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Effects of sulfate on cement mortar with hybrid pozzolan substitution

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ABSTRACT

Sulfate is one of the most important chemical risks which affect the durability of concrete and reinforced concrete structures. Therefore, this study investigates the effects of sulfate on blended cement mortars. In this paper, cement mortar specimens were prepared with the substitution of CEM I 42.5 R cement with Fly ash + Bottom ash + Blast-furnace Slag at the ratios of 5%, 10%, 15%, and 20% along with a control specimen without additives. These prepared cement mortar specimens were then cured for 2, 7, 28, 90, 180, and 360 days either in potable water or 10% sodium sulfate (Na_2SO_4) solution. Cement paste specimens were subjected to the initial setting, final setting, and volumetric expansion tests in accordance with the TS EN 196-3 standard. Cured for 2, 7, 28, 90, 180, and 360 days, cement mortars were subjected to compressive strength tests as per the TS EN 196-1 standard while length change tests were conducted as per the ASTM C 1012 standard.

It was found that the compressive strength of cement mortars blended with 5% Fly ash + Bottom ash + Blast-furnace Slag cured in sodium sulfate for 360 days was approximately 2% higher than that of the cement mortar without additives. The length change of specimens obtained from cured in sodium sulfate solution shows best results in higher additive ratio. These all length changes ratio are greater than 0.087% ratio which is maximum length change expansion in potable water. This study suggests that 15% and 20% additive ratios are effective in reducing unfavorable effects of sulfate.

1. Introduction

The use of fine-grain mineral additives may have an impact on a number of properties of fresh and cured concrete depending on the amount and properties of the materials used. One or more goals can be reached with the use of mineral additives in fresh concrete such as improving the workability, reducing bleeding or segregation, decreasing hydration temperature, reducing alkali-silica reaction, improving water tightness, improving strength, improving resistance to sulfate, producing cost-effective concrete, etc. [1,2]. Usage of blast furnace slag and fly ash enhances the mechanical qualities of the concrete [3–5]. It has been observed that compressive strength decreases when the quantity of fly ash is increased and the quantity of cement is decreased [6,7].

Recently, durability of concrete and its resistance to aggressive environments have been receiving interest. Sulfate is the origin of various significant problems in concrete operations. Magnesium sulfate and sodium sulfate are among the most devastating mineral salts (alkalis) which are dissolved and available in the ground and underground waters commonly in contact with concrete. Bonding with the calcium aluminates hydrated in the cement, sulfates form expanding crystals. Increasing in time, such an expansion is reported by many authors to lead to cracks in concrete and crumbling [8–13].

Several studies were conducted with the purpose to explore the effects of using mineral additives. Sulfate resistance of pozzolans was reported it was found that concrete produced with pozzolans performs well [14–18]. Monteiro et al., in their study on the effects of sulfate on concrete, suggested that there are critical thresholds for concrete's resistance to sulfate attack and reported that concrete did not suffer any damage over the 40 years of sulfate impact when the amount of C_3A was lower than 8% and the water/cement ratio was lower than 0.45. Authors also found that the use of 25% and 45% fly ash as a substitute for cement decreased the level of expansion [19]. In their study on the properties of fly ash, Garg et al. suggested that fly ashes have different impacts depending on the composition of the coal used, the burning type, burning temperature, ash collection method used, and oxidation conditions [20]. In their research on the effects of the fineness of the fly ash used, Monzo et al. noted that the fineness of fly ash has a significant effect on pozzolanic reactions, that fly ash can be sieved or

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ground in order to increase its fineness, and that large and small particles can be separated using air. Authors also suggested that pozzolanic reaction starts at the surface of the fly ash grain and that increased fineness of fly ash increases the pozzolanic reaction. They have also noted that fineness of the fly ash is important in improving the surface properties of the interface between aggregate and cement paste [21]. Having studied the long-term effects of fly ash, Chalee et al. explored the effects of the use of fly ash on concrete under high humidity, temperature and sea conditions at the end of 7 years. It was observed that increased substitution ratio with fly ash reduced chloride permeability and pitting corrosion. No rust formation was observed at the end of 7 years on the fittings embedded 5 cm into the concrete of 25–50% fly ash substitution and 0.6 water/binder ratio. Authors reported better results obtained from 0.45 water/binder ratio [22]. Zhuqing et al. reported that the use of fly ash in concrete affects the pore structure of concrete which is suggested as one of the most important factors in the durability of concrete [23]. Kurama et al., in their investigation aimed at defining and assessing the usability of bottom ash in concrete, substituted Portland cement up to 25% with bottom ash and bottom ash was subjected to grinding, separation and electrostatic separation in order to reduce the amount of unburned carbon. The results of the study showed that substitution of Portland cement up to 10% with bottom ash improves the mechanical properties of concrete and, therefore, this material is suitable to be used in concrete [24]. Jaturapitakkul et al., in their research on the use of bottom ash, have reduced the size and porosity of bottom ash after grinding and used the material obtained for their tests. The experimental study showed that ground bottom ash can be used as pozzolanic material [25]. Lopez et al. investigated the effects of blast-furnace slag in cement mortars and found that slag with finer grains acts favorably in the face of sulfate effect which in turn offered the minimum expansion ratio [26]. Having explored the effects of blast-furnace slag on the durability of concrete, Lukowski et al. reported better durability performance obtained from cement mortars modified with blast-furnace slag when compared to the control specimens [27]. Sadok et al. investigated the effects of blast-furnace slag use and reported that use of slag reduces porosity and water absorption. Moreover, authors reported lower chloride diffusion for 50% blast-furnace slag substitution [28].

The use of mineral additives as concrete components finds itself an important role in today's engineering activities with respect to their impact on the environment and cost-effective concrete manufacturing. The use of such additives reduces carbon dioxide (CO_2) emissions and energy consumption which in turn reduces the adverse impact of cement production on nature while decreasing concrete costs. Nevertheless, studies must focus on improving the durability of concrete and explore waste materials which can be used as mineral additives. The purpose of this study is to study the effect of sulfate on cement mortar with hybrid pozzolan substitution.

2. Materials and methods

2.1. Materials

2.1.1. Cement

Portland cement type CEM I 42.5 R which complies with TS 197-1 was used in this study. Physical and chemical properties of the cement used are shown in Table 2.1 [29].

2.1.2. CEN reference sand

Sand used in this study was CEN reference sand mentioned in the TS 196-1 standard [30].

Table 2.1
Chemical and physical properties of CEM I 42.5 R cement.

Chemical composition (%)	CEM I 42.5 R
CaO	67.46
SiO_2	13.48
Al_2O_3	3.69
Fe_2O_3	7.78
MgO	1.29
Na_2O	0.36
K_2O	0.98
SO_3	4.82
Physical properties	
Specific weight (g/cm3)	3.18
Specific surface area (Blaine) (cm^2/g)	3352
Loss on Ignition (%)	1.98

2.1.3. Bottom ash, blast-furnace slag and fly ash

Bottom ash used in this study was calcined at 900 °C in order to minimize the carbon content of the ash. The fineness of the bottom ash used was ensured using a ring grinder. Table 2.2 shows the chemical analysis results and Blaine fineness of the bottom ash and blast-furnace slag.

2.1.4. Water

Two types of curing liquids were used in this study. First was potable water (PW) and the second was 100 g/l Na_2SO_4 solution (SS) prepared as per the ASTM C 1012 standard [31].

2.2. Method

2.2.1. Mixture proportions

The proportions of all the mixture components are given in shown in Table 2.3. Three materials applied in equal proportions.

Mortar specimens were prepared as per the ASTM C 1012 standard for length change measurements and as per the TS EN 196-1 standard for compression tests [30,31].

2.2.2. Setting time and volumetric expansion

FA + BA + BFS was substituted for cement at the ratios of 0%, 5%, 10%, 15%, 20%. Setting time and volumetric expansion calculations of cement pastes with different additive ratios were performed in accordance with TS-EN 196-3 Standard [32], while flexural and compressive strength tests were performed in accordance with TS-EN 196-1 Standard for 7th, 28th, 90th, 180th, and 360th day [30].

2.2.3. Compressive strength test

Compressive strength test was performed as per the provisions of TS EN 196-1 standard [30]. Prepared in the size of 40 × 40 × 160 mm six prismatic specimens were then exposed to potable

Table 2.2
Chemical composition of bottom ash, blast-furnace slag and fly ash.

Chemical Composition (%)	Bottom Ash	Blast-Furnace Slag	Fly Ash
SiO_2	37.45	37.17	45.37
Al_2O_3	9.03	9.67	11.16
Fe_2O_3	8.02	0.99	7.40
CaO	18.08	39.63	14.15
MgO	5.79	5.40	4.69
Na_2O	1.67	0.28	2.07
P_2O_5	11.75	3.64	8.28
K_2O	1.88	1.25	4.19
SO_3	6.29	1.89	2.64
Specific surface area (Blaine) (cm^2/g)	4350	3750	2200
Loss on ignition	2.82	1.07	1.48

Table 2.3
Mix proportions of cement mortar.

Specimen Designation	Cement (g)	Water (g)	Fly Ash (g)	Bottom Ash (g)	Blast Furnace Slag (g)	Aggregate (g)
FA + BA + BFS 0	450.0	225.0	0.0	0.0	0.0	1350 ± 5
FA + BA + BFS 5	427.5	225.0	7.5	7.5	7.5	1350 ± 5
FA + BA + BFS 10	405.0	225.0	15.0	15.0	15.0	1350 ± 5
FA + BA + BFS 15	382.5	225.0	22.5	22.5	22.5	1350 ± 5
FA + BA + BFS 20	360.0	225.0	30.0	30.0	30.0	1350 ± 5

water (PW) and 10% Na_2SO_4 solution (SS) for 7, 28, 90, 180, and 360 days and their compressive strengths were measured. The compressive strength test was done after divide the 40 × 40 × 160 mm specimen in two parts. The average of six prismatic specimen's compressive strength were given as a result for each age.

2.2.4. Length change expansion test

Prepared in the size of 25 × 25 × 285 mm three prismatic specimens as per the ASTM C 1012 standard, specimens were then exposed to potable water and 10% Na_2SO_4 solution for 7, 28, 90, 180, and 360 days and their expansions were measured [31]. The average of three prismatic specimen's length change were given as a result for each age.

3. Experimental results and discussion

The findings obtained from the tests were explored in order to identify a cause and effect relationship.

3.1. Setting time and volumetric expansion

Table 3.1 shows the initial setting time, final setting time, hardening time and volumetric expansion values for the cement paste produced in accordance with the TS 196-3 standard [32].

In the FA + BA + BFS 0 series, setting starts after 190 min and the final setting is observed at the 255th minute. The time necessary for hardening is 65 min. In the FA + BA + BFS 5 series, setting starts after 200 min and the final setting is observed at the 270th minute. The time necessary for hardening is 70 min. In the FA + BA + BFS 20 substitution rate, on the other hand, setting starts after 225 min and the final setting is observed at the 305th minute. The time necessary for hardening is 80 min. As the rate of FA + BA + BFS used as a substitute for cement increases, the initial setting and final setting times of the cement paste also increases. When it comes to volumetric expansion, it was found at 1.3 mm for FA + BA + BFS 0 series, while it was 1 mm for FA + BA + BFS 20 substitution rate. Substitution of cement with FA + BA + BFS did not have a significant effect on the volumetric expansion (Table 3.1).

It was found that the increased use of compound pozzolan substitute also increases the initial setting time, final setting time and hardening time.

3.2. Compressive strength

3.2.1. Compressive strength of the specimens exposed to potable water curing

According to Table 3.2 and Fig. 3.1, an investigation of the compressive strength of cement mortars cured in potable water (PW) for 7 days showed that cement mortars without additives gave the highest compressive strength value with 34.65 MPa. The compressive strength of the specimens without additives was 44.60

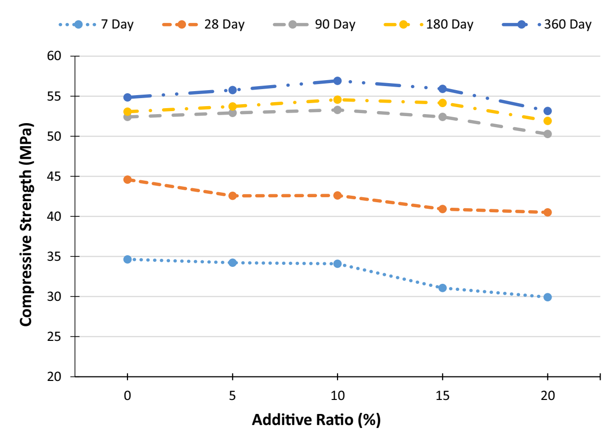

Fig. 3.1. Compressive strength of FA + BA + BFS mortars (PW).

Table 3.1
Initial setting time, final setting time, hardening time and volumetric expansion values.

Specimen	Initial Setting (min)	Final Setting (min)	Hardening Time (min)	Volumetric Expansion (mm)
FA + BA + BFS 0	190	255	65	1.3
FA + BA + BFS 5	200	270	70	1
FA + BA + BFS 10	210	285	75	1
FA + BA + BFS 15	220	295	75	1
FA + BA + BFS 20	225	305	80	1

Table 3.2
Compressive strength of FA + BA + BFS mortars and their rate of change (PW).

Age (days)	FA + BA + BFS 0 Compressive Strength (MPa)	FA + BA + BFS 5 Compressive Strength (MPa)	FA + BA + BFS 10 Compressive Strength (MPa)	FA + BA + BFS 15 Compressive Strength (MPa)	FA + BA + BFS 20 Compressive Strength (MPa)
7	34.65	34.23	34.09	31.07	29.93
28	44.60	42.58	42.61	40.92	40.51
90	52.43	52.92	53.29	52.41	50.28
180	53.07	53.72	54.57	54.17	51.92
360	54.85	55.77	56.93	55.91	53.17

MPa at the 28th day, while the highest compressive strength was found to be 42.61 MPa for the FA + BA + BFS 10 substituted cement mortar. At the day 90, however, the highest compressive strength was observed from the FA + BA + BFS 10 substituted cement mortar with 53.29 MPa. The compressive strength of the specimens without additives was 53.07 MPa at the 180th day, while the highest compressive strength was found to be 54.57 MPa for the FA + BA + BFS 10 substituted cement mortar. At the day 360, the highest compressive strength was observed from the FA + BA + BFS 10 substituted cement mortar with 56.93 MPa. Lower compressive strength for specimens with additives at 7 and 28 days is due to pozzolanic reactions are slow than clinker reactions [33–35].

As shown in Fig. 3.1, there are slight decreases in the compressive strength due to the decrease in the amount of cement used as the FA + BA + BFS substitution rate increases. For the substitution ratio of 10%, the measurements at the 28th day showed that 10% compound pozzolan substitution is viable when compared to the cement without additives. Moreover, Fig. 3.3 shows that the compressive strength of the specimens with 5% compound pozzolan substitution is comparable with those of the cement without additives. In this context, an investigation of the results obtained for 7th and 28th days revealed that FA + BA + BFS substitution decreases the compressive strength depending on the substitution ratio [36–38]. Measurements at the 90th day showed that compressive strength increases up to 10% substitution ratio and decreases for higher ratios. Measurements at the 180th and 360th days showed that compressive strength increases up to 15% substitution ratio and decreases for 20% substitution ratio.

3.2.2. Compressive strength of the specimens exposed to 10% sodium sulfate curing

According to Table 3.3 and Fig. 3.2, an investigation of the compressive strength of cement mortars cured in sodium sulfate (SS) for 7 days showed that cement mortars without additives gave the highest compressive strength value with 34.47 MPa. The compressive strength of the specimen without additives was 41.86 MPa at the 28th day, while the highest compressive strength was found to be 42.53 MPa for the FA + BA + BFS 10 substituted cement mortar. At the day 90, however, the highest compressive strength was observed from the FA + BA + BFS 10 substituted cement mortar with 51.31 MPa while it was 50.40 MPa for the specimen without additives. The compressive strength of the specimen without additives was 51.61 MPa at the 180th day, while the highest compressive strength was found to be 51.96 MPa for the FA + BA + BFS 5 substituted cement mortar. The compressive strength of the specimen without additives was 52.45 MPa at the 360th day, while the highest compressive strength was found to be 53.27 MPa for the FA + BA + BFS 10 substituted cement mortar. The results suggest that FA + BA + BFS 10 substitution offers beneficial results.

A closer look into Fig. 3.2 shows that the compressive strengths of 5% and 10% substitution ratio were higher than the one of the specimens without additives, therefore, compound pozzolan substitution increases the resistance in aggressive environment. Similar to the specimens cured in potable water, 15% and 20% compound pozzolan substitution have led to a decrease in the compressive strength due to the decrease in the amount of cement used. The specimens cured for 360 days, on the other hand, showed that resistance to aggressive environment increases in the long term for 5% and 10% compound pozzolan substitution ratio when compared to the specimen without additives, while it is very close to the specimen without additives for 15% and 20% compound pozzolan substitution ratio. The results show that compound pozzolan substitution increases the average resistance to aggressive environment up to 10% substitution ratio. In this context, an investigation of the results obtained for 7th day revealed that FA + BA + BFS substitution decreases the compressive strength depending on the substitution ratio. Measurements at the 28th, 90th, 180th and 360th days showed that compressive strength increases up to 10% substitution ratio and then decreases for higher ratios.

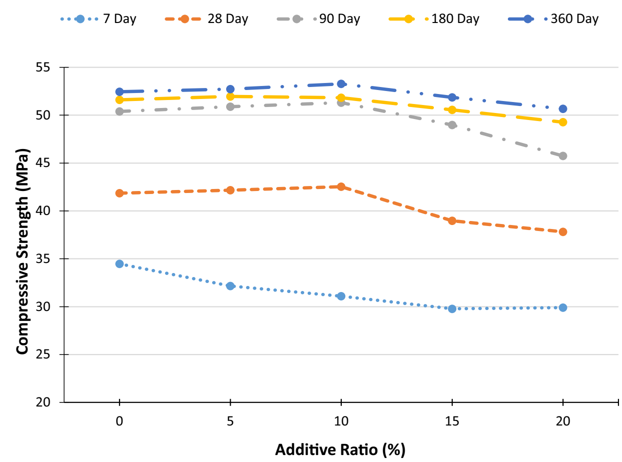

Fig. 3.2. Compressive strength of FA + BA + BFS mortars (SS).

In conclusion, it was found that cement mortars with FA + BA + BFS substitution up to 10% yield better compressive strength results in aggressive environment when compared to cement without additives.

3.2.3. Compressive strength comparisons of the specimens cured in potable water and sodium sulfate solution

Fig. 3.3 shows the changes in compressive strength for specimens cured in potable water and sodium sulfate solution. The values available in the figure were calculated taking the compressive strength of FA + BA + BFS 0 in potable water cure at the 7th day as the reference point, 100%.

A closer look into the compressive strength at the 7th day shows that for the specimens without additives cured in potable water it was approx. 14% higher than that of specimens cured in sodium sulfate solution. The compressive strength measurements at the 28th day show that for the specimens without additives cured in potable water it was approx. 20% higher than that of specimens cured in sodium sulfate solution. The compressive strength measurements at the 90th day show that for the specimens without additives

Table 3.3
Compressive strength of FA + BA + BFS mortars and their rate of change (SS).

Age (days)	FA + BA + BFS 0 Compressive Strength (MPa)	FA + BA + BFS 5 Compressive Strength (MPa)	FA + BA + BFS 10 Compressive Strength (MPa)	FA + BA + BFS 15 Compressive Strength (MPa)	FA + BA + BFS 20 Compressive Strength (MPa)
7	34.47	32.15	31.09	29.78	29.9
28	41.86	42.17	42.53	38.97	37.82
90	50.4	50.89	51.31	48.97	45.74
180	51.61	51.96	51.82	50.55	49.27
360	52.45	52.72	53.27	51.87	50.66

cured for 90 days in potable water it was approx. 3% higher than that of the specimens with 10% substitution and approx. 19% higher than that of the specimen with 20% substitution cured in sodium sulfate solution. The compressive strength measurements at the 180th day show that for the specimens without additives cured in potable water it was approx. 3% higher than that of the specimens with 10% substitution and approx. 9% higher than that of the specimen with 20% substitution cured in sodium sulfate solution. The compressive strength measurements at the 360th day show that for the specimens without additives cured in potable water it was approx. 5% higher than that of the specimens with 10% substitution and approx. 12% higher than that of the specimen with 20% substitution cured in sodium sulfate solution.

In conclusion, it was observed that the compressive strength of cement mortars with FA + BA + BFS substitution increases up to 10% substitution ratio in aggressive environment, however, it was found that all the measurements taken from specimens with any substitution ratio cured in aggressive environment were lower than that of the ones obtained from potable water cure.

3.3. Length change

Fig. 3.4 shows length change of FA + BA + BFS mortars curing in potable water (PW) and 10% Na_2SO_4 solution (SS).

Fig. 3.4 shows that the minimum expansion was measured for the specimen without additives cured for 28 days in potable water, while the maximum length change was measured for the specimen without additives cured for 28 days in sodium sulfate solution. The minimum expansion was measured for the specimen without additives cured for 90 days in potable water, while the maximum length change was measured for the specimen with FA + BA + BFS 20 substitution cured for 28 days in sodium sulfate solution. The minimum expansion was measured for the specimen without additives cured for 180 days in potable water, while the maximum length change was measured from the specimen with FA + BA + B FS 10 substitution cured for 180 days in sodium sulfate solution. The maximum length change was measured for the specimen without additives cured for 360 days in sodium sulfate solution, while the minimum length change was measured for the specimen with FA + BA + BFS 10 substitution cured for 360 days in sodium sulfate solution. The length change was increased from 10% substitution ratio to 15–20% substitution ratio. The minimum length change was measured for the specimen without additives cured for 360 days in potable water, while the maximum length change was measured for the specimen with FA + BA + BFS 20 substitution cured for 360 days in potable water. At the end of 360 days, a comparison of the specimens with the highest expansion showed that the length change of the specimen cured in sodium sulfate solution was approximately 7 times more than the one cured in potable water. The length change of specimens obtained from cured in sodium sulfate solution shows best results in higher additive ratio. These all length changes ratio are greater than 0.087% ratio which is maximum length change expansion in potable water.

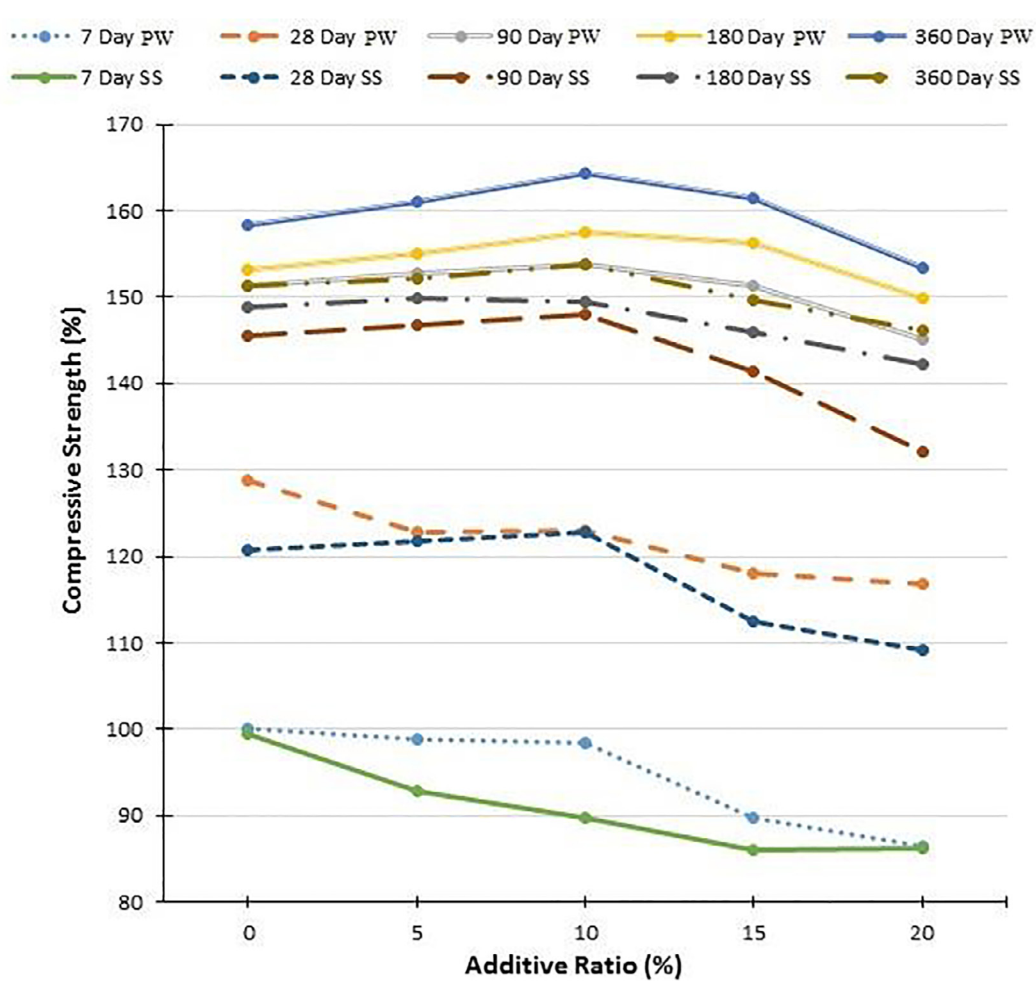

Fig. 3.3. Compressive strength comparisons of the specimens cured in potable water and sodium sulfate solution.

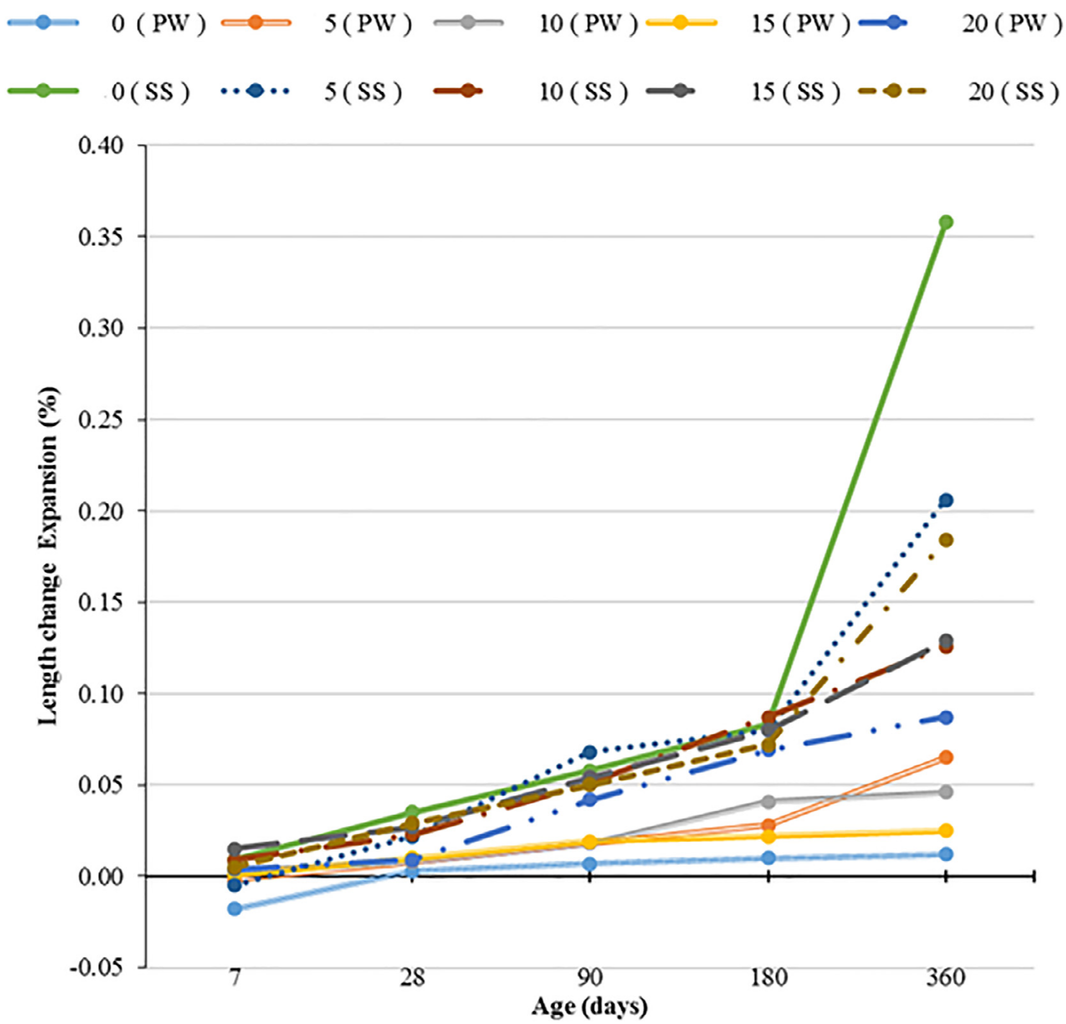

Fig. 3.4. Length change of FA + BA + BFS mortars (PW/SS).

In conclusion, a closer look into the length change of the specimens cured both in potable water and 10% sodium sulfate solution showed a general increase, while the expansion in sodium sulfate solution was higher.

3.4. Microstructure

Figs. 3.5–3.8 show the microstructural formation of specimens assessed using SEM. The images used represent (a) ×35 magnification, (b) ×500 magnification, (c) ×1000 magnification, (d) ×2000 magnification, (e) ×5000 magnification, and (f) ×10000 magnification.

A closer look into (a), (b) and (c) SEM images of the specimen at the 180th day available in Fig. 3.5 showed no adverse or beneficial formations as the magnification rate was insufficient. (d) and (e) images, on the other hand, offer clear images of Calcium-Silicate-Hydrate (C-S-H) gel. Image (f) reveals the decreased number of pores in the cement mortar due to C-S-H gels. Such a decrease in the porosity leads to an increase in compressive strength. As the specimens, available in Fig. 3.5 were not exposed to aggressive environment, there were no adverse formations in the microstructure.

A closer look into (a), (b) and (c) SEM images of the specimen at the 180th day available in Fig. 3.6 showed no adverse or beneficial formations as the magnification rate was insufficient. (d) and (e) images, on the other hand, offer clear images of Calcium-Silicate-Hydrate (C-S-H) gel. Image (f) reveals the decreased number of pores in the cement mortar due to C-S-H gels. As the specimens, available in Fig. 3.6 were not exposed to aggressive environment, there were no adverse formations in the microstructure. In addition, a comparison of the images (d) and (e) of the specimen without additives (Fig. 3.5) and the images (d) and (e) of the specimen with FA + BA + BFS 20 substitution (Fig. 3.6) reveals the distinct fibrous structure in Fig. 3.5 [1]. This finding is also supported by higher compressive strength in specimens without additives when compared to cement mortars with FA + BA + BFS 20 substitution.

A closer look into (a), (b) and (c) SEM images of the specimen cured in 10% sodium sulfate solution for 180 days available in Fig. 3.7 showed no adverse or beneficial formations as the magnification rate was insufficient. Significant amounts of C-S-H gels were found in images (d) and (e) and it was observed that scarce ettringite formation was the case due to sodium sulfate curing. Thus, adverse formations started to grow in concrete in aggressive environment. In addition, images (e) and (f) clearly show the portlandite formation. A comparison of Fig. 3.7 and Fig. 3.5 showed ettringite formation in specimens cured in sodium sulfate solution (Fig. 3.7). A review of the results in connection with compressive strength measurements showed that compressive strength values and formations in the microstructure support each other as specimens cured in sodium sulfate gave lower compressive strength values.

A closer look into (a), (b) and (c) SEM images of the specimen with 20% substitution ratio at the 180th day available in Fig. 3.8

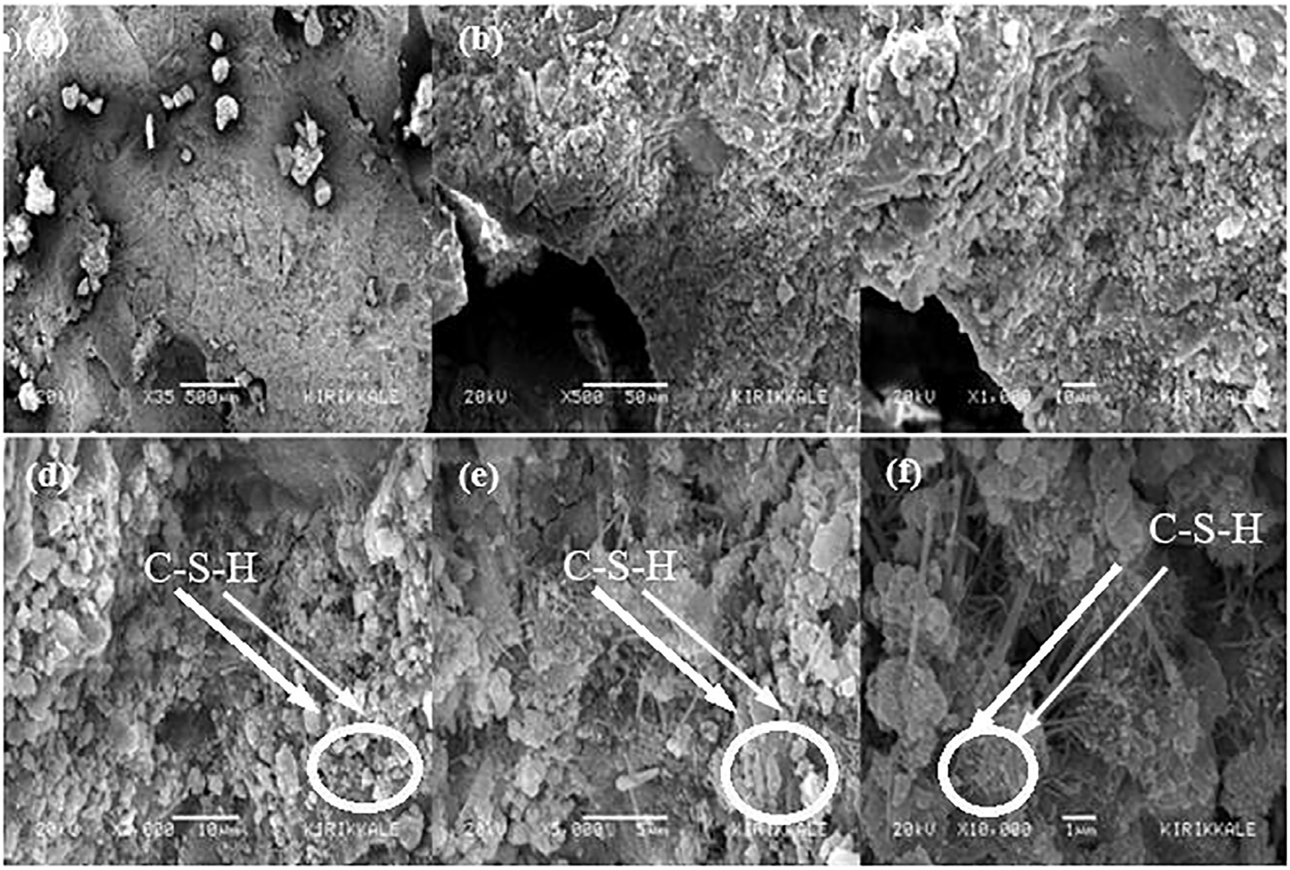

Fig. 3.5. SEM images of specimen without additives at the 180th day (PW).

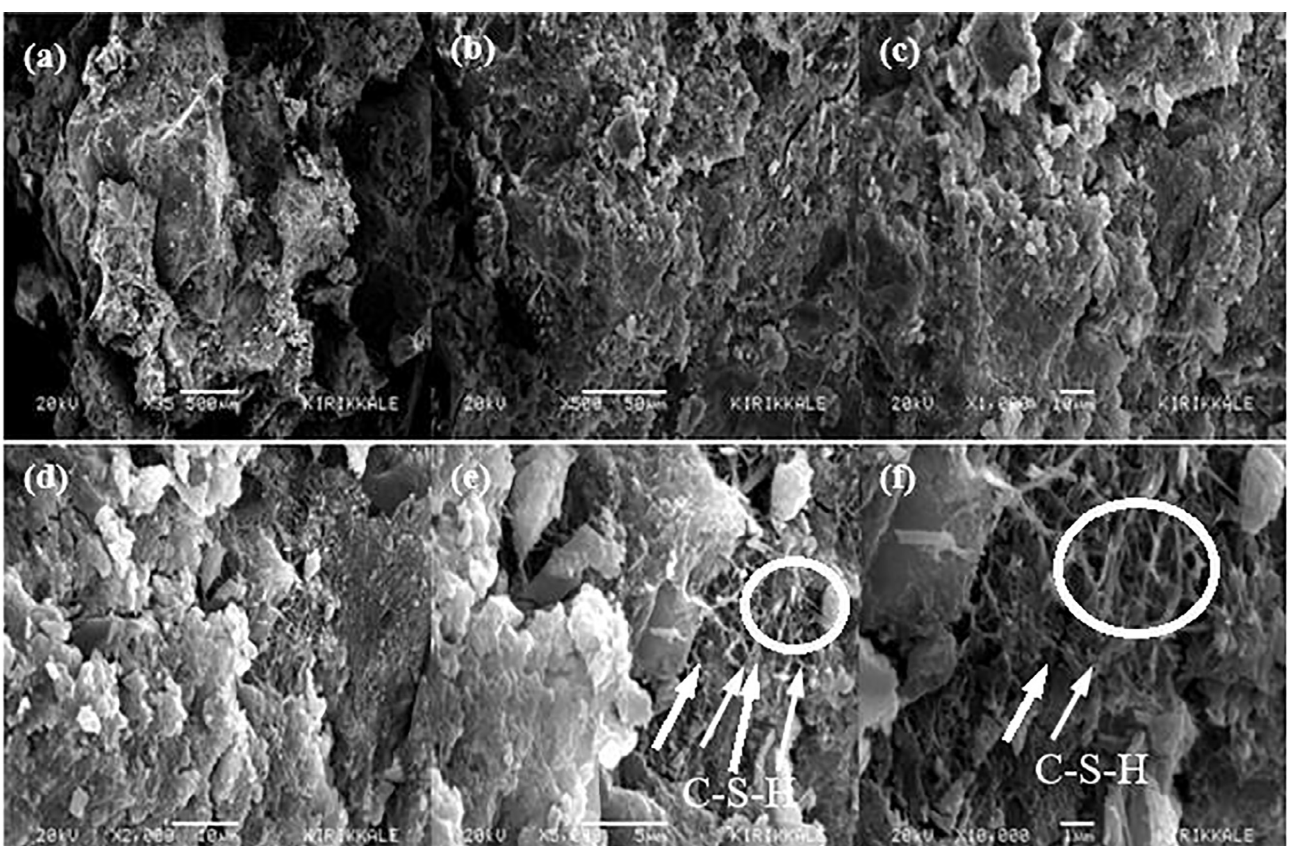

Fig. 3.6. SEM images of specimen with FA + BA + BFS 20 substitution at the 180th day (PW).

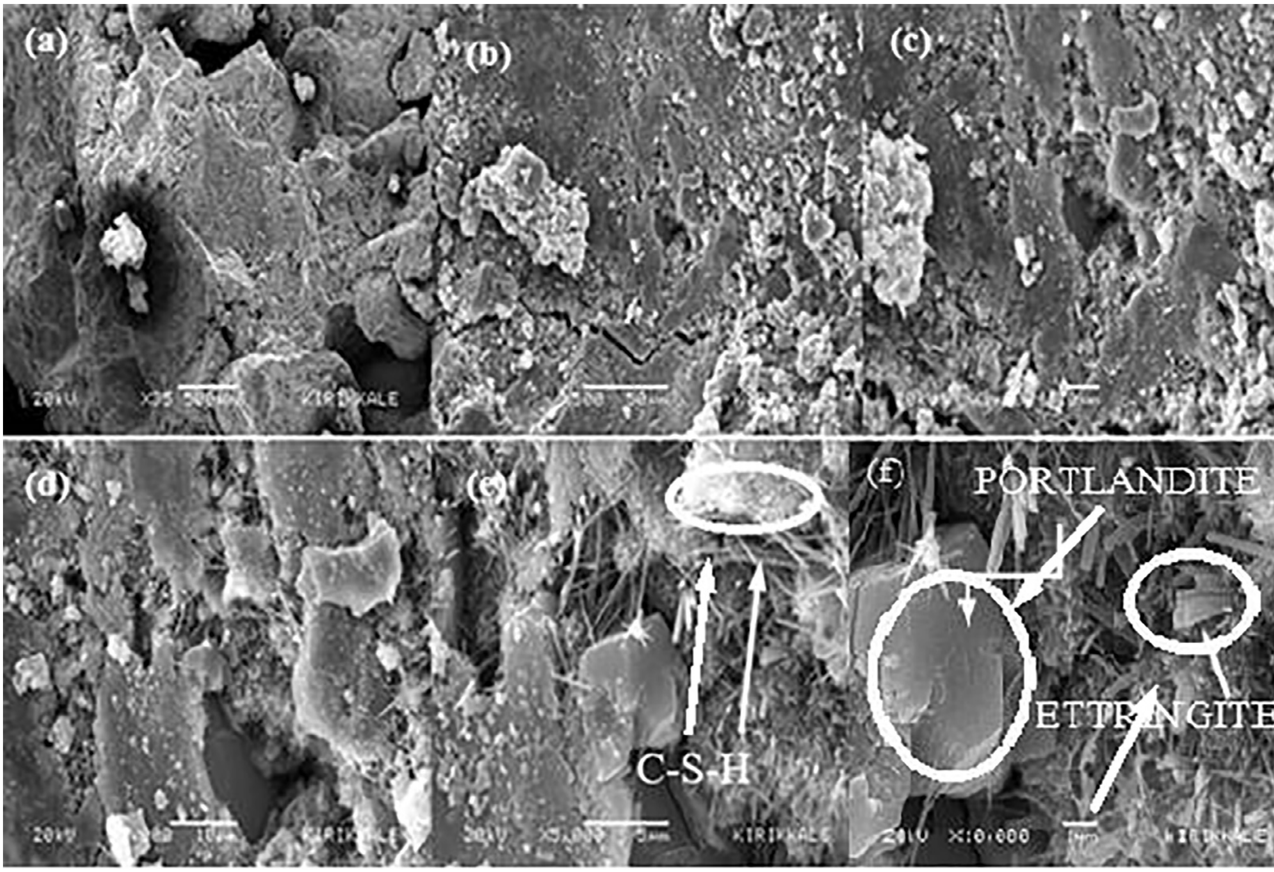

Fig. 3.7. SEM images of specimen without additives at the 180th day (SS).

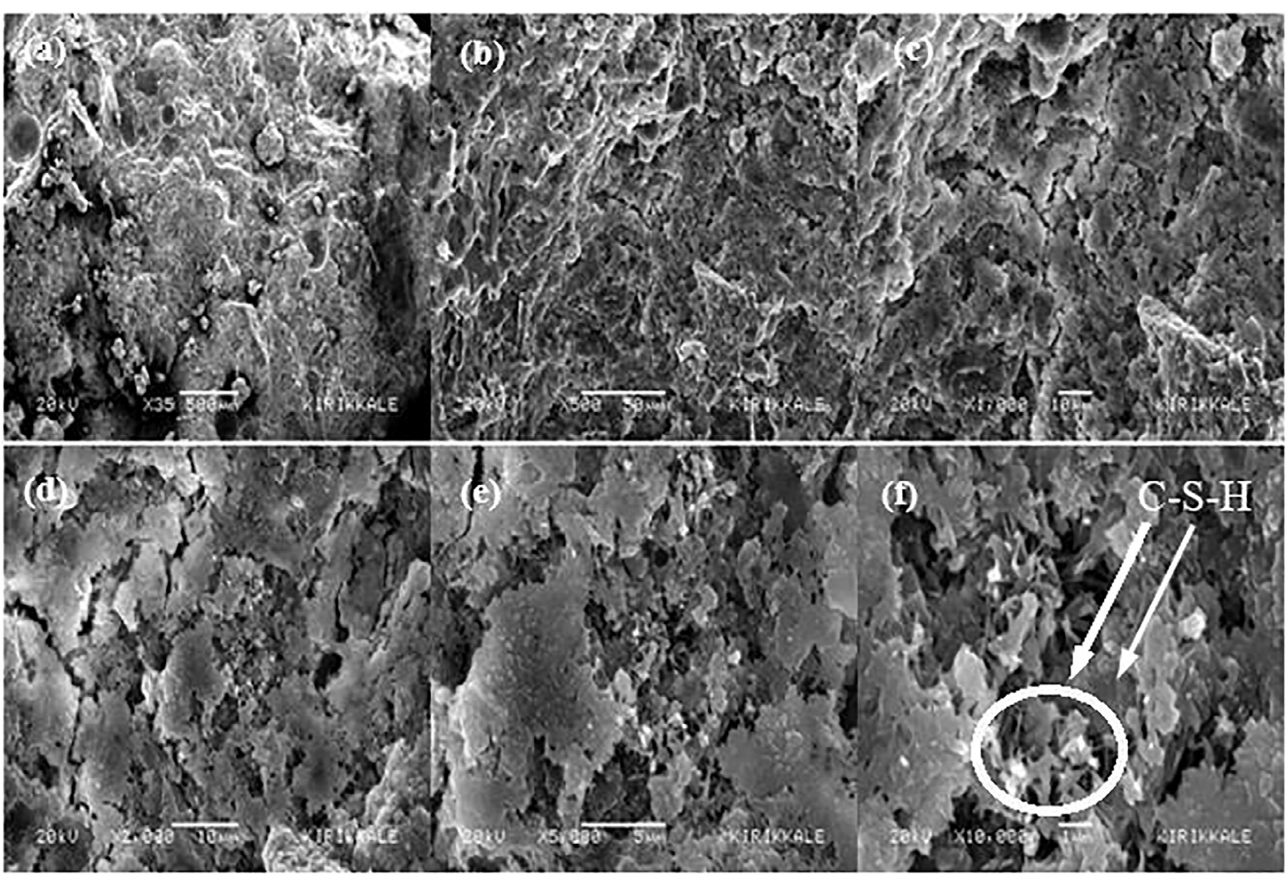

Fig. 3.8. SEM images of specimen with FA + BA + BFS 20 substitution at the 180th day (SS).

showed no adverse or beneficial formations as the magnification rate was insufficient. Image (f) offers clear images of Calcium-Silicate-Hydrate (C-S-H) gel. Image (f) reveals the decreased number of pores in the cement mortar due to C-S-H gels. In addition, a comparison of the images of the specimen without additives (Fig. 3.7) and the images of the specimen with FA + BA + BFS 20 substitution (Fig. 3.8) reveals the distinct fibrous structure in Fig. 3.8 [1]. This finding is also supported by higher compressive strength in specimens without additives when compared to cement mortars with FA + BA + BFS 20 substitution.

4. Conclusion

The study on the effect of sulfate on hybrid pozzolan substituted cement mortar offered the following results:

- Increased FA + BA + BFS substitution ratio in cement paste also increased the initial setting time.
- There were no changes due to substitution ratio in terms of volumetric expansion.
- A look into the specimens cured in 10% sodium sulfate for 360 days shows that 5% and 10% FA + BA + BFS substitution increases the compressive strength when compared to specimen without additives.
- FA + BA + BFS substitution at 15% and 20% was found to reduce the compressive strength.
- When the maximum length change of the specimens cured in potable water is compared, for the specimen without additives it was 0.012% at the 360th day and the length change of the specimen with FA + BA + BFS 20 substitution was 0.087%. This finding suggests a 7-times larger change in the length of the specimen with FA + BA + BFS 20 substitution.
- Maximum length change expansion, 0.087%, was found for the specimen with FA + BA + BFS 20 substitution cured in potable water.
- When the length change of the specimens cured in potable water and 10% sodium sulfate solution was investigated, it was found that the length change is increased in time. In addition, it was found that the length change is higher in the specimens cured in sodium sulfate solution.
- With respect to the microstructure of the specimens, it was observed that C-S-H gels are increase in quantity as the compressive strength increases, and that ettringite formation was first observed at the 180th day in the specimens cured in 10% sodium sulfate solution.

In conclusion, the length change of specimens obtained from cured in sodium sulfate solution shows best results in higher additive ratio. This study suggests that 15% and 20% additive ratios are effective in reducing unfavorable effects of sulfate.

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