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# Hybrid effect of micro-steel and basalt fibers on physico-mechanical properties and durability of mortars with silica fume

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ABSTRACT

This study investigated the hybrid effects of micro-steel (MS) and basalt fibers (BF) on the physico- mechanical properties and durability of mortars with and without silica fume (SF). Three groups of mixtures containing SF contents of 0%, 10 % and 20 % as cement replacement were produced with the inclusion of 0.25 %, 0.5 and 0.75 % steel fibers and 0.3, 0.6 and 0.9 % basalt fibers by volume at each SF content. In total, 28 mixtures were designed and fresh properties of mixtures were evaluated by workability using slump test and fresh unit weight. Hardened properties were tested at 28 days and compressive strength, flexural tensile strength, dry unit weight, porosity and water absorption were assessed. The results revealed that combined use of 0.75 % MS and 3% BF achieved the highest compressive strength of 64.4 MPa which was 62.21 % higher than control mixtures at 20 % SF content. The results also exhibited that the mixtures containing 0.3 % BF exhibited the highest compressive strength and compressive strength decreased slightly with increasing BF content in the mixtures in each MS content at all SF content. The results showed that combined use of 0.50 % MS and 0.9 % BF and without SF achieved the highest flexural strength of 8.90 MPa which was 27.14 % higher than control specimens.

## 1. Introduction

Normal concrete (NC) is a composite material most widely used worldwide as a building material with economic, component availability, high compressive strength and good performance in different environmental conditions. It has many advantages over other traditional materials such as desirable mechanical and durability properties, formability and economy, but also some disadvantages such as low tensile and bending strength, low strength per unit weight of the material, high carbon footprint, etc. The brittle behavior of normal concrete and its weakness under stress leading to low ductility were the two main sources of problems arising in structural applications. In general, the mechanical properties of concrete such as static flexural strength, split tensile strength, flexural toughness, fatigue resistance, impact strength and post-cracking tensile capacity can be improved significantly by the addition of fibers to the concrete mixture [1–4]. The effects of using different fibers in concrete or mortar have been studied by many researchers. Synthetic fibers such as polymer [5], polyester [6] polypropylene [7], polyethylene [8], natural fibers such as sisal [9], hemp [10], coconut [11] and others such as carbon fibers [12], glass fibers [13] and steel fibers [14,15] have been incorporated into concrete/mortar in order to remedy the brittle nature of concrete/mortar [16]. As the fibers increase tensile strength of concrete/mortar, they bridge and control the cracks and thus delay the propagation or initiation of cracks. The extent of behavioral improvement in concrete and compensating for the weakness in stress and ductile behavior and achieving a less cracked concrete turned out to be largely dependent on the type, shape and percentage of fibers to be applied [1,3,17]. Using two or more fiber types in concrete/mortar may be a better option for providing excellent performance, while concrete/mortar reinforced with a single type of fibers generally improves concrete properties in a limited range [18]. The addition of a single fiber can improve the performance of only one aspect of the concrete depending on the fiber type, diameter, length and elastic modulus, and the idea of hybridization of two or more fibers of different types and sizes has been developed to improve the overall performance of the concrete, to better apply the bridging effect of the fiber across cracks [19,20]. Steel fibers are materials with high tensile strength and high modulus of elasticity that can significantly increase the ultimate strength and toughness of cement-based materials by effectively restricting the development of macro cracks [21]. Steel fibers maintain their viability as a superior reinforcement material providing satisfactory tensile, compressive, and flexural

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and shear strength properties with a very high tensile strength of over 1200 MPa and an elastic modulus of about 200 GPa [22,23]. Steel fiber reinforced concrete (SFRC) increases strength per unit amount of material compared to NC, resulting in lower economic and environmental impact. One of the reasons for the inadequate use of steel fibers in fiber reinforced concrete is the failure of the concrete due to the interface between the fiber and the binder matrix as reported by Lee et al. [24].Yan et al. [25] studied the mechanical performance of high-strength concrete containing silica fume and steel fiber and they reported the initiation and propagation of cracks were limited, stress concentrations at the crack ends were reduced, and the damage process under impact and fatigue were delayed effectively due to the steel fiber. They also reported that the interface structure was improved, the weakness of the interface zone was eliminated, the number and size of cracks were reduced, and the ability of steel fibers to resist cracking was increased effectively due to silica fume.

Because the manufacturing process consumes less energy and contains no additives, basalt fibers are a cost-effective environmentally green inorganic silicate material with a working performance similar to that of carbon fiber. They can be widely used in many areas due to their environmentally friendly production process and excellent mechanical properties and appear to be a promising candidate for improving the properties of the cement matrix [26–32]. Basalt fibers, which adapt well to concrete, are produced from molten basalt rock and have cheaper production steps than other fibers. They have the potential to be an alternative to other fibers used in concrete composites due to good properties such as better modulus, high strength, better stability, reduced drying shrinkage, improved toughness, and ability to withstand repeated impacts [33]. Fiore et al. [34] demonstrated the contribution of basalt fibers in strengthening high strength concrete, improving tensile strength, fire resistance and impact, frost resistance and permeability [14] as chemical inertness, very low thermal conductivity, and highly resistant to corrosion. Various studies [30,35,36] have been carried out investigating the durability, thermal resistance and acoustic insulation of basalt fiber concrete. These properties of concrete are significantly improved by the addition of basalt fibers. The study on the chemical resistance of basalt fiber revealed the potential of using BF in reinforced cement in a study by Ramachandran et al. [37]. Sadrmomtazi et al. [38] carried out an investigation on the impacts of silica fume on mechanical strength and microstructure of basalt fiber reinforced cementitious composites. They noted that the flexural strength and toughness increased 2 and 6 times, respectively but, compressive strength decreased by 47 % with the inclusion of BF. Loh et al. [39] investigated the effects of polyvinyl alcohol and basalt fibers on the mechanical properties of cementitious composite. They found that the fibers had minimal effect on the compressive strength of cement composites but significant improvements in the splitting tensile and flexural strengths. Hu et al. [40] studied the singly or hybrid impact of the polypropylene and basalt fibers on the workability, mechanical, chloride resistance and pore structure characteristics of concrete. They pointed out that the combined use of polypropylene and basalt fibers at content of 0.1 % achieved the best mechanical performance and is recommended for practical usage. Wang et al. [41] investigated that the mechanical properties of high performance concrete reinforced with basalt and polypropylene fibers. They reported that the synergy effect of fiber mixing is the best with 0.15 % basalt fiber and 0.033 % polypropylene fiber content. The compressive strength, flexural strength and splitting tensile strength increased by 14.1 %, 22.8 % and 48.6 %, respectively as compared with those of concretes without fibers. However, there have been very limited studies in which micro-steel and basalt fibers are used together in concrete / mortar in the literature. This study focus on the hybrid effects of micro-steel and basalt fibers on the physico-mechanical properties and durability of mortars with silica fume. Three groups of mixtures containing SF contents of 0%, 10 % and 20 % as cement replacement were produced with the inclusion of 0.25 %, 0.5 and 0.75 % steel fibers and 0.3, 0.6 and 0.9 % basalt fibers by volume. In total, 28 mixtures were designed and fresh properties of mixtures were evaluated by workability using slump test and fresh unit weight. Hardened properties were tested at 28 days and compressive strength, flexural tensile strength, dry unit weight, porosity and water absorption were assessed.

## 2. Test programme

### 2.1. Materials

#### 2.1.1. Cement

CEM I 42.5 R Portland cement was used in this experimental study. The chemical composition of the cement and its physical

**Table 1**
The chemical compositions of cement.

| Oxides (%) | PC |
|---|---|
| $SiO_2$ | 19.12 |
| $Al_2O_3$ | 5.63 |
| $Fe_2O_3$ | 2.39 |
| CaO | 63.17 |
| MgO | 2.75 |
| $SO_3$ | 2.74 |
| $Na_2O$ | – |
| $K_2O$ | 1.00 |
| Loss in ignition | 2.33 |
| **Physical Properties** | |
| Specific weight (g / $cm^3$) | 3.09 |
| Specific surface ($cm^2$ / g) | 3144 |

properties are given in Table 1. The water / binder (cement + silica fume) ratio (w/b) was kept constant as 0.5.

#### 2.1.2. Silica fume

Silica fume (SF) in accordance with ASTM C1240 standards [42] was used in the study. Properties of SF are tabulated in Table 2 and the appearance of silica fume is shown in Fig. 1. SF used in mortar mixtures was supplied by Antalya Ferrochrome Power Plant, Turkey. Fig.1a shows XRD pattern of SF. As seen from Fig.1a, SF contains amorphous phase as well as fewer amounts of quartz crystals. SEM image of SF is given in Fig.1b. TGA result of the SF is plotted in Fig. 1c and d illustrates the particle size distribution SF. SF with the characteristics of having amorphous silica and a high specific surface area and the total content of $SiO_2$+$Al_2O_3$+$Fe_2O_3$ with a percent of 89.2 % shows very high pozzolanic activity which results in higher compressive strength on mortars. In the production of high-strength concrete and mortar, SF is an important component using to protect cement and additives to change concrete or mortar properties such as alkali-silica reaction, chemical attack, sulfate resistance, abrasion resistance and freeze-thaw resistance [43].

#### 2.1.3. Micro steel fibers

Micro OL type short cut steel fibers (MS) with a length of 0.6 cm and a diameter of 0.016 cm were used in the study. The properties of the short cut steel fiber used are given in Table 3. The appearance of the short cut steel fiber is given in Fig. 2

#### 2.1.4. Basalt fibers (BF)

Basalt fiber is an inorganic, green and environmentally friendly material produced by melting basalt ore that crushed to a certain size. BF has large modulus of elasticity, low price and high tensile strength slightly higher than E-glass fibers and higher than steel fibers. Properties of BF are shown in Table 4. The appearance of the BF is illustrated in Fig.2.

#### 2.1.5. Aggregate, mixing water and Superplasticizer (SP)

Limestone based fine aggregates were used in the production of mortar. It was obtained by crushing. Its specific gravity and water absorption were 2.63 and 0.98 %, respectively. Size distribution of the fine aggregate is given in Fig.3. City network water with an average temperature of 20 ± 2 °C was utilised as mixing water in the study. A polycarboxylate based Superplasticizer (SP) was used in order to increase workability of mortars. Its specific gravity was 1.08. The pH value is 5.7. And solid content is 40 % by weight.

### 2.2. Mixture proportions, production and testing

The mortar components-cement, sand and water were mixed in a ratio of 1: 3.0: 0.5 by weight. While producing the mixture, cement, aggregate, if any, silica fume were mixed in the first stage. Homogeneity was achieved by adding fibers in two stages and mixing again. In the last stage, water and Superplasticizer (SP) were added. The dry mix was mixed in the mortar mixer for 1 min, followed by the addition of water, for a total of 3 min. After the mixture is poured into the cement mold, it is removed from the mold 24 h and put into the curing pool. A total of 84 samples were produced for 28 different mixtures with dimensions of 40 × 40 × 160 mm. The cement was replaced with SF at 0, 10, and 20 %. In each SF content of mortars, micro steel fibers (MS) were added to the mortars at the rates of 0.25, 0.50 and 0.75 % by volume and in each MS content of mortars, basalt fibers (BF) were added to the mortars at the rates of 0.3, 0.6 and 0.9 % by volume. A total of 28 different mortar mixes including control sample were produced. Mortar mixture ratios are given in Table 5. The abbreviation in the mixtures names were defined as SF means silica fume, S refers to micro steel fibers (MS) and B refers to basalt fibers (BF). For instance; SF10S25B6 means that the mixture contains 10 % SF, 0.25 % micro steel fibers and 0.60 % basalt fibers. Fig.2d gives the SEM micrographs of mortars.

### 2.3. Testing procedures

The workability of the mortars was determined by carrying out slump test on the fresh mortars as per ASTM C1437−15 [44]. After

**Table 2**
The properties of SF.

| Oxides (%) | SF |
|---|---|
| $SiO_2$ | 85.4 |
| MgO | 1.5 |
| $Al_2O_3$ | 4.49 |
| $Fe_2O_3$ | 2.4 |
| CaO | 0.8 |
| $SO_3$ | 1.3 |
| Loss on ignition | 3.4 |
| **Physical properties** | |
| Specific gravity (g/cm$^3$) | 2.2 |
| Surface area (cm$^2$/g) | 9000 |
| Retaining on 45 μm sieve (%) | 0.58 |
| Bulk density | 0.55−0.65 kg/dm$^3$ |
| Moisture (%) | 0.19 |

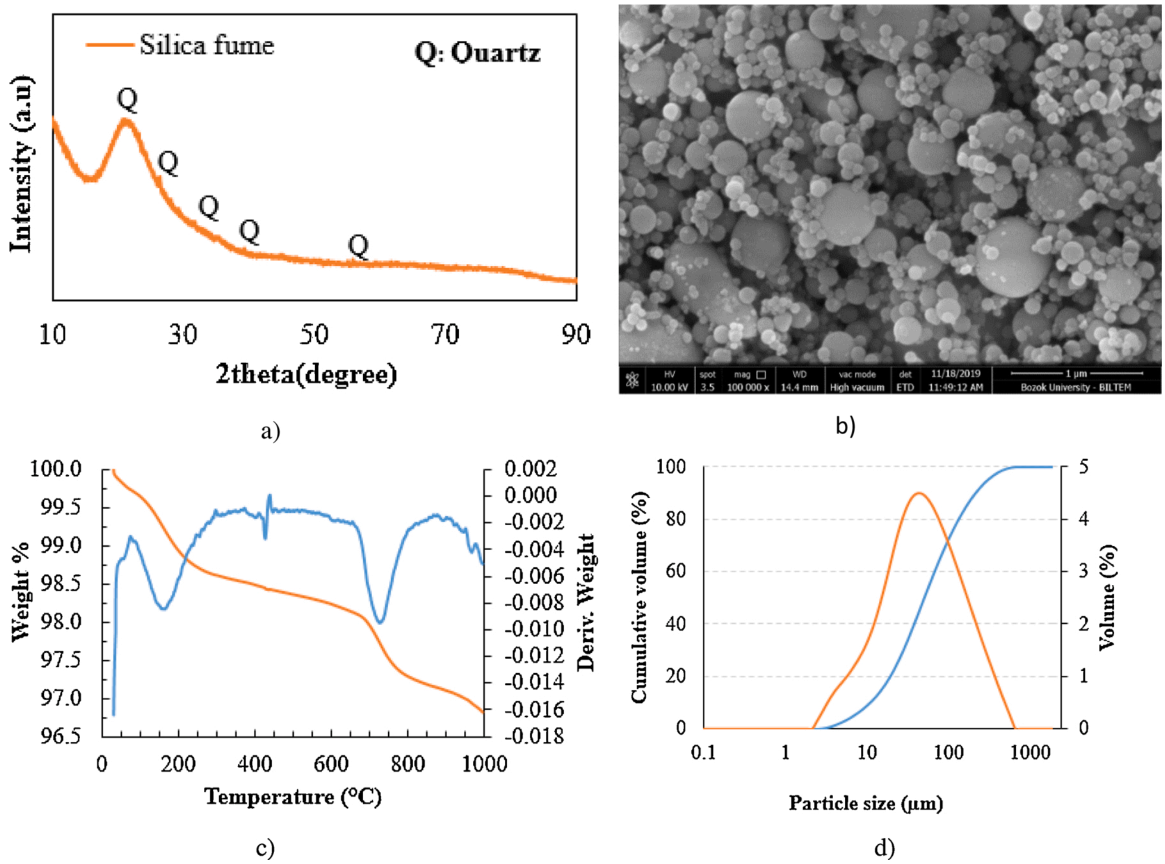


**Fig. 1.** a) XRD pattern of SF b) SEM view of SF c) TGA result of the SF (Blue line: Deriv. Weight; Orange line: weight %) d) Particle size distribution SF (blue line: cumulative curve; orange line: volume (%)) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

**Table 3**
Physical and mechanical properties of MS adopted.

| Fiber type | Micro OL |
|---|---|
| Length (l) cm | 0.6 |
| Diameter (d) cm | 0.016 |
| Aspect ratio (l / d) | 37.5 |
| Tensile Strength kg/cm$^2$ | 20000 |
| Specific weight g/cm$^3$ | 7.17 |

28 days of standard curing, since the durability of mortar/concrete depends on the transport properties indirectly, dry unit weight, porosity and water absorption tests were made as per ASTM C642 [45] to evaluate the transport properties. The saturated weight of the mortar samples after removing them from the curing pool for 28 days and then the dry weight of the mortar samples after they were kept in an oven at 100 °C (±5 °C) for 24 h were determined. The actual volume values were found by weighing in water with an Archimedean balance. Accordingly, the hardened unit weight, water absorption and porosity values were calculated. Three mortar prism samples were used for each mixture to evaluate water absorption, dry unit weight and porosity. The results were average of three three samples. The 3-point bending test was carried out by placing the mortar samples on supports with 100 mm opening and 30 mm outside the support. The flexural test was done on three samples with 40 × 40 × 160 mm size in accordance with ASTM C348−19 [46]. It was carried out at a loading speed of 50 N/s and on three samples for each mix group. As a result of the experiment, the average of three samples was taken. Compressive strength tests were done on samples obtained from flexural strength test as per ASTM C349−18 [47]. The Compressive strength test was carried out on a total of six samples obtained from the specimens divided into two parts after the flexural test. The result of the experiment was determined by taking the average of the results obtained from six samples.

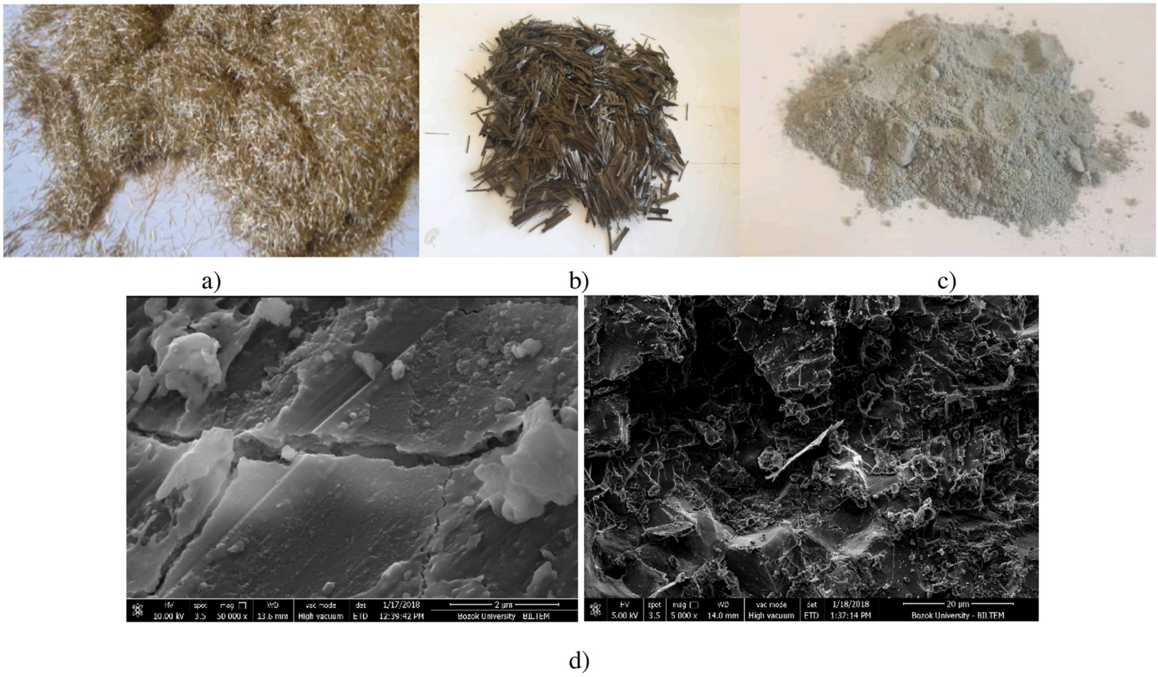


**Fig. 2.** a) Micro steel fibers b) basalt fibers and c) silica fume d) SEM micrographs of mortars (control and SF10S25B3 mixtures).

**Table 4**
Physical and mechanical properties of BF adopted.

| Physical and mechanical properties | | |
|---|---|---|
| Tensile Strength | $kg/cm^2$ | 48480 |
| Elasticity Module | GPa | 89 |
| Melting temperature | °C | 1450 |
| Length (l) | mm | 12 |
| Diameter (d) | μm | 13 |
| Specific weight | $g/cm^3$ | 2.65 |

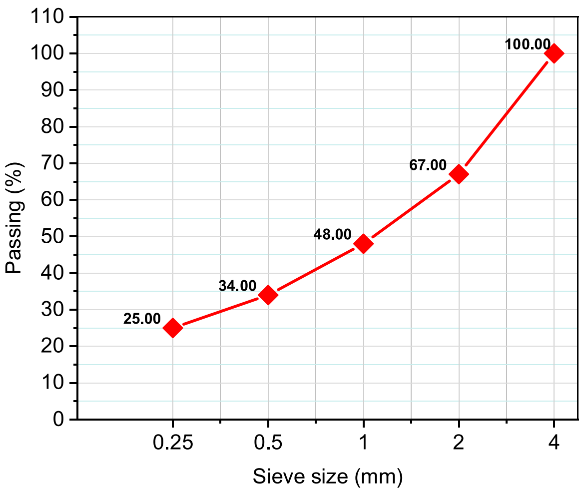


**Fig. 3.** Gradation of fine aggregate.

**Table 5**
Mixture proportions of mortars*.

| Mix Code | SF (%) | MS fibre (%) | BF (%) | Cement (g) | Sand (g) | Water (g) | SF (g) | MS fibre (g) | BF (g) | SP (g) |
|---|---|---|---|---|---|---|---|---|---|---|
| Control | – | – | – | 450 | 1350 | 225 | – | – | – | – |
| SF0S25B3 | | | 0.3 | 450 | 1350 | 225 | 0 | 20 | 7.8 | 0 |
| SF0S25B6 | | 0.25 | 0.6 | 450 | 1350 | 225 | 0 | 20 | 15.6 | 0 |
| SF0S25B9 | | | 0.9 | 450 | 1350 | 225 | 0 | 20 | 23.4 | 0 |
| SF0S50B3 | | | 0.3 | 450 | 1350 | 225 | 0 | 39 | 7.8 | 0 |
| SF0S50B6 | 0 | 0.5 | 0.6 | 450 | 1350 | 225 | 0 | 39 | 15.6 | 0 |
| SF0S50B9 | | | 0.9 | 450 | 1350 | 225 | 0 | 39 | 23.4 | 0 |
| SF0S75B3 | | | 0.3 | 450 | 1350 | 225 | 0 | 59 | 7.8 | 0 |
| SF0S75B6 | | 0.75 | 0.6 | 450 | 1350 | 225 | 0 | 59 | 15.6 | 0 |
| SF0S75B9 | | | 0.9 | 450 | 1350 | 225 | 0 | 59 | 23.4 | 0 |
| SF10S25B3 | | | 0.3 | 405 | 1350 | 225 | 45 | 20 | 7.8 | 3 |
| SF10S25B6 | | 0.25 | 0.6 | 405 | 1350 | 225 | 45 | 20 | 15.6 | 3 |
| SF10S25B9 | | | 0.9 | 405 | 1350 | 225 | 45 | 20 | 23.4 | 3 |
| SF10S50B3 | | | 0.3 | 405 | 1350 | 225 | 45 | 39 | 7.8 | 3 |
| SF10S50B6 | 10 | 0.5 | 0.6 | 405 | 1350 | 225 | 45 | 39 | 15.6 | 3 |
| SF10S50B9 | | | 0.9 | 405 | 1350 | 225 | 45 | 39 | 23.4 | 3 |
| SF10S75B3 | | | 0.3 | 405 | 1350 | 225 | 45 | 59 | 7.8 | 3 |
| SF10S75B6 | | 0.75 | 0.6 | 405 | 1350 | 225 | 45 | 59 | 15.6 | 3 |
| SF10S75B9 | | | 0.9 | 405 | 1350 | 225 | 45 | 59 | 23.4 | 3 |
| SF20S25B3 | | | 0.3 | 360 | 1350 | 225 | 90 | 20 | 7.8 | 3 |
| SF20S25B6 | | 0.25 | 0.6 | 360 | 1350 | 225 | 90 | 20 | 15.6 | 4 |
| SF20S25B9 | | | 0.9 | 360 | 1350 | 225 | 90 | 20 | 23.4 | 4 |
| SF20S50B3 | | | 0.3 | 360 | 1350 | 225 | 90 | 39 | 7.8 | 4 |
| SF20S50B6 | 20 | 0.5 | 0.6 | 360 | 1350 | 225 | 90 | 39 | 15.6 | 4 |
| SF20S50B9 | | | 0.9 | 360 | 1350 | 225 | 90 | 39 | 23.4 | 4 |
| SF20S75B3 | | | 0.3 | 360 | 1350 | 225 | 90 | 59 | 7.8 | 4 |
| SF20S75B6 | | 0.75 | 0.6 | 360 | 1350 | 225 | 90 | 59 | 15.6 | 4 |
| SF20S75B9 | | | 0.9 | 360 | 1350 | 225 | 90 | 59 | 23.4 | 4 |

* Mix Code (Example): SF10S50B6: SF/silica fume: 10 % – S/micro steel fibers: 0.50 %-B/basalt fibers: 0.6 %.

## 3. Results and discussion

### 3.1. Fresh properties of mortar mixtures

The slump values of fresh mortars at SF contents of 0, 10 and 20 % and different percentages of basalt fibers and micro steel fibers were evaluated in Fig. 4. As shown in Fig.4, SF had a negative impact on the slump values but this negative effect was eliminated by addition of SP and therefore slump values slightly increased as compared to mortars without SF and decreased with the inclusion of MS and BF. Fig. 4a gives the slump values of all fresh mortar mixtures with no SF varied between 18 cm and 10 cm. The highest slump value of 18 cm was obtained from control mixtures. With the addition of MS and BF to the mortars, the slump values dropped in the ranges of 12.5−10 cm as shown in Fig. 4a. The decrease in the slump values enhanced slightly as BF content increases. No SP was added to those mortar mixtures without SF. Fig. 4b illustrates the slump values of all fresh mortar mixtures containing 10 % SF varied between 18 cm and 12 cm. Adding MS to the mortar mixtures decreased the slump from 18 cm at 0.25 % MS content to 16.5 cm at 0.75 % MS content. Contrary to the increase in MS rate, the increase in the BF rate significantly reduced the slump value as plotted in Fig.4b. This can be attributed to the spatial network structure is formed due to the random distribution of BF. In addition, increasing basalt fiber ratio will consume more cement pastes to cover the fibers, resulting in a smaller amount of paste that provides fluidity [48]. Fibers enhance the mortar viscosity and limit the dispersion of the cement matrix, leading to reduced workability [49–51]. Therefore, the flowability of reference mixture decreases after addition of BF which causes to keep the fresh mix together and then enhance the cohesiveness of the fresh mixture. This is in agreement with the result of the previous studies in which flowability tends to be reduced by adding BF to the mixture [52,53]. Due to the high fineness and low density of SF, SP was added to eliminate its negative effect on the slump of the mortar as given in Table 5. Fig. 4c plots the slump values of mortar mixtures containing 20 % SF varied between 18 cm and 12.5 cm. SP content was increased to achieve the desired slump values. Similar to the slump values of mortars containing 10 % SF, more decrease in the slump of mortars was observed as BS content increased. However, the decreased workability still remains at a good level (18 cm to 10 cm) for large application. The workability of the mortar mixes has been observed always lower than that of reference mortar but good placement and uniformity can be achieved by the proper vibration method.

Fresh unit weight with respect to slump results of mortar specimens at 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers was plotted in Fig.5. Fig. 5a gives the fresh unit weight relations with slump values of fresh mortar mixtures with no SF content. It can be seen from Fig.5a, control mixtures exhibited the lowest fresh unit weight with the highest slump value, with the addition of MS and BF, all mixtures showed higher fresh unit weight with lower slump values than control mixtures and SF0S5B6 mixture exhibited the highest fresh unit weight of 8.20 % higher than control mixture. Fig. 5b exhibits the fresh unit weight relations with slump values of fresh mortar mixtures incorporating 10 % SF. It seems from Fig.5b that fresh unit weight of all mortars containing MS and BF was higher than control mixtures except SF10S50B6 3.63 % lower than control mixture. Fig. 5b exhibits the fresh unit

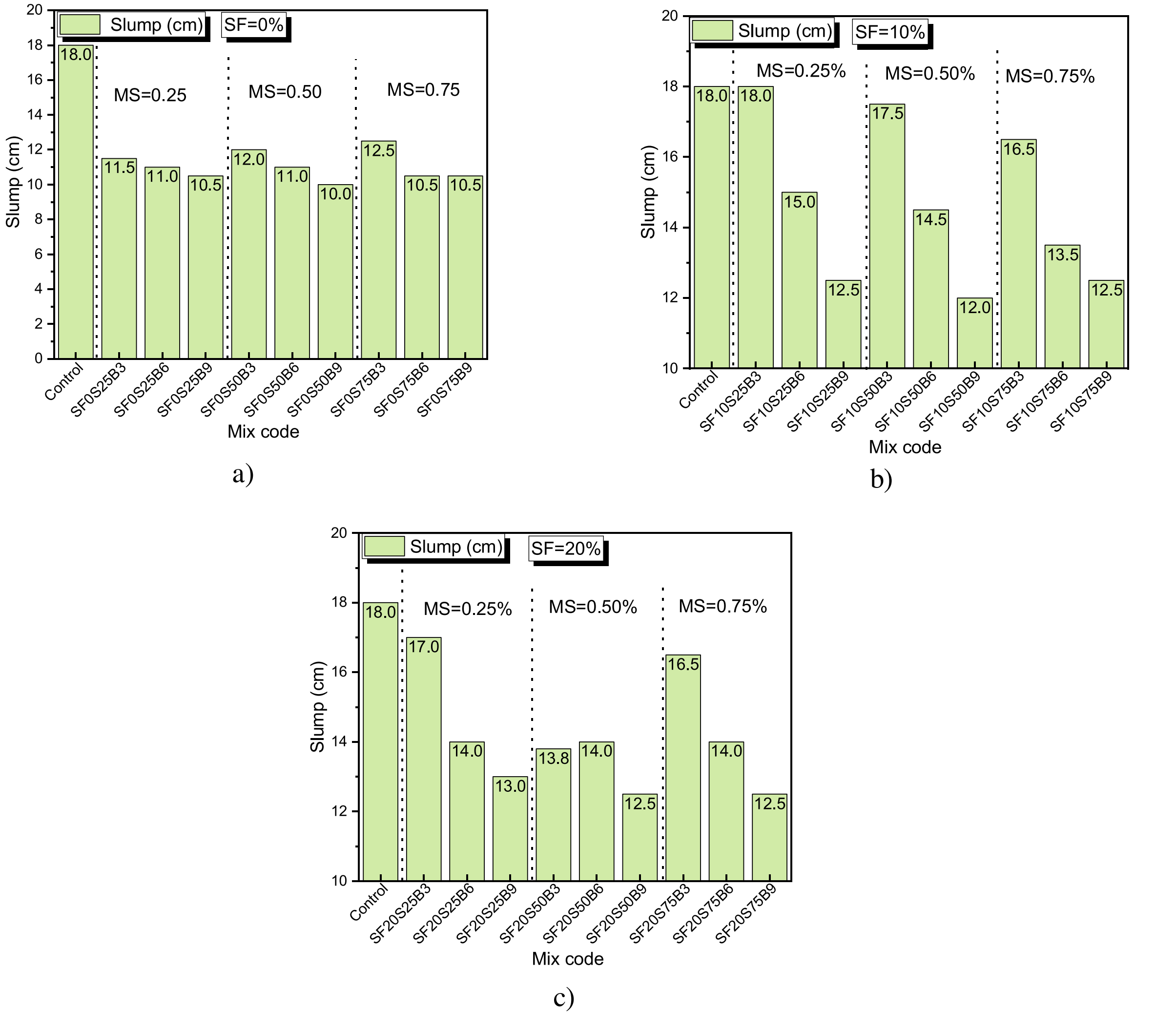


**Fig. 4.** Slump values of mortar mixtures at a) SF = 0% b) SF = 10 % c) SF = .20 %.

weight relations with slump values of fresh mortar mixtures incorporating 10 % SF. Fig. 5c illustrates the fresh unit weight relations with slump values of fresh mortar mixtures incorporating 20 % SF. Considering Fig.5c that fresh unit weight of control mixtures was higher than that of mortars containing 0.25 and 0.50 % MS but a little lower than that of mortars containing 0.75 % MS and 0.3 and 0.6 %BS. The higher fresh unit weight of control mixtures can be attributed to 20 % SF content.

### 3.2. *Compressive strength*

The compressive strength test results of mortar specimens containing 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers are plotted in Fig. 6. As shown in Fig.6, compressive strength increased with the inclusion of SF and MS fibers. The compressive strength enhancement due to the fibers can be attributed to the effect of the fibers on limiting and retarding crack propagation and decreasing the extent of stress concentration at the crack tip [1]. The highest compressive strength of 64.4 MPa which was 62.21 % higher than control mixtures was obtained for the mortar mixtures containing 20 % SF, 0.75 % MS and 3% BF. This increase in compressive strength may be a result of the strengthening of the aggregate-paste bond and the chemical reaction between SF and calcium hydroxide, producing an additional C—S—H gel that thickens the microstructure and ultimately leads to an increase in strength [54,55]. In each MS content, the mixtures containing 0.3 % BF exhibited the highest compressive strength and compressive strength decreased slightly with increasing BF content in the mixtures without SF. In SF blended mortar mixtures, the compressive strength decreased at 0.6 % BF content as compared to the mixtures with 0.3 % BF but it increased again at 0.9 % BF content as compared to the mixtures with 0.6 % BF content. The compressive strength decrease with the inclusion of BF was also found by the authors [53,56]. The mixtures with SF and 0.6 % BF had lower compressive strength than that of the mixtures with 0.3 and 0.9 % BF. Fig. 6a presents the compressive strength of mortar mixtures without SF content. As seen in Fig.6a, all mortar specimens containing MS

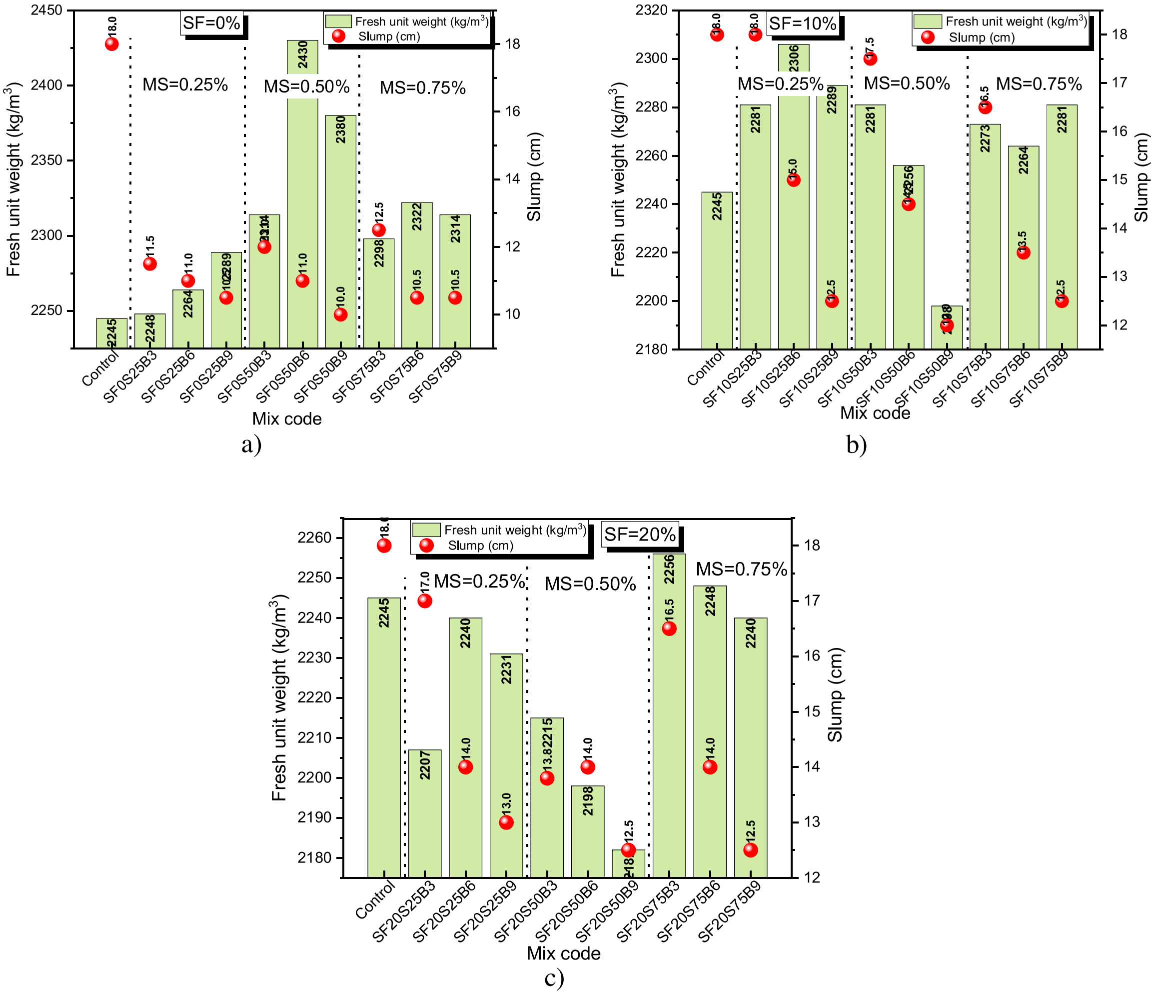


**Fig. 5.** Fresh unit weight vs. slump results of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = .20 %.

and BF exhibited higher compressive strength than control specimens and SF0S75B3 mixture which contains 0.75 % MS and 0.3 % BF achieved the highest compressive strength of 47.1 MPa which gained 18.64 % increase as compared with control specimens. Considering Fig.6a, compressive strength of mortar specimens increased with the addition of MS and decreased slightly with the addition of BF. The decrease in the compressive strength with increasing content of BF was recorded as highest of 8.7 % in the mortar specimens containing 0.75 % MS and 0.9 % BS when compared to mortar specimens at 0.25 % and 0.50 % MS contents. It can be observed from the compressive strength of mortar specimens without SF that increase in the content of MS resulted in the enhancement of compressive strength and increase in the content BF resulted in slight decrease in the compressive strength of mortar specimens. This results are consistent with the results obtained by the authors [35,57,58] that reported that BS reduced the compressive strength after 0.3 % content. Fig. 6b provides the compressive strength of mortar mixtures incorporating 10 % SF content. As shown in Fig.6a, b, all mortar specimens containing MS and BF and 10 %SF revealed higher compressive strength than mortar specimens containing MS and BF and without SF. The compressive strength of mortars increased with the inclusion of MS and achieved the maximum value of 55.3 MPa for the mixture SF10S50B3 which gained 39.29 % increase with comparison to control mixture. It was evident from Fig.6b that at 0.75 %MS content, a slight decrease in the compressive was observed as compared to mortar specimens with 0.25 % and 0.50 % MS content. With increasing rate of BF in each MS content mortar specimens, compressive strength showed a slight decrease and didn't change much at the content of 0.6 % and 0.9 % BF. SF had a better effect in improving compressive strength, while the combined use of SF and MS had best effect in improving compressive strength. The improvement in the compressive strength of mortars can be attributed to highly refined pore structure and accordingly increased the compactness of the modified mortars resulted from adding SF [59]. Fig.6c illustrates the compressive strength of mortar mixtures containing 20 % SF. The compressive strength enhancement of all mortar mixtures was higher than that of the mixtures with 10 % SF and without SF. In other words, all mixtures containing 20 % SF revealed the highest compressive strength for all SF and BF contents. As shown in Fig.6c, the mixtures with 0.5 % MS had slightly lower compressive strength than the mixtures with 0.25 % MS. The mixture with 0.75 % MS and 0.3 % BF (SF20S75B3) achieved the highest compressive strength of 64.4 MPa which was 62.21 % in comparison with control specimens. It can be concluded from the results that

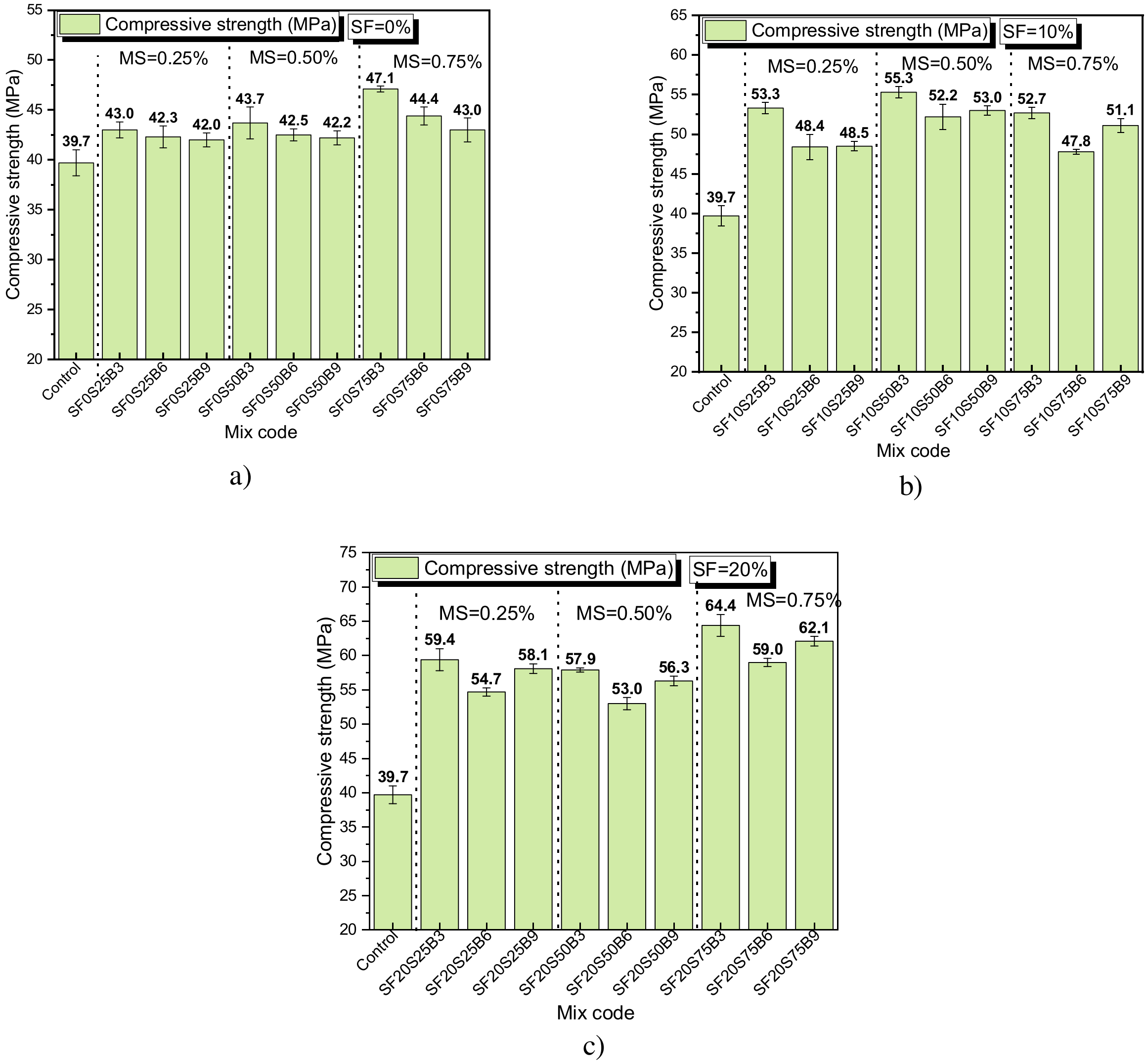


**Fig. 6.** The compressive strength results of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = .20 %.

coupling use of 0.75 % MS and 0.3 % BF leads to the highest compressive strength in the mortar mixtures with 0% and 20 % SF. In the mixtures containing 10 % SF, coupling use of 0.50 % MS and 0.3 % BF leads to the highest compressive strength. Loh et al. [39] found that polyvinyl alcohol and basalt fibers had minimal effect on the compressive strength of cement composites but significant improvements in the splitting tensile and flexural strengths. Hu et al. [40] pointed out that the combined use of polypropylene and basalt fibers at content of 0.1 % achieved the best mechanical performance and is recommended for practical usage. Wang et al. [41] reported that the synergy effect of fiber mixing is the best with 0.15 % basalt fiber and 0.033 % polypropylene fiber content. The compressive strength, flexural strength and splitting tensile strength increased by 14.1 %, 22.8 % and 48.6 %, respectively as compared with those of concretes without fibers. While it contains silica fume, increases the mechanical strength due to its pozzolanic reactions, it has positive effects on the fiber-matrix transition zone structure. It reduced portlandite, thus improving bond quality as well as uniformity and density [38].

### 3.3. Flexural strength

Fig. 7 presents the flexural strength test results of mortar specimens containing 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers. As plotted in Fig.7, the highest flexural strength of 8.90 MPa which was 27.14 % higher than control specimens was obtained for the mixture containing 0.50 % MS and 0.9 % BF and without SF. Fig.7a presents the flexural strength of the mortar mixtures without SF. As seen in Fig.7a, with the inclusion BF, flexural strength increased in each MS content. The highest flexural strengths were obtained for the mixtures containing 0.50 % MS in comparison with control specimens. Two mixtures (SF0S25B3 and SF0S75B3) containing 0.3 % BF in 0.25 % MS and 0.75 % MS contents had lower strength than control specimens with

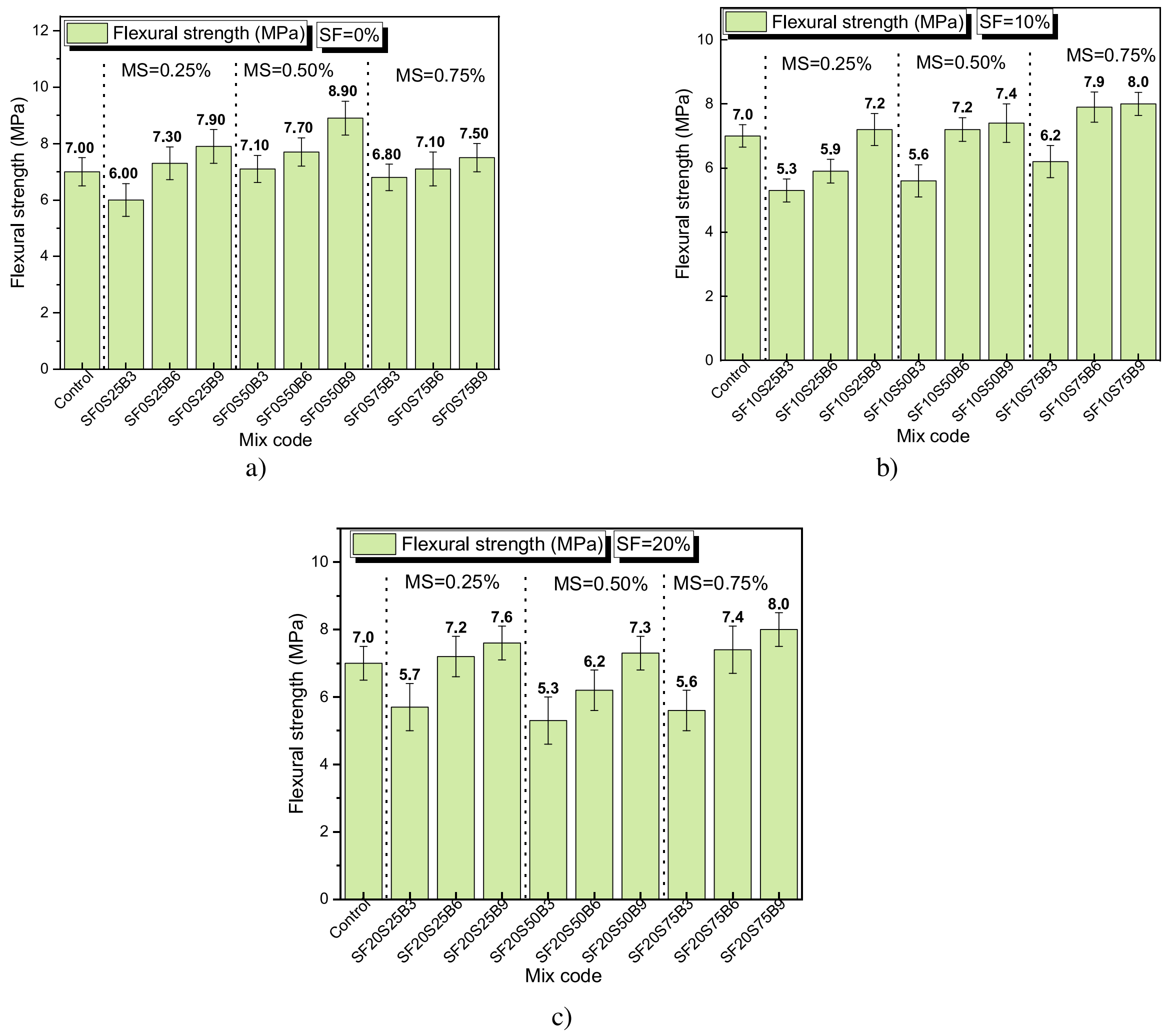


**Fig. 7.** The flexural strength results of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = .20 %.

the reduction rates of 14.28 % and 2.85 % respectively. It can be said that addition of 0.3 % BF reduced the flexural strength at 0.25 % MS and 0.75 % MS contents. Fig.7b illustrates the flexural strength of the mortar mixtures with 10 % SF. Similarly, flexural strength enhanced with the inclusion of BF and MS and reached the highest value at 0.9 % BF content at each MS content. When compared the mixtures without SF, all mixtures showed lower strength except two mixtures containing 0.6 and 0.9 % BF and 0.75 % MS. It can be concluded that addition of SF affected the strength negatively but inclusion of BF and MS affected the flexural strength positively. The highest flexural strength reduction of 24.28 % was obtained for the mixture SF10S25B3 and the highest enhancement of 14.28 % in the flexural strength was obtained for the mixture SF10S75B9. The addition of steel fibers improved the flexural behavior of the concrete, prevented brittle fracture of the concrete and allowed the specimen to carry loads even after the first crack [60]. Fig.7c shows the flexural strength of the mortar mixtures containing 20 % SF. Similarly, flexural strength enhanced with the inclusion of BF and reached the highest value at 0.9 % BF content at each MS content. When compared the mixtures without SF, all mixtures showed lower strength except two mixtures containing 0.6 and 0.9 % BF and 0.75 % MS. The mixtures containing 0.3 % BF had lower strength than control specimens at each MS content and the mixture with 0.6 % BF and 0.50 % MS had also lower strength than control mixtures. It can be pointed out that coupling use of SF and 0.3 % BF had negative impact on the flexural strength. The mixtures with 0.5 % MS performed the worst flexural performance in comparison with the mixtures with 0.25 and 0.75 % MS. The improvement in the flexural strength by the addition of BF was also found by the authors [53,56]. It is also well known that MS addition into the mortar and concrete mixtures enhances the flexural strength. This can be attributed to the fibers' ability to improve interfacial transition zone (ITZ) and bridge crack growth. The fibers will also help relieve tension from the ITZ [61].

### 3.4. Unit weight of hardened mortar

Fig. 8 shows the dry fresh unit weight results of mortar specimens containing 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers. Fresh unit weight of mortars increased with the addition of BF and MS and decreased with the increasing rate of SF due to lower specific gravity of SF than cement. Fig.8a illustrates the unit weight of the mixtures without SF. It is seen that inclusion of BF tended to increase the fresh unit weight of mortars at each MS content. The highest increase by 8.24 % in the fresh unit weight was obtained for the mixture SF0S50B6 containing 0.5 %MS and 0.6 % BF. When the dry unit weight was considered, it seems that addition of MS increased the dry unit weight and inclusion of BF decreased it slightly. All mortar mixtures exhibited lower dry unit weight than control mortars. The lowest dry unit weight which was 4.6 % lower than control specimens was obtained for the mixture SF0S25B9 incorporating 0.25 % MS and 0.9 % BF. The mixture SF0S75B3 had the highest dry unit weight with a decrease of 0.41 % in comparison with control mixture.Fig.8b presents the unit weight of the mixtures 10 % SF. It appears that inclusion of BF and MS increased the fresh unit weight of mortars at each MS content except the mixture containing 0.50 % MS and 0.9 % BF. The highest fresh unit weight increase by 2.71 % was obtained for the mixture SF10S25B6 containing 0.25 %MS and 0.6 % BF. When the dry unit weight of 10 % SF blended mortars was considered, it seems that addition of MS increased the dry unit weight and inclusion of BF decreased it slightly. The increase in the dry unit weight was higher at 0.5 MS content than that of other MS contents and the highest dry unit weight was obtained for the mixture containing 0.5 % MS and 0.3 % BF (SF10S50B3), which had 1.38 % higher than control mixture. The lowest dry unit weight which was 3.28 % lower than control specimens was obtained for the mixture SF10S25B9 incorporating 0.25 % MS and 0.9 % BF as in the mixtures without SF. Fig.8c shows the unit weight of the mixtures 20 % SF. The lowest fresh and dry unit weight values were obtained for the mixtures with 20 % SF in comparison with the mixtures with 10 % SF and without SF. This can be attributed to the lower specific weight of SF than cement. Inclusion of BF and MS increased the fresh unit weight of mortars. The effect of MS content was more obvious on the increase of fresh unit weight. Increasing BF content slightly decreased the unit weight. The highest fresh unit weight increase by 0.48 % was obtained for the mixture SF20S75B3 containing 0.75 %MS and 0.3 % BF. When the dry unit weight of 20 % SF blended mortars was considered, it is clearly seen that addition of MS increased the dry unit weight and

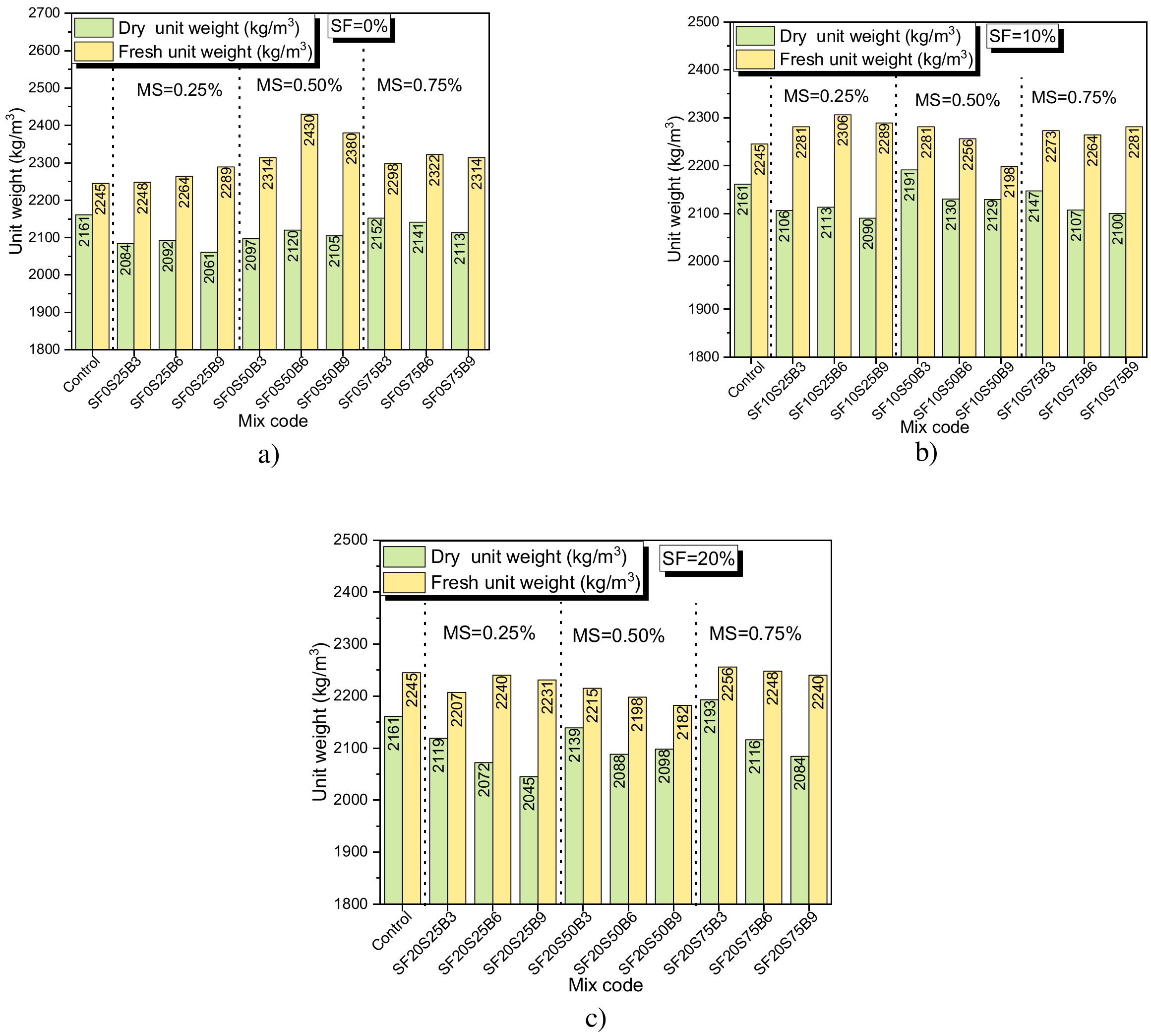


**Fig. 8.** The unit weight results of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = .20 %.

inclusion of BF decreased it slightly. The highest dry unit weight was obtained for the mixture containing 0.75 % MS and 0.3 % BF (SF20S75B3), which had 1.48 % higher than control mixture. The lowest dry unit weight which was 5.36 % lower than control specimens was obtained for the mixture SF20S25B9 incorporating 0.25 % MS and 0.9 % BF as in the mixtures with SF and without SF.

Fig. 9 plots the variations of the compressive strength with respect to the dry unit weight of mortar specimens containing 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers. Fig.9a shows the variations of the compressive strength with respect to dry unit weight of the mixtures without SF. The control mixtures exhibited the highest unit weight but the lowest compressive strength. The mixture SF0S25B9 had the lowest strength with corresponding lowest dry unit weight among the BS and MS blended mixtures. The mixture SF0S75B3 exhibited the highest compressive strength with the highest dry unit weight and the compressive strength decreased with decreasing dry unit weight at 0.75 % MS content. It can be pointed out that although addition of basalt fibers reduces the unit volume weight, it does not cause much reduction in compressive strength. Fig.9b presents variations of the compressive strength with respect to dry unit weight of the mixtures with 10 % SF.

### 3.5. Porosity

Fig. 10 exhibits the porosity results of mortar specimens containing 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers. As shown in Fig.10, control mixtures showed the highest porosity value and as expected, porosity of mortar mixtures decreased with increasing SF content due to filler effect of SF. It has been proven in many studies that adding silica fume to concrete increases the adhesion strength between cement paste and aggregate by increasing the strength of the concrete at the same water-cement ratio, reducing the permeability and refining the pore structure, making the interface area denser [43,62–64]. The effect of basalt fibers and micro steel fibers on the porosity of the mortar mixtures changes depending on the content of SF, BF and MS. Fig.10a shows the porosity of the mortar mixtures without SF. As seen in Fig.10a, control mixture had the highest porosity and the porosity values decreased with the addition of MS and BF. The lowest porosity with a reduction of 16.75 % in comparison with control specimens was obtained for the mixture containing 0.75 % MS and 0.9 % BF and at MS content of 0.25 and 0.50 %, a slight increase in the porosity was obtained at 0.9 % BF content compared to the mixtures at 0.6 % BF content as given in Fig.10a. Fig.10b illustrates the

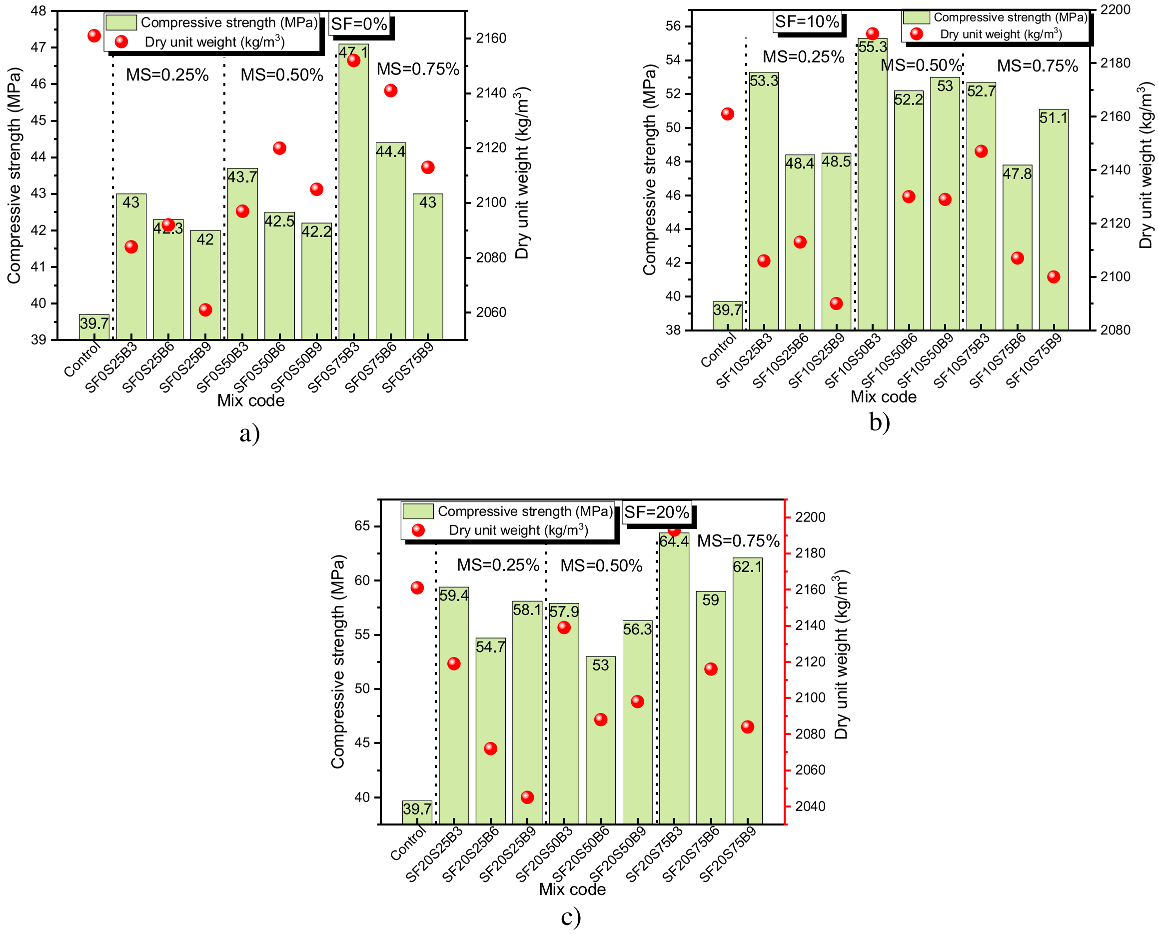


**Fig. 9.** Compressive strength vs. dry unit weight of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = .20 %.

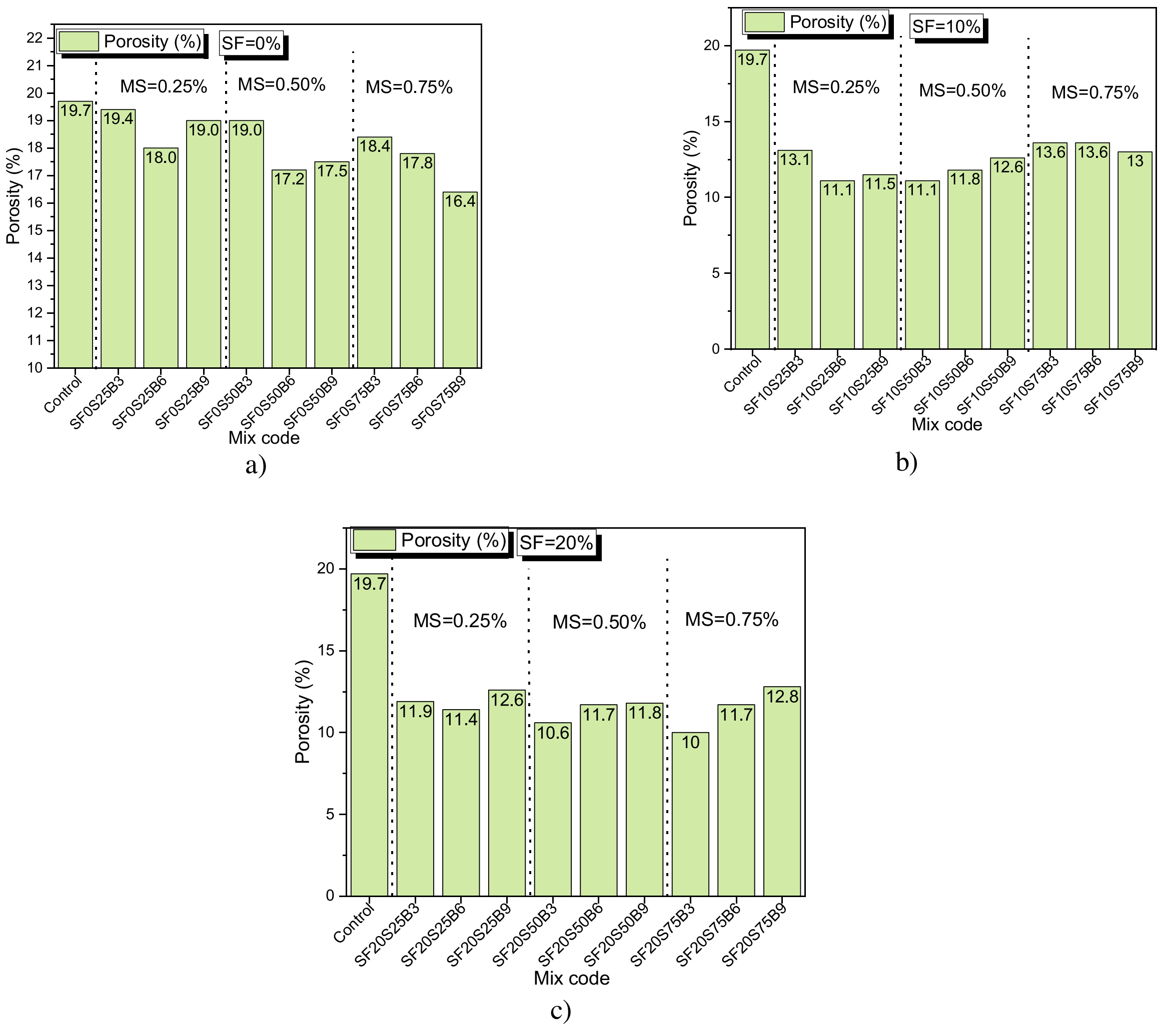


**Fig. 10.** the porosity results of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = .20 %.

porosity of the mortar mixtures containing 10 % SF. More reduction in the porosity values was obtained with the addition of SF in comparison with the mixtures without SF. The highest porosity reduction of 43.65 % was obtained for the mixture with 0.25 % MS and 0.6 % BF and the mixture with 0.50 %MS and 0.3 %BF. Reduction of porosity increased slightly with the inclusion of MS. The impact of BF on the porosity seems depending on MS content. For example, at 0.75 %MS content, reduction increased with the addition of BF but at 0.50 %MS content, reduction decreased with the addition of BF, at 0.25 %MS content, porosity reduction increased at 0.6 %BF but decreased slightly at 0.9 %BF content. Fig.10c presents the porosity of the mortar mixtures containing 20 % SF. The highest porosity reduction was observed at this SF content as compared to the mixtures with 10 % SF and without SF. The maximum porosity reduction of 49.23 % was obtained for the mixture with 0.75 %MS and 0.3 % BF. Reduction of porosity also increased slightly with the inclusion of MS but BF addition generally increased the porosity reduction and the highest porosity value of 12.8 % was obtained at combined use of 0.50 %MS and 0.9 %BF content. It can be pointed out that addition MS generally decreased the porosity but BF inclusion affected the porosity positively and negatively depending on SF content.

Fig. 11 illustrates the variations of the compressive strength with respect to porosity results of mortar specimens containing 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers. The variations of the compressive strength with respect to the porosity of the mixtures without SF was given in Fig.11a. It can be seen in Fig.11a, the control specimen had the highest porosity corresponding to the lowest compressive strength and the mixtures with MS and BF generally showed higher compressive strength with relatively low porosity. Fig.11a gives the variations of the compressive strength with respect to the porosity of the mixtures with %10SF. The higher the compressive strength, the lower the porosity is clearer at this SF content, the mixture with 0.50 %MS and 0.3 % BF exhibited the highest compressive strength with the lowest porosity. The same behavior was also observed for the mixtures containing 20 % SF. The mixture with 0.75 %MS and 0.3 %BF revealed the highest compressive strength with the lowest porosity as shown in Fig.11c. Fig.11d presents the relation between the compressive strength and porosity in terms of MS content. Good relations with the relation coefficients of 0.87, 0.92 and 0.72 were achieved.

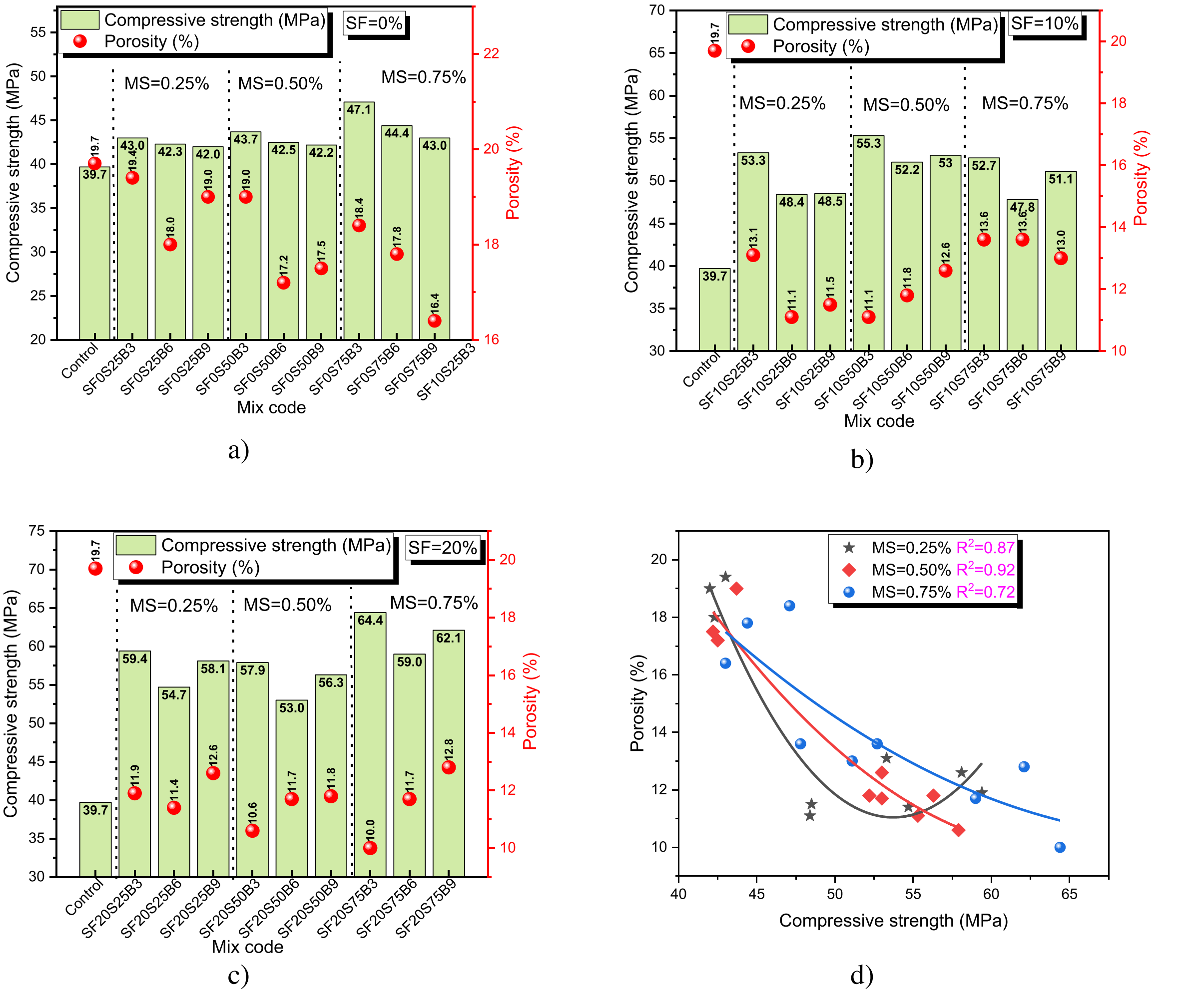


**Fig. 11.** Compressive strength vs. porosity of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = 20 % d) compressive strength vs. porosity.

### 3.6. *Water absorption*

The resistance of concrete to aggressive ions is related to the durability of concrete/mortar. The water absorption test is one of the tests investigating the durability and is a method that indirectly evaluates the porosity of concrete/mortar [65]. Fig. 12 presents the relation between the porosity and water absorption of mortar specimens containing 0%, 10 %, 20 % SF and different percentages of basalt fibers and micro steel fibers. It is clearly seen from Fig.12 that porosity and water absorption decreased with the addition of SF. The impact of MS and BF on the water absorption values depend on SF content. The mixtures without SF as shown in Fig.12a, had reduced water absorption with the addition of MS and BF as compared to the control specimen which showed the highest water absorption. The mixture containing 0.75 % MS and 0.9 %BF exhibited the lowest water absorption of 7.8 % by a reduction of 14.28 % at 0%SF content. In general, the fibers in concrete/mortar block the capillary pores, reducing water absorption [66]. Niu et al. [67] reported that adding the appropriate amount of BF to the concrete/mortar can lead to the significant water absorption reduction of concrete/mortar; however, more amounts of BF will increase water absorption. The mixtures with 10 %SF as shown in Fig.12b, revealed lower water absorption values than the mixtures without SF. Maximum water absorption reduction of 45.05 % was achieved for the mixture containing 0.50 %MS and 0.3 %BF which also had the highest compressive strength at 10 %SF content as shown in Fig.12b and Fig.6b. BF has affected the water absorption positively and negatively depending on MS content. For example, at 0.50 % MS content, water absorption increased with the inclusion of BF and the mixture with 0.75 % MS and 0.6 % BF showed the highest water absorption among the MS and BF blended mixtures at this SF content. The mixtures with 20 %SF as shown in Fig.12c, revealed lowest water absorption values as compared to the mixtures with 10 %SF and without SF. Maximum water absorption reduction of 50.55 % was achieved for the mixture containing 0.75 %MS and 0.3 %BF which also had the highest compressive strength at 20 %SF content as shown in Fig.12c and Fig.6c. Increasing content of BF increased the water absorption at nearly all MS content. In addition to increasing the fiber amount increases the risk of balling and clumping of the blend, this situation may have arisen due to the mixing method and distribution of the fibers in the concrete volume. Since the basalt fibers are hydrophobic after the concrete mixture has

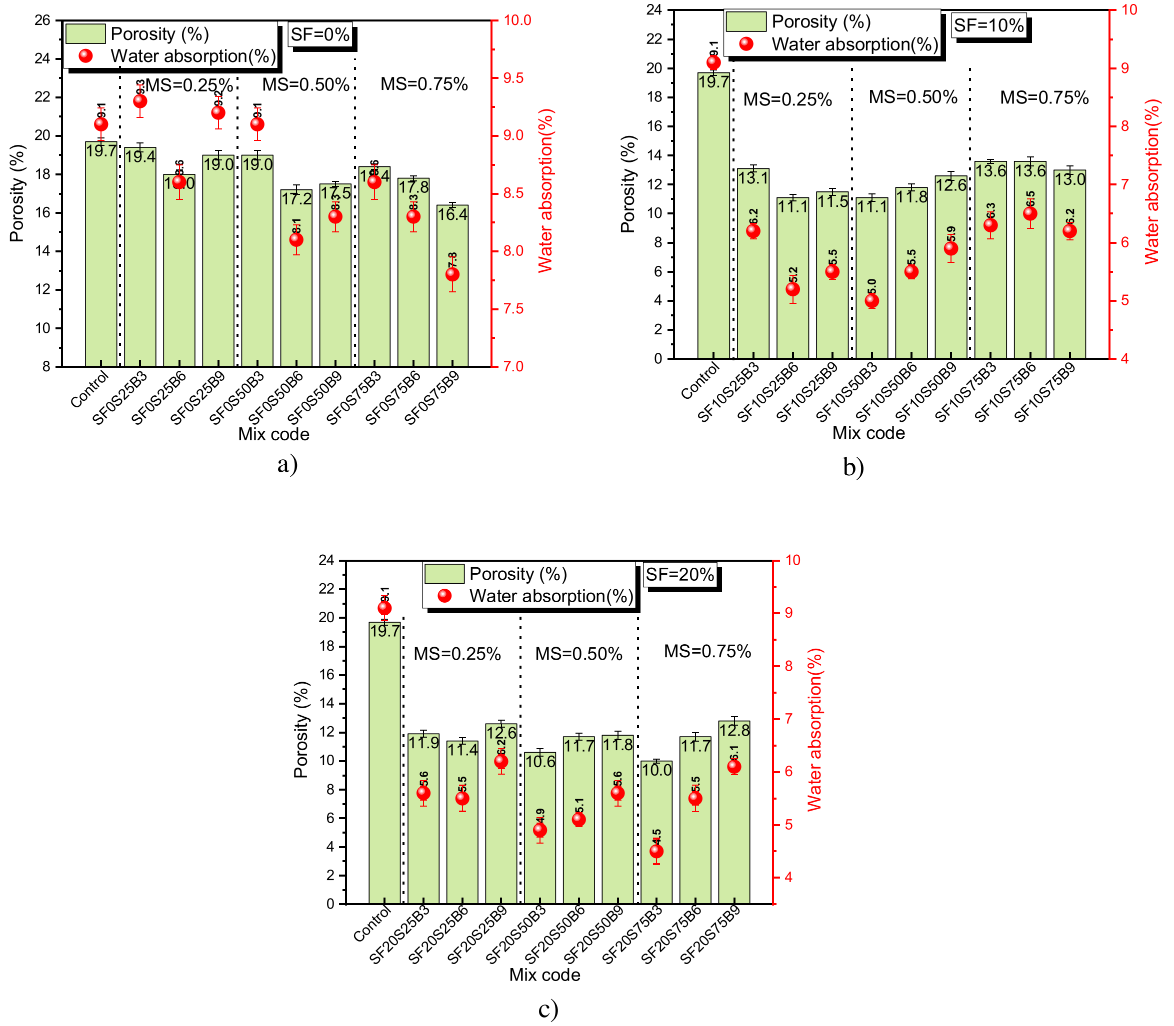


**Fig. 12.** The porosity vs. water absorption results of mortar specimens at a) SF = 0% b) SF = 10 % c) SF = .20 %.

been poured into the molds, some of the water that accumulates in the lower part of the fibers due to the efficiency is absorbed by the cemented matrix, causing micro pores, resulting in a decrease in water absorption and compressive strength [53]. On the other hand, increasing MS content decreased the water absorption.

## 4. Conclusion

Hybrid effects of micro-steel and basalt fibers on mechanical properties and durability of mortars with silica fume was investigated evaluated in this study and following are the conclusions drawn from this experimental work:

- SF had a negative impact on the slump values but this negative effect was eliminated by addition of SP and therefore slump values slightly increased as compared to mortars without SF and decreased with the inclusion of MS and BF.
- Control mixtures exhibited the lowest fresh unit weight with the highest slump value, with the addition of MS and BF, all mixtures showed higher fresh unit weight with lower slump values than control mixtures and the mixture with 0.5 MS, 0.6 BF and without SF (SF0S5B6) exhibited the highest fresh unit weight of 8.20 % higher than control mixture.
- Combined use of 0.75 % MS and 3% BF with 20 % SF achieved the highest compressive strength of 64.4 MPa which was 62.21 % higher than control mixtures.
- In each MS content, the mixtures containing 0.3 % BF exhibited the highest compressive strength and compressive strength decreased slightly with increasing BF content.
- In SF blended mortar mixtures, the compressive strength decreased at 0.6 % BF content as compared to the mixtures with 0.3 % BF but it increased again at 0.9 % BF content as compared to the mixtures with 0.6 % BF content.

- Combined use of 0.50 % MS and 0.9 % BF and without SF achieved the highest flexural strength of 8.90 MPa which was 27.14 % higher than control specimens.
- The highest flexural strength reduction of 24.28 % was obtained for the mixture SF10S25B3 and the highest enhancement of 14.28 % in the flexural strength was obtained for the mixture SF10S75B9.
- Fresh unit weight of mortars increased with the addition of BF and MS and decreased with the increasing rate of SF due to lower specific gravity of SF than cement.
- The mixture (0.75 % MS, 0.3 % BF and 20 %SF) with the highest compressive strength also exhibited the highest dry unit weight which was 1.48 % higher than control mixture.
- Control mixtures showed the highest porosity value and as expected, porosity of mortar mixtures decreased with increasing SF content due to filler effect of SF.
- The mixture containing 0.75 % MS, 0.9 % BF and 20 % SF exhibited the lowest water absorption of 7.8 % by a reduction of 14.28 %.

The findings of this article expand the knowledge of fiber reinforced mortars/concrete and provide a reference for the application of micro steel and basalt fibers reinforced concrete in civil engineering. However, more research is needed to investigate the effect of hybridization of micro steel and basalt fibers on other properties of concrete, particularly durability and dynamic performances.

## Declaration of Competing Interest

The authors report no declarations of interest.

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