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ORIGINAL RESEARCH ARTICLE

EFFECTS OF HIGH TEMPERATURE ON HIGH-PERFORMANCE CONCRETE PRODUCED FROM CEMENT PARTIALLY REPLACED WITH SUGARCANE BAGASSE ASH

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ABSTRACT

Conventional concrete deteriorates under fire, leading to strength loss, durability and reduction in performance of concretes. High-Performance Concrete (HPC) concrete mix designs are limited and constrained by the type of aggregates and Cementous materials used. There is a need to explore mix-design that can incorporate Sugar Cane Bagasse Ash (SCBA) and local aggregates as viable alternative for HPC with fire resistance properties. This study investigated the effect of elevated temperatures on the performance of High-Performance Concrete (HPC) with cement partially replaced with Sugar Cane Bagasse Ash (SCBA). HPC mixes for grades 50, 60, and 65 N/mm² were prepared with varying replacement levels of cement with SCBA up to 20%. The mix ratios used included grade 65 N/mm², 1:0.34:0.19:0.68 and 0.21% water by weight basis. A total of 162 concrete samples were cast and subsequently cured for 28 days, then exposed to fire in brick incinerator for 100 to 220 minutes. Weight loss, residual compressive strength, physical changes, and calcination time were evaluated. Results showed that fire exposure caused irreversible damage with losses increasing at higher concrete grades and SCBA levels. At 1000°C, concrete samples with 20% SCBA disintegrated into powder at slight touch. The maximum strength loss (81.46%) occurred for Grade 65 HPC with 20% SCBA. Control samples (0% SCBA) performed best with lowest strength losses. The study concluded that while SCBA was viable under ambient conditions, it did not enhance fire resistance. However, the predictive model could serve as a starting guide in the design of fire-prone concrete applications. The findings highlighted a significant limitation of SCBA in HPC intended for fire-prone applications.

1.0 Introduction

Concrete remains the dominant construction material worldwide due to its versatility and availability. However, conventional concrete is prone to deterioration over time due to chemical and physical processes, leading to strength and durability challenges (Onundi *et al.*, 2018, Xiao *et al.*, 2022). This has led to the development of advanced concretes like High-Performance Concrete (HPC), which offers more superior strength (typically > 50 N/mm²) and durability (Higaze *et al.*, 2020, Wei *et al.*, 2024).

The production of Portland Limestone Cement (OPC) is expensive and has a significant environmental impact, contributing approximately 9% of global CO_2 emissions (Nik *et al.*, 2017). Consequently, there is growing interest in using Supplementary Cementitious Materials (SCMs) like agricultural wastes as partial cement replacements. Sugarcane Bagasse Ash (SCBA), a by-product of the sugar industry, is rich in silica (SiO_2) and is a promising pozzolanic material (Rukzon & Chinda-prasirt, 2012, Ahmed *et al.*, 2023). Recent studies have confirmed that SCBA can enhance the mechanical and durability properties of concrete under ambient conditions by refining pore structure and consuming calcium hydroxide (Adesanya & Ohenoja 2022, Yin *et al.*, 2023).

While many studies focused on the mechanical properties of SCBA-based concrete under ambient conditions, its behavior under high temperature conditions is critical for durability and safety. However, reports dedicated to investigating this objective have not provided adequate results for better understanding so far. Elevated temperatures cause physical and chemical changes in concrete, including water evaporation, decomposition of hydration products (like C-S-H gel and Ca $(OH)_2$), and aggregate expansion, leading to cracking, spalling, and strength loss (Makinta *et al.,* 2021, Memon *et al.,* 2019). Emerging research indicated that agricultural ashes, due to their porous nature and unburnt carbon content, may accelerate strength degradation at high temperatures (Roy & Kumar 2024). For instance, Khankhaje *et al.,* (2025) found that rice husk ash concrete lost 70% of its strength at 800°C, while Thomas and Gupta (2022) reported that SCBA-based mortars exhibited severe spalling above 600°C due to increased internal vapor pressure. However, systematic data on HPC with varying SCBA percentages under controlled fire exposure up to 1000°C remained scarce (Mahdi *et al.,* 2024).

This study aimed to fill this research gap by systematically investigating the effect of elevated temperatures (up to 1000°C) on the performance of HPC made with SCBA, using local aggregates (Bama gravel and crushed stones). The findings will provide crucial insights for the safe application of sustainable SCBA-based HPC in fire-risk environments such as large-scale building fires and Tunnel fires involving tankers.

2. Materials and Method

2.1 Materials and Their Properties

2.1.1 Cement

Portland limestone Cement (PLC, Dangote Brand) Grade 42.5 N/mm² was used as the primary binder.

2.1.2 Sugarcane bagasse ash (SCBA)

SCBA was obtained by open burning sugarcane bagasse in an opened drum, perforated to provide for air supply, in line with that of Kanokkanjana and Garivait (2012) and Nugraha *et al.*, (2023). The open burning process, consistent with Kanokkanjana and Garivait (2012), typically achieved temperatures between 400–700°C, which was sufficient for organic matter combustion but below the threshold (>800–900°C) required for transformation of amorphous silica into inert crystalline forms. Its chemical composition, determined by X-ray fluorescence (XRF), is presented in Table 1. The sum of SiO_2, Al_2O_3, and Fe_2O_3 was 80.45%, exceeding the 70% minimum requirement of ASTM C618 (2008) for Class F pozzolan (ASTM C618-08a. 2008). Specific gravity of the SCBA was 1.93.

2.1.3 Aggregates

Fine aggregate (river sand), local coarse aggregate (Bama gravel), and crushed stones (19 mm and 38 mm) were used. All aggregates met the requirements of BS 812-110 (1990) standards for properties such as specific gravity, crushing value, impact value, and water absorption (Table 2).

2.1.4 Chemical admixture

Conplast SP430, a sulphonated naphthalene polymer-based superplasticizer, was used at a dosage of 0.75 liters per 100 kg of cement as recommended by Wille *et al.*, (2011) to improve workability and reduce the water-cement ratio.

2.1.5 Water

Water used for mixing and curing was based on BS EN 1008 standard.

2.2 Mix Design and Specimen Preparation

Three target HPC grades of 50, 60, and 65 N/mm² were designed. For each grade, cement was replaced by weight with SCBA at levels of 0% (control), 5%, 10%, 15%, and 20% respectively. An additional control mix containing superplasticizer was also prepared. The mix proportions were expressed in ratios relative to cement. For Grade 50, the ratio of cement to river sand to Bama gravel to crushed stone was 1:0.44:0.24:0.87

with a water-to-cement ratio of 0.25. For Grade 60, the ratio was 1:0.38:0.21:0.77 with a water-to-cement ratio of 0.23, and for Grade 65, the ratio was 1:0.34:0.19:0.68 with a water-to-cement ratio of 0.21. Moreover, Plasticizer of 0.75l/100kg of cement weight was used. The mixed proportions are given in Table 1a and 1b. Concrete mix design was done using Microsoft Excel spreadsheet, an application based on BS 8500 Mix Design Method and Concrete Mixture Matrix Design Method, by Onundi, 2024. A total of 162 specimens were cast for compressive strength (150 x 150 x 150 mm). All specimens were water-cured for 28 days.

Table 1a: Mix Proportions for HPC Grades by weight (kg)

Target Grade	**Cement**	**River Sand**	**Bama Gravel**	**Crushed Stone**		**Water***
(N/mm²)				**(19mm)**	**(38mm)**	
50	26.60	11.63	6.28	4.10	23.25	6.39
60	28.73	11.05	6.00	3.90	22.10	6.53
65	30.89	5.70	3.70	3.70	21.20	6.39

*Water values include the water content of the superplasticizer. Plasticizer dosage: 0.75 L/100 kg cement (equivalent to ≈0.24–0.28 kg per batch).

Table 1b: Mix Proportions for HPC Grades by ratio

Target Grade	**Cement**	**River Sand**	**Bama Gravel**	**Crushed Stone**		**Water**
(N/mm²)				**(19mm)**	**(38mm)**	
50	1	0.44	0.24	0.15	0.87	0.25
60	1	0.38	0.21	0.13	0.77	0.23
65	1	0.34	0.19	0.12	0.68	0.21

2.3 Fire Exposure Test

After curing, the specimens were subjected to elevated temperatures using a brick incinerator equipped with a blower to simulate real fire conditions. The test was conducted in accordance with ASTM E119 (2022), test methods for fire. The experimental matrix involved three target temperatures: 600°C, 800°C, and 1000°C. The exposure durations were determined based on the thermal diffusivity of HPC ($\alpha \approx 0.7 \times 10^{-6}$ m^2/s) to ensure that the thermal front reached the core of the 150 mm cubes ($\mathrm{Fo} \geq 1$). This yielded approximate equilibrium times of 100, 130, and 220 minutes for 600°C, 800°C, and 1000°C, respectively. These durations also aligned with the time–temperature profiles specified in ASTM E119 for comparable fire severity levels. During and after exposure, four parameters were recorded. Weight loss was measured by weighing specimens before and after firing. Residual compressive strength was tested using a compression testing machine and expressed as a percentage of the original strength. Physical changes including crack width (measured with a crack microscope), color changes, and spalling were documented photographically and visually. Finally, calcination time, the time taken to reach each target temperature, was logged to model the temperature-time relationship. Figure 1 shows the schematic diagram of the experimental setup for the fire resistance test.

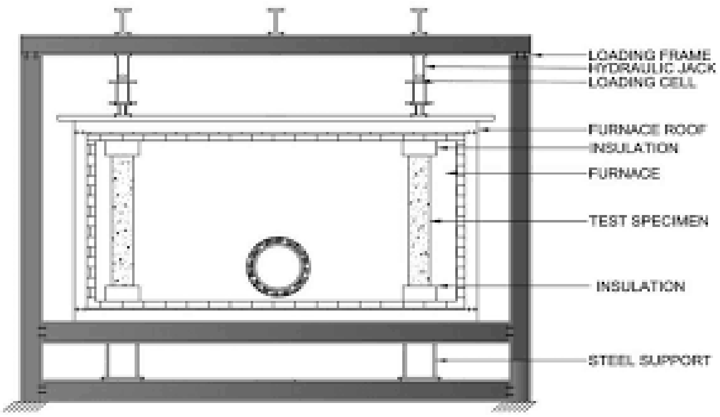


Figure 1: Schematic diagram of the experimental Setup for Fire Resistance Test

3. Results and Discussion

The result of the chemical analysis of sugarcane bagasse ash is presented in Table 2 which shows that BA has very high percentage of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3). According to this investigation the amount of silica contained in bagasse ash is 49.68%, aluminium oxide 17.34% and iron oxide 13.43% respectively with other trace elements. This meets the requirements for pozzolanic material as per ASTM- C618, (2008) which specifies that for a material to be considered a pozzolana of Class C (fly ash), the summation of the percentages by weight of silica, alumina and ferric contents must not be less than 70%. However, results obtained from this study gave 80.45% and therefore meets the minimum requirement for pozzolanic material. Moreover, the results for aggregates qualification tests were presented in Table 3. The results showed that all the materials were within the limit of the standards for concrete aggregates materials and were used as aggregates material for production of concrete grades.

Table 2: Chemical Composition of Sugarcane Bagasse Ash (SCBA)

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	LOI*
Percentage (%)	49.68	17.34	13.43	4.12	12.62

*Loss on Ignition

Table 3: Aggregates qualification test results

Test	**Result (Range)**	**Standard Limit**	**Standard code**
Aggregate Crushing Value (19mm & 38mm)	15.05 - 15.07%	≤ 25%	BS 812:110-90
Aggregate Impact Value (19mm & 38mm)	20.08 - 25.53%	≤ 25%	BS 812:110-90
Water Absorption (Bama Gravel)	3.35%	≤ 3.0%	ASTM C33-23
Water Absorption (River Sand)	4.18%	≤ 3.0%	BS 812:110-3

3.1 Physical Deterioration Observed After Fire Exposure

The visual inspection of concrete cubes after exposure to elevated temperatures revealed significant physical changes (Table 4). At 600°C, all the grades the cubes appeared largely intact but showed hairline micro-cracks approximately 0.04 mm wide, accompanied by a shift in surface color to a light greyish purple. This color change was characteristic of the dehydration of iron hydroxides or portlandite, Calcium-Hydrates (CH) in the aggregate (Plate 1a). Similar pattern of surface cracks was reported by Poon *et al.*, (2003) for temperature above 300°C for High Strength Concrete (HSC).

However, Lee *et al.*, 2010 observed that whitish grey color for temperature between 600 – 900°C and a buff color at temperature between 900 -1000°C. This result was achieved using mix proportion of Coarse aggregate, fine aggregate, Cement and Fly ash admixture. Neville (2002) also reported grey color which changes to buff color at 600°C and 900°C respectively. However, concrete is made with siliceous or limestone aggregate. Subsequently, at 800°C, the deformation for grade 50, 60, and 65, became more evident with visible cracks ranging from 0.7 to 0.8 mm appearing which exceeds the 0.5 mm limit considered acceptable by ACI 224R for structural concrete (Plate 1b). The color deepened to greyish purple, and some surface spalling was also observed. By the time the specimens reached 1000°C, the concrete had lost all structural integrity for all the grades as shown in Plates 2 (a and b) respectively.

Table 4: Physical Changes due to Elevated Temperatures

Temperature	**Crack Size (mm)**	**Color**	**Condition**
600°C	~0.04 (hair-like)	Light greyish purple	Micro-cracks visible
800°C	0.7 - 0.8 (visible)	Greyish purple	Significant visible cracks
1000°C	Extensive spalling & crumbling	Ash/grey	Complete disintegration

The most severe case of deterioration was observed at 1000°C, for Grades 50, 60, and 65 N/mm^2 and 20 % bagasse ash replacement samples, the cubes crumbled under light finger pressure, with some portions turning into loose powder, as shown in Plate 2 because of higher quantity of bagasse ash replacement which led to higher loss in strength when compared with the 10% bagasse replacement which gave higher strength. This complete disintegration is attributed to the total decomposition of the calcium-silicate-hydrate (C-S-H) gel, the primary strength-bearing phase of cement paste, which breaks down above 800°C (Arioz 2007).

3.2 Weight Loss

Weight loss analysis is an indication of microstructural damage. The percentage weight loss for concrete cubes after fire exposure are presented in Figures 2 (a and b) and 3 respectively for grades 50, 60 and 65 HPC at 20% SCBA. The percentage weight loss increased systematically with both concrete grade and SCBA replacement level. For Grade 50 HPC containing 20% SCBA, weight loss was 10.2% at 600 °C and rose to

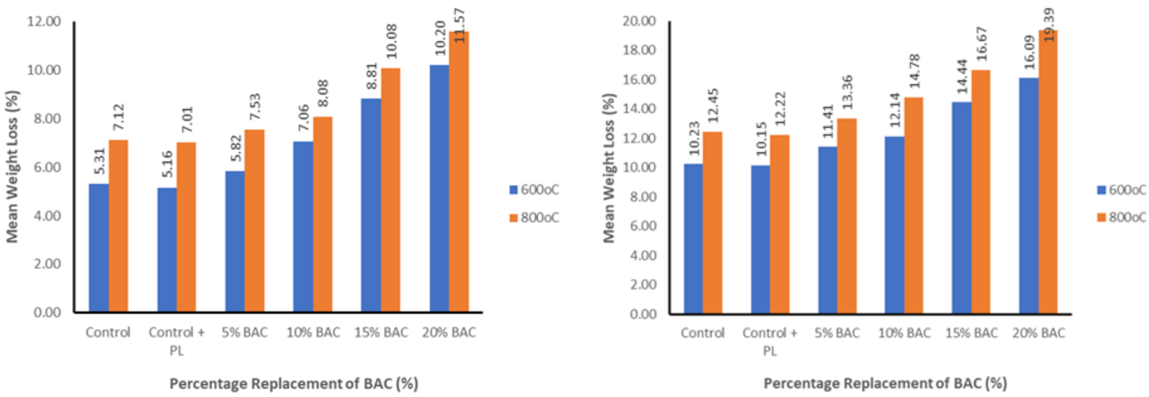
11.57% at 800°C Figures 2 (a and b). However, for Grade 65 HPC with the same 20% SCBA, weight loss jumped dramatically from 20.40% at 600°C to 32.58% at 1000 °C (Figure 3). The highest weight losses were recorded for the 20% SCBA mix in all grades.

(a) 600°C (b) 800°C

Plate 1: Physical Deterioration of Grade 50 (600◦C) and Grade 60 (800◦C) at 20% BAC

(a) Complete disintegration (b) crumbled with slight touch

Plate 2: Physical Deterioration of grades BAC at 20% 1000°C



(a) Grade 50 HPC at 600◦C and 800◦C (b) Grade 60 HPC at 600◦C and 800◦C

Figure 2: Weight Loss due to Temperature Variation

Two mechanisms explained this trend. First, higher-grade concrete had a denser microstructure with smaller capillary pores and higher uncoated grains leading to higher uncoated specific surface by cement, bagasse ash and water respectively. These phenomena gave rise to higher spaces for higher fire or temperature penetration leading to higher aggressive burning of the concrete specimen. These observations are in accordance with the findings reported by Makinta *et al.*, 2021, Nadeem *et al.*, 2013, Shyamala *et al.*, 2020 and Tattukolla *et al.*, 2022. It claimed that during a fire, water or vapor trapped in this dense matrix cannot escape easily, building up internal vapor pressure that causes expansive and explosive spalling and mass loss of the concrete. Secondly, SCBA specifically was porous and contained up to 12.6% unburnt carbon (from the loss on ignition). This carbon not only absorbed more mixing water due to higher specific surface but also underwent combustion at high temperatures, further contributing to weight loss. Thus, while SCBA improved strength at room temperature and lower concrete grades or lower SCBA percentage replacement by filling pores and providing fewer specific surfaces, it became a liability in fire for higher SCBA percentage replacement and higher concrete grades respectively.

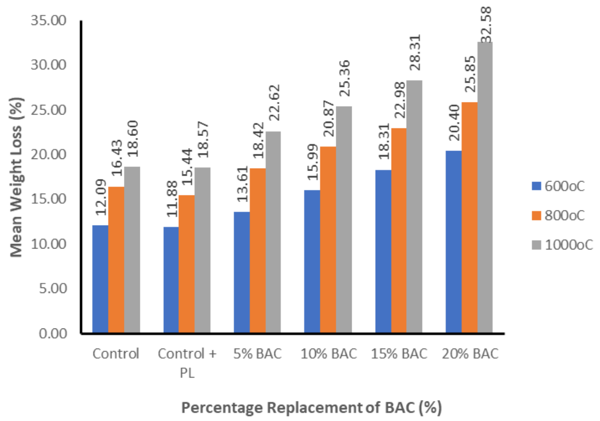
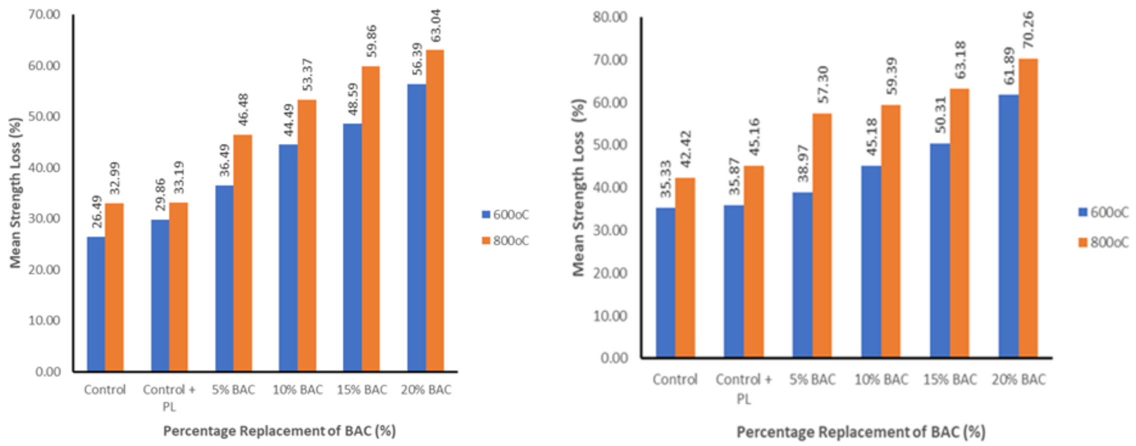


Figure 3: Weight Loss due to Temperature Variation on Grade 65 HPC

3.3 Compressive Strength Loss

The fire exposure caused a drastic reduction in compressive strength Figures 4 (a and b), especially for higher-grade concretes and higher SCBA replacements (20% SBAC), as presented in Figure 5. For Grade 50 HPC the strength loss values obtained were 56.39% at 600°C and 63.04% at 800°C (Figure 4a). While for Grade 60 HPC at 600°C and 800°C were 61.89 and 70.26% respectively (Figure 4b). The control samples (0% SCBA) consistently showed the lowest strength losses. For Grade 65 concrete, the control mix with 0% SCBA lost 42.54% of its strength at 800°C (Figure 5).



(a) Grade 50 HPC at 600°C and 800°C (b) Grade 60 HPC at 600°C and 800°C

Figure 4: Strength Loss due to Temperature Variation

In contrast, the 20% SCBA mix of the same grade lost 73.70% at the same temperature, which is three times more degradation when compared with the control results. At 1000°C, the 20% SCBA grade 65 samples could not even be tested because they had turned to powder, representing a 100% practical loss. The maximum measurable loss was 81.46% for this mix at 1000°C. However, this value is higher than what was reported by Setiyarto and Fira (2019) for compressive strength loss of 70% at 1000°C for all grades. The authors further mentioned that at ambient temperature, the pozzolanic reaction of SCBA consumed calcium hydroxide (Ca $(OH)_2$) to form additional C-S-H gel, which increased strength. However, Ca $(OH)_2$ crystals, when heated to around 450–550°C, decomposed into calcium oxide and water vapour. This decomposition was actually beneficial because it released pressure; it is known to help prevent explosive spalling in ordinary concrete.

When SCBA consumed Ca $(OH)_2$, it removed this safety valve. As a result, the denser, Ca $(OH)_2$-poor matrix underwent severe shrinkage and cracking with no sacrificial phase to absorb thermal stress. Therefore, despite SCBA's sustainability benefits, its use in fire-exposed HPC is not recommended without protective measures.

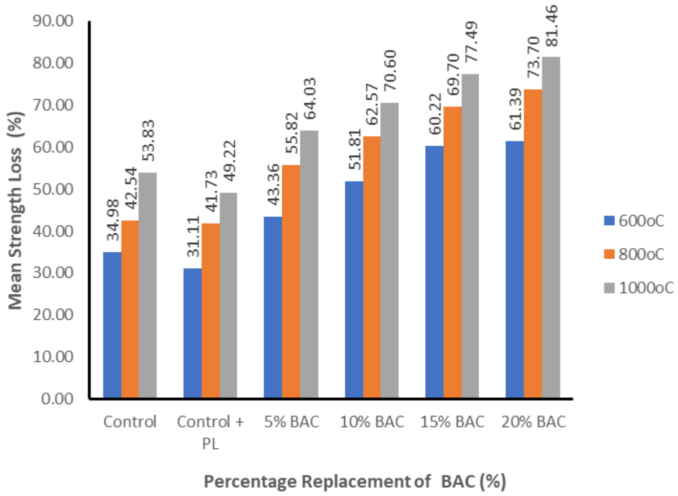


Figure 5: Strength Loss due to Temperature Variation on Grade 65 HPC

It can therefore be inferred that SCBA replacement, despite its benefits at ambient temperature, is detrimental to the fire resistance of HPC. The decomposition of additional hydration products from the pozzolanic reaction, and the porous nature of SCBA due to higher uncoated specific surface by the cement matrix consequently accelerated the strength degradation at high temperatures.

3.4 Fire Effects and Temperature Model for BA HPC

The calcination time for bagasse ash concrete was carried out as a result of fire effects from 0oC to 600°C, 800°C and 1000°C for 100 minutes, 130 minutes and 220 minutes respectively. As presented in Figure 6.0, the time required to reach each target temperature followed a quadratic trend. For 1000°C, the relationship between temperature (T) in °C and time (t) in minutes was best described by the equation $T = -0.016t^2 + 8.05t$, with an R^2 value between 0.964 and 0.986 indicating an excellent fit. This equation can serve as a practical engineering tool to estimate how quickly a fire will affect an SCBA-based HPC element. Therefore, this model is a useful aid for practical design of fire-resistant coatings or insulation thickness and the general assessment of the structural integrity and reliability of HPC subjected to fire effect up to 1000°C.

3.5 Density, Porosity and Strength Relationships

It is a general knowledge as expressed by many authors Scott (1992), Punmia *et al.,* (2003), Lian *et al.,* (2011) and Sánchez-Mendieta *et al.,* (2024), that concrete types are classified according to densities. Heavyweight concrete, 3000 to 4000 kg/m³; normal concrete, 2200 to 2600 kg/m³; lightweight concrete, 300 to 1850 kg/m³ respectively. Figure 7 (a and b) presents the variations of density and compressive strength, before and after fire effects in all grades of concrete respectively.

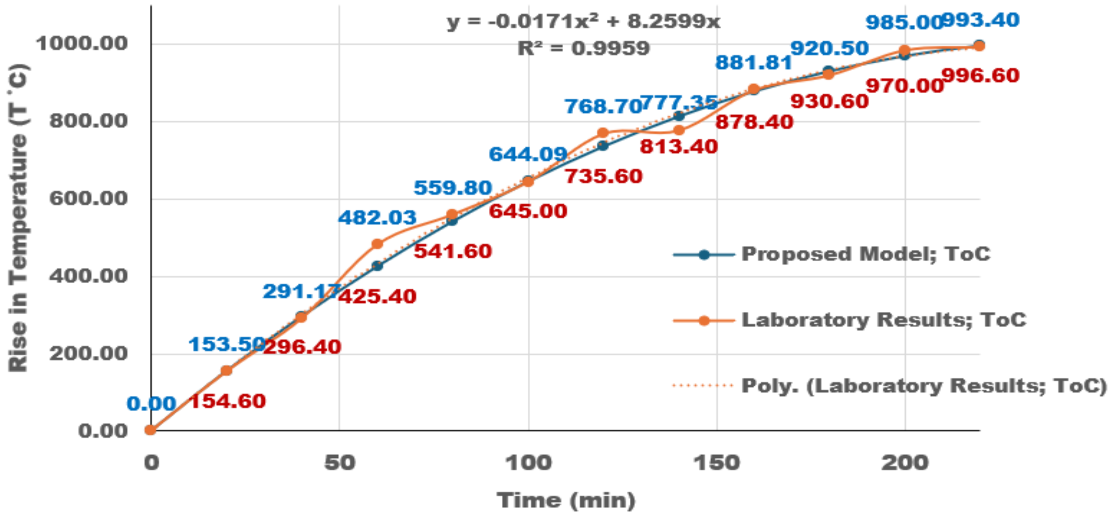


Figure 6: Proposed Model of Temperature Variation on HPC for Cement Partially Replacement with BA

As presented from Figure 7 (a and b), it can be deduced that elevated-temperature effects on concrete caused microcracking but limited weight loss at approximately 420°C. Between 420–550°C, CH decomposition created internal pressure, explosion risks, porosity, visible cracks, and strength loss. From 550–620°C, matrix deterioration worsened. Higher density improved strength, but fire increased porosity, reducing load capacity and raising permeability. At 620–800°C, calcium carbonate breakdown caused up to 81.46% strength loss (Figure 5); near-total failure occurs at 850–1000°C. Additionally, SCBA replacement in HPCs negatively affected strength and stability, with fire further degrading structural reliability.

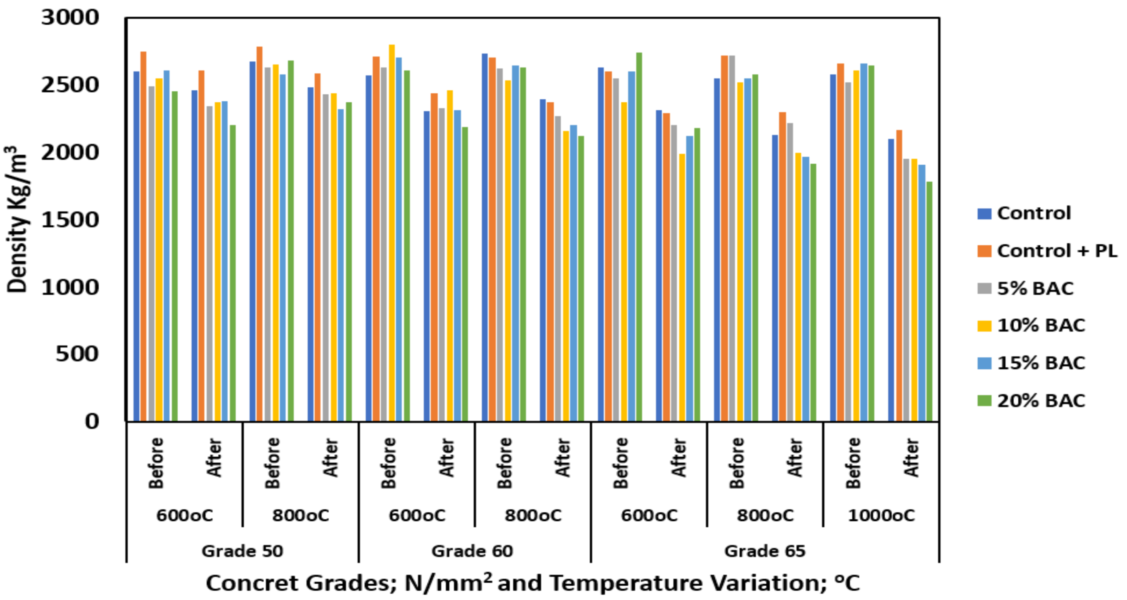


Figure 7a: Variation of Density Before and After Fire Effects as Functions of Concrete Grades

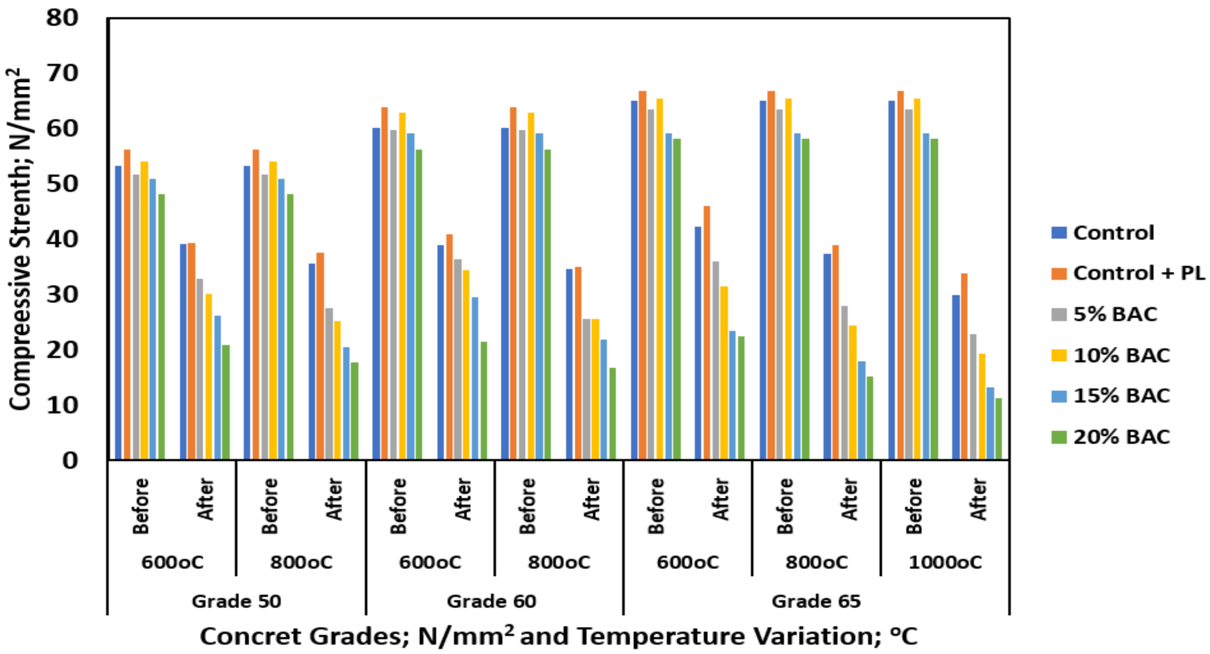


Figure 7b: Variation of Compressive Strength Before and After Fire Effects as Functions of Concrete Grades

4. Conclusion

Based on the experimental investigation into the effect of elevated temperature on HPC containing cement partially replaced with SCBA, the following conclusions are drawn:

1. Severe Degradation: Exposure to elevated temperatures (600°C - 1000°C) caused significant and irreversible damage to HPC, including cracking, spalling, color change, and massive weight and strength losses. At 850 to 1000°C, concrete was completely disintegrated.

2. Detrimental Effect of SCBA: Unlike its beneficial role at ambient temperatures, SCBA as a cement replacement worsened the fire resistance of HPC. Higher replacement levels (e.g., 20%) consistently resulted in greater weight and compressive strength loss compared to control mixes. Therefore, SCBA as partial replacement of cement has a negative or detrimental influence on the strength and structural integrity of HPCs, and the effect of elevation fire further led to further degradation and later total loss of the structural strength, stability and reliability of HPC.
3. Grade Dependency: Higher-grade concretes (e.g., 65 N/mm^2) were more susceptible to fire damage than lower-grade ones, likely due to their denser microstructure leading to higher internal pore pressure.
4. Optimal Mix for Fire Resistance: For applications where fire risk is a concern, the control mix (0% SCBA) with a superplasticizer demonstrated the best performance, with the lowest residual strength and weight losses.
5. Predictive Models: The developed quadratic models accurately predicted the detrimental effects of temperature rise in HPC over time with fire aggression as indicated by the negative sign of the quotient of quadratic component; the positive sign of the quotient of the non-quadratic component of equation was the net resistance offered by all the materials regardless of the fire aggression which made the proposed model very useful for structural design for fire safety and liability
6. Future studies should note that SCBA is a promising sustainable SCM for general construction, its use in HPC for fire-exposed structures (e.g., high-rise buildings, tunnels, industrial plants) is not recommended unless further research can mitigate this negative effect, possibly through fiber reinforcement or fire-resistant coatings are incorporated.
7. Future studies should employ XRD analysis to quantitatively confirm the amorphous/crystalline ratio of the SCBA and optimize controlled burning conditions to reduce LOI while maintaining pozzolanic reactivity.

Declaration

During the preparation of this work, the authors used Grammarly (online version) to assist with the language and readability of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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