Properties of High-Performance Concretes made of Black Sand at High Temperature

Khaled A. Eltawil [1*], Ahmed M. Tahwia [2], Mohamed G. Mahdy [3], Ahmed H. Abdelraheem [2]

[1] Ph.D. Candidate, Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt.

[2] Professor, Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt.

[3] Professor and Vice-dean for Students and Education Affairs, Faculty of Engineering, Mansoura University, Mansoura, Egypt.

Abstract

To modify High-Performance Concrete (HPC) fireproofing properties, Black Sand (BS) was partially substituted as fine aggregate at various levels. This study aims at evaluating the BS reliability in improving HPC durability properties for various construction applications based on its unique heavy minerals. To achieve this, five HPC series blends were setup to substitute fine aggregate independently with BS. Substitution percentages ranged from 15 to 100% with consistent supplementary cementing materials (SCMs) proportion for each gathering. Tests were performed to assess compressive strength before and after fire exposure under various temperatures of 250, 500, and 750 °C at different curing age. Generally, blending FA with BS was better than using SF with BS. Utilizing BS in the range of 15 to 60% as fine aggregate with 10% FA improves HPC fire-insulating properties. Besides, Z1 SEM analysis observed homogenously and compacted HPC microstructure at 250 and 500 °C.

Keywords: High-Performance Concrete; Black Sand; SEM; Fly Ash; Silica Fume; Fireproofing Properties.

1. Introduction

For several years, scientists have looked all over to solve fire concrete structure issues. The fire has an extremely significant effect on the protection of the concrete structure and fire losses cannot be overlooked, particularly for the concrete structures in coastal areas, because of the durability of concrete structures [1]. For example, nuclear power plants (NPPs) concrete faced high temperature and sulfate chloride attack. The high temperature of over 300 °C deteriorated concrete due to cracks that began to occur in the microstructure. Several new strategies are proposed to improve concrete fireproofing properties such as using mineral admixture. Concrete technology manufacturing improves and presents new advanced concrete that can achieve specified performance for the given arrangement of materials, utilization, monetary, service life and durability known High-Performance Concrete (HPC).

The HPC concept has unquestionably improved with time. HPC is utilized in various large-scale concrete construction fields needed high strength, flowability, durability, least porousness and different necessities that are unmistakable as demonstrated by use. It rejoins a particular blend of performance and consistency necessities, which

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generally can't be achieved by customary constituents and ordinary blending, placing and remedial practices. It needs extraordinary industry operation to accomplish all past HPC purposes [2].

Several new strategies are proposed to develop a material with a longer life cycle due to its high strength and high workability, HPC is widely used and has been widely applied in modern engineering applications like fire protection, concrete repair, offshore engineering, security industry, prefabricated structures. Lower water to binder (w/b). HPC is more durable, more compact and it has higher strength than normal concrete (NC). At the same time, high self-desiccation and high-temperature lead to crack HPC that are the product of the low w/b ratio [3, 4]. The HPC can produce high material ductility according to type and scale of the aggregate collection or use of fiber [5].

HPC is experienced as "durable" concrete. This industry advancement chiefly utilizes various kinds of SCMs. Specifically, fresh and hardened concrete properties are developed using ternary systems. These HPCs are affordable and environmentally sustainable. SCMs are generally utilized as an insubstantial cost substitution material either as a base material in road construction or as a replacement material in Portland cement. Studies observed the ideal substitution proportion ranges between 15% to 30% for FA and 15% for SF [6,7]. With the addition of zeolites up to 10%, the HPC flowability and the compressive strength contributed to beneficial effects, however Higher zeolite content could reduce workability and compressive strength [8].

HPC is manufactured cautiously by selecting high-quality segments and optimizing mixture designs with the highest industry operating standards [2]. Coarse aggregate can be the most fragile connection in HPC when the strength of the hydrated cement paste is radically expanded by decreasing its w/b. HPC failure can begin to form inside the coarse aggregate, while results improve when using our method for the strongest aggregate. Thus, the compactness of the matrix is expanded and the durability of HPC is improved [9]. When HPC is affirmed under high temperatures such as fire, its properties may separate. Where HPC is considered an incredible fireproofing material among different construction substances, but basic breakdown occurs under a high fire temperature. High temperature causes sensational physical and non-reversible synthetic changes disintegrating the concrete [10–12].

Concrete's imperviousness to fire is influenced by factors such as w/b, the type of aggregate type, the use of cement in its composition, the presence of SCMs, the use of fiber, temperature and duration of the fire, and the content of concrete dampness [11, 13, 14]. The chief effects of fire are summed up as a loss of strength, spalling and cracking, and destruction of the bond in the interfacial transition zone (ITZ) between the cement paste and the aggregates, similar to the piecemeal disintegration of hardened concrete [15]. Their probability of occurrence increases within the hardened cement paste hydrated components, yet additionally within the aggregates relying on the type of rock concerned [16], except for the crystal transformations occurring mostly within the aggregates. Thus, the processes involve the so-called degradation responses of cement paste, which are reactions that achieve a progressive breakdown within the concrete structure. The final stage of calcium silicate hydrate (CSH) dehydration is the arrangement of silicates with a relative anhydrous cement structure type C_2S [17, 18].

As expected, a significant increment in temperature influence is observed on the binder and aggregate. First, CSH slightly decreases, and the free dampness contained within the concrete mass evaporates from the binder in the range of 100 to 450 °C [11]. Then, interior steam pressures are created and the loss of the non-evaporable water begins. Compressive strength diminishes considerably by 15 to 40%. Microcracks in the cement matrix and ITZ begin to propagate and their intensity increases with temperature [19]. Compressive strength is reduced at 550 °C [20]. At a temperature of over 600°C, α−silica transforms into β−silica which causes volume expansion and increases the inner pressure. Thus, surface cracks start discernibly and become more evident especially at 800 and 1000°C [11].

Another factor of concrete fireproofing is its aggregate nature. It does not affect compressive strength considerably up to 300°C. In the range between 100 °C to 300°C, the siliceous concrete records a higher strength than the limestone one. Above 300 °C, strength is reduced for both types of aggregates, but the reduction is higher for the siliceous aggregate concrete. Aggregates such as siliceous or calcareous are changed, and cracks crossing the aggregates are formed above 500 °C. This behavior has an inverse influence on the bonding between the paste and aggregate in the ITZ. At higher temperatures of up to 800°C, the crystalline transformation of aggregates occurs, that is, α to β quartz transformation in siliceous aggregates [11, 21].

BS is ordinary sand blended with high, heavy economic radioactive minerals, which are assembled into two essential kinds; BS is shiny and heavy and BS source is found near a spring of gushing lava, and it has qualities such as dim shading and abundant mineral, particularly iron substance [22, 23]. This BS contains an enormous amount of uncommon, massive, economic, strategic radioactive minerals, which are utilized in various industrial applications such as the nuclear industry or other metallurgical and engineering industries. BS is one of the uncommon monetary radioactive mineral-rich sources on the planet depicted by its dull grains that contain extra resources other than precious metals, such as rare earth elements, thorium, and titanium [24]. The authors of this paper aim to exploit the unique composition of BS that is rich in various minerals to improve the durability properties of HPC, particularly imperviousness to fire at high temperature. No previous study has used this to investigate the effects of using BS as

fine aggregate on the HPC fire resistance properties. This study aims at making most of the unique mix of heavy metals contained in BS to improve the HPC fire resistance properties. This paper is divided into four main sections. These sections are experimental details, results, discussion, conclusion, and recommendations.

2. Experimental Details

2.1. Materials Properties

Raw materials containing CEM I 42.5 N (PC), fly ash class F (FA), silica fume (SF), BS, normal sand (NS), and water were used in this paper. NS fineness modulus was 2.9 and the specific gravity was 2.55. BS was collected from the Baltium shore with a particle size in the range between 0.15 to 0.3 mm, a fineness modulus of 2.2, a surface area of 92 cm^2/gm, and a specific gravity of 2.65. Figure 4 shows the NS grading curve. All sand types were washed at the site to remove useless components. Chemical properties of PC, FA, SF, and BS are recorded in Table 1. The SF was provided by the Egyptian Ferro Alloys Corporation (EFACO). The SF is used to confirm with ASTM C 1240. The physical properties of utilizing SF and FA are recorded in Table 2. The specific gravity of FA and SF are illustrated in 2.2 and 2.3 respectively. A superplasticizer supported by a modified polycarboxylate ether was employed to get the highest durability and performance that are required for the various mixes. Its density at 20 °C is 1.1 gm/cm^3.
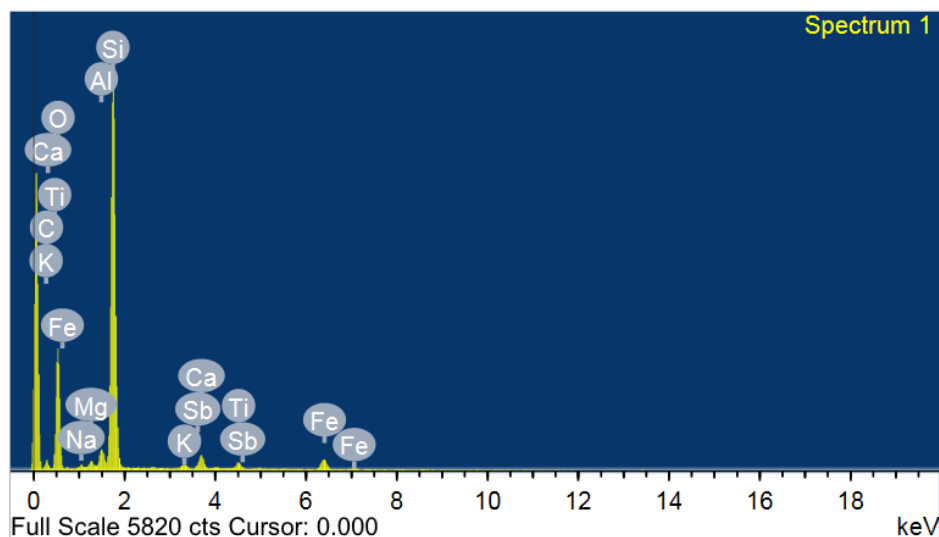

Figure 1. Used black sand

Figure 2. Egyptian Black Sand EDS analysis

2.2. Mixing Procedures

Mixture proportion demonstrates in table 3. Dry ingredients (PC, FA or SF, BS, and NS) were blended in a laboratory drum rotary mixer with a capacity of 60 L for 1.5 min, followed by presenting the third mixing water for another 30 s. The remaining mixing water was blended with SP solution. Two steps were performed for the remaining solution separately:

- Half of the solution was added initially to wet the mixture to prevent binder flow. This progression required approximately 1 min.

- During mixing, another part of the solution, which was sufficient to wet components without performing binder, was added and left for 1 min.

After mixing, the concrete mixture was cast in the molding samples, compacted for 30 s by vibrating tables, and remained 24 h to cast. All samples were placed in a water curing tank until the test deadline. The fresh concrete pastes were thrown into the cube specimens that measured 70×70×70 mm and well compacted by a vibration table for 30 s. The curing specimens depended on restoring them in water until experimental time.

2.3. Testing

The compressive strength variations of concrete before and after high-temperature exposure was assessed. Three specimens were exposed to each temperature and three others were kept in laboratory conditions. Each specimen was tested and the arithmetical averages were utilized. Specimens were exposed to a high temperature of 250, 500 and 750 °C at the age of 28 and 90 days for 3 h. The temperature was increased at a consistent heating rate of 6.7 °C/min. After firing, samples left to cool within the furnace for 1 h after opening the furnace door. They were removed from the furnace and chilled off for 24 h in the air in the laboratory. Specimens were weighed and tested using a compression machine test.
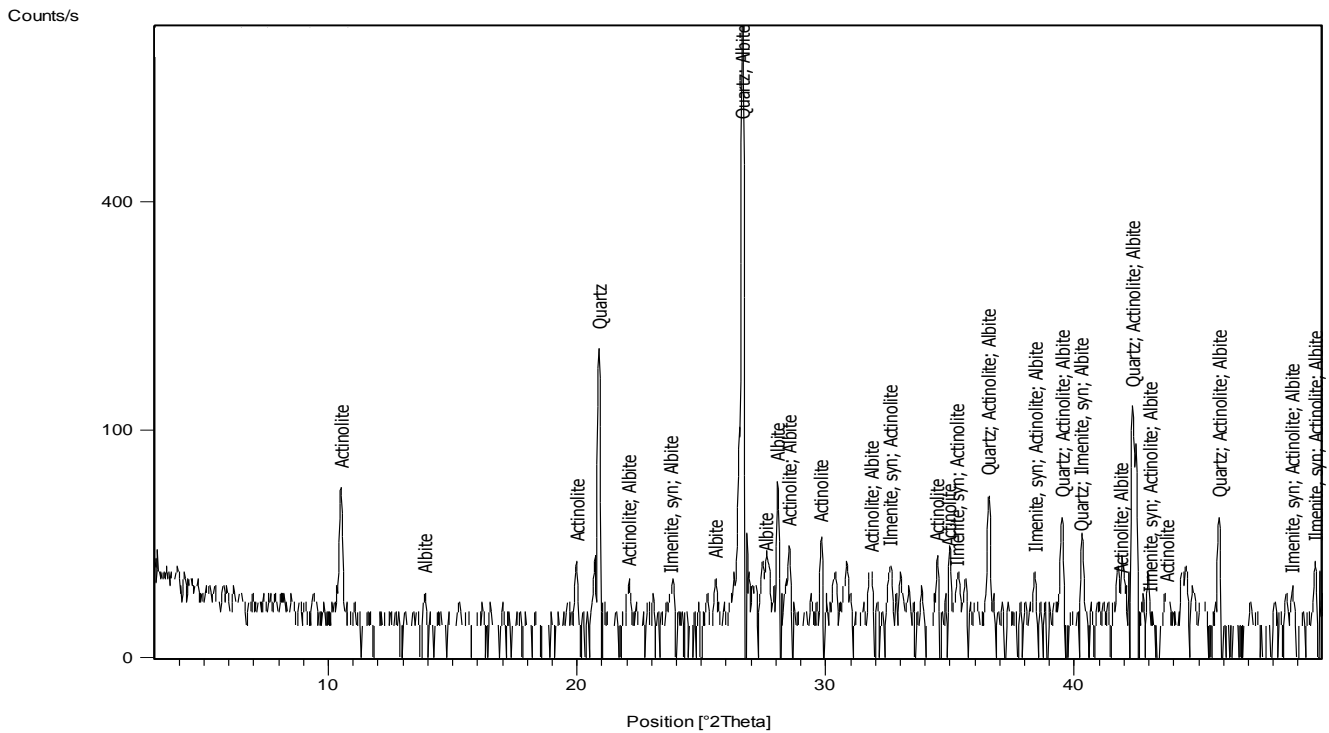

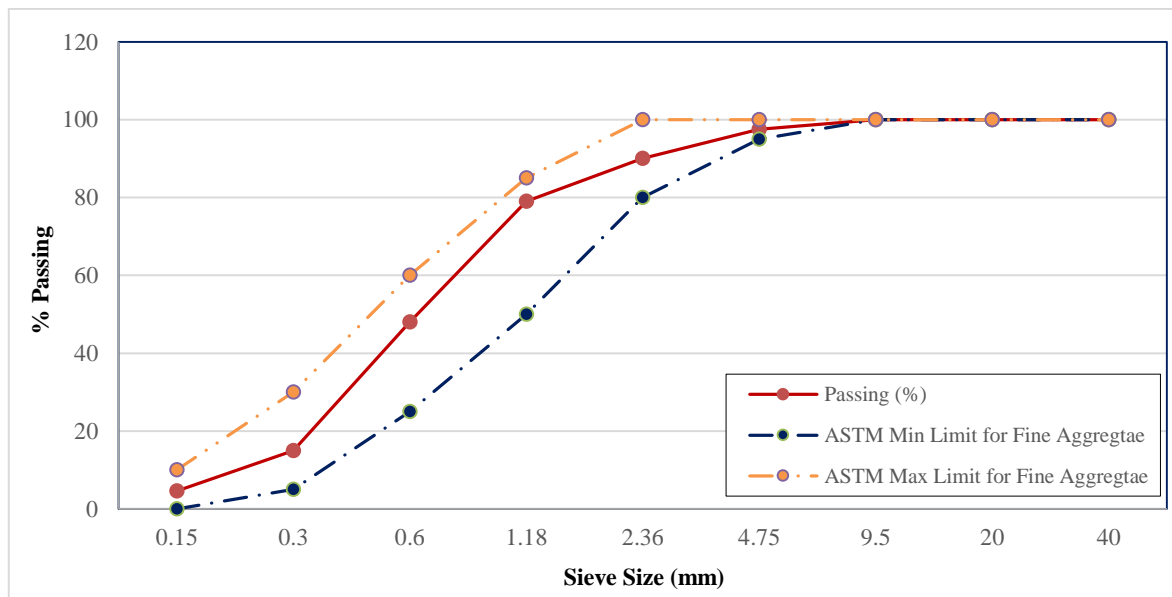
Figure 3. Black Sand XRD analysis

Figure 4. Particle Size Distribution of Normal Sand

Table 1. **Oxide Composition of utilizing materials results, wt%**

	PC	BS	FA	SF
SiO₂	21.25	60.9	60.27	95.9
Al₂O₃	4.67	4.41	27.99	0.52
Fe₂O₃	3.65	9.71	4.54	0.05
CaO	61.8	7.95	1.16	0.20
MgO	2.72	2.75	0.37	0.18
SO₃	3.06	0.27	0.35	0.1
Na₂O	0.18	0.67	0.15	-
K₂O	0.12	0.27	0.98	0.4
TiO₂	-	6.41	-	-
P₂O₅	-	0.36	-	-
Cl⁻	-	0.39	-	-
Cr₂O₃	-	0.27	-	-
MnO	-	0.43	-	-
ZrO₂	-	0.53	-	-
L.O.I	2.5	4.52	0.91	2.9
Total	99.95	99.83	96.72	96.95

Table 2. Utilizing SCMs Physical properties

Property	SF	FA
Fineness (m²/Kg)	23420	< 10% retained on a 45-micron sieve
Bulk density (t/m³)	0.6	1.1
Specific gravity (t/m³)	2.2	2.35
Color	Grey	-
Particle shape	Spherical	Spherical
Loss-on-ignition (L.O.I)	-	< 2.5%

3. Results and Discussion

3.1. Compressive Strength due to Exposure under Various Temperatures

Generally, compressive strength changes according to the BS substitution proportion of specimens. A higher substitution proportion decreases the compressive strength in all series, but drastic changes in compressive strength were observed before and after high-temperature exposure. Regardless of the presence of BS, all HPCs achieved high strength under various conditions. Compressive strength was enhanced at 250 and 500 °C compared with that and without exposure. It slightly decreased at 500 °C. The lowest strength was noted at 750 °C. Fire resistance improved with increasing the curing age.

Table 3. Mixes proportion

Mix Group	Mix No.	Binder			W/B	Sand		SP %
		PC %	SF %	FA %		NS %	BS %	
Control	X0	100	0	0	0.3	100	0	1.5
	Z0	90	0	10	0.28	100	0	1.5
	V0	85	0	15	0.27	1.5	0	1.5
	S0	90	10	0	0.28	100	0	1.5
	P0	85	15	0	0.27	1.5	0	1.5
Z	Z1	90	0	10	0.30	85	15	1.5
	Z2				0.31	70	30	1.5
	Z3				0.32	55	45	1.5
	Z4				0.33	40	60	1.5
	Z5				0.34	25	75	1.5
	Z6				0.35	0	100	1.5

	V1				0.29	85	15	1.5
	V2				0.30	70	30	1.5
V	V3	85	0	15	0.31	55	45	1.5
	V4				0.32	40	60	1.5
	V5				0.34	25	75	1.5
	V6				0.35	0	100	1.5
	S1				0.30	85	15	1.5
	S2				0.31	70	30	1.5
S	S3	90	10	0	0.32	55	45	1.5
	S4				0.33	40	60	1.5
	S5				0.34	25	75	1.5
	S6				0.35	0	100	1.5
	P1				0.29	85	15	1.5
	P2				0.30	70	30	1.5
P	P3	85	15	0	0.31	55	45	1.5
	P4				0.32	40	60	1.5
	P5				0.34	25	75	1.5
	P6				0.35	0	100	1.5

NS: Normal Sand; BS: Black Sand

a. Compressive Strength at an early age

- **Control Group**

The strength of HPC deteriorated when the exposure temperature over 500 °C. Compressive strength greatly improved below 500 °C. The strength slightly decreased beyond 500°C and drastically dropped to at 750 °C as shown in Figure 6. Besides, SCMs improved the compressive strength before and after exposure at various temperatures. The compressive strength of HPC with FA or SF under various exposure conditions of HPC with FA (Z0 and V0) was superior to that of HPC with SF (S0 and P0). This finding implies that FA may fairly contribute to the compressive strength of HPCs at elevated temperatures and SF has adverse effects beyond 500°C [25]. Considerable compressive strength increases of 26, 15, 16 and 40% were recorded for Z1 before and after exposure at various fire temperatures of 250, 500 and 750 °C compared with Z0.
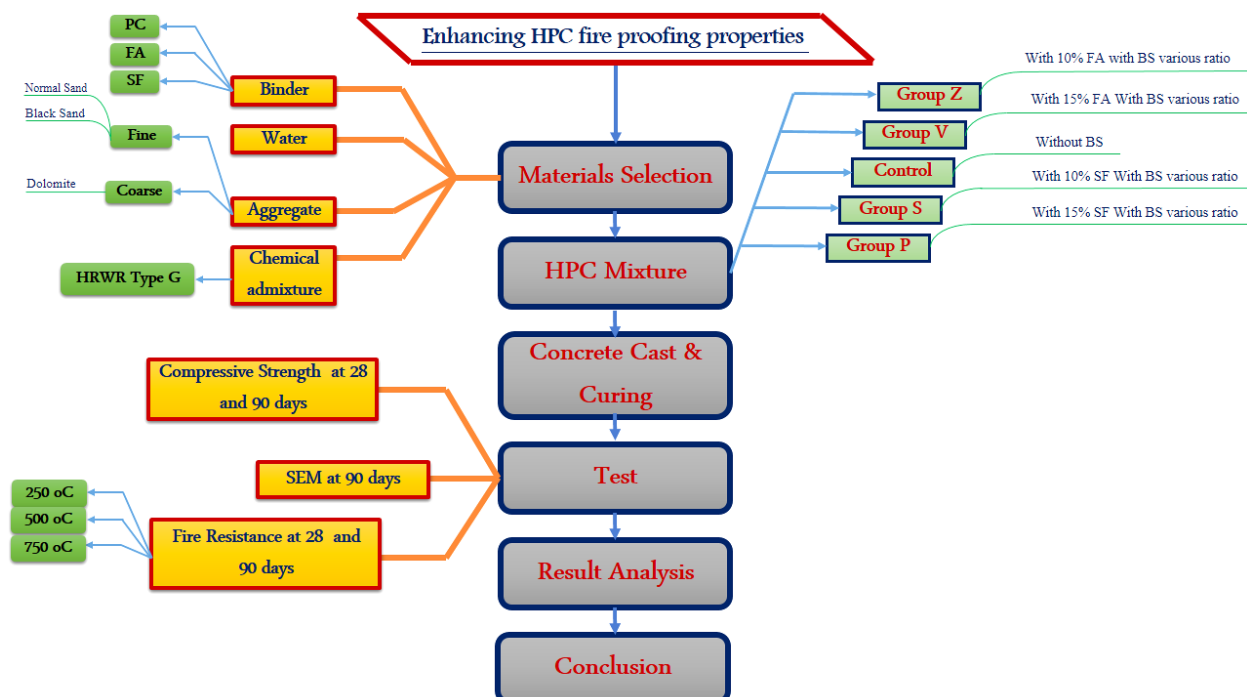

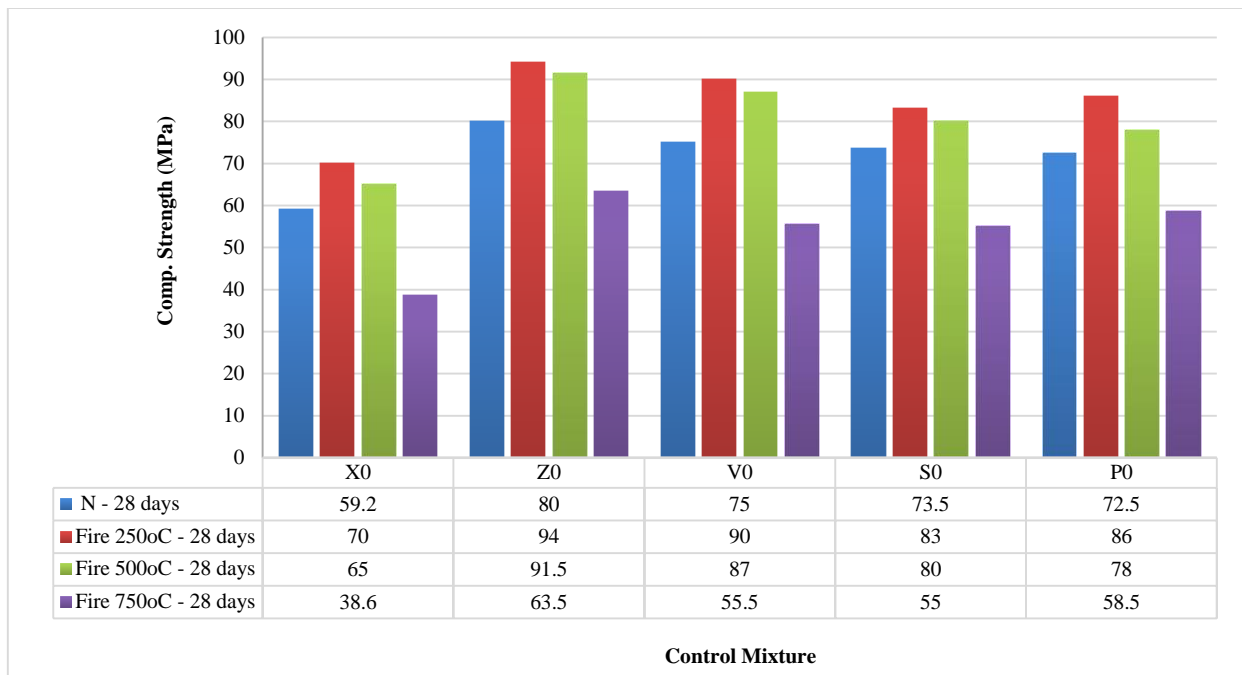**Figure 5. Research Methodology Flow Chart**

Figure 6. Control Group Results due to exposure under various temperature at 28 days

- **Group Z**

All strength results are appropriate and in the high-strength range. Strength marginally decreased up to 60% from BS replacement ratio. Small compressive strength increases of 1.1 and 11.8% were reported for Z1 at 250 and 750 °C compared with Z0. Strength decreased by over 30%, but exposure under 500 °C resulted in decreases in strength with increased BS proportion as shown in Figure 7. The strength improved significantly by raising the BS ratio to 60% below 250 °C. All mixtures reported a drop in strength with rising BS ratio, especially at a ratio above. The strength of Z6 decreased by 16% compared with Z0 at 250 °C. Exposure results below 500 °C showed declining strength with increased BS ratio. Compressive strength gains of 12, 11.2 and 4% were reported at 750 °C for Z1, Z2, and Z3 compared with Z0.
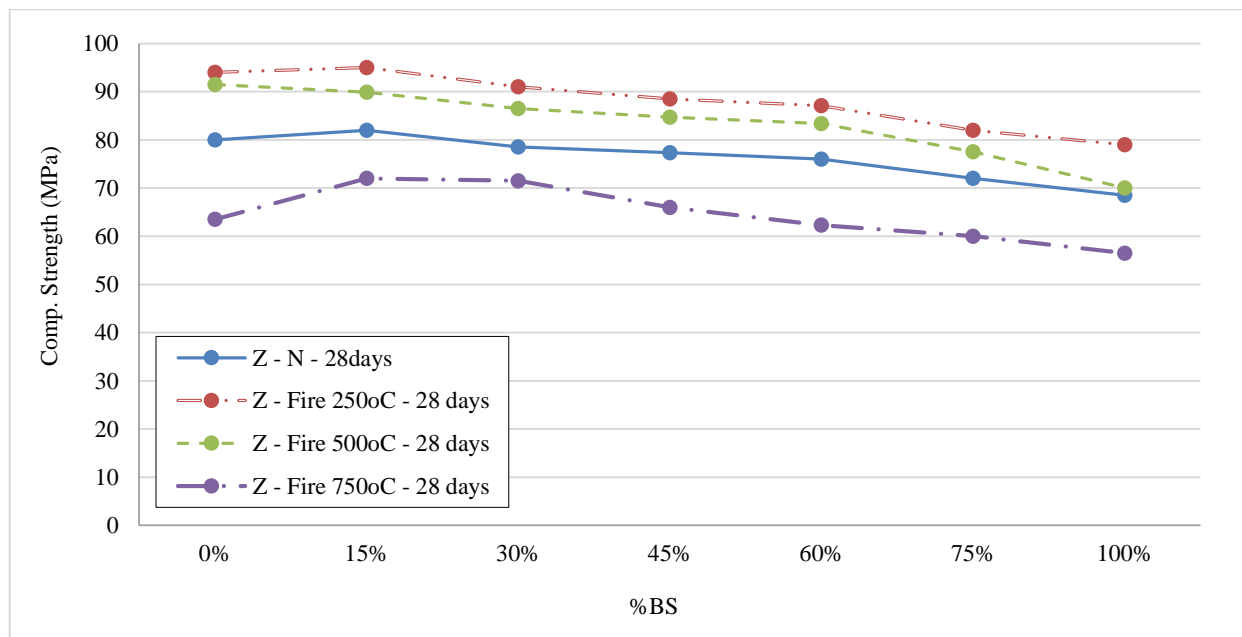

Figure 7. Group Z Results due to exposure under various temperature at 28 days

- **Group V**

Figure 8 demonstrates the shift in compressive strength by using different BS ratios as fine aggregate with 15% FA as SCM and various exposure conditions. Compressive strength decreased with increased BS. All fire-resistant

mixtures displayed a significant strength increase compared to that under normal conditions. At higher fire temperatures, all BS mixtures obtained greater strength compared to X0. V6 recorded a 25% decrease in strength compared with V0 at normal condition. However, strength improved at 250 °C than normal conditions. The strength under 500 °C slightly decreased compared with that under 250 °C. Group V mixes recorded an average decrease of 7.7% compared with that under 250 °C with an identical material proportion.
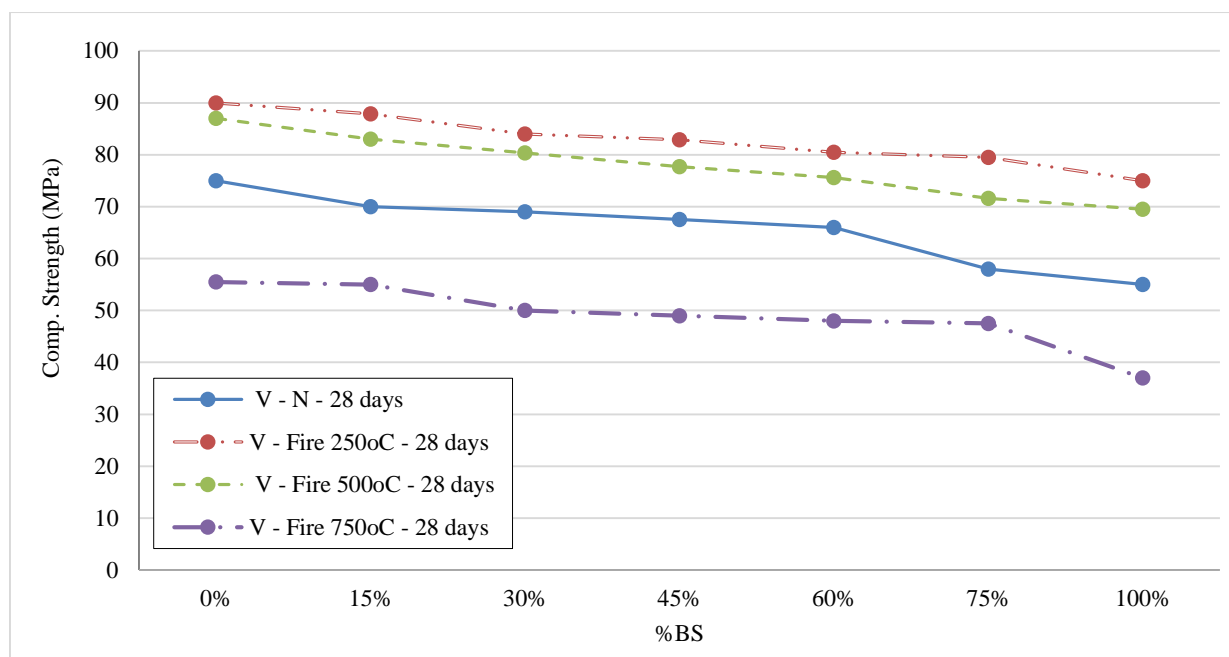

Figure 8. Group V Results due to exposure under various temperature at 28 days

- **Group S**

Figure 9 demonstrates the shift in compressive strength by using various BS proportions as fine aggregate with 10% SF such as SCM and different exposure conditions. The strength increased to 30% BS. Over 30% of BS strength deterioration began. S6 recorded a drop of 9.1% compared with S0. Most of the mixtures, except S5 and S6, showed perceptible improvement contrasted to X0, however compressive strength increases of 4.1 and 5.7% were observed for S1 and S2 at 250 °C compared with S0. The strength under 500 °C slightly decreased compared with that under 250 ºC. Besides, exposure findings below 750 °C indicate strength degradation relative to the normal setting.

- **Group P**

Figure 10 shows the change in compressive strength when utilizing various BS ratios as fine aggregate with 15% SF such as SCM and various exposure conditions. Generally, the strength increased to 15% and BS is dissimilar to group S that at 30% where over 15% strength decrease showed. A drastic drop occurred at the highest BS ratio. P6 recorded considerable decreases of 16.4% and 14% compared with P0 and X0, respectively. The results of exposure under 500 °C demonstrate strength enhancement with increasing the BS proportion to 15%. Strength began to break down by increasing the BS ratio over 30%. The strength under 500 °C recorded an average decrease in strength compared with the exposure at 250 °C with a similar material proportion by 7.7%. Outcomes of exposure below 750 ° C indicate intensity deterioration relative to normal condition.

Finally, fire resistance strength results at 28 days show that using SF with a high percentage (15%) harmed the concrete properties. All Group S results demonstrate an improvement in strength because of fire under 500 °C compared with group P. BS typically affects fire-resistance. The BS mixtures achieved the highest strength compared to control. Using a high BS percentage with SF, particularly over 45% is not recommended. The findings are summarized as follows:

- All results reveal high strength that is adequate for construction, especially fire resistance purpose.

- Over utilizing high BS percentage with SF particularly over 45% is not recommended.
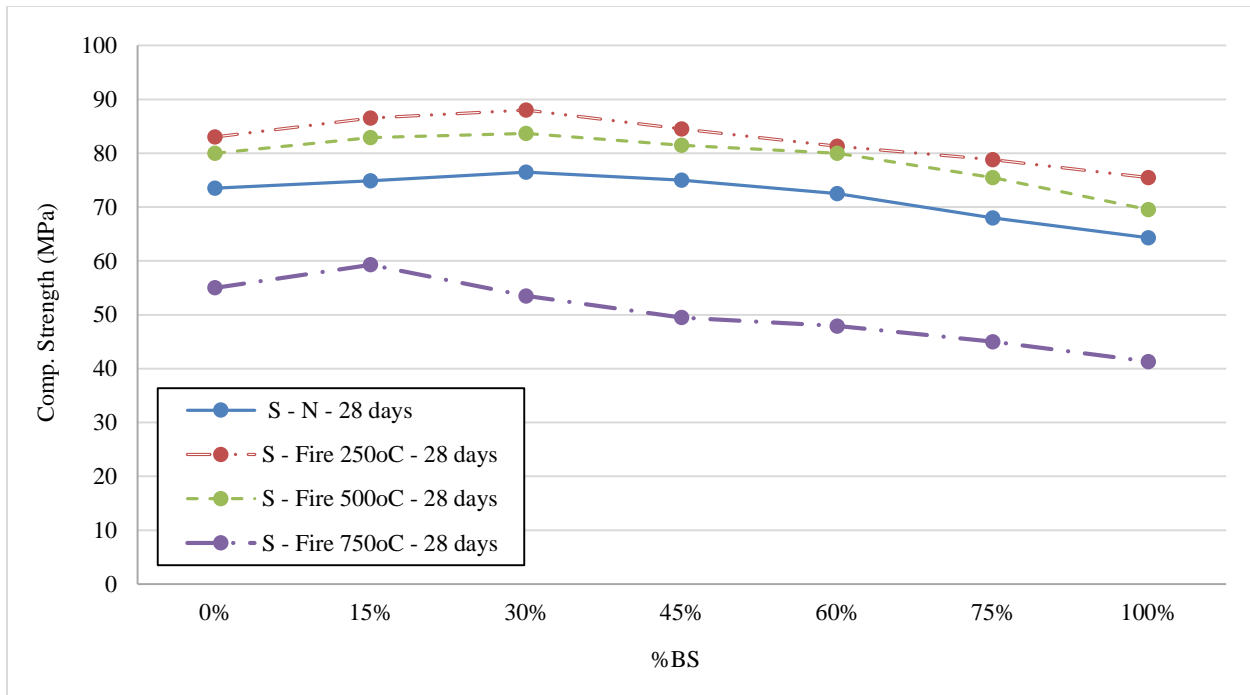
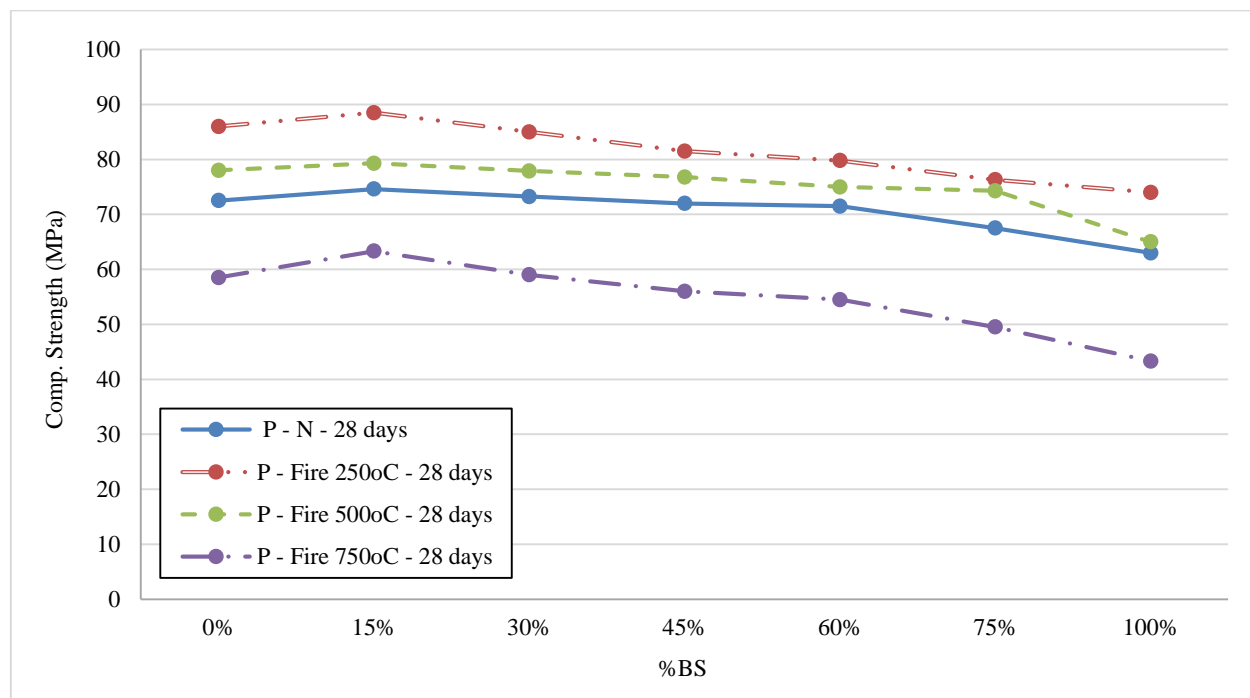**Figure 9. Group S Results due to exposure under various temperature at 28 days**

Figure 10. Group P Results due to exposure under various temperature at 28 days

b. Compressive Strength at 90 days

Generally, all strengths considerably improve with increasing curing ages.

- **Control Group**

Figure 11 shows the concrete compressive strength at various temperatures. The strength of HPCs broke down when the exposure temperature exceeded 500 °C. The compressive strength improved considerably below 500 °C, slightly decreased beyond 500 °C, and dropped at 750 °C.

When in doubt, SCMs improved the compressive strength under all exposure conditions. Compressive strength increases of 12, 16 and 45% were recorded for Z1 at various fire temperatures 250, 500 and 750 °C compared with Z0.
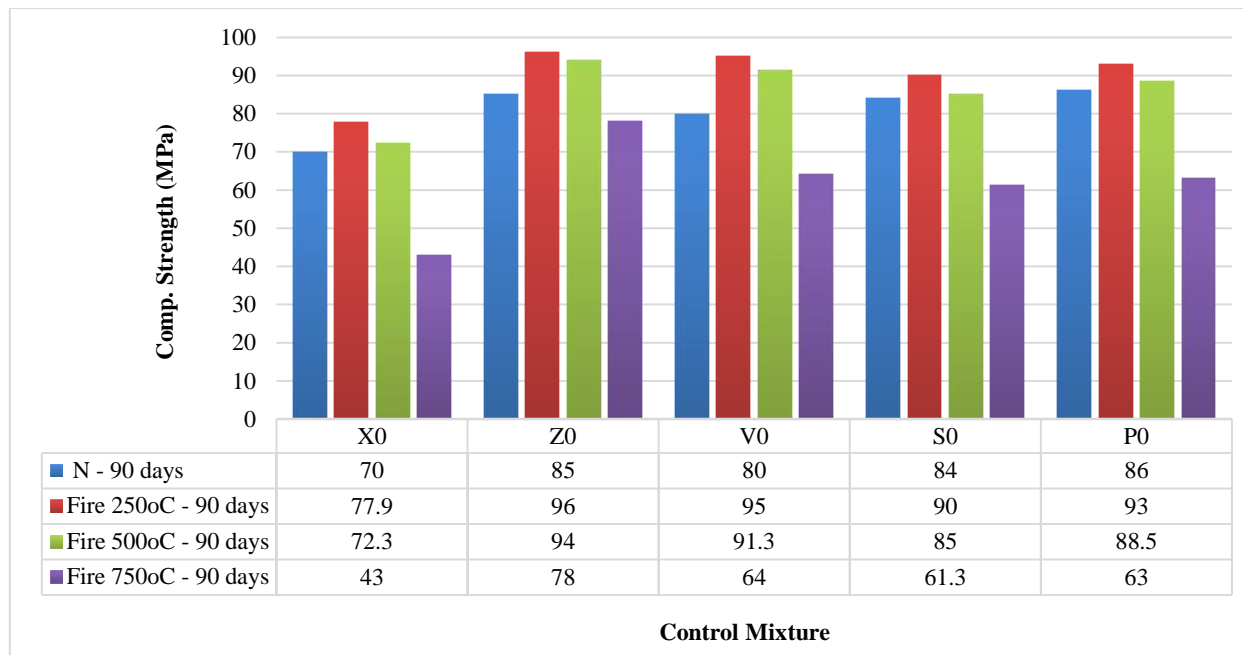
Figure 11. Control Group Results due to exposure under various temperature at 90 days

- **Group Z**

Figure 12 shows the change in compressive strength when utilizing various BS ratio as fine aggregate with 10% FA as SCM and various exposure conditions. All strength outcomes are sensible for construction purpose and in a high-strength range. Substantial compressive strength improvements of 7, 6 and 5% were recorded for Z1 at typical condition, 250 and 500 °C compared with Z0, individually. No changes were observed at 750 °C. Over 30%, strength decreased. The strength greatly improved with increasing the BS proportion up to 15% under 250 °C, slightly decreased at 60%, and extremely declines over 60%. Z6 recorded a strength decrease of 19% compared with Z0 contrasted with 16% at 28 days under 250 °C. By contrast, the strength at 250 °C greatly improved, diverging from the typical condition. It recorded an average improvement of 10.9% compared with identical before exposure. The strength decreased, but the results display adequate strength for fire resistance. The results of exposure under 500 °C demonstrate diminishing strength with increasing BS proportion. The strength slightly decreased compared with that under 250 °C. Before long, all mixtures indicated a substantial improvement in strength particularly that which contain BS within the range of 15 to 60%, compared with that under a standard condition. Nevertheless, they recorded a small average strength decline of 4% compared with that under 250 °C.
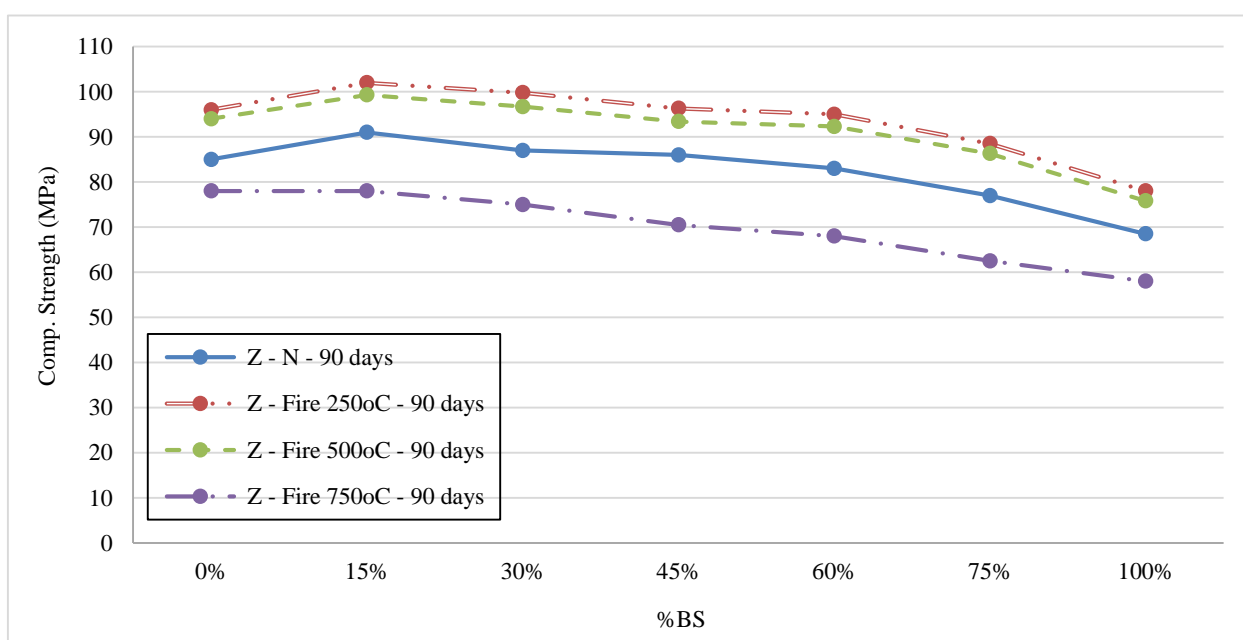

Figure 12. Group Z Comparison Results at 90 Days under Various Fire Condition

- **Group V**

Figure 13 demonstrates the change in compressive strength when utilizing various BS ratios as fine aggregate with 15% FA such as SCM and various exposure conditions. The strength decreased with increasing BS replacement ratio and dropped at a higher BS ratio (over 60%). V6 recorded a decrease of 14% compared with V0 under 250 °C. In any case, the same BS ratio with 10% FA (Z6) recorded 19% compared with Z0. The strength decreased, but the results display adequate strength for construction. The strength substantially improved at 250 °C compared with that under normal conditions.

Most of the mixtures, except V5 and V6, indicated a noticeable improvement in contrast to X0. All mixtures under a fire condition displayed a considerable improvement in strength compared with that under typical condition. Moreover, the strength under 500 °C was very close to that under 250 °C. The results of exposure under 750 °C display enhanced strength up to 30% BS. Beyond 30%, strength started to deteriorate slightly to 60% BS. In this manner, strength dropped drastically over 60% of BS.

Finally, all results show that all mixtures demonstrated similar behaviors under 500 °C. Their strength slightly decreased at 250 °C. Group Z achieved the highest strength improvement at various concrete ages, however it achieved a higher strength at 28 and 90 days compared with group V at 90 days, similar to compressive strength results and imperviousness to fire under 250 °C. Using BS in a range of 15 to 60% with 10% FA is the best choice for imperviousness to fire under 500°C because the BS range exhibits better strength results than X0 as well.
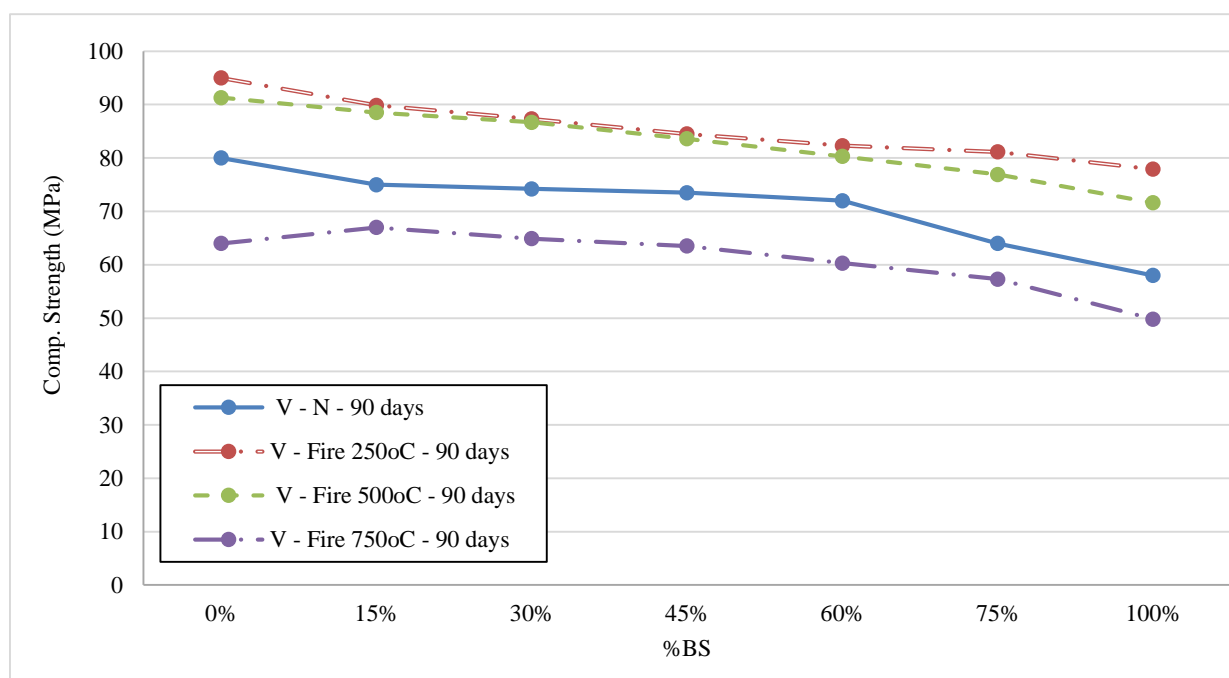

Figure 13. Group V Comparison Results at 90 Days under Various Fire Condition

- **Group S**

Figure 14 demonstrates the change in compressive strength when utilizing various BS ratios as fine aggregate with 10% SF such as SCM and various exposure conditions. In contrast to Groups Z and V, the strength after exposure at 250 and 500 °C slightly increased compared with that without exposure condition. Moreover, the strength reduced with increasing fire exposure to 750 °C. At 250 and 500 °C, the strength improved with increasing BS ratio to 30% in the blend. Over 30% of the BS ratio, the strength slightly decreased. The samples under 750 °C exposure showed a considerable decrease compared to the same samples before and after exposure. S1 achieved the best strength at 15% BS ratio under 750 °C. At that point, the compressive strength decreased with increasing BS ratio in blends.

The strength at 90 days under 250 °C slightly improved at 30% BS proportion (S2) which recorded an increase by 3.4% compared with S0. In this manner, the strength decreased with increasing BS ratio, particularly at 100% BS ratio. S6 recorded a decrease of 13.8% compared with S0. The results of exposure under 500 °C show a slight enhancement at 30% BS proportion (S2) which recorded an increase of 4.4% compared with S0. The strength under 500 °C slightly strength decreased compared with that under 250 °C. They recorded an average decrease of 4.85% compared with that under 250 °C with the same material proportion. The results of exposure under 750 °C results show drastic drops in strength in contrast to mixtures before exposure. The strength increased by 7.2 to 15% of BS compared with Z0. Accordingly, the deterioration in strength occurred at a higher BS replacement ratio.
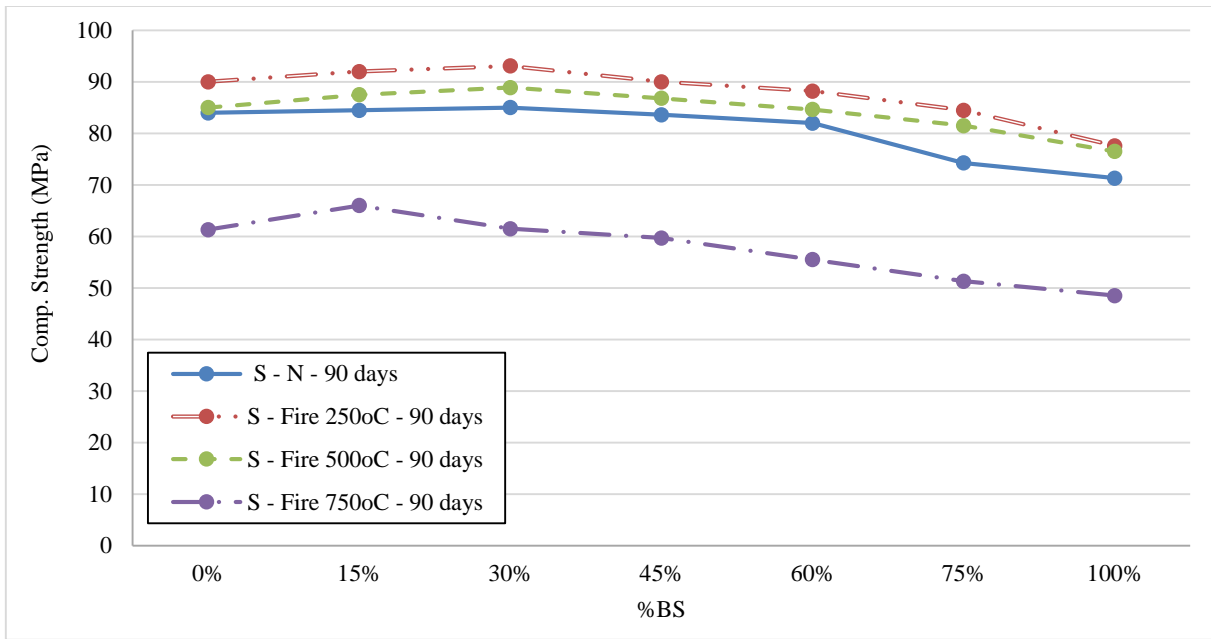
Figure 14. Group S Comparison Results at 90 Days under Various Fire Condition

- **Group P**

Figure 15 indicates the change in compressive strength when utilizing various BS ratios as fine aggregate with 15% SF such as SCM and various exposure conditions. Similar to group S, the strength after exposure at 250 °C and 500 °C slightly improved compared with that without exposure condition. Moreover, the strength reduced with increasing fire exposure to 750 °C. At all tested conditions, the strength improved with increasing BS ratio to 15% in the blend. Over 15% of BS ratio, the strength gradually reduced. The samples under 750 °C exposure displayed a substantial decrease compared with the same samples before and after exposure. The concrete strength improved after exposure under 250 °C with increasing curing age compared with that at 28 days. The strength improved with increasing the proportion of BS that is up to 15%. At that point, the strength started to decrease at a higher BS proportion, particularly over 15%. P6 recorded a considerable decrease of 17.4% compared with P0. The concrete strength slightly improved after exposure under 500 °C. These blends showed a high fire resistance, particularly at 500 °C. They were satisfactory for construction, which is prone to high temperature. The strength dropped under 750 °C compared with that under normal conditions. Strength increased by 9.35% compared with P0 at 15% BS replacement proportion. Similar to group S, the strength began to deteriorate over 15% BS ratio.
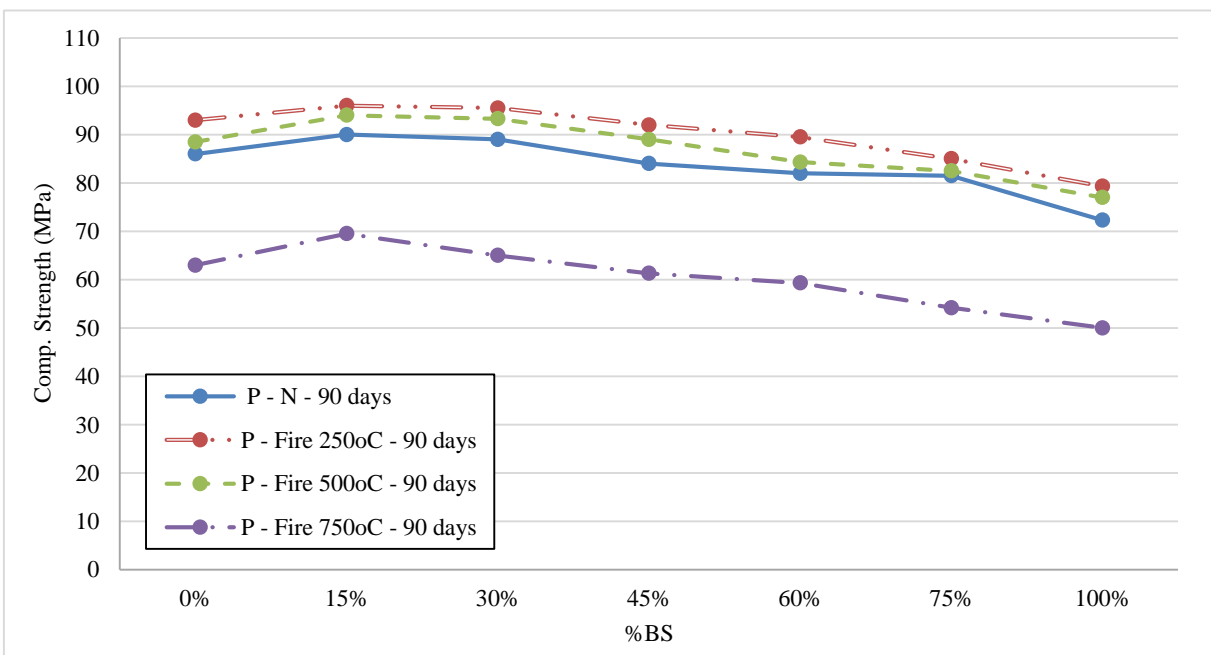

Figure 15. Group S Comparison Results at 90 Days under Various Fire Condition

Generally, BS clearly influences fire strength resistance. The BS mixtures accomplished a higher strength than control, particularly at a small BS proportion in the range from 15 to 45%. Then, the strength started to break down with increasing BS. Utilizing BS in a range of 15 to 45% with 15% SF is recommended to optimize BS utilization. The findings can be summarized as follows:

- All results achieved high strength which is acceptable for construction, especially for fire resistance purposes.

- Using a high BS percentage with SF, especially more than 45%, is not recommended.

This study results showed that concrete fireproofing properties is a complex phenomenon and relied on various factors such as aggregate type, binder component, w/b, exposure to temperature, fire duration, type of cooling, the presence of fiber, and the presence of moisture in the concrete. Numerous examinations revealed that reasonable aggregate sort did not play a substantial role in the improvement of HPC thermal properties only but their compressive strength too [26, 27]. Several examinations indicated that essential concrete deterioration is caused by thermal contrary qualities of the aggregates and the binder paste matrix. Changes in the volumetric dependability of cement paste compounds have likewise been exhibited to happen at high temperatures [14, 28]. The highest compressive strength under various exposure temperatures is caused by two principal reasons; compressive strength is related to the binder component and SCMs, especially FA, play a considerable role in improving the imperviousness of concrete to fire strength. Nevertheless, SF mixtures display decreased strength compared with FA mixtures, especially over 500 °C due to the increase of micro-cracks in concrete microstructure [28]. In addition, BS contains various minerals such as quartz, ilmenite, actinolite, and albite which play a substantial role at exposure under various temperatures, especially at 750 °C.

BS enhanced HPC ITZ between aggregate as shown in Figure 16. Figure 16 showed strong ITZ between aggregate and binder. No cracks observed between them at 500 °C. This finding is consistent with [29] which reported that the quartz aggregate is the most resistant to exposure to temperature. Another study reported that the granite and quartz aggregate show good behavior at a high fire temperature too [30]. However, ilmenite aggregate exhibits the highest fireproofing at a high temperature [31]. Thus, the mineral unity in BS overcomes the different thermal property problems between the aggregate and binder materials which cause deterioration at a high temperature.
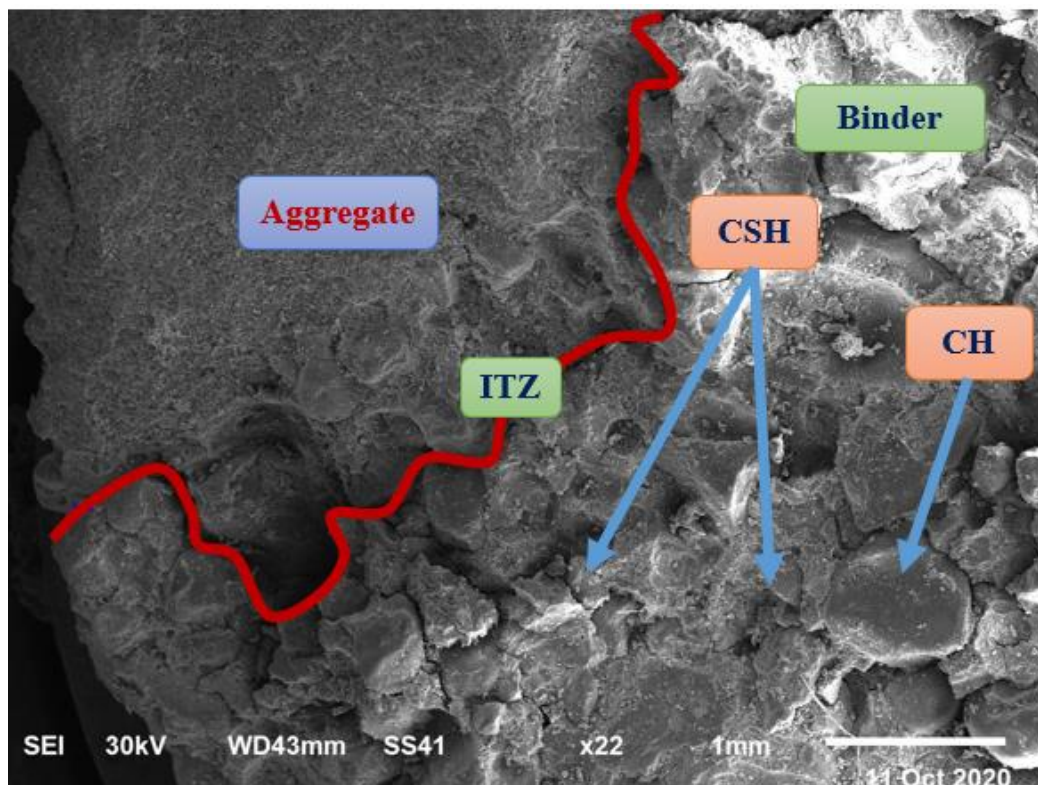

Figure 16. ITZ SEM for Z1 samples under 500 °C fire exposure

Figure 17 shows the effect of incorporation BS on HPC microstructure and SEM analysis for Z1 sample under normal (A), fire 250 °C (B) and 500 °C (C) at 90 days. The BS mineral unity plays a great role in enhancing the microstructure as shown in Figure 14 B and C. They showed the compacted microstructure at various temperatures. Nevertheless, Figure 17 A showed non-homogeneous microstructure with pores and microcracks. The mineral BS unity enhanced the HPC microstructure by formed denser CSH crystalline as shown in Figures 17 B and C.
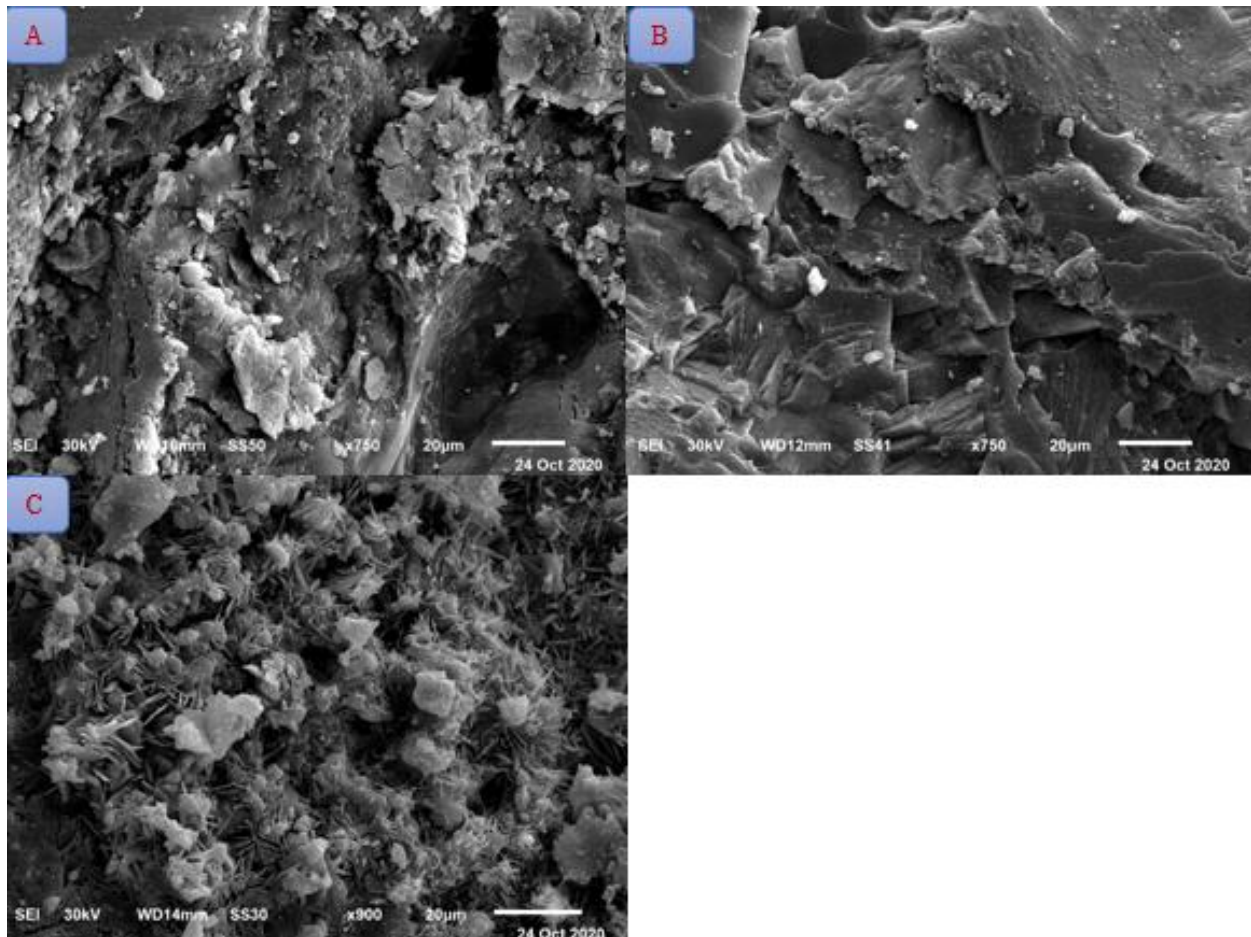
Figure 17. Z1 samples SEM under various exposure condition (A) under normal exposure condition, (B) under 250 °C fire exposure, and (C) under 500°C fire exposure

4. Conclusions

In this paper, a new material (BS) for enhancing fireproofing HPC properties at high fire exposure degrees especially at 750 °C was examined. The examination aimed at a better understanding of using BS for HPC fireproofing properties evolution in the situation of exposure to fire, when the temperature of the material surface may rise to 750 °C. Another key parameter was the comparison between reference HPC mixes with NS and HPC mixes with BS. It shows great fireproofing improvement. Besides, HPC microstructure becomes denser and compacted due to BS's unique mix of rare heavy metals and its fineness particle as shown in ZI SEM samples image with increasing fire degree exposure, however showing decreasing in strength at 750 °C compared to that under normal exposure conditions.

The mechanical properties exposed to different fire temperatures were examined. The specific findings were as follows:

- All mixture showed an improvement compared with control mixtures under various exposure test conditions.

- FA played an important role in enhancing the fireproofing properties of concrete better than SF.

- Utilizing BS with SCMs clearly enhanced the properties of concrete under a high exposure temperature, especially at 750 °C.

- BS ratio replacement ratio in the range of 15 to 60% as fine aggregate was preferred for fireproofing construction purpose such as in nuclear power plants.

- The drastic reduction in concrete fire resistance strength occurred before and after exposure at a high BS replacement ratio especially at 75 and 100%.

From the previous BS can be relied on in construction structures that exposed to high temperatures, such as the concrete of nuclear power plants (NPPs).

4.1. Future Work Recommendation

This study results show the ability to use BS as fine aggregate materials and its useful effect in enhancing HPC fireproofing properties. Thus, it is suitable for high fire concrete faced applications such as Nuclear Power Plants (NPPs). To achieve this, the previous study mixture needs to make an extensive study on the HPC which contain BS with SCMs durability properties, especially fire resistance at the temperature over 750 °C, sulfate attack resistance, chloride penetration resistance, permeability, and attenuation shielding. Besides, it is suggested to study the effect of using BS as fine aggregate with other SCMs such as slag cement.

5. Declarations

5.1. Data Availability Statement

The data presented in this study are available in article.

5.2. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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