

Article

Physical, Mechanical and Durability Performance of Pastes Containing Carbon Fiber

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Abstract: The damage caused by global warming is rapidly increasing, and its adverse effects become more evident with each passing day. Although it is known that the use of alternative binder materials in concrete would decrease this negative effect, reluctance to new composites continues. Waste use plays a vital role in sustainability studies. In this study, pure cement paste was prepared and enriched with carbon fiber. This study investigated the wide range of volume fraction of carbon fiber in cement-based composites. Two different industrial wastes, marble dust, and bottom ash were chosen and mixed with cement and four different (0.3%, 0.75%, 1.5%, and 2.5%) carbon fiber volume fractions. Based on physical, mechanical, and durability tests at 7, 28, and 56-days of curing, the composites were resistant to sulfate and seawater attack. The 0.75% carbon fiber addition seems to be an optimum volume percentage beyond which both physical and mechanical properties were adversely affected. The composites with 0.75% carbon fiber have reached 48.4 MPa and 47.2 MPa at 56-days of curing for marble dust and bottom ash mixture groups, respectively.

Keywords: carbon fiber; cement; sustainability; marble powder; bottom ash; paste

1. Introduction

Annual cement consumption has increased to approximately 4.6 billion tons worldwide [1], and this number is expected to increase by about 6 billion by the year 2050 [2]. Humans have been dealing with the problems caused by global warming for a long time. The rapidly increasing population and need for shelter caused the concrete industry to spread carbon dioxide to the environment, accounting for approximately 7-8% of the total emissions [3,4]. Mainly clinker is responsible for this problem. It is a crucial phase of cement production, and the burning of raw materials around 1450 °C generates carbon-dioxide [5]. Efforts to reduce carbon emissions started with the use of high-volume fly ash in the 1950s, and they have continued rapidly with the evaluation of different industrial wastes today. These efforts have not reached the desired level [6]. This does not allow the existing standards to be used in high quantities of these wastes, or the fact that the quality of the resulting product cannot be controlled regularly. Huge demand for construction material contributes to environmental problems and poses a risk for living organisms. The term sustainability, first introduced in the Brundtland Report in the 1980s [7], offers the use of alternative supplementary cementitious materials in concrete construction. Cement can either partially replace various wastes or be used during the manufacturing stage of the cement to attain sustainability goals. Nations have accepted to reduce carbon emission using alternative binder materials in building construction by 2050 [2]. During concrete production, natural resources, such as aggregates, are used, and they are the main components of the concrete, accounting for 70-85% of its volume [8]. The scarcity of natural resources has forced the building sector to find alternative solutions. To attain more sustainable construction, the consumption of natural resources should be minimized to a larger extent [9]. Besides

the fly ash [10], marble powder [11], bottom ash [6], and rice husk ash [12] are commonly utilized as cementitious materials to improve the fresh and hardened properties of the composites.

Bottom ashes are composed of larger particles and collected at the bottom of the furnace. Bottom ashes contain mainly silica (55 %), alumina (20-25 %), and iron (8-10 %) oxides (5-10%). Less amount of calcium oxide is present [13]. They are mainly in the form of a glassy and amorphous structure composed of irregular and sphere particles [14]. Many studies have focused on concrete. Recently, some researchers have evaluated its properties in cement pastes. In these studies, the addition of bottom ash reduced the composite's strength and its durability against the harsh environment. The researchers tried to find alternative solutions to improve the hardened properties to satisfy the general concrete requirements. However, up to date, none of them have been fully satisfied. Pant et al. [15] evaluated the performance of bottom ash as a filler material in fiber enriched soil structures. They concluded that the number of reinforcement layers is significantly smaller when bottom ash was used. Zhou et al. [16] studied the sustainable management of bottom ash pellets for removing the phosphate ion with the help of various foaming agents. The results showed that phosphate ion being absorbed by the bottom ash pellets and foaming agents enhanced the porosity of the pellets. Li et al. [17] studied the feasibility of using bottom ash as a sand replacement in aerated concrete applications. They reported that the microstructure of bottom ash concrete of up to 40% replacement improved significantly. Additionally, needle-like tobermorite transformed into a plate-like tobermorite structure, resulting in lower leaching of heavy metals compared to the allowable international limits. Tang et al. [18] evaluated the possibility of using bottom ash as supplementary cementitious material in building construction. They concluded that the optimum utilization rate of bottom ash should not exceed 20% for better strength properties. Additionally, the microstructure of bottom ash up to that level showed better reactivity. Khongpermgonson et al. [19] prepared samples using bottom ash with various ranges of water to binder ratio and tested chloride resistance and strength development. They observed that samples containing bottom ash had adequate strength, and the composites were resistant to chloride ingress. Argiz et al. [20] also evaluated the performance of bottom ash as a cement constituent against chloride resistance. They mentioned that concrete made with cement containing 25% had better resistance compared to reference concrete beyond 28-days. Rani and Jain [21] evaluated the performance of bottom ash used as a mine filler. They concluded that the bottom ash of up to 30% could be used as a safe material for mine filler. Abdulmatin et al. [22] examined the possibility of using bottom ash as a pozzolanic material. They reported that mortar containing up to a 20% bottom ash could be satisfactorily be used as a pozzolanic material in concrete construction. The No. 325 sieve was found to be an ideal sieve size for bottom ash particles to produce excellent pozzolanic activity. Singh et al. [23] compiled the published literature on the utilization of bottom ash as a fine aggregate replacement. They mentioned that the incorporation of a larger amount of bottom ash reduced the compressive strength of concrete. Additionally, bottom ash improved the microstructure of concrete, and a 25-30% replacement level was found optimum for bottom ash. Le et al. [24] examined the triaxial behavior of the composites composed of bottom ash. They found that the bottom ash performed the same as dense sand and satisfied the requirements for designing road base structures.

Marble dust is another waste that causes environmental problems. During production, a huge amount of it goes to the dumpsite near the manufacturing units. Disposal of this waste affects not only the ecology but also the groundwater quality. Bostanci [25] evaluated the marble dust for sustainable concrete construction. He concluded that marble dust causes a significant reduction in compressive strength at day 1. However, this can be compensated for at later ages. Ashish [26] evaluated the use of marble wastes as a sand replacement together with two different supplementary cementitious materials in concrete. Based on the experimental tests, no adverse effect of using marble wastes was observed. Additionally, marble wastes help the hydration process and improve the concrete microstructure. Ma et al. [27] used marble powder in cement-based materials to improve mechanical properties. They reported that 10% waste marble and 3% of nano-silica was optimum for better strength properties. They suggested that the negative effect of marble powder at higher rates

can be offset by using nano-silica. Nežerka et al. [28] investigated the microstructure of cement pastes composed of marble powder. They mentioned that marble powder increases the porosity of cement pastes. Additionally, they concluded that marble powder incorporation had minor effects on the stiffness of the cement paste and the interfacial transition zone. Singh et al. [11] studied the replacement of dried marble powder as a replacement for cement in concrete. They reported that up to 15% replacement rate is optimum for physical and mechanical properties. Additionally, at higher replacement level, a negative effect was recorded by abrasion tests. Kabeer and Vyas [29] produced mortar mixes composed of marble powder as a fine aggregate replacement. Their results revealed that 20% is an optimum replacement level for better sustainable building construction, as it helps reduce the demand for river sand. Singh et al. [23] studied the economic and environmental effects of using marble powder in concrete. They concluded that 15% of marble powder utilization saves the concrete sector approximately 10% of the cost. Additionally, carbon dioxide emission was reduced by 60 kg/m³ compared to the conventional concrete mixture at the same replacement level. Khodabakhshian et al. [30] investigated the durability performance of the structural grade concrete composed of marble powder. They reported that 10% is the optimum value, and beyond this replacement, level strength tends to decrease. Sutcu et al. [31] studied the effect of the addition of 35% marble powder to laboratory-produced bricks. They reported a decrease in bulk density and compressive strength. However, bricks containing up to 30% marble powder addition satisfied the building requirements. Corinaldesi et al. [32] studied the characterization of marble powder in concrete and mortar. They concluded that a 10% replacement of sand by marble powder was stronger. Furthermore, Vardhan et al. [33] evaluated the performance of concrete by incorporating marble powder as a fine aggregate replacement. They reported that strength and drying shrinkage improved by 20% and 30%, respectively, with marble powder incorporation. The addition of fibers can improve the weakness in tension and other strength properties. The cracks and drying shrinkage can be minimized by using various fibers [34]. Especially the cement-based materials are very vulnerable to temperature changes and loading. Recently, carbon fiber was introduced into concrete to improve the flexural strength and reduce the crack width. Carbon fibers contain mainly carbon atoms and are commonly used in civil engineering works. The optimum carbon fiber amount should be 0.3% by volume of concrete. The best performance was reported in carbon fiber and basalt fiber. Polypropylene fiber also shows superior performance [34–37]. Pirmohammad et al. [36] investigated the fracture toughness of asphalt concrete containing carbon fiber, indicating that fracture toughness improved by 42% compared to plain concrete. Additionally, they mentioned that 4 mm in length showed superior performance compared to 8 mm and 12 mm ones. Ostrowski et al. [38] investigated the effect of carbon fiber on the strengthening of concrete columns. They stated that carbon fiber improved the resistance of concrete columns to buckling and enhance the strength against confining pressure. Liu et al. [39] examined the flexural behavior of coral concrete composed of carbon fibers. They concluded that using carbon fibers extended the deformation, and the fibers absorbed more energy compared to reference concrete. Additionally, flexural toughness increased by 367 to 586% with different concrete grades. The optimum carbon fiber was found to be 1.5% for coral concrete. Safiuddin et al. [40] investigated the mechanical and microstructure of carbon fiber self-compacting concrete. The concrete was prepared with various carbon fiber content (0-1% by volume) and two different water to binder ratios (0.35 and 0.40). They concluded that due to the high length to diameter ratio of carbon fiber, they are not able to resist the compression. The reduction in compression strength was recorded in the range between 35-60%. Song et al. [41] studied the flexural strength, drying shrinkage, and creep behavior of concrete composed of slag and carbon fiber. They concluded that carbon fiber decreased the compressive strength but increased the flexural strength of composites. They stated that drying shrinkage decreased by 29% when incorporated with 0.3% carbon fiber. Additionally, creep development was reported to decrease with carbon fiber. Yakhlaf et al. [42] investigated the new properties of self-compacting concrete containing carbon fiber (0-1% by volume). They stated that carbon fiber had no significant effect on segregation, but it decreased the workability of the mixes by reducing the passing ability of the fresh concrete. They found that 0.75% of carbon fiber was optimum for fresh concrete workability. Rangelov et al. [43] investigated

the possibility of using carbon fiber in pervious concrete applications. They mentioned that using carbon fiber had a beneficial effect on pore structure and helped improve the strength of the composites. Tanyıldız [44] evaluated the effect of carbon fiber on the mechanical properties of lightweight concrete. He prepared the samples composed of various carbon fiber percentages from 0 to 2% by a mass fraction. He concluded that the optimum carbon fiber should not exceed 0.5% for the best compressive strength. Giner et al. [45] examined the dynamic properties of concrete containing carbon fiber and silica fume. They stated that the addition of carbon fiber is more effective for reducing vibrations compared to silica fume additions. Additionally, the addition of carbon fiber decreased the compressive strength but increased the flexural strength. Díaz et al. [46] investigated the phase changes of cement pastes with carbon fibers. They concluded that carbon fiber increased the pores significantly. The poor microstructure of cement pastes affected the permeability of the cement paste. This can be more effective beyond higher carbon fiber volume fractions. Hambach et al. [47] produced pastes containing carbon fiber (3% by volume) having flexural strength greater than 100 MPa. They reported that if the carbon fiber aligned in the stress direction, this could help the tremendous improvement in flexural strength. Kim et al. [48] investigated the effect of carbon fibers on autogenous shrinkage and electrical properties of cement pastes and mortars. They reported that flow values declined significantly with carbon fiber addition. However, the electrical resistivity of pastes improved with carbon fiber addition. They also mentioned that the negative effect of fine aggregate was mitigated with the addition of carbon fibers. Fu and Chung [49] studied the effect of carbon fibers on the thermal resistance of cement pastes. They reported that the addition of short carbon fibers (0.5-1% by weight of cement) decreased the thermal conductivity. Belli et al. [50] examined the effect of recycled carbon fibers up to 1.6% by volume fraction on the thermal conductivity of mortars. They stated that the carbon fibers decreased water absorption by 39%. Additionally, their analyses revealed a decrease in thermal conductivity. Wei et al. [51] evaluated the performance of carbon fiber lightweight concrete. The toughness of the composites increased by 26-37% when carbon fiber was added. Additionally, the tensile strength of the composites increased significantly with the addition of carbon fiber.

The use of bottom ash and marble dust wastes has increased recently, reducing the amount of cement. Although it is recommended to use fiber to improve the strength and durability of composites produced using these materials, the studies on this subject are limited. Most studies focused on concrete. In this study, composites from cement paste were prepared by mixing 20% of bottom ash and marble powder with cement. Four different carbon fiber ratios (0.3 %, 0.75 %, 1.5 %, and 2.5 %) were added to improve the performance of the composites, and their physical, mechanical, and durability properties were investigated. The material has been designed as a cement paste, and an alternative binder material has been attempted to be used in the concrete component by using waste materials. No previous study on strengthening the cement paste of carbon fiber has been encountered. In addition, this study contributes to the concrete industry by using two different wastes and investigating the physical, mechanical, and durability of these composites produced in a laboratory environment. Using bottom ashes in structural grade applications could be the best solution for future sustainability trends.

2. Experiment:

2.1 Materials

2.1.1. Cement

Ordinary Portland Cement (42.5 grade) conforming to the ASTM C150M-12 [52] standard was used. The chemical composition of cement is presented in Table 1. The specific gravity of cement was 3.10, and its fineness was 2930 cm²/g.

2.1.2. Bottom ash (BA)

BA was obtained from a local brick factory plant. The specific gravity of the BA was 1.47. Its chemical composition is presented in Table 1. Particles smaller than 200 μm were used in the tests.

2.1.3. Marble dust (MD)

The marble dust was obtained from the manufacturing unit of a marble factory. The marble dust contains particles of approximately 3 μm in size. Before use, the larger particles were ground to fine size and sieved through 50 μm . The moisture content of the marble dust was first determined, and water content in the mix was adjusted. The moisture content of marble dust was 0.73%. The specific gravity was 2.51. The chemical composition of marble dust is presented in Table 1.

2.1.4. Carbon fiber

The length and diameter of carbon fiber used in this study were 6 mm and 7.2 μm , respectively. The density of carbon fiber was 1.81 gr/cm^3 . Its tensile strength was 3800 MPa, and the modulus of elasticity was 228 GPa.

2.1.5. Water

Tap water was used for both tests and preparation of the mixtures.

Table 1. Chemical composition of cement, bottom ash and marble dust

Oxides (%)	Cement	Bottom ash	Marble dust
SiO ₂	20.7	56.6	10.1
Al ₂ O ₃	5.4	26.8	0.5
Fe ₂ O ₃	2.7	7.4	0.9
CaO	65.2	1.3	45.3
MgO	0.4	0.1	5.7
K ₂ O	0.1	1.2	0.04
SO ₃	1.6	0.5	0.02
LOI ^a	2.3	3.5	36.3

^aLoss on ignition.

2.2 Preparation of samples

A Hobart mixer of 2.5-L capacity was used to prepare pure cement paste composites. Bottom ash, marble dust, and cement were mixed in dry form for 45 sec, and tap water was added slowly within 30 sec. The fresh paste was placed into molds and then consolidated with a vibrating table for 1 min. After 24 hrs., the samples were removed from the molds and cured in water until testing ages (7, 28, and 56-days).

Cubic molds of 50 mm³ in size were used for compressive strength tests. Mortar prisms of 40 mm \times 40 mm \times 160 mm in size were used for flexural strength tests. ASTM C109M-20 [53] standard for compressive strength and ASTM C348-19[54] standard for flexural strength tests were used.

Six samples were cast for each testing age. The apparent specific gravity and water absorption experiments were performed according to the ASTM C127–15 [55] procedure. The consistency of prepared mixtures was determined using a flow table test according to the ASTM C230M-14 [56] procedures. The sulfate tests of all prepared mixtures were determined according to the ASTM C88-18 [57] procedure. The specimens were subjected to a sulfate solution until cracked. At the end of each cycle, the samples were removed from the sulfate solution and dried in an oven at 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 was applied for sulfate tests. The tests were continued until the first visible crack. The mass changes were then recorded.

2.3 Mixture proportions

The composites comprised of two series of mixtures. First series composed of 80% cement, 20% marble dust, and carbon fiber ranging from 0% to 2.5% by volume of the cement paste. The second series composed of 80% cement, 20% bottom ash, and carbon fiber ranging from 0% to 2.5% by volume of the cement paste. Fiber volumes of 0.30%, 0.75%, 1.5%, and 2.5% were evaluated. The water binder ratio was kept constant for all mixture groups and taken as 0.40. The picture of carbon fiber used is shown in Figure 1, and Figure 2 shows the sample composites prepared at the laboratory (Carbon fiber-enriched bottom ash cement paste composites).



Figure 1. Carbon Fiber used in this study



Figure 2. Carbon fiber enriched bottom ash composites

3. Results

3.1 Effects of carbon fiber on physical properties

The flow of cement paste containing carbon fiber is shown in Figure 3, and Figure 4 shows the effect of carbon fiber on the flow properties of marble dust and bottom ash mixture groups.



Figure 3. Flow of cement paste containing carbon fiber.

Figure 4 shows the effect of carbon fiber on the flow properties of marble dust and bottom ash mixture groups. For both mixture groups, carbon fiber addition decreased the flow properties compared to the reference mixture. The addition of fiber minimized the movement of the particles and thus reduced the flow of the composites. Considering the reference mixture, marble dust had a higher flow compared to bottom ash mixture groups. This can be attributed to the higher paste volume in the marble dust group compared to the bottom ash mixture groups. Inflow decreased more for marble dust mixture groups. At higher volume fraction, this difference diminished. This can be due to the higher absorption capacity of the bottom ash particles. Additionally, reduction in workability did not affect the mechanical properties of both mixture groups and thus provided better densification and bonding at all curing ages. Furthermore, the addition of more than 0.3% of carbon fiber made the paste more viscous and increased the resistance to flow. At high carbon fiber dosages, a greater reduction in workability was reported. Similar findings can be found in [40–42].

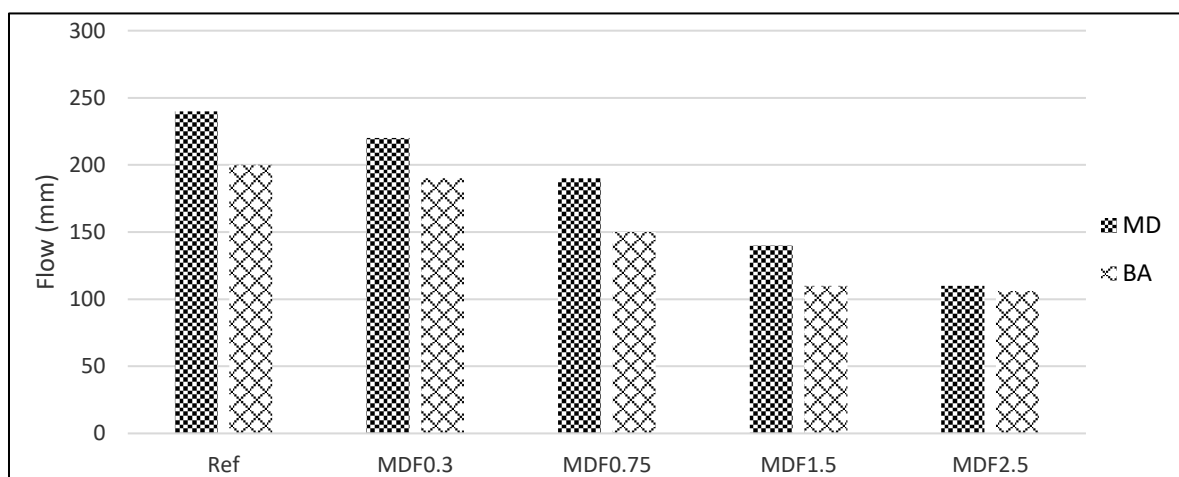


Figure 4. Effect of carbon fiber on flow properties of marble dust and bottom ash mixture groups

Figure 5 shows the effect of carbon fiber on apparent specific gravity (ASG) for marble and bottom ash mixture groups at 7, 28, and 56-days of curing. In Figures, MD denotes marble dust, BA denotes bottom ash, and F denotes carbon fibers. ASG increased with the amount of carbon fiber for

both marble dust and bottom ash mixture groups. This increase was greater in marble dust mixture groups. This can be attributed to the porous structure of the composites, as the marble dust mixture had high porosity values compared to bottom ash mixture groups. ASG is a property related to the availability of impermeable pores inside the matrix composites, and it affects the composite's behavior [58]. Due to the hydration reaction, the ASG values in our study tended to decrease. This can be explained by the fact that more gel formation blocked the pores of the composites and reduced the impermeable pores. Marble contains more calcium oxide, and this can help the creation of a densified matrix. Marble composites seemed to be more stable, and carbon fiber worked well with marble dust compared to bottom ash particles. Compatible results from the previous researches were reported in previous studies [48,50].

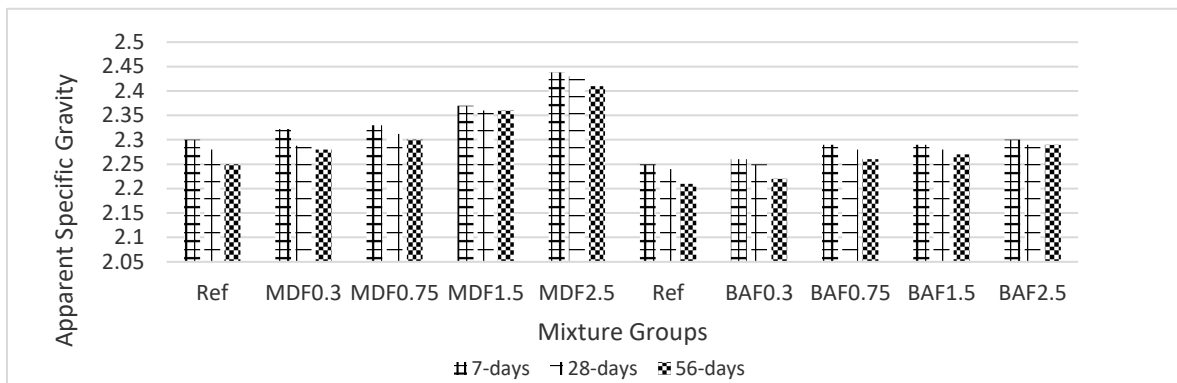


Figure 5. Effect of carbon fibers on apparent specific gravity for marble dust and bottom ash mixture groups at 7-28 and 56-days of curing.

Figure 6 shows the effect of carbon fiber on water absorption (WA) for marble dust and bottom ash mixture groups at 7, 28, and 56-days of curing. Carbon fiber decreased the WA values at all ages for both mixture groups. WA values for both marble dust and bottom ash mixture group increased beyond 0.75% carbon fiber addition. Bottom ash mixture groups had higher WA values compared to marble dust mixture groups. In bottom ash mixture groups, fewer impermeable voids were available. Bottom ash particles directly absorbed all the water in capillaries, and less amount of water became available for chemical reactions at later ages. Notably, carbon fiber addition beyond 0.75% showed an adverse effect on both mixture groups. Belli et al. [50] observed the same findings.

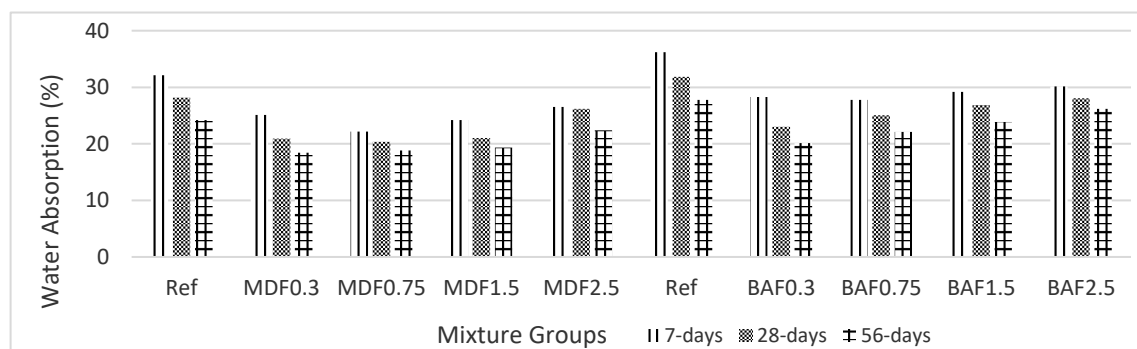


Figure 6. Effect of carbon fiber on water absorption for marble and bottom ash mixture groups at 7, 28, and 56-days of curing.

Figure 7 shows the effect of carbon fiber on porosity for marble dust and bottom ash mixture groups at 7, 28, and 56-days of curing. The same trend as with WA was observed for both mixture groups. The addition of carbon fiber decreased the porosity for both mixture groups due to the excellent dispersion of the carbon filament in the cement paste matrix and reduced the micro pores of the composites. The 0.75% carbon fiber addition seems to be the optimum value above which the porosity tends to increase. Carbon fiber addition beyond 0.75% resulted in the formation of pores and holes. This is the case for both marble dust and bottom ash mixture groups. As the carbon fiber content increased, the rate of decrease in porosity decreased at later ages. Similar findings were found in many studies [43,46,47,50].

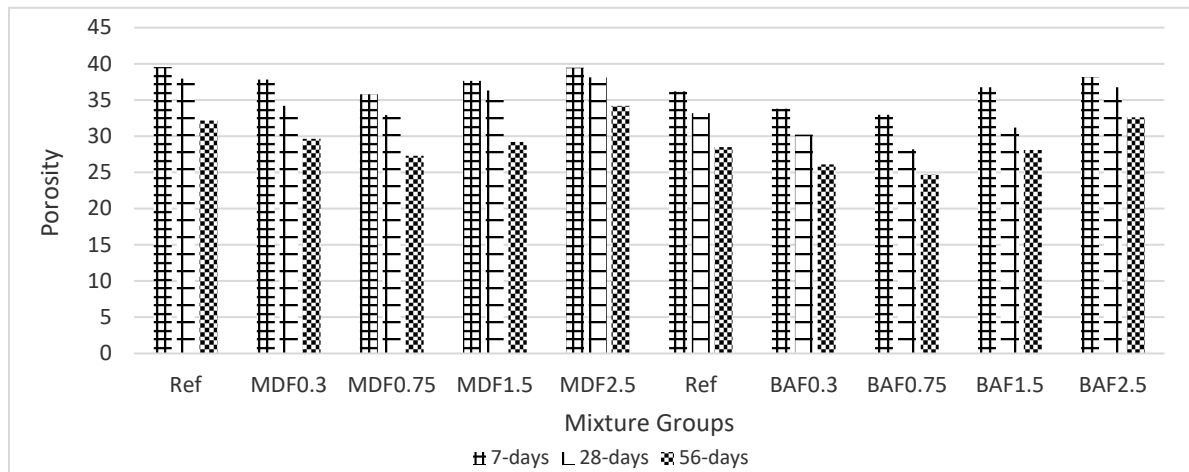


Figure 7. Effect of carbon fiber on porosity for marble and bottom ash mixture groups at 7, 28, and 56-days of curing.

Many studies have reported that bottom ash particles alone have higher porosity. However, this study revealed that carbon fiber dispersed well with bottom ash particles, and less porosity was reported in bottom ash mixture groups compared to marble dust groups. ASG values also validated the results. Lower ASG values were found in bottom ash mixture groups.

3.2 Effect of carbon fiber on the mechanical properties

Figure 8 shows the effect of carbon fiber on unconfined compressive strength for marble dust and bottom ash mixture groups at 7, 28, and 56-days of curing. Marble dust mixture groups had higher compressive strength compared to bottom ash mixture groups. It might be due to the marble dust containing higher calcium oxide and providing more gel during hydration. Additionally, marble dust mixture groups had lower WA values. This could help the formation of densified matrix. All added water was used for chemical reactions, and thus more strength (i.e. due to formation of more gel) was recorded. The carbon fiber increased the ASG values of the composites; thus, the volume of impermeable pores increased. The water inside these pores created some pressure on the fiber interface and cement paste, which likely decreased the effectiveness of the carbon fibers at higher volume fraction and decreased the strength beyond 0.75% addition. This implies that improper fiber dispersion above 0.75% carbon fiber addition decreased the UCS values beyond this value. The reduction in UCS values beyond the 0.75% carbon fiber addition also proved that the formation of large pores decreases the ability of carbon fiber and that compatibility of the composites at higher fiber volume fraction led to significant loss of strength. Similar findings were reported in previous studies [36,38,42,43,46,47].

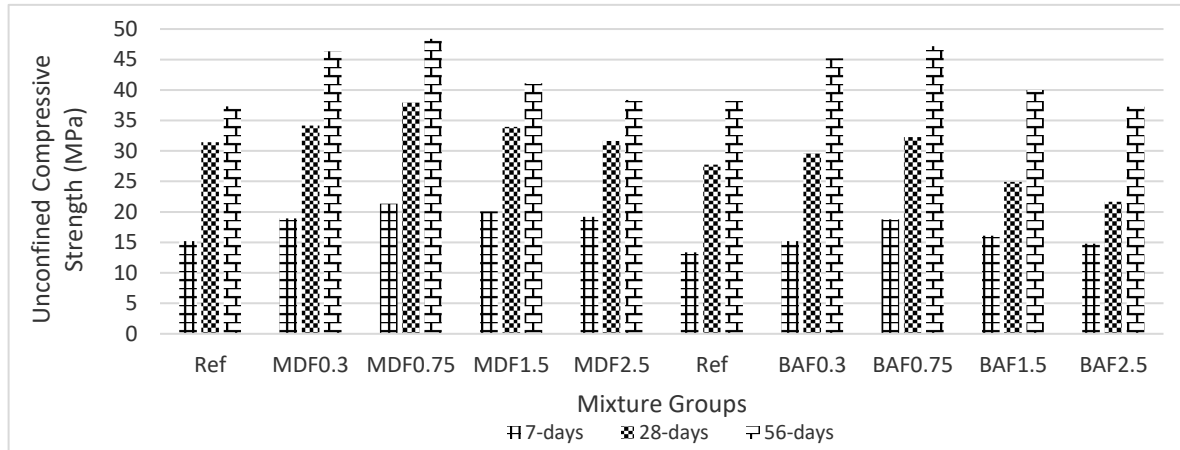


Figure 8. Effect of carbon fiber on unconfined compressive strength for marble dust and bottom ash mixture groups at 7, 28, and 56-days of curing.

Figure 9 shows the effect of carbon fiber on flexural strength for marble dust and bottom ash mixture groups at 7, 28, and 56-days of curing. The same trend as in UCS was observed for flexural strength. However, the rate of increase compared to UCS was more for FS. Carbon fiber improved the bonds and held the matrix together. Moreover, carbon fiber adhered better to the cement paste. Carbon fiber showed better improvement at 56-days due to the slow reactions of the bottom ash and marble dust wastes. The 0.75% carbon fiber addition yielded better results. Beyond this value, the FS tended to decrease. This might be due to the tensile forces created at the interface of the cement paste and fiber-matrix, which reduced the strength. The bond lost its capacity to carry more loads. Similar findings were reported in the literature [43,46,50].

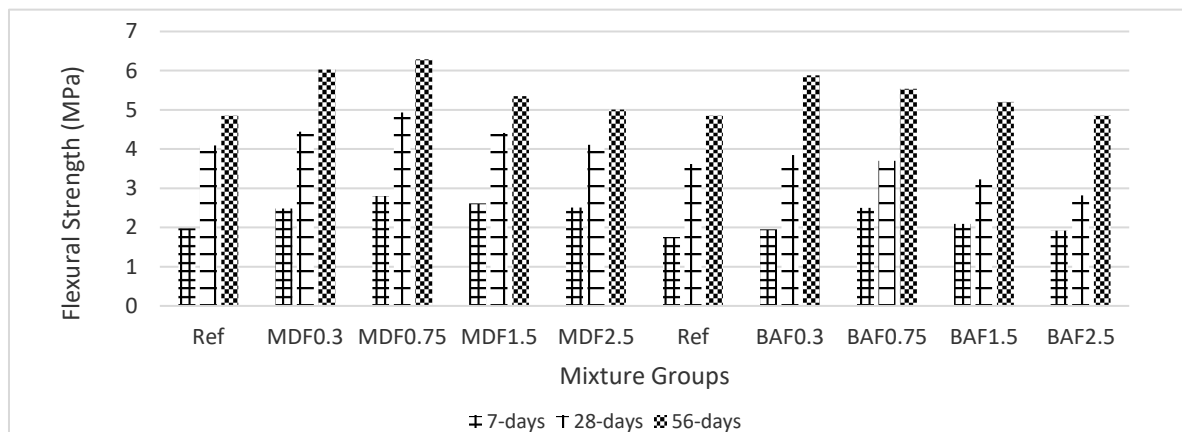


Figure 9. Effect of carbon fiber on flexural strength for marble dust and bottom ash mixture groups at 7, 28, and 56-days of curing.

3.3 Effect of carbon fiber on the durability properties

Figure 10 shows the effect of carbon fiber on sulfate resistance for marble dust and bottom ash mixture groups at 28 and 56-days of curing. The addition of carbon beyond 0.75% increased the expansion for both mixture groups. Marble dust mixtures showed less expansion. This can be attributed to better matrix properties. The bond between the cement paste and fiber formed densified matrix, and carbon fiber acted as a barrier to protect the formation of an expansive gel. All values were below 10%, and at 56-days, they decreased below 5%. With continued hydration, the bonds became more robust, and with the help of bottom ash and marble dust wastes, additional calcium

silicate hydrate gels were formed [59,60]. Thus, the composites became more stable, and the atomic arrangement became closer.

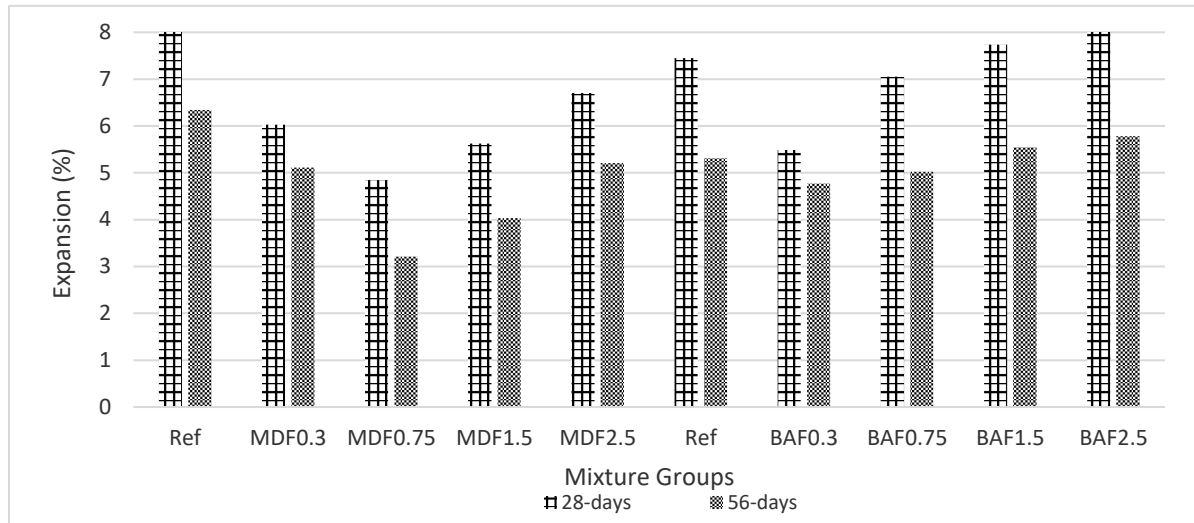


Figure 10. Effect of carbon fiber on sulfate resistance for marble dust and bottom ash mixture groups at 28 and 56-days of curing.

Figure 11 shows the effect of carbon fiber on seawater resistance for marble dust and bottom ash mixture groups at 28 and 56-days of curing. Bottom ash mixtures showed less resistance against seawater compared to marble dust mixture groups. Carbon fiber addition above 0.75% for both mixtures increased weight loss due to seawater. Upon curing, weight loss decreased. Bottom ash mixture groups had lower compressive and flexural strength and thus formed weaker bonds to hold the system. Weight losses are less than 1.5% and do not create any problem.

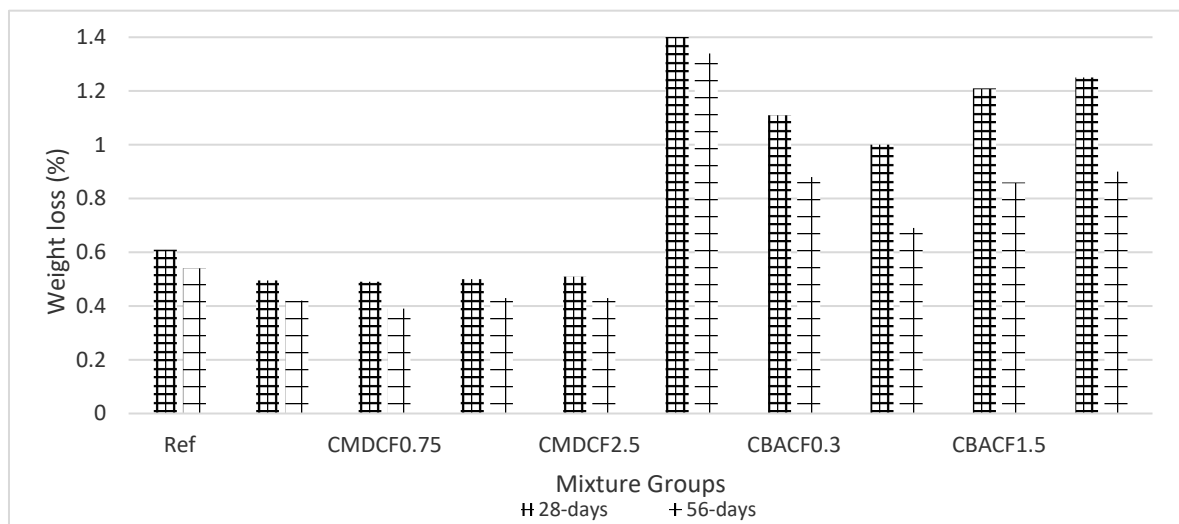


Figure 11. Effect of carbon fiber on sea water resistance for marble dust and bottom ash mixture groups at 28 and 56-days of curing.

4. Conclusions

Based on the experimental results, the following conclusions can be drawn.

- 1- Carbon fiber was effective up to 0.75% for both marble dust and bottom ash mixture groups.
- 2- Decreased inflow was more notable in marble dust mixture groups compared with bottom ash mixture groups. Carbon fiber addition above 0.75% was associated with significantly reduced inflow in marble dust mixture groups.
- 3- Porosity was higher in marble dust mixture groups. Carbon fiber addition increased the porosity values for both marble dust and bottom ash mixture groups beyond 0.75% addition.
- 4- Water absorption values decreased with the addition of carbon fiber. However, carbon addition beyond 0.75% increased water absorption values for both mixture groups. However, the increase was greater in bottom ash mixture groups.
- 5- Unconfined compressive and flexural strength values increased with the addition of carbon fiber. However, beyond 0.75% carbon fiber addition level, both strength values decreased. The decrease in intensity was greater for bottom ash mixture groups. The compressive strength reached 48.4 MPa and 47.2 for marble dust and bottom ash mixture groups, respectively, at 56-days of curing. The strength gain was greater after 28-days for both mixture groups.
- 6- Both composites were resistant to sulfate and seawater attack. Carbon fiber seemed to be useful for protecting the composites against harsh environments at low volume fraction. Carbon fiber addition beyond 0.75% adversely affected the composite's resistance.
- 7- It is highly recommended to investigate the effect of carbon fibers on the microstructure of these novel based composites. Additionally, different water binder ratios might be helpful for a better understanding of the behavior of such composites.

5. Patents

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

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