

Effect of fire-protective coatings on residual properties of self-compacting concrete

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Article Info	Abstract
Article History: Received 26 Jun 2026 Accepted 15 Sep 2026 Keywords: Fire protective coating; Gypsum plaster; Intumescent coating; Residual mechanical properties; Self-compacting concrete; SiO₂ aerogel plaster	Self-compacting concrete (SCC) generally experiences considerable deterioration in its mechanical properties during fire exposure because of its dense microstructure and low permeability. This study investigates the influence of different fire-protective coatings on SCC reinforced with 1% glass fiber and evaluates their ability to preserve its residual mechanical properties after fire exposure. Four fire-protective coatings were evaluated: SiO₂ aerogel plaster, gypsum plaster, Paris plaster, and intumescent paint. The furnace temperature followed the initial portion of the ASTM E119 standard fire curve until the target temperature of 600 °C was reached. Coated and uncoated SCC specimens were exposed to fire in a steel furnace for 60, 90, and 120 min. Following fire exposure, the specimens were gradually air-cooled. Residual mechanical performance was assessed through compressive, splitting tensile, and flexural strength tests. The uncoated specimens exhibited severe fire-induced strength degradation, which increased with exposure duration. After 120 min, the SiO₂ aerogel coating demonstrated high efficiency, with retention of 87.78%, 76.32%, and 81.75% of the compressive, flexural, and splitting tensile strength, respectively. The gypsum and Paris plaster coatings resulted in moderate protection, whereas the intumescent paint showed limited performance. The findings indicate that fire-protective coatings remarkably enhance the residual mechanical performance of glass-fiber-reinforced SCC at a high temperature and after prolonged fire exposure.

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1. Introduction

In concrete technology, self-compacting concrete (SCC) is known as one of the most important innovations in the construction field due to its high flowability, which enables it to flow through congested reinforcement under its own weight and fill the formwork without mechanical vibration, segregation, or bleeding [1–3]. These properties make SCC suitable for heavily reinforced structural elements and complex concrete applications. Its use can also reduce construction time, labor requirements, and noise associated with vibration while providing uniform compaction. Consequently, SCC has been adopted in modern concrete construction where placement quality, efficiency, and structural integrity are important [4–7]. Despite these practical advantages, SCC can be vulnerable to fire because of its dense microstructure and relatively low permeability [8–10]. When SCC is subjected to fire, free water evaporates and the products of cement hydration begin to decompose, resulting in increased pressure within the pores [11,12]. At the same time, internal stresses and microcracks are generated by the different thermal reactions of the cement paste and aggregates. These changes cause surface cracking, strength loss, mass loss and, in some cases, spalling. As fire exposure continues, the cracks gradually spread, the bond between the cement paste and aggregates weakens, and the mechanical properties of SCC deteriorate, resulting in a considerable loss of compressive, splitting tensile, and flexural strengths [13,14].

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Fire-protective coatings play a crucial role in limiting the deterioration of SCC during fire exposure. They are considered an effective passive fire-protection approach because they reduce heat transfer, slow temperature rise within the concrete and limit structural deterioration. In addition, these coatings preserve the residual compressive, flexural, and splitting tensile strengths of SCC after fire exposure [15–17]. However, their protection efficiency depends upon certain factors, including coating material, coating thickness, and duration of fire exposure. Therefore, it is important to choose a suitable coating to improve the residual mechanical properties of SCC exposed to high temperatures.

Several experimental studies have investigated the application of fire-protective coatings on different types of concrete. Various coating materials and thicknesses have been investigated under different heating regimes and exposure durations. Overall, their research findings showed that protective coatings can restrict heat transfer and reduce the degradation of the residual mechanical properties after fire exposure compared to uncoated specimens. Table 1 summarizes the recent studies on fire-protective coatings applied to concrete, with the main findings of each study.

Previous studies have investigated either fire-protected SCC with internal modification or modified SCC mixtures without external protective coatings. However, the combined use of internal modification and external fire-protective coatings has received limited experimental attention. Therefore, this study offers a new integrated approach by incorporating glass fibers into SCC and evaluating four fire-protective coatings under the same fire-exposure and testing conditions. This consistent experimental framework allows a direct and reliable assessment of the fire-protective coatings based on their ability to preserve the residual compressive, flexural, and splitting tensile strengths of SCC. The findings also provide valuable evidence regarding the performance of these coatings in protecting SCC reinforced with fiber during prolonged fire exposure.

Table 1. Summary of recent studies on fire-protective coatings applied to concrete

Study	Concrete type	Protective coating	Durations (min)	Thickness (mm)	Key findings
[18]	Self-compacting geopolymer concrete	Ceramic-wool and alumina-bauxite plasters	Standard fire curve for 30, 60, 90, 120, and 180 min (ISO 834)	10, 20	After 120 min, the ceramic wool-coated specimens retained 52.50–69.88% of their original strength, compared with 47.15–56.82% for the alumina bauxite-coated specimens.
[16]	RC	Perlite and vermiculite plasters	Standard fire curve for 60, 90, 120, and 180 min (ISO 834)	20	After 120 min, expanded perlite plaster provided the best performance, retaining 65% to 79% of the original strength respectively, compared with 60% to 76% for vermiculite plaster.
[19]	OPC concrete	Alkali-activated slag with phosphogypsum	EN 1364-1 fire curve for 180 min	10	The coating containing 3% phosphogypsum retained 84% of the original compressive strength, compared with only 57% for uncoated concrete.
[15]	SCC	SiO ₂ aerogel-cement paste	HC fire curve for 150 min	40	Retained approximately most of the original compressive strength after 150 min of HC fire exposure.

Abbreviations: SCC: Self-Compacting Concrete; RC: Reinforced Concrete; OPC: Ordinary Portland Cement; NC: Normal Concrete; HC: Hydrocarbon; ISO: International Organization for Standardization; EN: European Standard; SiO₂: Silicon Dioxide; min: minutes.

2. Materials and Testing Program

2.1 Material of SCC mix

In this experimental program, 14 materials were used to produce SCC and different fire protective coatings.

2.1.1 Cement

Ordinary Portland Cement (OPC) classified as (CEM I-42.5 R) used in this research satisfies the physical and chemical requirements listed in [20]. The characteristics of cement are shown in Tables 2 and 3.

Table 2. Physical properties of OPC [20]

Property	Test Results	Limit of [20]
Specific surface area, Blaine Method (m ² /kg)	305	> 280
Initial setting time (min)	85	≥ 45
Final setting time (h)	4.67	≤ 10
Compressive Strength (MPa) - 2 days	23.2	≥ 20
Compressive Strength (MPa) - 28 days	45.7	≥ 42.5

Table 3. Chemical composition and main component of OPC [20,21]

Chemical Composition (%)	Test Results	Limit of [20]
Lime (CaO)	61.47	---
Silica (SiO ₂)	21.28	---
Alumina (Al ₂ O ₃)	4.03	---
Iron Oxide (Fe ₂ O ₃)	3.56	---
Magnesia (MgO)	2.10	Max 5.0 %
Sulfate (SO ₃)	1.82	≤ 2.8 If C ₃ A > 3.5
Insoluble residue (I.R)	1.20	Max 1.5 %
Loss on ignition (L.O.I)	0.70	Max 4.0 %
Main Compounds of OPC using Bogue's equations [21]		
Tricalcium silicate (C ₃ S)	51.13	---
Dicalcium silicate (C ₂ S)	22.44	---
Tricalcium aluminate (C ₃ A)	4.66	---
Tetra calcium aluminate ferrite (C ₄ AF)	10.83	----

2.1.2 Fine Aggregates

Natural sand was utilized as fine aggregate to produce SCC mix. The sand gradation lies in zone (2). Table 4 displays the properties of sand, while the grading of sand is shown in Table 5. All sand specifications met the limits of [22].

Table 4. Physical and chemical properties of fine aggregate [22]

Property	Test Results	Limit of [22]
SO ₃ (%)	0.36	Max 0.5
Fine particles passing from sieve 75 µm, (%)	3.5	Max 5
Clay lumps (%)	0.72	Max 1
Bulk density (Kg/m ³)	1633	---
Specific gravity	2.62	---

2.1.3 Coarse Aggregates

Crushed graded gravel with grading size of 5–14 mm was used to make SCC mix. The gravel complies with [22]. The physical properties are presented in Table 6 and sieve analysis is displayed in Table 7.

Table 5. Grading of fine aggregate [22]

Sieve size (mm)	Passing (%)	Limit of [22] Zone 2
10	100	100
4.75	95	90-100
2.36	76	75-100
1.18	65	55-90
0.60	54	35-59
0.30	27	8-30
0.15	7	0-10
Fineness Modulus	2.76	

Table 6. Physical and chemical properties of coarse aggregate [22]

Property	Test Results	Limit of [22]
SO ₃ (%)	0.086	Max 0.1
Fine particles passing from sieve 75 µm, (%)	1.05	Max 3
Clay lumps (%)	1.3	Max 2
Bulk density (Kg/m ³)	1595	---
Specific gravity	2.65	---

Table 7. Coarse aggregate grading [22]

Sieve size (mm)	Passing (%)	Limit of [22]
20	100	100
14	100	90-100
10	78.4	50-85
5	5.7	0-10

2.1.4 Limestone

Limestone powder (CaCO₃) was used as mineral filler in SCC mix. The chemical composition and physical properties are summarized in Table 8. All the limits complied with [23]

Table 8. Chemical composition and physical properties of limestone [23]

Property (%)	Content	Limits of [23]
CaO	97.95	----
Fe ₂ O ₃	0.140	----
SiO ₂	0.285	----
ZnO	0.016	----
MgO	0.643	----
SO ₃	0.840	----
Strength Activity Index at 28 days	87	≥ 75 %

2.1.5 Silica Fume

Silica fume is a dark gray powder used in this study. The physical properties and chemical composition are presented in Tables 9 and 10, respectively. All limits comply with [24].

Table 9. Physical properties of silica fume [24]

Property	Test results	Limit of [24]
Percentage Retained on 45µm (No.325) Sieve (%)	6	≤ 10
Strength Activities Index at 7 days (%)	116	≥ 105
Specific gravity	2.2	-----

Table 10. Chemical composition of silica fume [24]

Property (%)	Test Result (%)	Limits of [24]
Silicon Oxide (SiO ₂)	93	≥ 85%
Aluminum Oxide (Al ₂ O ₃)	0.32	-
Magnesium Oxide (MgO)	0.33	-
Iron Oxide (Fe ₂ O ₃)	1.20	-
Calcium Oxide (CaO)	2.60	-
Sulfur trioxide (SO ₃)	0.63	-
Sodium oxide (Na ₂ O)	0.10	-
Loss of Ignition (L.O.I)	1.6	≤ 6 %
Moisture Content	0.34	≤ 3.0 %

2.1.6 Mixing Water

Tap water conforming to [25] was used throughout all stages of the experimental work.

2.1.7 Superplasticizer

Hyperplast PC800, a polycarboxylate-based superplasticizer complying with [26], Type G, with a yellowish color, was used to improve the flowability of SCC without increasing the mixing-water content. It was added at a dosage of 2.9 L per 100 kg of cementitious materials and had a specific gravity of 1.07 ± 0.02 .

2.1.8 Glass Fiber

Chopped white E-glass fibers were incorporated into the SCC mix at 1% by volume to improve crack control during fire exposure. The properties of glass fiber are presented in Table 11.

Table 11. Properties of glass fiber

Property	Value / Range
Glass Type	E-glass
Chopped Length (mm)	12
Diameter (μm)	10
Modulus of Elasticity (GPa)	72
Density (kg/m ³)	2700

2.2. Materials Of the Fire Protective Coatings

2.2.1 Ordinary Gypsum

Gypsum is composed primarily of calcium sulfate hemihydrate (CaSO₄·1/2H₂O) produced by mixing hemihydrate and anhydrous gypsum rocks. The physical properties of gypsum are shown in Table 12. All results are within acceptable limits of [27].

Table 12. Physical properties of Gypsum [27]

Property	Test results	Limit of [27]
Fineness (Retained on Sieve No. 16) (%)	3.4	≤ 8
Setting Time (min)	11	8-25
Compressive Strength at 7 days (Kg/cm ²)	40.8	≥ 30

2.2.2 Paris Plaster

Processed product derived from gypsum with high degree of purity; it is chemically identified as calcium sulfate hemihydrate. The physical properties of Paris plaster are listed in Table 13. All limits comply with [27].

2.2.3 SiO₂ Aerogel

Silicon dioxide aerogel has exceptionally low density, very high porosity more than 90% and a highly porous structure. It has a white color. Table 14 presents the properties of the SiO₂ Aerogel.

Table 13. Physical properties of Paris plaster [27]

Test Name	Test results	Limit of [27]
Fineness (Retained on Sieve No. 16) (%)	0	≤ 0
Setting Time (min)	18	8-25
Compressive Strength at 7 days (Kg/cm ²)	61.6	≥ 50

Table 14. Properties of SiO₂ Aerogel

Property	Sample Value
Specific surface area (m ² /g)	385
Thermal conductivity (W/m·K)	0.023
35 μ m sieve residue (mg/kg)	20
Density (Kg/m ³)	52
Silica content (%)	99.94
Carbon content (%)	0.04
Chloride content (%)	0.0039

2.2.4 Fly Ash

Fly ash is a pozzolanic industrial by-product. The particle sizes range from 0.5 to 100 μ m. The fly ash used is characterized as class F. The physical characteristics and the chemical composition of the fly ash are shown in Tables 15 and 16. The results confirm the requirements of [28].

Table 15. Physical characteristics of fly ash [28]

Test Name	Test results	Limit of [28]
Amount retained sieved on 45 μ m (No. 325) (%)	26.9	Max 34
Pozzolanic activity index at 7 days (%)	89	Min 75
Pozzolanic activity index at 28 days (%)	106.2	Min 75

Table 16. Chemical composition of fly ash [28]

Oxide	Contents (%)	Limits of [28]
Fe ₂ O ₃	5.35	All combined not less than 70%
Al ₂ O ₃	17.59	
SiO ₂	65.63	
SO ₃	0.21	Max 5%
MgO	0.84	-----
CaO	0.98	Max 18%
L.O.I	2.76	Max 6%

2.2.5 Foam Agent

A water-soluble liquid foam agent was used to produce stable air bubbles in the cementitious mortar. It was diluted with water at a ratio of 1:30, producing foam with a density of 90 kg/m³. The properties of the foam agent are presented in Table 17.

Table 17. Properties of foam agent

Property	Value / Description
Application	Additive for lightweight concrete, light plaster
Physical State	Liquid
Color	Dark brown
Density of the liquid	1050 kg/m ³
pH	6 – 7
Solubility	Soluble in water

2.2.6 Intumescent Paint

It is a one component water-based white intumescent paint. The product adheres without primer on clean surfaces. Its properties are presented in Table 18.

Table 18. Properties of intumescent paint

Property	Specification
Density (25°C, Kg/m ³)	1050
pH (25°C)	7.0 – 9.0
Viscosity (25°C, mPa·s)	10,000 – 12,000
Solids Content (% by Weight)	64 ± 2
Solids Content (% by Volume)	55 ± 2

2.3 Mix Proportion, Casting and Curing

2.3.1 Mix Proportion, Casting and Curing of SCC

The reference SCC mix proportions were prepared according to [29] and are presented in Table 19. (Fig. 1) illustrates the materials used in the production of SCC. The mixing procedure was conducted according to [1] using a concrete mixer. Cement, silica fume, and limestone powder were mixed under dry conditions for 1 min; then, sand and gravel were added and mixed for 1 min each. After that, one-third of the water was added and mixed for 3 min. The superplasticizer was dissolved in the remaining water, slowly added to the mixer, and mixed for a further 2 min. Finally, 1% of glass fibers by volume were slowly sprinkled into the mixer to avoid agglomeration and mixed for 3 min. The mixture was left for 2 min before casting. After completing the SCC mixing process, the fresh mix was cast into cube, cylinder, and prism molds. Before casting, all molds were thoroughly cleaned and lightly coated with oil to facilitate demolding. All specimens were left under laboratory conditions at 23 ± 2 °C and $50 \pm 5\%$ relative humidity for 24 h, after which they were demolded and placed in water-curing tanks for 28 days. They were then removed from the tanks and stored under the same laboratory conditions for another 28 days to allow air drying before the fire test [30]. The mixing, casting, and curing processes of the SCC specimens are shown in (Fig. 2).

Table 19. Mix proportion of reference SCC mix per 1 m³ (kg/m³)

Cement	Sand	Gravel	Silica fume	Limestone	SP	Water	Glass fiber	w/p*
510	779	870.6	30.6	60	18.81	156.6	27	0.29

*Powder: cement and silica fume.

2.3.2 Mix Proportion, Casting and Curing of Fire Protective Coatings

Four fire-protective coatings were investigated: SiO₂ aerogel plaster, gypsum plaster, Paris plaster, and intumescent paint. The mixed proportions and application of fire protective coatings details are summarized in Table 20. Before coating, all SCC specimens' surfaces were roughened manually using abrasive paper to improve the adhesion between the SCC and the protective layer and cleaned. Gypsum and Paris plaster were prepared by gradually adding the powder to water and mixing until homogeneous pastes were obtained; the compressive strengths of gypsum and Paris plaster at 7 days were 40.79 and 61.6 kg/cm², respectively. For the SiO₂ aerogel plaster, cement, silica fume, and fly ash were dry-mixed, followed by water containing the superplasticizer, SiO₂ aerogel, and finally the preformed foam using low-speed mixing. To evaluate its properties, the fresh mortar was cast into 50 × 50 × 50 mm cubes, and the compressive strength was measured according to [31]. The SiO₂ aerogel plaster had a fresh density of 700 kg/m³ and a compressive strength of 10.5 MPa. As for intumescent paint, it was applied directly on all the faces of the SCC specimens using a roller (as recommended by manufacturers) in multiple layers to achieve the required thickness. All faces of the cubes, cylinders, and prisms were encapsulated with gypsum plaster, Paris plaster, and SiO₂ aerogel plaster using specially fabricated molds; the details of these molds are presented in (Fig. 3). These molds were used to provide a uniform plaster thickness of 20 mm for all the faces of the specimens. After applying the coatings, the specimens were air-cured under laboratory conditions at 23 ± 2 °C and $50 \pm 5\%$ relative humidity for seven days before the fire exposure test. (Fig. 4) displays the procedure for fire protective coatings application.



Fig. 1. Materials of SCC production

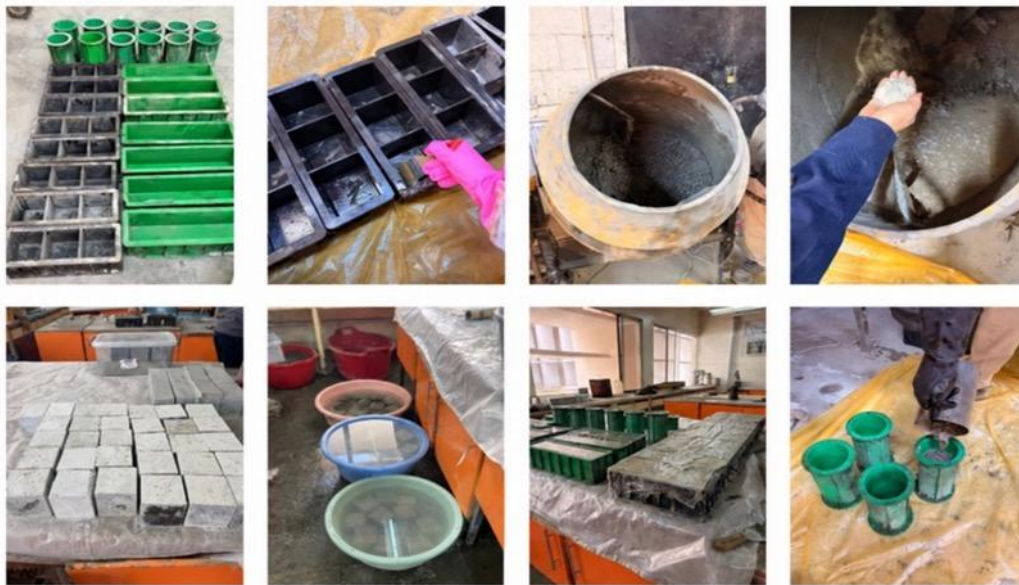


Fig. 2. Preparation procedure of SCC mix

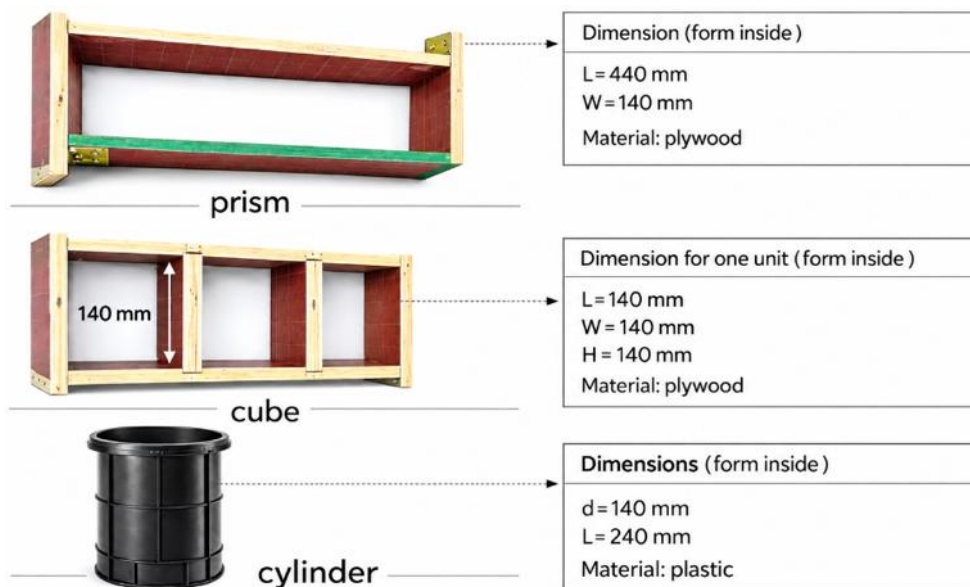


Fig. 3. Details of fabricated molds for the fire protective coatings

Table 20. Details of fire protective coatings mixes

Fire protective coatings	Mix proportions	Exposure durations	Thickness	Temperature	Remarks
Gypsum plaster	Water: Gypsum 1:3 by weight	(60, 90, 120) min	20 mm	600 °C	Applied on cube, cylinder and prism specimens
Paris plaster	Water: Paris plaster 1:2 by weight	(60, 90, 120) min	20 mm	600 °C	Applied on cube, cylinder and prism specimens
Intumescent paint	Applied directly using a roller	(60, 90, 120) min	5 mm	600 °C	Applied on cube, cylinder and prism specimens
SiO ₂ aerogel plaster (Kg/m ³)	Cement = 324	(60, 90, 120) min	20 mm	600 °C	Applied on cube, cylinder and prism specimens
	Water = 200				
	SiO ₂ Aerogel = 35				
	Silica Fume = 36				
	Fly Ash= 90				
	Foam Agent = 4.5				
	SP= 2.5				



Fig. 4. Procedure for applying all fire protective coatings



Fig. 5. Fresh properties tests of SCC (A) Slump flow test, (B) V-Funnel test, (C) L-Box test

2.4 Testing Program

2.4.1 Fresh Properties of SCC

Five experiments were conducted to investigate the fresh characteristics of SCC. Flowability was evaluated by the slump flow test, passage ability was examined by the L-box test, viscosity and

flowability were assessed by the T500 mm and V-funnel tests, and resistance to segregation was measured by the sieve segregation test. These tests were carried out in compliance with [29]. (Fig. 5) shows the fresh properties tests of SCC.

2.4.2 Hardened Properties of SCC

This section shows details of the hardened properties for the SCC conducted during the experimental work:

- Compressive strength test: This test was conducted on 100×100×100 mm cubes using a 3000 kN testing machine according to [32]. The specimens were centrally aligned and loaded at a rate of 0.6 ± 0.2 MPa/s until failure as shown in (Fig.6). Eq. (1) was utilized to measure the average strength of three specimens.

$$F_c' = \frac{P}{A} \quad (1)$$

Where: F_c' : Compressive strength in (MPa), P: Maximum applied force in (N), A: Area exposed to force in (mm²).



Fig. 6. Compressive strength test set up

- Flexural strength test: According to [33], prism specimens of 100x100x400 mm, supported by a central point force as demonstrated in (Fig 7). The specimens were centrally aligned and loaded continuously at a rate of 0.04–0.06 MPa/s until failure. Eq. (2) was used to get the mean flexural strength of three specimens.

$$R = \frac{3PL}{2bd^2} \quad (2)$$

Where: R: Flexural strength in (MPa), P: Maximum applied force in (N), L: Span length in (mm), b: Specimen width in (mm), d: Specimen depth in (mm).



Fig. 7. Flexural strength test set up

- Splitting tensile strength test: Cylinder specimens were used of 100 mm in diameter and 200 mm in height using a 3000 kN testing machine according to [34]. The specimens were aligned using wooden strips and loaded at 1.2 MPa/min until failure, as seen in (Fig. 8). Eq. (3) is used to calculate the average splitting strength for three specimens.

$$T = \frac{2P}{\pi ld} \quad (3)$$

Where: T: Splitting tensile strength in (MPa), P: Maximum applied force in (N), d: Cylinder diameter in (mm), l: Cylinder length in (mm)



Fig. 8. Splitting tensile strength test set up

2.4.3 Fire Test Procedure

After 28 days of water curing, all specimens were removed from the water tank and air-cured for an additional 28 days. This process reduces internal moisture and minimizes vapor pressure that builds up during the fire test, as reported by [30]. The fire test was conducted in a steel furnace with dimensions of 3500 × 2000 × 900 mm.

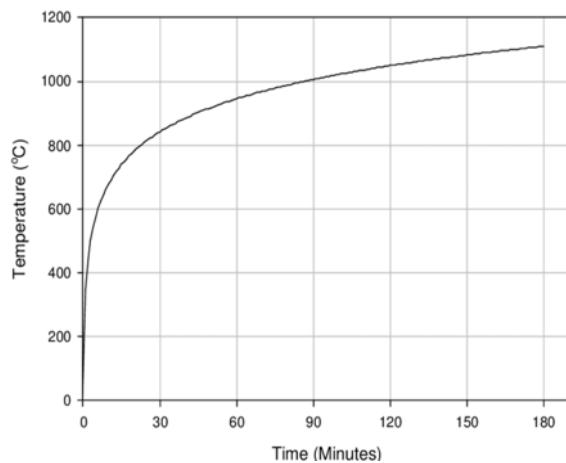


Fig. 9. Standard fire curve [35]

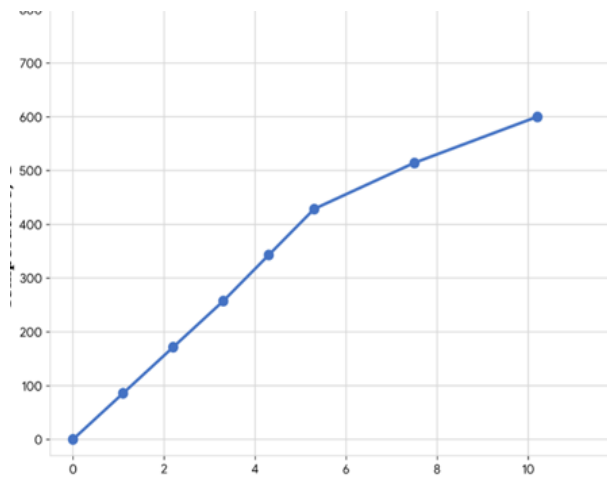


Fig. 10. Temperature-time fire curve used in this study

Both uncoated and coated specimens were exposed to 600 °C using a regime adapted from the initial rising portion of the standard fire curve specified in [35] and presented in (Fig. 9), the temperature-time fire curve used in this study is shown in (Fig. 10). Specimens were first placed inside the furnace, which was then ignited to reach the specified temperature. The furnace reached the target temperature of 600 °C within approximately 10 min, the specimens were maintained for durations of 60, 90, and 120 min. The furnace temperature was monitored using a DT-612 digital thermometer connected to a UNI-T UT-T05 contact probe with a measurement range of 50 to 900 °C, a probe length of 156 mm, and a wire length of 1000 mm. Measurements were taken at different locations around the furnace to monitor the temperature distribution and maintain the target

temperature of 600 °C. After each exposure period, the specimens were taken out of the furnace and allowed to cool gradually to laboratory temperature for 24 h. The coatings were carefully removed manually. Then, the specimens were tested to determine their residual compressive, flexural, and splitting tensile strengths. The fire exposure procedure is presented in (Fig. 11).



Fig. 11. (A) Placing of specimens in the furnace, (B) Steel furnace, (C) Digital thermometer

2.4.4 Residual Strength

The residual strength after fire exposure was calculated relative to the corresponding reference strength before fire exposure. In this study, the reference strength was measured at 56 days for all exposure durations. The residual strength was calculated using Eq. (4).

$$\text{Residual strength (\%)} = \frac{\text{Strength after fire exposure (MPa)}}{\text{Strength at 56 days (MPa)}} * 100 \quad (4)$$

3. Results and Discussion

This section assesses the fresh properties and the residual mechanical properties of self-compacting concrete after fire exposure. The specimens include Uncoated SCC specimens (PC0) as reference value; SiO₂ aerogel plaster-coated specimens (PC1); gypsum plaster-coated specimens (PC2); Paris Plaster-coated specimens (PC3); and intumescent paint-coated specimens (PC4). Five groups of specimens were prepared and tested after fire exposure test.

The residual mechanical properties were compared with reference values at 56 days: a compressive strength of 63 MPa, a flexural strength of 9.5 MPa and a splitting tensile strength of 6.3 MPa.

3.1 Fresh Properties

The fresh properties test results of glass reinforced self-compacting concrete are presented in Table 21. These results corresponded to the SF2, VS2, VF2, PA1 and SR1 classes, respectively, confirming that the mixture satisfied the requirements for filling ability, passing ability, and segregation resistance of EFNARC 2005 [29].

Table 21. Fresh properties test results of SCC reference mix

Mix	Slump Flow (mm)	T ₅₀₀ (sec)	V-funnel (sec)	L-box	SR %
SCC reference mix	690	4.1	12.8	0.84	15.7
Limits of [29]	SF1 550-650	VS1 ≤ 2	VF1 ≤ 8	> 0.80	SR1 ≤ 20
	SF2 660-750	VS2 > 2	VF2 9 to 25	with 2	SR2 ≤ 15
	SF3 760-850			bars	

3.2 Residual Compressive Strength

Compressive strength is one of the main characteristics used to evaluate the mechanical properties of SCC [36]. The reference compressive strength measured at 56 days before fire test was 63 MPa.

This value was used as reference strength for calculating the residual compressive strength of all specimens after fire exposure. The compressive strength results and the corresponding residual compressive strengths after fire exposure are presented in Table 22 And Table 23, respectively. The results showed reduction in compressive strength for all tested specimens as the exposure duration increased.

The uncoated specimen PC0 showed severe deterioration, with compressive strength decreasing from 45.00 MPa after 60 min to 32.10 MPa after 90 min and 22.90 MPa after 120 min of fire exposure. These values correspond to residual compressive strengths of 71.43%, 50.95%, and 36.35%, respectively. The strength loss was 12.90 MPa between 60 and 90 min and a further 9.20 MPa between 90 and 120 min, indicating that deterioration continued with increased fire exposure durations. This trend is consistent with previous studies [8,37], which associated the loss of compressive strength in unprotected SCC with dehydration of the cementitious matrix, development of internal cracking and thermally induced incompatibility between the paste and aggregate, causing high reduction in residual strengths after long fire exposure, this highlights the vulnerability of SCC when directly exposed to high temperatures without protection.

The SiO₂ aerogel plaster coated specimens PC1 maintained high residual compressive strength. Its compressive strength decreased gradually from 62.10 MPa after 60 min to 58.50 MPa after 90 min and 55.30 MPa after 120 min, retained residual strengths of 98.57%, 92.86%, and 87.78%, respectively. The strength losses were 3.60 MPa between 60 and 90 min and 3.20 MPa between 90 and 120 min. Only a small reduction was recorded between each exposure duration and shows that the protective effect of aerogel plaster remained relatively stable as the exposure continue. Compared with PC0 at the same exposure duration, PC1 showed 38.00%, 82.24%, and 141.48% higher compressive strength. This increasing difference indicates that this coating provided effective protection for SCC specimens during all exposure durations. This behavior is consistent with previous research [38], which linked the thermal performance of aerogel containing cementitious materials to the low density and highly porous structure of SiO₂ aerogel. The air-filled pores of the coating may have slowed heat transfer through the coating and reduced the rate of strength deterioration in the underlying SCC.

Gypsum plaster coated specimens PC2 and Paris plaster coated specimens PC3 demonstrated moderate protection. Their residual strengths were 87.30% and 84.13% after 60 min, 80.95% and 75.71% after 90 min and 73.81% and 66.67% at 120 min, respectively. PC2 retained more strength than PC3, the compressive strength of PC2 was higher by 3.77% at 60 min, 6.92% at 90 min, and 10.71% at 120 min. Compared with PC0, the compressive strength of PC2 was 22.22%, 58.88%, and 103.06% higher, while that of PC3 was 17.78%, 48.60%, and 83.41% higher at the corresponding exposure durations. These results show that both coatings reduced the strength reduction of SCC. Previous studies [39,40] related the protection of these coatings to the endothermic dehydration of hydrated calcium sulfate, during which chemically bound water is released and absorbed heat. This slows heat transfer through the coating and limits strength deterioration in underlying SCC specimens. During this process, calcium sulfate dihydrate gradually transforms into hemihydrate and then into anhydrous calcium sulfate. The release of water vapor also leaves a porous layer which offers additional thermal insulation. However, extended exposure duration causes degradation within the coating and gradually reduces its protective efficiency. The different protective performances of PC2 and PC3 are attributed mainly to differences in their physical properties and coating mixture proportions.

The intumescent paint coated specimens PC4 retained 76.19%, 58.73% and 48.81% of its reference compressive strength after 60, 90, and 120 min, respectively. Their measured compressive strengths decreased from 48.00 MPa after 60 min to 37.00 MPa after 90 min and 30.75 MPa after 120 min. The compressive strength decreased by 22.92% between 60 and 90 min and by a further 16.89% between 90 and 120 min. The high reduction during the first interval demonstrates that the coating began to lose part of initial protective effect. However, compared with PC0, the compressive strength of PC4 was 6.67%, 15.26%, and 34.28% higher after 60, 90, and 120 min, respectively at the same exposure durations. According to [41] intumescent coatings give initial thermal protection by forming an insulating char layer that slows the heat transfer. This coating

helps preserve the compressive strength during the early stages of fire exposure. However, its protective effectiveness gradually decreases during prolonged fire exposure. Although PC4 was only 5mm in thickness but it is still considered to preserve strength and maintained a higher residual strength than the uncoated specimens PC0. (Fig. 12) illustrate the compressive strength results at different fire exposure durations and (Fig. 13) presents the corresponding residual compressive strength. The failure patterns of the SCC specimens are shown in (Fig. 14).

Table 22. Compressive strength results after fire test (MPa)

Specimen type / Durations	60 min	90 min	120 min
PC0	45.00	32.10	22.90
PC1	62.10	58.50	55.30
PC2	55.00	51.00	46.50
PC3	53.00	47.70	42.00
PC4	48.00	37.00	30.75

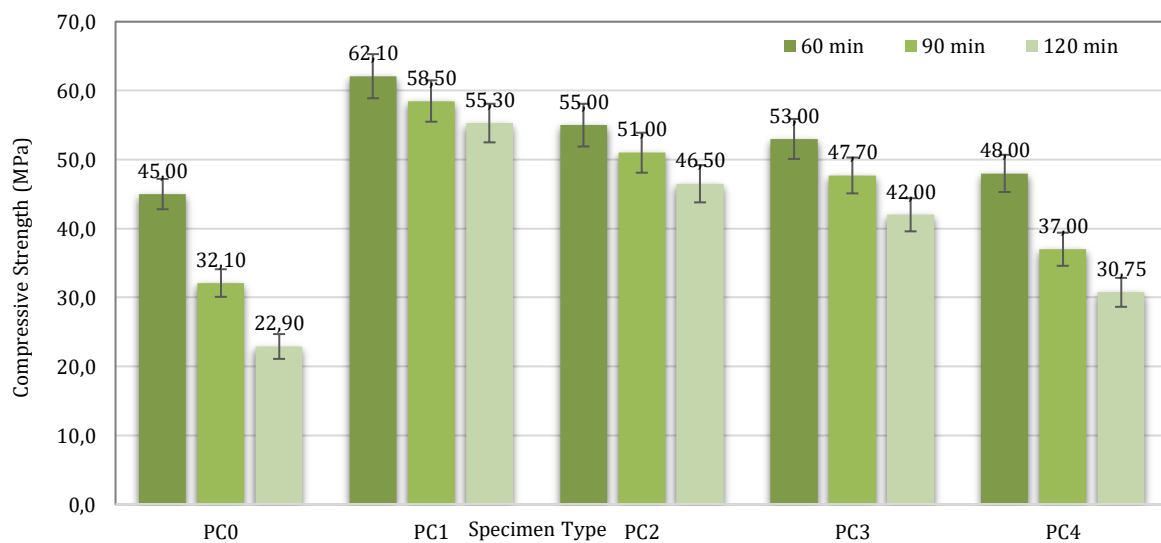


Fig. 12. Compressive strength test results after fire test (MPa)

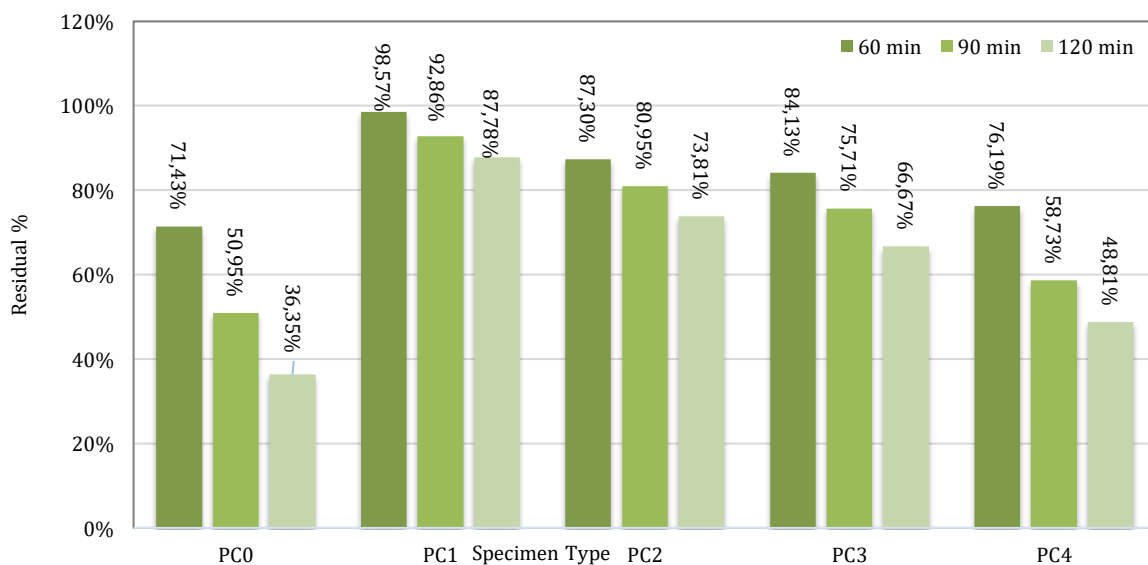


Fig. 13. Residual of compressive strength (%)

Table 23. Residual compressive strength (%)

Specimen type / Durations	60 min	90 min	120 min
PC0	71.43%	50.95%	36.35%
PC1	98.57%	92.86%	87.78%
PC2	87.30%	80.95%	73.81%
PC3	84.13%	75.71%	66.67%
PC4	76.19%	58.73%	48.81%



Fig. 14. Cubes pattern of failure after fire test

3.3 Residual Flexural Strength

The reference flexural strength at 56 days before fire exposure test was 9.5 MPa. This value was used to calculate the residual strength of all specimens after fire exposure. Table 24 presents the flexural strength results after fire exposure, while the corresponding residual flexural strengths are shown in Table 25. A clear reduction in flexural strength was observed as fire exposure increased with the most severe deterioration occurring after exposure to 600 °C for 120 min.

The uncoated specimens PC0 showed high degradation, as their flexural strength decreased from 6 MPa at 60 min, to 4.04 MPa at 90 min, and 3.01 MPa at 120 min, corresponding to residual strengths of 63.16%, 42.53%, and 31.68%, respectively. The flexural strength dropped by 32.67% between 60 and 90 min and by 25.50% between 90 and 120 min, indicating that specimens were highly affected by prolonged fire exposure, which is consistent with findings of [42] who attributed this deterioration to the decomposition of cement matrix, increased microcracking and the development of internal thermal stresses, that severely weaken the SCC matrix during long exposure to fire.

The SiO₂ aerogel coated specimens PC1 maintained flexural strength of 8.20, 7.60, and 7.25 MPa, corresponding to residual strengths of 86.32%, 80.00%, and 76.32% after 60, 90, and 120 min, respectively. The strength decreased by only 7.32% between 60 and 90 min and by 4.61% between 90 and 120 min, indicating a relatively slow loss of strength during prolonged fire exposure. Compared with PC0 at the same exposure durations, PC1 recorded higher flexural strengths by 2.20, 3.56, and 4.24 MPa after 60, 90, and 120 min, respectively. This outperformed behavior can be attributed to the porous structure of SiO₂ aerogel, which delays heat transfer to the underlying SCC specimens that limit the deterioration responsible for the loss of flexural strength [15].

The gypsum plaster coated specimens PC2 and Paris plaster coated specimens PC3 showed moderate performance with flexural strength of 7.00, 6.00, and 5.27 MPa and 6.60, 5.80, and 4.95 MPa after 60, 90, and 120 min, respectively. The corresponding residual strengths were 73.68%, 63.16%, and 55.47% for PC2 and 69.47%, 61.05%, and 52.11% for PC3. For PC2, the strength decreased by 14.29% between 60 and 90 min and by 12.17% between 90 and 120 min. For PC3, the corresponding reductions were 12.12% and 14.66%. Compared with PC0 at the same exposure durations, PC2 recorded higher flexural strengths by 1.00, 1.96, and 2.26 MPa, while PC3 recorded higher values by 0.60, 1.76, and 1.94 MPa, respectively. The fire protection of these coatings is mainly because of endothermic dehydration, where chemically bound water absorbs

heat during evaporation. This causes a delay in heat transfer to the SCC specimens underneath the coating layers. This process provides effective insulation during early fire exposure. However, this mechanism becomes weaker with long fire exposure due to the available bound water is gradually consumed, reducing the heat absorbing capacity of the coating, this aligns with the findings of [43].

The intumescent paint coated specimens PC4 provided limited improvement, maintaining a strength of 6.30 MPa, 5.12 MPa and 3.99 MPa and residual flexural strength of 66.32%, 53.89% and 42.00% at 60, 90 and 120 min, respectively. The flexural strength decreased by 18.73% between 60 and 90 min and by a further 22.07% between 90 and 120 min, indicating a faster loss of strength during the second interval. Compared with PC0, PC4 improved its flexural strength by 5.00%, 26.73%, and 32.56%, respectively after 60, 90, and 120 min. The coating exhibits decreased efficiency with extended fire exposure due to the gradual degradation of protective char layer which reduces the ability of fire protection. As the insulation capacity of char layer decreased, heat penetration and formation of microcracks increased causing failure in the residual flexural strength during prolonged fire exposure, similar observation was reported by [44]. (Fig.15) and (Fig.16) show flexural strength and residual flexural strength results after fire exposure. (Fig. 17) presents the failure patterns of tested prism specimens.

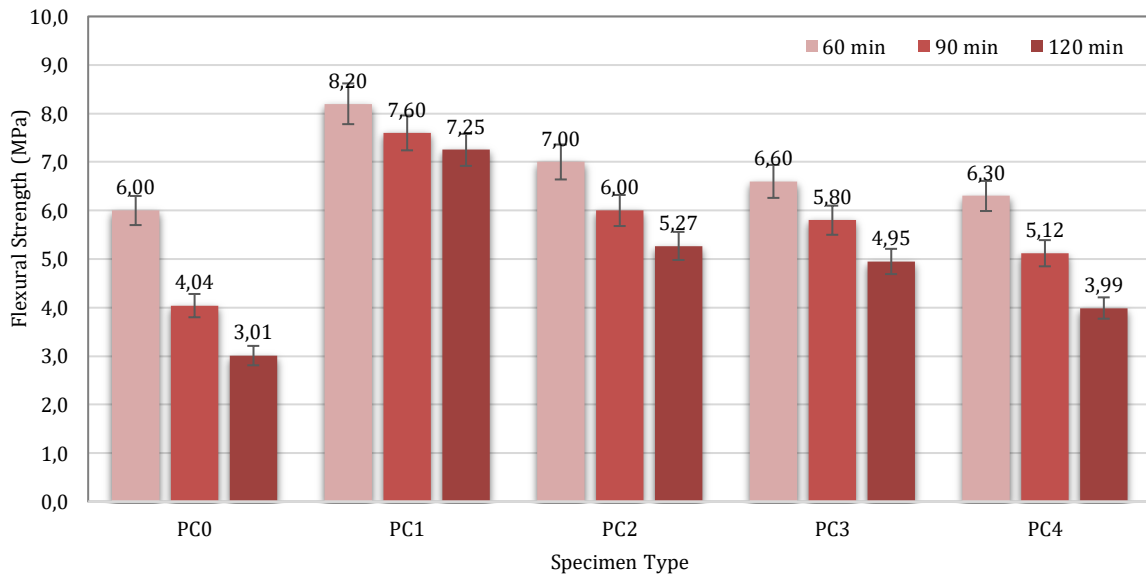


Fig. 15. Flexural strength results after fire test (MPa)

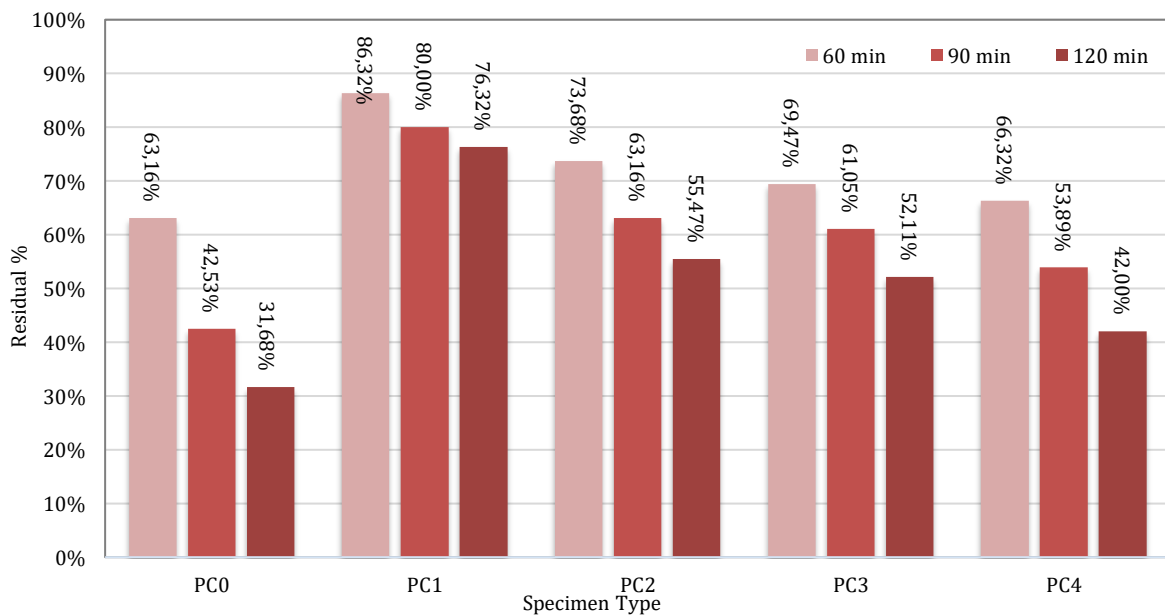


Fig. 16. Residual of flexural strength (%)

Table 24. Flexural strength results after fire test (MPa)

Specimen type / Durations	60 min	90 min	120 min
PC0	6.00	4.04	3.01
PC1	8.20	7.60	7.25
PC2	7.00	6.00	5.27
PC3	6.60	5.80	4.95
PC4	6.30	5.12	3.99

Table 25. Residual flexural strength (%)

Specimen type / Durations	60 min	90 min	120 min
PC0	63.16%	42.53%	31.68%
PC1	86.32%	80.00%	76.32%
PC2	73.68%	63.16%	55.47%
PC3	69.47%	61.05%	52.11%
PC4	66.32%	53.89%	42.00%



Fig. 17. Prisms pattern of failure after fire test

3.4 Residual Splitting Tensile Strength

The reference splitting tensile strength at 56 days was 6.3 MPa before fire exposure. This value was used to calculate the residual splitting tensile strength of all specimens after different fire exposure durations. Table 26 and Table 27 present the measured splitting tensile strength and the corresponding residual splitting strength, respectively. Splitting tensile strength decreased for all specimens as the exposure durations increased to 120 min. This reduction highlights the sensitivity of splitting tensile strength to fire induced damage.

The splitting tensile strength of the uncoated specimens PC0 decreased extremely from 4.40 MPa after 60 min, 2.95 MPa after 90 min and 2.20 MPa after 120 min of fire exposure, retaining residual strength of 69.84%, 46.83%, and 34.92% of reference strength, respectively. The largest decrease occurred between 60 and 90 min, when the strength dropped by 1.45 MPa, compared with 0.75 MPa during the following 30 min because these specimens had no protective layers, heat transferred directly to the SCC. The continued fire exposure may have increased cracking within cement paste and around aggregates, resulting in considerable loss of tensile strength. Similar mechanism has been reported in previous studies [45,46].

The SiO₂ aerogel coated specimens PC1 maintained splitting tensile strength of 5.80, 5.50, and 5.15 MPa after 60, 90, and 120 min, corresponding to residual strengths of 92.06%, 87.30% and 81.75%, respectively. Its strength decreased by only 5.17% between 60 and 90 min and by 6.36% between 90 and 120 min, resulting in an overall reduction of 11.21% from 60 to 120 min. In comparison, PC0 showed a great reduction of 32.95% and 25.42% during the same exposure intervals. This behavior showed that PC1 provided more protection and slowed the loss of splitting tensile strength during prolonged fire exposure. This superior performance may be attributed to the highly porous structure and low thermal conductivity of SiO₂ aerogel reported in previous studies [38]. These properties limit thermal damage of SCC specimens, reducing crack development and

deterioration of cement matrix. Consequently, the reduced damage enables the coated specimens to keep much higher residual strength than uncoated specimens under prolonged fire exposure.

The gypsum plaster coated specimens PC2 and Paris plaster coated specimens PC3 provided moderate performance. PC2 maintained splitting tensile strengths of 5.00, 4.60, and 3.70 MPa after 60, 90, and 120 min, corresponding to residual strengths of 79.37%, 73.02%, and 58.73%, respectively. Its strength decreased by 8.00% from 60 to 90 min and by 19.57% from 90 to 120 min. The greater reduction in the last 30 min suggests that the protective effectiveness of PC2 decreased with the prolonged fire exposure. The reduction of PC2 from 60 to 120 min was 26.00% which was lower than the reduction of PC0. While PC3 maintained splitting tensile strengths of 4.76, 3.99, and 3.40 MPa, representing residual strengths of 75.56%, 63.33%, and 53.97%, respectively. Unlike PC2, PC3 experienced higher decrease between 60 and 90 min, with a strength loss of 16.18%. Between 90 and 120 min a smaller decrease by 14.79% was recorded. The overall reduction of 28.57% from 60 to 120 min was also lower than that of PC0. Both PC2 and PC3 showed higher splitting tensile strengths than the uncoated specimens at all exposure times. According to [47] gypsum- based coatings reduced heat penetration through endothermic dehydration, when chemically bound water absorbed a considerable amount of heat which delayed heat transfer to the SCC specimens. However, prolonged exposure causes deterioration and cracks in the coatings, gradually reducing their protective ability.

The intumescent paint coated specimens PC4 maintained splitting tensile strengths of 4.67, 3.50, and 3.00 MPa, retaining 74.13%, 55.56% and 47.62% at 60, 90 and 120 min, respectively. The strength decreased by 1.17 MPa between 60 and 90 min, followed by a smaller reduction of 0.50 MPa between 90 and 120 min. The reduction from 60 to 120 min was 35.76%. Moreover, PC4 retained higher splitting tensile strength than PC0 at all exposure durations, indicating better protection of splitting tensile strength than uncoated specimens due to the formation of an insulating char layer, which acts as a thermal, similar observation was noted by [48]. However, the gradual degradation of the char layer during prolonged exposure reduced its protective effectiveness.

This trend is in line with the findings for flexural and compressive strength, where coated specimens outperformed uncoated specimens in terms of residual performance, confirming that the application of protective coatings effectively enhances the residual mechanical performance of SCC reinforced with glass fiber after prolonged fire exposure. (Fig.18) and (Fig.19) present the splitting tensile strength results and residual splitting tensile strength, respectively. As for (Fig. 20) it presents the pattern of failure for tested cylinder specimens.

Table 26. Splitting tensile strength results after fire test (MPa)

Specimen type / Durations	60 min	90 min	120 min
PC0	4.40	2.95	2.20
PC1	5.80	5.50	5.15
PC2	5.00	4.60	3.70
PC3	4.76	3.99	3.40
PC4	4.67	3.50	3.00

Table 27. Residual splitting tensile strength (%)

Specimen type / Durations	60 min	90 min	120 min
PC0	69.84%	46.83%	34.92%
PC1	92.06%	87.30%	81.75%
PC2	79.37%	73.02%	58.73%
PC3	75.56%	63.33%	53.97%
PC4	74.13%	55.56%	47.62%

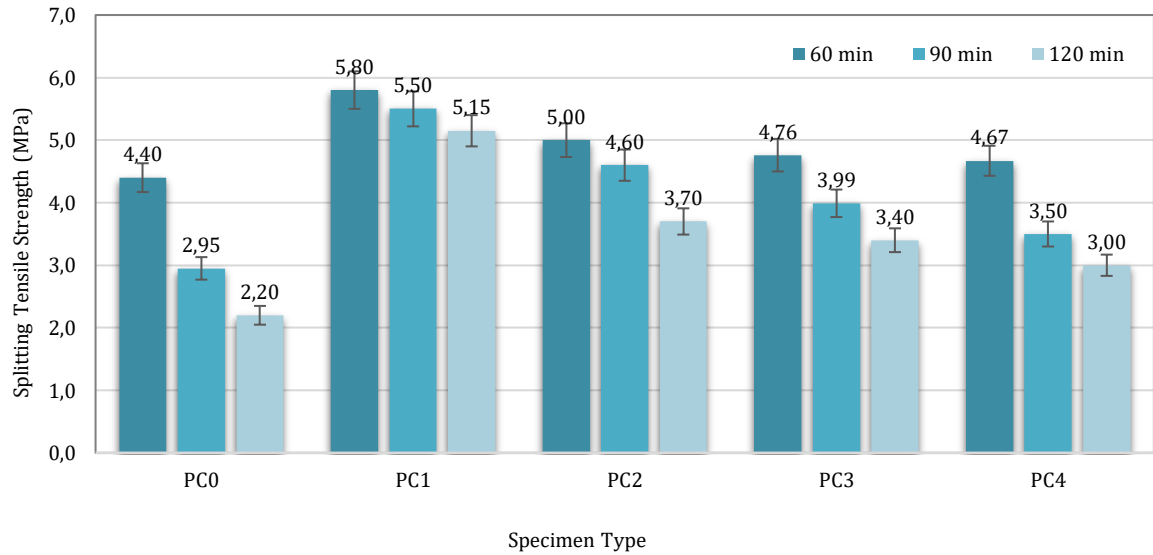


Fig. 18. Splitting tensile strength results after fire test (MPa)

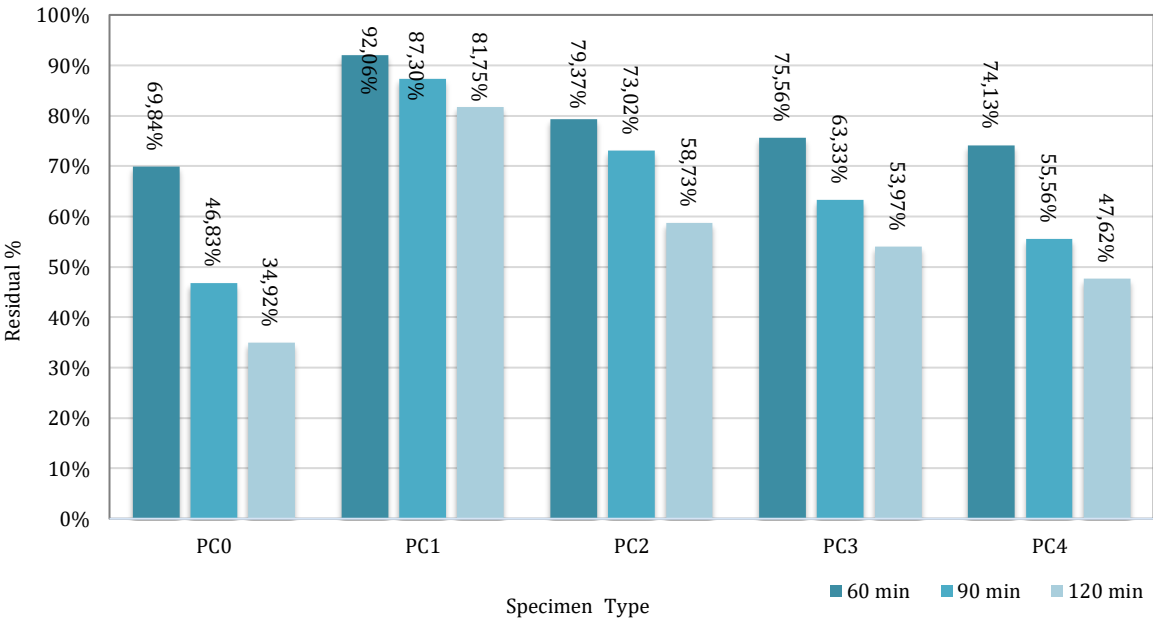


Fig. 19. Residual splitting tensile strength (%)



Fig. 20. Cylinders pattern of failure after fire exposure

3.5 Statistical Analysis of Replicate Test Results

A total of 162 specimens were tested for compressive, flexural and splitting tensile strength, consisting of 135 fire-exposed specimens for five groups and three exposure durations and 27 unexposed reference specimens tested at 7, 28 and 56 days. Each condition was tested on three independent specimens. The statistical assessment shown in Table 28 summarizes the adopted three-replicate dataset for compressive, flexural, and splitting tensile strength after 60, 90, and 120 min of fire exposure. The coefficient of variation (CV) was used as the main normalized measure of dispersion, while standard deviation (SD) represents the absolute scatter of the replicate readings using error bars.

- Each reported strength value is the mean of three replicate readings in the adopted dataset.
- CV was calculated as $SD/Mean \times 100$, allowing direct comparison of variability among properties with different strength levels.
- The ranges below represent the minimum and maximum values among specimens PC0–PC4 at each exposure duration.

Table 28. Coefficient of variation (CV) ranges of the replicate strength results

Property	CV (%) 60 min	CV (%) 90 min	CV (%) 120 min	Brief assessment
Compressive strength	4.89–5.64	5.13–6.49	5.06–7.86	Low-to-moderate dispersion. Variability rises slightly at 120 min, where the maximum CV reaches 7.86%, but the replicate results remain relatively consistent.
Flexural strength	4.92–5.15	4.74–5.94	4.55–6.64	Narrow CV range, particularly at 60 min. The wider range at 90–120 min indicates a modest increase in scatter, consistent with the sensitivity of flexural response to cracking.
Splitting tensile strength	5.14–5.46	5.09–6.10	4.85–6.82	CV values remain clustered around about 5–6%. The slightly wider range at 120 min suggests somewhat greater variability after prolonged thermal exposure.

3.6 Visual Inspections

Table 29. presents the surface condition of the uncoated and coated specimens before exposure to fire, after 60, 90 and 120 min of fire exposure and after the removal of the protective coatings. The images show the gradual change in the coatings with increasing exposure including cracking, discoloration and localized damage. After the coatings were removed, no visible cracks or surface spalling were observed on the underlying SCC samples, indicating that most of the visible damage was limited to the coating layers. The severe appearance of the intumescent coating was mainly caused by the expansion and deterioration of its char layer and did not reflect the same level of visible damage to the underlying SCC. Direct visual comparison was made using uncoated reference specimens as well.

4. Conclusions

Based on the experimental investigation conducted in this study, the effect of different fire protective coatings on the residual mechanical properties of self-compacting concrete (SCC) reinforced with 1% glass fiber by volume were evaluated under controlled conditions. All specimens were exposed to 600 °C for short, medium and long-term exposure durations, represented by 60, 90, and 120 min, respectively. The plaster coatings were applied at a thickness of 20mm while the intumescent coating was 5 mm thick.

Table 29. Visual appearance of uncoated and coated specimens before and after fire test at 600 °C for a duration of 60, 90 and 120 min

Specimen type	Before fire exposure	60 min	90 min	120 min	After removing the protective coatings
PC0 Reference mix					No fire protective coating was used
PC1					
PC2					
PC3					
PC4					

The residual compressive, flexural and splitting tensile strengths were assessed to determine the effectiveness of each coating layer and a visual inspection was performed to evaluate the extent of surface damage, including cracking and coating deterioration. Based on the results obtained, the following conclusions can be drawn:

- The uncoated specimens PC0 experienced a continuous reduction in mechanical strength as the exposure duration increased. After 120 min, PC0 retained only 36.35%, 31.68%, and 34.92% of its reference compressive, flexural, and splitting tensile strengths, respectively.

These results demonstrate the considerable deterioration of the uncoated SCC specimens during prolonged fire exposure at 600 °C, highlighting the necessity of using effective fire-protection measures for this type of concrete

- All coated specimens maintained higher residual compressive, flexural, and splitting tensile strengths than PC0 at the same exposure conditions. This confirms that the application of fire-protective coatings effectively improves the residual mechanical performance of SCC compared to uncoated specimens under the conditions investigated in this study.
- The SiO₂ aerogel plaster coated specimens PC1 achieved high residual strengths. After 120 min, PC1 retained 87.78%, 76.32%, and 81.75% of its reference compressive, flexural, and splitting tensile strengths, respectively. It also showed relatively small strength reduction as the exposure duration increased, indicating that its protective performance remained stable during prolonged fire exposure.
- The gypsum plaster coated specimens PC2 and Paris plaster coated specimens PC3 showed moderate fire protection. PC2 retained 73.81%, 55.47%, and 58.73% of its compressive, flexural, and splitting tensile strengths, respectively. The corresponding values for PC3 were 66.67%, 52.11%, and 53.97%, respectively. PC2 consistently maintained higher residual strength than PC3 under prolonged fire exposure.
- Intumescent paint coated specimens PC4 provided limited protection at the early stages of fire exposure. However, its performance becomes comparatively lower on long-term exposure. After 120 min, it retained 48.81%, 42.00%, and 47.62% of its reference compressive, flexural, and splitting tensile strengths, respectively.
- The SiO₂ aerogel plaster exhibited the best strength retention under the tested conditions but practical application of it requires consideration of material preparation, mixing and application procedures to obtain uniform coating properties.
- Overall, the experimental results indicate that selecting fire-protective coatings can improve post-fire residual mechanical performance of SCC and reduce fire-induced damage to the underlying substrate.

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