THE PERFORMANCE OF SUPERABSORBENT POLYMER BEADS ON FIBER REINFORCED SELF-COMPACTING CONCRETE EXPOSED TO FIRE FLAME

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Abstract
Concrete structures, particularly self-compacting concrete (SCC), are highly vulnerable to elevated temperatures, which can lead to strength degradation, cracking, and explosive spalling. Improving the fire resistance and residual performance of SCC remains a significant challenge in construction engineering. Therefore, this study aims to investigate the effectiveness of Superabsorbent Polymer (SAP) beads in enhancing the performance of basalt fiber-reinforced SCC under fire exposure. An experimental program was conducted using four SCC mixtures with a constant basalt fiber content and varying SAP dosages of 0%, 3%, 4%, and 5% by weight of cementitious materials. The fresh properties were evaluated using slump flow, T500, V-funnel, and L-box tests, while mechanical properties were assessed through compressive, tensile, and flexural strength tests. Specimens were then exposed to elevated temperatures of 300°C, 500°C, and 700°C to evaluate residual performance. The results showed that SAP incorporation improved workability but reduced early-age strength due to increased porosity. However, at later ages, internal curing enhanced hydration and strength development. After fire exposure, SAP-modified mixes exhibited significantly improved residual strength compared to the control mix, with the 5% SAP mixture showing the best performance due to reduced vapor pressure and minimized spalling. In conclusion, the combined use of SAP beads and basalt fibers effectively enhances the fire resistance and long-term performance of SCC, making it suitable for high-temperature applications.

Keywords: Self-compacting concrete; Superabsorbent polymer; Basalt fibers; Fire resistance; Residual strength; Internal curing

1.0 INTRODUCTION

The rapid development in construction engineering has led to the emergence of advanced concrete technologies designed to meet increasing performance and durability demands. Among these, Self-Compacting Concrete (SCC) has gained widespread attention due to its ability to flow under its own weight, fill congested reinforcement zones, and achieve full compaction without vibration. This property improves construction efficiency and ensures uniform quality. However, despite its advantages, SCC is highly sensitive to elevated temperatures, which can significantly reduce its mechanical performance and structural stability under fire conditions.

To overcome these limitations, fiber reinforcement has been widely introduced into SCC mixtures. Basalt fibers, in particular, have attracted considerable interest due to their high tensile strength, durability, and resistance to thermal degradation. Recent studies have shown that basalt fiber reinforcement enhances crack resistance, tensile strength, and post-cracking behavior, while also improving residual mechanical performance after exposure to high temperatures (Li et al., 2024; Hu et al., 2024). In addition, basalt fibers contribute to improved toughness and durability, making them suitable for applications where thermal resistance is required.

Alongside fiber reinforcement, internal curing has emerged as an effective technique for improving concrete performance. Superabsorbent Polymer (SAP) beads are widely used in this context due to their ability to absorb large quantities of water and release it gradually over time. This mechanism promotes continued hydration, reduces autogenous shrinkage, and enhances the microstructure of cementitious materials. Recent research has highlighted that SAP-modified concrete exhibits improved durability, crack mitigation, and long-term performance due to its internal curing capability (Sokołowska, 2024; Kumar & Thakur, 2025). Furthermore, the voids created after water release can act as pressure-relief zones, which are particularly beneficial under high-temperature exposure.

The behavior of concrete under fire or elevated temperatures remains a critical concern in structural engineering. High temperatures lead to dehydration of cement paste, internal microcracking, and significant reductions in mechanical strength. In dense materials such as SCC, the buildup of internal vapor pressure can also result in explosive spalling. Recent studies indicate that incorporating fibers and internal curing agents can significantly enhance the fire resistance of concrete by reducing crack propagation and facilitating moisture migration (Palamarchuk et al., 2024; Vijaymurugan et al., 2024).

Although considerable research has been conducted on fiber-reinforced concrete and SAP-modified concrete independently, limited studies have addressed the combined effect of basalt fibers and Superabsorbent Polymer beads in Self-Compacting Concrete subjected to fire exposure. In particular, there is a need to better understand how SAP content influences the thermal and mechanical behavior of fiber-reinforced SCC under elevated temperatures.

Therefore, this study aims to investigate the performance of Superabsorbent Polymer (SAP) beads in basalt fiber-reinforced self-compacting concrete exposed to fire flame. The study focuses on evaluating fresh properties, mechanical strengths, and residual performance after exposure to high temperatures, with the goal of developing more durable and fire-resistant concrete materials.

2.0 MATERIAL CHARACTERIZATION

a. Cement

Ordinary Portland Cement (OPC) (CEM I 42.5 N) was used. The chemical and physical properties are shown below:

Table i: OPC Chemical Properties

Oxides	Content (%)	IQS, limits for CEM I-42.5 N
(CaO)	63.33	-
(SiO2)	22.14	-
(Al2O3)	5.31	-
(Fe2O3)	2.89	-
(MgO)	3.39	Max (5) %
(SO3)	2.13	[SO3 ≤ 2.8] If C3A > 3.5
(L.O.I)	1.88	Max 4 %
(I.R)	0.92	Max 1.5 %

Calculated from Bogue's equations

Compound	Value
(C_3S)	49.68
(C_2S)	25.86
(C_3A)	9.18
(C_4AF)	8.78

Table ii: OPC Physical Properties

Physical properties	Results	IQS, limits for CEM I-42.5 N
Surface area (Blain method)	354	≥ 280
Initial setting time (min)	155	≥ 45 min
Final setting time (h)	3:47	≤ 10 hrs
Compressive strength (2 days)	18.60	≥ 10 MPa
Compressive strength (28 days)	44.71	≥ 42.5 MPa
Autoclave expansion (%)	0.19	≤ 0.8

b. Fine Aggregate

Locally available natural sand was used as fine aggregate. The physical properties and sieve analysis are presented in Tables iii and iv.

Table iii. FA Physical Properties

Physical properties	Results	Limits
Specific gravity	2.59	-
Absorption ratio (%)	0.9	-
Sulphate content (%)	0.447	Max 0.5%
Dry rodded density (kg/m^3)	1632	-

Table iv. FA Sieve Analysis

Sieve opening (mm)	Passing (%)	Standard limits
9.50	100	100
4.75	94	90–100
2.36	83	75–100
1.18	74	55–90
0.60	42	35–59
0.30	11	8–30
0.15	3	0–10

c. Coarse Aggregate

Locally crushed coarse aggregate with a nominal size of 10 mm was used.

Table v. CA Physical Properties

Property	Results	Limits
Specific gravity	2.68	-
Absorption (%)	0.5	-
Sulphate content (%)	0.068	≤ 0.5
Dry rodded density (kg/m³)	1597	-

Table vi. CA Sieve Analysis

Sieve size (mm)	Passing (%)	Limits
12.5	100	100
9.5	98	85–100
4.75	18	0–25
2.36	3	0–5

d. Silica Fume

Silica fume was used as partial replacement of cement.

Table vii. SF hysical Characteristics

Property	Results	Limits
State	Amorphous	-
Color	Grey	-
Specific surface area (m²/g)	19	Min 15
Strength activity index	119	Min 105
Retained on 45 µm sieve (%)	8	Max 10

Table viii. SF Chemical Analysis

Oxide	Content (%)	Limits
SiO_2	92.14	Min 85%
Fe_2O_3	0.98	-
CaO	0.65	-
MgO	0.73	-
LOI	3.56	Max 6%

e. Limestone Powder

Limestone powder was used to improve workability and density.

Table ix. LM Chemical Composition

Oxide	Content (%)
SiO_2	0.21
Fe_2O_3	3.33
Al_2O_3	0.03
CaO	48.28
MgO	3.94
SO_3	0.07
LOI	43.12

f. Superplasticizer

A high-range water-reducing admixture was used.

Table x. Properties of Superplasticizer

Property	Description
Form	Viscous liquid
Color	Light yellow
Specific gravity	1.06 g/cm^3
Dosage	1–2.9 L/100 kg

g. Basalt Fibers

Basalt fibers were used with a length of 10 mm, diameter of 15 µm, and density of 2.6 g/cm^3. They possess high tensile strength and thermal resistance.

h. Superabsorbent Polymer (SAP) Beads

SAP beads are spherical polymers capable of absorbing large amounts of water and releasing it gradually, providing internal curing.

i. Water

Potable water conforming to standard requirements was used for mixing and curing of all specimens.

j. Mix Proportions

Four SCC mixes were prepared with constant material content and varying SAP percentages.

Table xi: Mix Proportions

Mix ID	Cement (kg/m³)	SF (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	SAP (%)
BF0.4	510	30.6	779	870.6	0
BF0.4+P3	510	30.6	779	870.6	3
BF0.4+P4	510	30.6	779	870.6	4
BF0.4+P5	510	30.6	779	870.6	5

k. Fresh Concrete Properties

Fresh properties were evaluated using slump flow, V-funnel, L-box, and segregation tests.

Table xii: Fresh Properties of SCC

Mix	Slump Flow (mm)	T500 (s)	V-Funnel (s)	L-Box
BF0.4	716	9	15	0.88
BF0.4+P3	750	8	12.6	0.91
BF0.4+P4	772	7.4	11.1	0.92
BF0.4+P5	787	6.9	9.8	0.94

l. Hardened Concrete Testing

Mechanical properties including compressive, tensile, and flexural strength were tested at different curing ages.

m. Burning Procedure

Specimens were exposed to temperatures of 300°C, 500°C, and 700°C for 1 hour. After heating, samples were cooled to room temperature before testing.

3.0 METHODOLOGY

a. Mix Design

Four self-compacting concrete (SCC) mixtures were prepared with constant proportions of cementitious materials, aggregates, and water content. Basalt fibers were added at a fixed dosage, while Superabsorbent Polymer (SAP) beads were incorporated at varying percentages (0%, 3%, 4%, and 5%) by weight of cementitious materials.

Table xiii: Mix Design Details

Mix ID	Cement (kg/m³)	SF (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	Water (kg/m³)	BF (%)	SAP (%)
BF0.4	510	30.6	779	870.6	156.6	0.4	0
BF0.4+P3	510	30.6	779	870.6	156.6	0.4	3
BF0.4+P4	510	30.6	779	870.6	156.6	0.4	4
BF0.4+P5	510	30.6	779	870.6	156.6	0.4	5

b. Specimen Preparation
All materials were mixed in a mechanical mixer. Dry components were first blended, followed by the addition of water and superplasticizer. SAP beads were pre-soaked for 24 hours before mixing. The fresh concrete was then cast into molds without vibration due to its self-compacting nature.

c. Curing Procedure
Specimens were demolded after 24 hours and cured in water for 28 days. Afterward, selected samples were subjected to air curing up to 56 days before testing.

d. Fresh Concrete Tests
Fresh properties were evaluated using slump flow, T500 time, V-funnel, and L-box tests to assess flowability, viscosity, and passing ability.

e. Hardened Concrete Tests
Mechanical properties were evaluated through compressive strength (cube specimens), splitting tensile strength (cylindrical specimens), and flexural strength (prismatic specimens) at different ages.

f. Fire Exposure Procedure
Specimens were exposed to elevated temperatures of 300°C, 500°C, and 700°C for a duration of 1 hour. After heating, samples were allowed to cool naturally before testing residual properties.

4.0 RESULT AND DISCUSSION

a. Fresh Properties of SCC
The fresh properties of the SCC mixes were evaluated using slump flow, T500, V-funnel, and L-box tests. The results are summarized in Table xiii:

Table xiii: Fresh Properties of Scc

Mix	Slump Flow (mm)	T500 (s)	V-funnel (s)	L-box	SI (%)
BF0.4	716	9	15	0.88	11.76
BF0.4+P3	750	8	12.6	0.91	13.15
BF0.4+P4	772	7.4	11.1	0.92	14.42
BF0.4+P5	787	6.9	9.8	0.94	15.51

The results indicate that the incorporation of SAP improved the flowability of SCC. This is attributed to the spherical shape of SAP particles, which reduces internal friction between aggregates and fibers. The slump flow increased progressively with SAP content, while T500 and V-funnel times decreased, indicating improved viscosity and flow characteristics. However, a slight increase in segregation index was observed with higher SAP content due to increased free water release.

b. Mechanical Properties

i) Compressive Strength

Table xiv: Compressive Strength before Fire (MPa)

Mix	28 days	56 days
BF0.4	62.92	68.84
BF0.4+P3	57.05	65.91
BF0.4+P4	49.15	60.11
BF0.4+P5	44.85	57.02

The compressive strength decreased with increasing SAP content at 28 days, with a reduction of approximately 28% observed at 5% SAP. This reduction is attributed to the formation of voids after water release from SAP particles, leading to lower density. However, at 56 days, the strength improved due to internal curing, which enhanced hydration and densified the matrix.

Table xv: Residual Compressive Strength (%)

Mix	300°C	500°C	700°C
BF0.4	79.68	54.71	32.91
BF0.4+P3	84.7	59.71	36.95
BF0.4+P4	88.93	63.88	41.89
BF0.4+P5	93.53	67.81	46.84

After exposure to elevated temperatures, all mixes experienced strength reduction. However, mixes with SAP showed improved residual strength, with the 5% SAP mix achieving the highest values. This is due to reduced internal vapor pressure and improved moisture migration, minimizing spalling.

ii) Splitting Tensile Strength
The tensile strength showed a decreasing trend with increasing SAP at early ages, followed by improvement at later ages due to internal curing. After fire exposure, SAP mixes retained higher tensile strength compared to the reference mix.

iii) Flexural Strength
Flexural strength decreased initially with SAP addition but improved at later ages. After fire exposure, higher SAP content resulted in better residual flexural strength due to reduced cracking.

4) Thermal Conductivity
The thermal conductivity increased with SAP content due to the formation of hydration products surrounding SAP particles.

5.0 Conclusion

This study investigated the performance of Superabsorbent Polymer (SAP) beads in basalt fiber-reinforced self-compacting concrete exposed to elevated temperatures. The results showed that the incorporation of SAP significantly influenced both fresh and hardened properties of SCC. The workability of concrete improved with increasing SAP content, as indicated by higher slump flow and reduced viscosity parameters, due to the lubricating effect of SAP particles. However, the compressive strength decreased at early ages with higher SAP content, mainly due to the formation of internal voids after water release.

At later ages, the internal curing effect of SAP enhanced hydration, leading to improved strength development. Under fire exposure, all mixes experienced strength degradation; nevertheless, SAP-modified mixes demonstrated superior residual performance compared to the control mix. The highest residual strength was observed at 5% SAP content, attributed to reduced internal vapor pressure and minimized spalling. Additionally, basalt fibers contributed to improved crack resistance and structural integrity at elevated temperatures.

The combined use of SAP beads and basalt fibers proved effective in enhancing the fire resistance and long-term performance of self-compacting concrete, making it a promising approach for durable and high-performance construction applications.

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