concrete samples

3. Conclusion

Crack analysis of concrete samples with different proportions of basalt fiber was performed using physical, mechanical and image processing methods and the following results were obtained:

- In the 1BF sample where 1 kg/m^3 of basalt fiber was used, an increase in compressive strength was observed compared to the reference sample, while decreases in compressive strength were observed with increasing fiber ratio.
- While splitting tensile strength increased at low basalt fiber ratios (1BF), a decrease was observed as the fiber ratio increased.
- When a fiber ratio of over 1 kg/m^3 was used, a decrease in mechanical strength was observed due to the irregular distribution of fibers, the tendency of fibers to tangle and negatively affecting homogeneity.
- A decrease in capillary water absorption coefficient was observed in the 1BF sample compared to the reference sample, indicating that low-ratio fiber addition improved the water absorption capacity of the concrete. A significant increase in capillary water absorption coefficients was observed with increasing fiber ratio.
- At low fiber ratios (1BF and 2BF), the electrical resistivity of the concrete decreased compared to the reference sample, indicating that the electrical conductivity of the concrete increased. The low resistivity values obtained especially at low frequencies indicate that the basalt fibers form a more conductive network in the internal structure of the concrete.
- It was observed that low-ratio basalt fiber addition (1BF) provided a decrease in both water absorption and porosity values, but these values increased when high-ratio fibers were used (especially 3BF and 4BF). It was observed that high fiber ratios led to an increase in microcracks in the internal structure of the concrete and pore formation.

As a result, basalt fiber reinforcement has the potential to improve the performance of concrete, but determining the optimum fiber ratio is critical in terms of both strength and physical properties. The findings obtained reveal that basalt fiber reinforcement can increase the performance of concrete when used at the right ratios, but excessive fiber use may lead to undesirable results.

Author's Contributions

Emriye Çınar Resuloğulları: Drafted and wrote the manuscript, performed the experiment and result analysis.

Ethics

There are no ethical issues after the publication of this manuscript.

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