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*Research Article*

# Fiber-Reinforced Cement Paste Composites for Better Sustainability

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**Abstract:** Extinction of natural resources builds up pressure on governments to invest in research to find more sustainable resources for construction sector. Earlier studies on mortar and concrete show that bottom ash and basalt fiber are independently alternative binder in the concrete sector. This study aims to use bottom ash and basalt fiber blends as alternative novel-based composites in pure cement paste. Strength and durability properties of two different percentages of bottom ash (40% and 50%) and three volume fractions of basalt fiber (0.3%, 0.75%, and 1.5%) were used at three curing periods (7, 28, and 56 days). In order to measure physical properties of the basalt-reinforced bottom ash cement paste composites flowability, dry unit weight, porosity and water absorption measurements at 7, 28, and 56 days of curing were performed. Furthermore, mechanical properties of composites determined by unconfined compressive strength and flexural strength tests. Finally, to assess the durability sulfate-resistance and seawater-resistance tests have been performed on composites at 28 and 56 days of curing. Results showed that addition of basalt fiber improves physical, mechanical and chemical stability properties of paste up to a limiting basalt fiber addition (0.3% volume fraction) where above an adverse effect have been monitored. It is clear that observed results can lead to development of sustainability strategies in the concrete industry by utilizing bottom ash and basalt fiber as an alternative binder.

**Keywords:** Bottom Ash, Basalt Fiber, Paste, Strength, Durability, Sustainability

## 1. Introduction

Rapid increments in urbanization and construction work have resulted in greater demand for construction materials, i.e., materials for which natural resources and energy are further consumed in order to manufacture, which results in harmful materials such as greenhouse gasses being produced in the process. These consequences harnessed the attention of scientists and governments toward the idea of sustainability or clean production, such as incorporating byproduct waste as a replacement for cement. Although intense research has been done and many developments have been made in the field of sustainable materials, they are still not widely used due to various reasons, such as the high processing costs and the lack of total understanding of the mechanical and engineering properties for these materials. However, according to statistics [1], civil works and building construction consume around 60% of raw materials extracted from the lithosphere and are estimated to use up to 40% of global energy consumption. Moreover, construction work has been

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found as one of the highest carbon emissions industries [2] due to the production, processing, and transportation of construction materials [3,4]. Previous studies estimated that 50% of $CO_2$ emissions worldwide come from cement manufacturing sectors [5]. Recently, the tendency to replace such materials with sustainable admixtures such as waste is growing around the world. Some of the commonly used sustainable admixtures are bottom ash [6,7] and marble dust [8,9].

Coal bottom ash is a byproduct produced largely from coal-powered plants; thus, utilizing coal bottom ash in the concrete industry can be an economic and sustainable method for its disposal [10]. In general, bottom ash is believed to adversely affect the workability of concrete [11,12]. However, some published studies reported increased workability when using bottom ash as a replacement of natural sand [13,14]. Wongkeo et al.'s [15] investigation on the effects of replacing Portland cement with BA showing that BA mixes had improved bulk density, thermal conductivity, and flexural and compressive strength. Furthermore, Aydin's [16] study on the effects of adding BA to a pure cement matrix showed that composites with up to 70% replacement of BA demonstrated suitable physical and mechanical properties to be used in construction.

Concrete is the main material used in the growing sector of construction. However, concrete is known for its brittleness, which inspired scholars to search for methods to alleviate this problem. One popular solution is the use of fiber reinforcement in a concrete matrix, which is a toughening material that has the potential to improve compressive strength as well as shearing and fracture resistance of concrete. Over the past years, developments have been achieved and better understanding of the behavior of fiber-reinforced concrete has developed due to the vast research that was and is still ongoing in this field; more recently, these materials are being fabricated for hydraulic and civil buildings all around the world. Steel, carbon, glass, and polymer [17] are among the most popular types of these fibers. The most-used type of polymer fiber is polypropylene. The effects of these fibers on cement have been intensively studied. Many researchers [18–24] reported an increase in the compressive and flexural strength when adding fibers to cement composites. Valeria and Nardinocchi [18], for example, observed a reduction in the drying shrinkage upon adding fiber to cement composites. Moreover, Hwang et al. [25] reported enhanced flexural strength, toughness indices, plastic cracking, and impact resistance from the addition of natural fibers to cement composites.

Basalt fiber is one of the most popular fibers worldwide. It is a material that is usually made from the fine fibers of basalt. This fiber is similar in shape to glass fiber (GF). However, it has better physiochemical properties than GF; further, it has been reported to make better contributions to the properties of concrete [26]. In addition, the price of basalt is cheaper compared with carbon fiber, which makes it an ideal substitute for carbon fiber. More recently, basalt fibers have been widely used in civil and hydraulic engineering [26]. Regarding concrete, many studies have been conducted on the behavior of basalt fiber on the durability and strengths of concrete. Khan et al. [27] investigated the properties of concrete mixes enhanced with basalt and steel fibers, reporting an enhancement on the mechanical properties of concrete up to 0.68% of basalt inclusion. The authors also observed up to 74% reduction in workability. Sun et al. [26] also investigated the addition of both short and long basalt fibers to concrete, finding that the compressive and splitting tensile strength of concrete increased with the addition of fiber up to 2% by volume and started to decrease after that, while bending strength kept increasing with increasing the fiber volume. The authors further found that short fibers were more effective in improving the strength of concrete. Sim et al. [28] reported that basalt fiber performed better than glass fiber under accelerated weathering conditions and provided higher resistance to temperature than that of glass fiber. Gamal et al. [29] conducted another study concerning the use of basalt fiber in concrete construction. They reported that the use of basalt fibers helped in retaining and improving the strength of concrete that is exposed to vegetable and mineral oils. The basalt-fiber-reinforced concrete could withstand the acidic, chemical, and salty effects that result in reduction of the strength of concrete. Dong et al. [30] evaluated the potential of using basalt fibers to enhance the mechanical properties of concrete made with recycled earthquake waste. The authors also found that using basalt fibers can make up for the reduction in the mechanical properties when increasing the ratio of waste replacement. Similarly, Wang et al. [31] suggested the use of basalt fiber with nano-silica to enhance the mechanical properties of recycled aggregate concrete.

Ahmad and Chen [32] studied the water and high-temperature resistance of mortars containing various proportions of basalt fibers and silica fume. They reported increased resistance with increasing the amount of silica fume and fibers as well as decreased porosity. Padalu et al. [33] investigated the use of basalt-reinforced mortar for wallettes strengthening. The strengthened wallettes showed four times higher strength, 29 times higher deformability, and 139 times higher energy-absorption capacity. Fenu et al. [34] also studied the dynamic behavior of mortars reinforced with basalt and glass fibers, investigating their influence on energy absorption and tensile strength. They reported increased energy absorption at high strains with the addition of fibers, while the dynamic increase factor was not significantly affected by the addition of fibers.

In this study, two different percentages of bottom ash (40% and 50%) and three volume fractions of basalt fiber (0.3%, 0.75%, and 1.5%) were used to investigate the physical, mechanical, and durability properties of the laboratory-produced composites. In the literature, to the best of our knowledge, no research consists of pure cement paste enriched with basalt fiber. This study was composed of comprehensive laboratory tests at three curing periods (7, 28, and 56 days). Additionally, the prepared composites were composed of bottom ash at high levels of utilization rate. The composites could be a promising alternative binder in the concrete sector and could be used as alternative novel-based composites. Durability properties of those composites were evaluated based on real scale conditions. The samples were immersed in a seawater and sulfate solution to check their performance. In the literature, all studies focused on mortar and concrete properties; further, none of them were composed of pure cement paste enriched with basalt fiber. This research will fill the research gap in that particular area.

## 2. Materials and Methods

### *2.1. Materials*

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2.1.1. Cement and bottom ash

Ordinary Portland cement CEM 1, in accordance with the Turkish Standards Institution (TS EN 197-1), was used to prepare the cement pastes in this study. This cement has a blain fineness of 305 m2/kg and a specific gravity of 3.15. The loss of ignition for this cement is 2.5.

The used bottom ash was collected from a brick factory after the burning process. Coal was used for burning in the kiln at a temperature of around 1100°C. The left-out ash was collected from the bottom of the kiln. Before being used, the bottom ash was sieved through the 1.18 mm sieve, and a fine powder was obtained. This powder was then dried in the oven at around 100°C to ensure the absence of moisture. The resulting powder has an ignition loss of 3.9. The chemical compositions of these materials are provided in Table 1.

**Table 1.** Chemical compositions of the both used cement and bottom ash.

| Oxides (%) | Cement | Bottom ash |
|---|---|---|
| $SiO_2$ | 21.7 | 57.3 |
| $Al_2O_3$ | 4.8 | 28.1 |
| $Fe_2O_3$ | 3.9 | 6.1 |
| CaO | 63.6 | 1.4 |
| MgO | 0.3 | 0.2 |
| $K_2O$ | 0.3 | 0.8 |
| $SO_3$ | 1.4 | 0.7 |
| LOI[a] | 2.1 | 3.2 |

[a]Loss on ignition.

2.2.2. Basalt fiber

Basalt fiber used in this study was obtained from Dost Kimya Ltd., Turkey. The specific gravity of basalt fiber is 2.60 g/cm3. The length of the basalt fiber is 24 mm, and its diameter is 15 µm. Elastic modulus and tensile strength of the basalt fiber are 89 and 4840 MPa, respectively. Figure 1 shows the used basalt fiber.

**Figure 1.** Basalt fiber used in this study

*2.2. Sample preparation*

A Hobart mixer (2.5 L capacity) was used to prepare pure cement paste composites. Bottom ash, cement, and basalt fiber were mixed in dry form for 30 s, and tap water was added slowly within 30 s. The fresh paste was placed into molds and then consolidated with a vibrating table within 1 min. After 24 hr, the samples were removed from the molds and cured in water until testing ages (7, 28, and 56 days).

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Cubic molds, 50 mm3 in size, were used for preparation of compressive strength samples. Mortar prisms, 40 mm × 40 mm × 160 mm in size, were used for the flexural strength samples. ASTM C109M-20 [35] standard for compressive strength and ASTM C348-19 [36] standard for flexural strength tests were used.

The testing program consists of two groups of mixtures, one with 40% bottom ash content, the other with 50%. Each group includes various basalt fiber contents ranging from 0% to 1.5% by volume. The water binder ratio was kept constant for both groups and was taken as 0.37. Figure 2 shows both flexural and cubic samples prepared at the laboratory that contain bottom ash and basalt fiber.

Six specimens were prepared for each testing age. The apparent specific gravity and water absorption experiments were performed according to the ASTM C127–15 [37] procedure. Consistency of the prepared mixtures was determined using a flow table test according to the ASTM C230M-14 [38] procedures. The sulfate tests of all the prepared combinations were determined according to the ASTM C88-18 [39] procedure. The specimens were subjected to sulfate solution until cracked. At the end of each cycle, the samples were removed from the sulfate solution and dried in an oven at around 105°C. The mass changes were recorded in each cycle. For seawater tests, the samples were immersed in seawater for one week, and the same procedure for sulfate tests was applied. The tests were continued until the first visible crack. The mass changes were then recorded.


(**a**)


(**b**)

**Figure 2.** Basalt-fiber-enriched bottom ash composites: (a) flexural samples; (b) cubic samples.

## 3. Results and Discussion

### *3.1. Effects of basalt fiber on physical properties*

Figure 3 shows the flow values for basalt-reinforced bottom ash cement paste composites. Increasing the amount of bottom ash decreases the flow value. This is due to coarser particles of bottom ash. The interparticle friction hinders the movement. The addition of basalt fiber improves the flowability of the mixtures for both bottom ash mixture groups at low volume fraction (0.3%). However, going beyond the 0.3% basalt fiber addition slightly decreases the flow values. The absorption of available water, due to the large surface area of basalt fiber, caused a marginal decrease in flow values, especially beyond 0.3%. Also, basalt fiber might absorb more cement paste at high volume fraction. However, the cohesiveness of the composites improved with addition of basalt fiber. Similar results were found in Li et al. [40], Qin et al. [41], and Sadrmomtazi et al. [42]. Further, the composites are said to be workable if the flow values are approximately 150 mm [43]. In this study, all mixture groups except BA40C60B1.5 mixture groups had flow values lower than 150 mm (containing 1.5% basalt fiber). However, this mixture group can also be easily cast into molds without extra workmanship. In this study, only one basalt fiber length (6 mm) was utilized. There are also 12 and 24 mm basalt fibers in length. One study performed on concrete showed that the increase in length of basalt fiber results in a decrease in workability being more visible [44]. Based on the flow test results, all composites can be considered as sustainable. It is believed that addition of basalt fiber improves the consistency of the mix and decreases the energy requirements during

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casting. This could be a positive addition to basalt fibers, especially during formwork operations on site; it also requires less workmanship. If the percentage of basalt fiber is kept at 0.3%, it will maximize the performance of the composites.

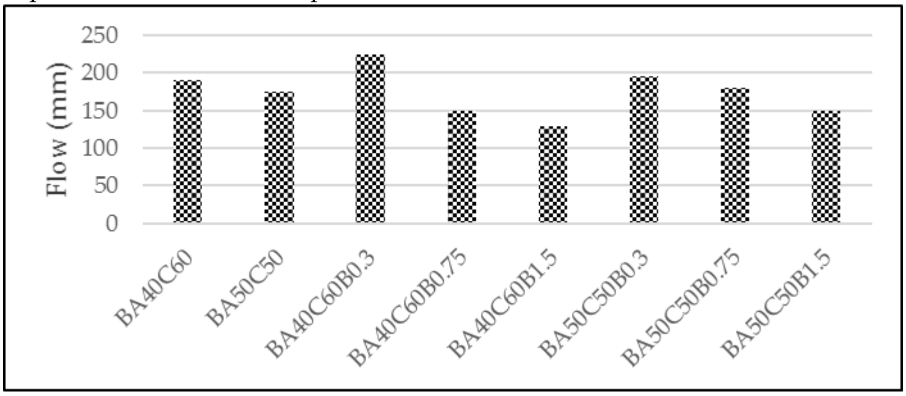


**Figure 3.** Flow values for basalt-reinforced bottom ash cement paste composites.

Figure 4 shows the dry unit weight (DUW) values for basalt-reinforced bottom ash cement paste composites at 7, 28, and 56 days of curing. The DUW values decrease with curing ages. The highest decrease (approx. 10%) was reported in the BA40C60B1.5 mixture groups. The basalt fiber decreases the DUW values for both mixture groups when compared with the control sample. The average reduction for all series was about 7%. The decrease is more pronounced at high volume fractions. This might be due to the fact that, when basalt fiber is introduced into a system, it needs more paste to coat. This results in a reduction of composite density. However, the decrease in DUW was higher in the higher cement amount group (BA40C60). This can also prove that more paste formation causes more reduction. The same findings can be found in [31,41]. Based on the DUW values, all composites can be categorized as lightweight material; further, composites could be an alternative sustainable building material for the construction sector.

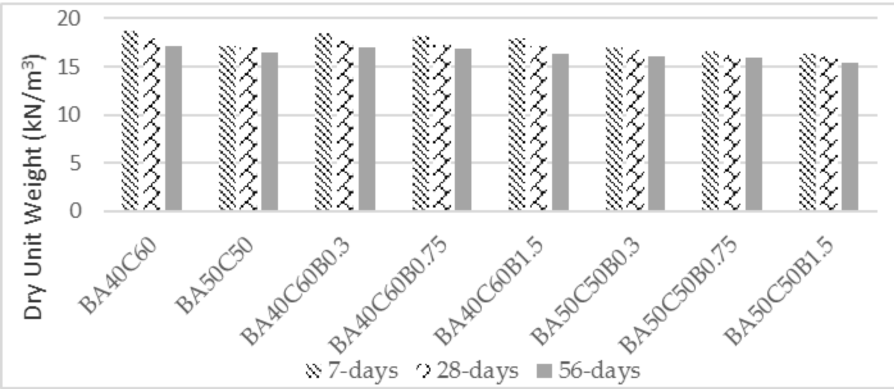


**Figure 4.** Figure Dry unit weight for basalt-reinforced bottom ash cement paste composites at 7, 28 and 56-days of curing.

Figure 5 shows the porosity values for basalt-reinforced bottom ash cement paste composites at 7, 28, and 56 days of curing. Porosity decreases with curing ages. The rate of decrease increases beyond 28 days. This is due to the slow reaction of bottom ash particles. Addition of basalt fiber decreases the porosity at low volume fraction (0.3%). For beyond a 0.3% basalt fiber addition, the porosity values tend to increase. The compactness of the composites become less effective beyond 0.3% basalt fiber volume fraction, which can cause the formation of more voids. Additionally, basalt fiber increments require more cement paste, since the paste volume constant for all mixtures' more porous matrix can form at high volume fractions. Also, the decrease in the dispersion ability of fibers and cement paste can cause an increase in porosity values. The increase for water demand due to addition of basalt fiber, especially at higher volume fraction, can be considered another factor for such increase. Compatible results can be found in [41,43,45,46].

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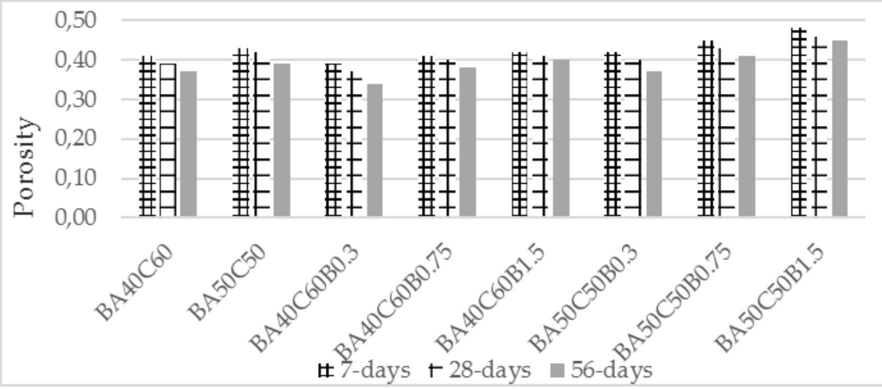


**Figure 5.** Porosity values for basalt-reinforced bottom ash cement paste composites at 7, 28 and 56-days of curing.

Figure 6 shows the water absorption (WA) values for basalt-reinforced bottom ash cement paste composites at 7, 28, and 56 days of curing. The WA values tend to decrease with curing age. However, the basalt fiber addition increases WA values beyond 0.3% volume fraction. Increase in bottom ash amount also increases the WA values. This can be explained by the fact that the addition of basalt fiber increases the pore connection at high volume fraction. Additionally, it can be seen from the flow values that addition of basalt fiber decreases the flow values due to higher absorption capability of basalt-enriched mixtures. Similar findings were found in [31,42].

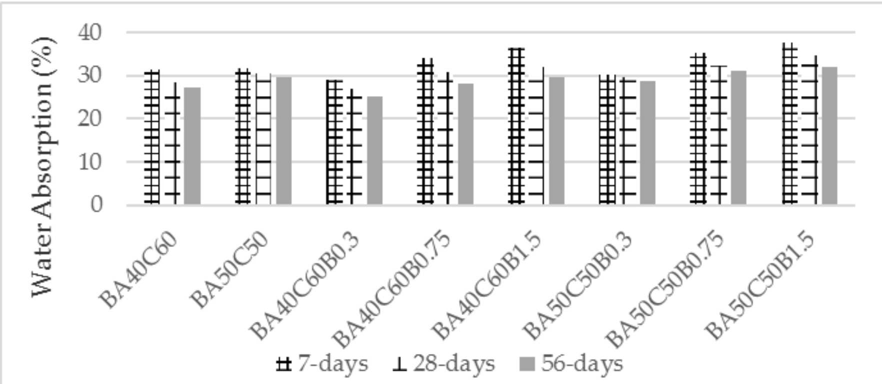


**Figure 6.** Water absorption values for basalt-reinforced bottom ash cement paste composites at 7, 28 and 56-days of curing.

*3.2. Effects of basalt fiber on mechanical properties*

Figure 7 shows the unconfined compressive strength values for basalt-reinforced bottom ash cement paste composites at 7, 28, and 56 days of curing. Addition of basalt fiber increases compressive strength. However, this increase was diminished at beyond 0.75% basalt fiber addition. Also, increase in the capillary pores can cause a reduction in strength at higher volume fraction of basalt fibers, as these fibers mostly affect the capillary porosity and not the gel porosity due to its large surface area; thus, at low volume fractions more strength can be achieved. More gel formation via bottom ash particles in composites also helps in the increase in compressive strength. In this study, basalt fiber having 6 mm in length was used. This can also be a factor for strength increase. This length of basalt fiber seems to have better compactability and shows superior adhesion with cement paste. Similar findings are reported in [26,27,29]. The average increase from 7 to 56 days was approximately 27% for both mixture groups. The rate of increase was higher at low volume fraction. Beyond a 0.3% volume fraction of basalt fibers showed a lower rate of increase. This might be due to the weakening of the bond at high basalt fiber, increase of water absorption, and porosity of the composites. Finally, one study [45] mentioned that the increase in compressive strength is due to the amorphous character of the basalt fiber.

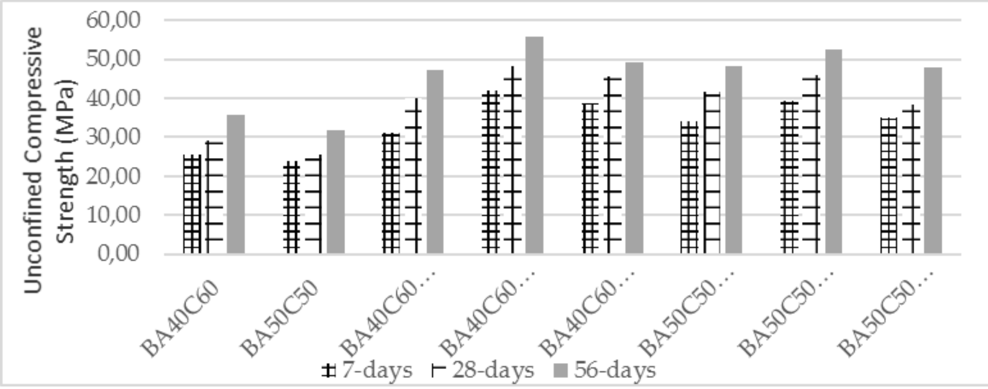


**Figure 7.** Unconfined compressive strength values for basalt-reinforced bottom ash cement paste composites at 7, 28 and 56-days of curing.

Figure 8 shows the flexural strength (FS) values for basalt-reinforced bottom ash cement paste composites at 7, 28, and 56 days of curing. The same trend as observed in compressive strength was reported here. Addition of basalt fibers densified the matrix and better bonds were formed. The addition of basalt fiber seems to be effective until 0.75% volume fraction; beyond this value, a decrease in FS was reported. The loss of bridging effect and weakening of the matrix bonds between the cement pastes results in difficulty in compaction at higher rates and decrease in FS. Additionally, the addition of basalt fiber affects the fluidity of the composites and thus decreases the workability and FS at all curing ages. The rate of increase was reported higher at early ages. Similar results can be found in [41–43,45,47,48].

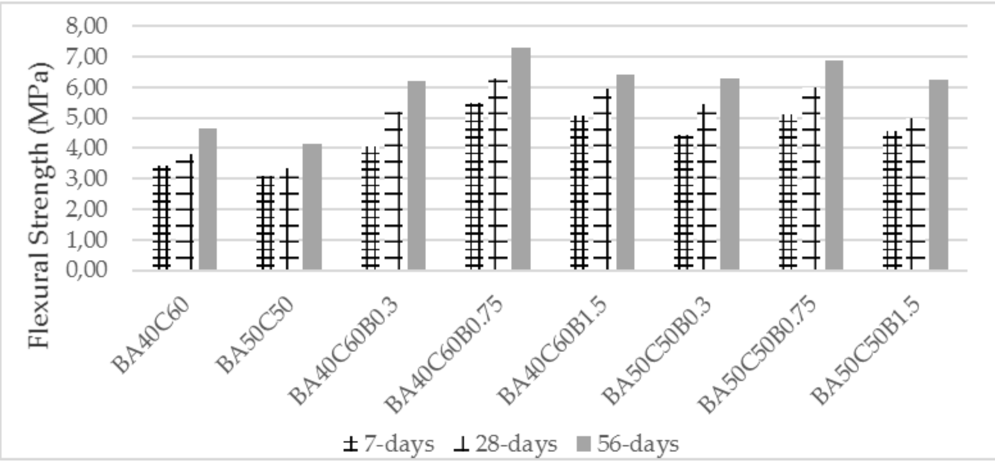


**Figure 8.** Flexural strength values for basalt-reinforced bottom ash cement paste composites at 7, 28 and 56-days of curing.

*3.3. Effects of basalt fiber on durability properties*

Figure 9 shows a sulfate-resistance test for basalt-reinforced bottom ash cement paste composites at 28 and 56 days of curing. Interestingly, sulfate-resistance improves with the addition of basalt fiber for all volume fractions. Actually, the resistance is governed by pore structure and amount of fiber. The addition of basalt fiber improves the bonding cement paste composites. The basalt fiber bridging mechanisms hold the matrix together and does not allow for weakening of the bonds. The rate of expansion decreases with increasing the amount of basalt fiber for both mixture groups. The average reduction of expansion due to addition of basalt fiber was 30% for all mixture groups. The improvement might be due to the densification of the matrix and increments in FS values. This proves that sulfate ions did not result in adverse effects on basalt fiber. Similar conclusions can be found in [43,49].

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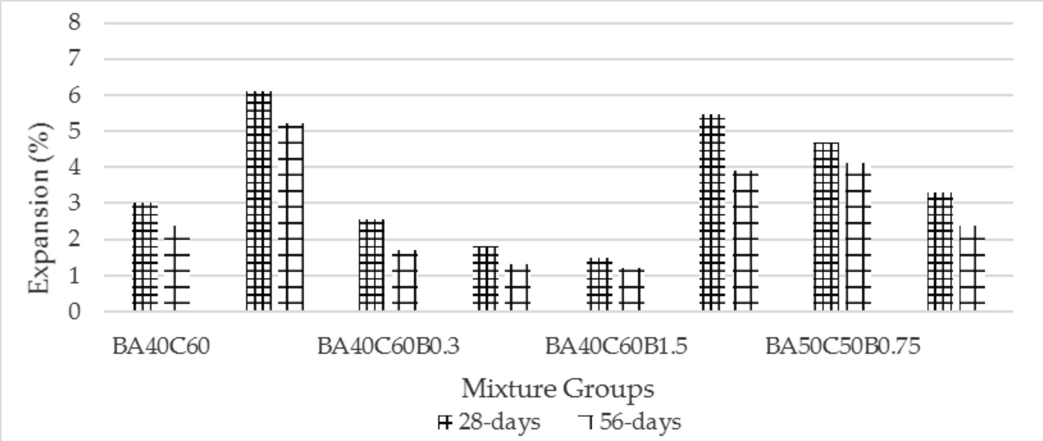


**Figure 9.** Sulfate resistance test for basalt-reinforced bottom ash cement paste composites at 28 and 56-days of curing.

Figure 10 shows the seawater-resistance test for basalt-reinforced bottom ash cement paste composites at 28 and 56 days of curing. The addition of basalt fiber decreases the weight loss by seawater and improves chemical resistance of the composites. Negligible weight loss due to seawater was recorded for both mixtures and curing ages. The resistance becomes higher at later ages with the help of basalt fiber. The second control mixture group (BA50C50) has higher weight loss by seawater. However, the addition of basalt fiber diminishes this increase. The reason is mostly due to the addition of basalt fiber, which blocks the open-pore channels and connectivity of the pores and thus reduces the diffusion of ions into the composites. There is little information available about the chemical stability of composites composed of basalt fiber [43,44,49].

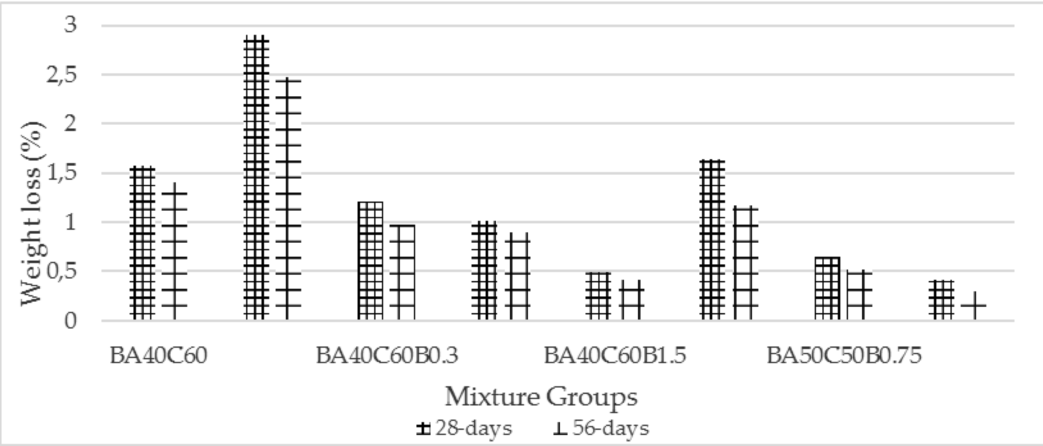


**Figure 10**. Seawater resistance test for basalt-reinforced bottom ash cement paste composites at 28 and 56-days of curing.

## 4. Conclusions

Based on the experiments in this study, the following conclusions can be reached:

- The addition of basalt fiber improves the workability of the composites at lower volume fraction. Beyond a 0.3% basalt fiber addition, the decrease in flow values was reported for all mixture groups.
- The porosity of the composites increases as the basalt fiber volume fraction increases. The compactability of the fiber is adversely affected beyond 0.3% volume fraction.
- The dry unit weight of the composites is classified as light weight. The produced composites have superior physical, mechanical, and chemical stability, which makes them an alternative sustainable construction material. Additionally, the mixture proportioning in this study can

help for the development of sustainability strategies in the concrete industry by utilizing bottom ash and basalt fiber as an alternative binder.

- The addition of basalt fiber increases the water absorption of both mixture groups beyond 0.3% volume fraction. More cement paste is needed when basalt fiber is introduced into the system. This affects the pore system of the composites.
- The addition of basalt fiber increases the compressive and flexural strength. Both strengths tend to be decrease beyond 0.75% volume fraction.
- The addition of basalt fibers seems to be effective in chemical stability. Basalt fiber improves the resistance of the composites against sulfate and seawater.
- Microscopic investigation should be conducted for better understanding of these novel-based pure cement paste composites, which contain basalt fiber and industrial waste. The authors believe that the formation of calcium silicate hydrates and dispersion of basalt fiber in the matrix govern the overall behavior of the composites and need further investigation.

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**Conflicts of Interest:**

The authors declare no conflict of interest.

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