

INFLUENCE OF ELEVATED TEMPERATURES ON THE MICROSTRUCTURE AND COMPRESSIVE STRENGTH OF SUGARCANE BAGASSE ASH-BASED HIGH-PERFORMANCE CONCRETE

Kadai, B.^{1*}, Waziri, B.S.¹, Abdulrahman, S.A.², Onundi, L.O.¹ and Grema, L.U.³

¹Department of Civil and Water Resources Engineering, University of Maiduguri, Borno State, Nigeria

²Department of Mechanical Engineering, University of Maiduguri, Borno State, Nigeria

³Department of Mechanical Engineering, Ramat Polytechnic Maiduguri, Borno State, Nigeria

*Corresponding email: Bukarkadai2@gmail.com

ABSTRACT

The deterioration of concrete structures exposed to elevated temperatures remains a critical concern in construction engineering, particularly in regions susceptible to fire outbreaks and high ambient temperatures. This study investigates the effect of high temperatures on the microstructure and compressive strength of high-performance concrete (HPC) produced from cement partially replaced with sugarcane bagasse ash (SCBA). Sugarcane bagasse ash was incorporated at replacement levels of 0%, 5%, 10%, 15%, and 20% by weight of cement, with a superplasticizer (Conplast SP430) added at 0.75 litres per 100 kg of cementitious material. A total of 540 cube specimens (150 mm × 150 mm × 150 mm) were produced for three concrete grades: 50, 60, and 65 N/mm². After 28 days of curing, specimens were subjected to elevated temperatures of 600°C, 800°C, and 1000°C for durations of 100, 130, and 220 minutes, respectively. The compressive strength, weight loss, crack formation, colour change, and microstructure were evaluated. Results showed that compressive strength losses increased with temperature and bagasse ash content. At 800°C, the highest strength losses of 63.04%, 70.26%, and 73.70% were recorded at 20% SCBA replacement for grades 50, 60, and 65 N/mm², respectively. The control specimens exhibited the lowest strength losses of 32.99%, 42.42%, and 42.54% for the same grades. Scanning electron microscopy (SEM) analysis revealed that spherical particles and black spots present in unburnt samples disappeared after heating, resulting in irregular shapes with heat-induced cracks. The study concludes that while SCBA improves ambient-temperature properties, its presence significantly compromises fire resistance, with concrete grades 50 and 60 turning to ash at 1000°C. These findings provide critical insights for the design and application of sustainable HPC in fire-prone environments.

Keywords: Compressive Strength; Elevated Temperature; High-performance Concrete; Microstructure; Fire resistance; Sugarcane Bagasse ash

1 INTRODUCTION

Concrete is the most widely used construction material globally, with an annual production exceeding 6 billion tons [1, 2]. Its versatility, durability, and mouldability have made it indispensable in civil engineering infrastructure. However, conventional concrete deteriorates under physical and chemical processes, particularly when exposed to aggressive environmental conditions [3]. This has necessitated the development of high-performance concrete (HPC), a specialized concrete with enhanced mechanical and durability properties that cannot be achieved through conventional constituents and normal mixing, placing, and curing practices [4]. High-

performance concrete is characterized by compressive strengths exceeding 50 N/mm², low permeability, high durability, and superior workability [5, 6]. The production of HPC typically incorporates supplementary cementitious materials (SCMs) such as fly ash, silica fume, ground granulated blast furnace slag, and agricultural by-products [7, 8]. Among these, sugarcane bagasse ash (SCBA) has emerged as a promising pozzolanic material due to its high silica content and availability as an agricultural waste product. Sugarcane is a major global crop, with Brazil and India being the largest producers. Nigeria produces over 15 million tons of sugarcane annually [9]. The extraction of sugar from sugarcane generates approximately 50% bagasse, which is often burned as fuel in sugar mills, producing SCBA as the final waste product [10, 11]. The chemical composition of SCBA, particularly its high silicon dioxide (SiO₂), aluminium oxide (Al₂O₃), and iron oxide (Fe₂O₃) content, makes it suitable for use as a pozzolanic material in concrete [12]. Despite the advantages of SCBA in improving concrete properties at ambient temperatures, the behaviour of SCBA-blended HPC under elevated temperatures remains inadequately understood. Fire represents one of the most severe risks to concrete structures, causing irreversible damage through dehydration of cement paste, decomposition of calcium silicate hydrate (C-S-H) gel, and thermal expansion of aggregates [13, 14]. The mechanical properties of concrete are significantly affected by temperatures beyond 500°C, with concrete becoming fragile when temperatures exceed 1000°C [15]. Previous studies have investigated the fire resistance of concrete containing various SCMs, including fly ash, metakaolin, and silica fume [16, 17, 18]. However, limited research exists on the fire performance of HPC incorporating SCBA and local aggregates such as Bama gravel. This study addresses this knowledge gap by evaluating the effect of elevated temperatures on the microstructure and compressive strength of HPC produced from cement partially replaced with SCBA. The specific objectives of this study are: to determine the compressive strength losses of SCBA-blended HPC at temperatures of 600°C, 800°C, and 1000°C; to evaluate the weight loss and physical changes (cracks, colour) due to fire exposure; and to analyse the microstructural changes using scanning electron microscopy (SEM).

2 LITERATURE REVIEW

2.1 High-Performance Concrete

High-performance concrete (HPC) is defined by the American Concrete Institute as “concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices” [4]. The development of HPC began in the late 20th century when engineers sought materials capable of meeting complex and demanding construction needs [19]. Matej [5] characterized HPC as concrete with compressive strength greater than 50 N/mm², emphasizing strength and durability as the most important properties. Sachin [20] defined HPC as concrete with a compressive strength grade of 45 N/mm² and above, capable of performing satisfactorily in terms of strength, permeability, workability, durability, and response to long-term environmental effects. [6] provided specific compressive strength requirements for HPC: 4-hour strength ≥ 17.5 N/mm², 24-hour strength ≥ 35 N/mm², and 28-day strength ≥ 60 N/mm², with a water-cement ratio ≤ 0.3 . The application of HPC has extended to long-span bridges, offshore platforms, nuclear and hydro power stations, dams, high-rise buildings, marine structures, and highway pavements [6, 19]. Viaceslav [21] noted that HPC is created through high cement content and low water-cement ratio, offering advantages such as high strength, volume stability, high abrasion resistance, low permeability, and high chemical resistance.

2.2 Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) are essential components of modern HPC, contributing to improved mechanical and durability properties through pozzolanic reactions [22, 23]. These materials include industrial by-products (fly ash, ground granulated blast furnace slag, silica fume) and agricultural wastes (rice husk ash, palm oil fuel ash, bagasse ash, millet husk ash) [24, 25, 26]. The incorporation of SCMs enhances the concrete matrix through improved workability, strength, durability in harsh environments, controlled cracking, and reduced heat generation [27]. The presence of SCMs also improves microstructure by refining disconnected capillary pores [28]. The high pozzolanic reactivity of SCMs consumes calcium hydroxide, accelerating cement hydration and increasing C-S-H gel content at the expense of calcium hydroxide, resulting in higher strength and

durability [29, 30]. Surendra [31] noted that SCMs with high silica content, low density, and high surface area possess pozzolanic reactivity with calcium silicate hydrates. Olubajo [32] described the incorporation of SCMs as an effective means of minimizing waste, cost, and energy consumption.

2.3 Sugarcane Bagasse Ash

Sugarcane bagasse ash (SCBA) is the final waste product from sugar production, obtained after the combustion of bagasse for energy generation. Approximately 25-40 kg of SCBA is produced per ton of bagasse [10, 11]. The main component of SCBA is SiO_2 , with the summation of major oxides typically ranging from 59.2% to 87.7% by mass [12]. The chemical composition of SCBA varies depending on the source and burning conditions. Rukzon and Chindaprasirt [33] reported SiO_2 content of 65.0%, while [34] reported 55.4%. Olubajo [32] found SiO_2 content of 60.33%, and Ahmed [12] reported 75.0%. The specific gravity of SCBA ranges from 1.93 to 2.20 [12, 35, 36, 37]. Chusilp [38] investigated the utilization of bagasse ash as a pozzolanic material, finding that concrete containing up to 30% ground bagasse ash exhibited higher compressive strength and lower permeability than control specimens at 28 and 90 days. Rukzon [33] studied the utilization of bagasse ash in high-strength concrete, identifying 10% as the optimal replacement ratio, with concrete containing up to 30% BA exhibiting compressive strengths of 65.5-68.6 N/mm² at 28 days. Otuoze [39] studied the effect of SCBA as partial replacement of cement, with specimens incinerated at 600°C. The results showed that SCBA is a good pozzolana, with an optimum of 10% SCBA blend suitable for reinforced concrete, while higher blends of 15-35% are acceptable for plain or mass concrete. Lavanya [40] found that SCBA can increase concrete strength when used up to 15% replacement with a water-cement ratio of 0.35.

2.4 Effect of Elevated Temperature on Concrete

Elevated temperature is one of the most harmful effects causing durability problems in concrete structures. Exposure to high temperatures induces important changes in mechanical, physical, and thermal properties, leading to multidimensional failures [15]. The mechanical properties of concrete are largely affected by temperatures beyond 500°C and become fragile when temperatures exceed 1000°C. Tattukolla [18] reported that exposure to 100-200°C causes no reduction in strength at 28 days, as free water evaporates slowly. However, at 300-500°C, compressive strength drops by 50-60% compared to control samples. Concrete with SCMs like metakaolin exposed at 800°C experienced 81% loss in compressive strength, with higher strength losses observed in higher concrete grades due to pore pressure development within dense internal structures. Shyamala [41] observed that residual compressive and tensile strengths for high-strength concrete after heating to 800°C were 44%. High-strength concrete and HPC lose a large quantity of compressive strength at 400°C, achieving approximately 75% strength loss at 800°C. The change in intensity in the 100-400°C temperature range is marginal. Mervin [42] found significant strength reductions in all concrete grades, with losses of 39%, 41%, 42%, and 46% for M20, M30, M40, and M50 grades, respectively. The general reduction in strength was attributed to thermal crack formation and disruption of calcium silicate hydrate (C-S-H). Setiyarto [43] reported significant compressive strength reductions up to 70% when concrete is exposed to temperatures up to 1000°C. This is mainly caused by decomposition of hydrated cement paste: $\text{Ca}(\text{OH})_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$. The released water evaporates at 100°C, causing concrete to dry and become brittle, leading to crack formation, surface peeling, porosity, and colour changes. At 750°C, carbonization produces calcium carbonate (CaCO_3), which is whitish in colour. Arioz [13] reported that concrete exposed to elevated temperatures experiences physical changes such as surface cracking and spalling, with colour changes depending on fire intensity. These changes become more evident when temperature exceeds 500°C and are irreversible. The decomposition of C-S-H gel, the major strength attribute of cement paste, occurs at temperatures above 600°C. Concrete crumbles at 800°C and turns to ashes when temperature exceeds 1000°C. Lee [44] observed notable colour changes in concrete exposed to high temperatures: red (300-600°C), whitish grey (600-900°C), and buff (900-1000°C). Neville [45] reported similar findings, with siliceous or limestone aggregate concrete turning pink or red at 300-600°C, grey at 600-900°C, and buff above 900°C.

2.5 Microstructural Changes Due to Elevated Temperature

Scanning electron microscopy (SEM) is a powerful analytical technique for studying the microstructure of concrete, providing high-resolution images of the concrete matrix [46]. Muthumani [8] defined SEM as a technique for studying internal microstructure, chemical composition, size, shape, orientation, and binding of particles in concrete. Mali [47] observed through SEM that most particles in bagasse ash concrete (BAC) did not exhibit distinct shapes, with rough surfaces, large surface areas, and high porosity affecting durability and mechanical properties. Chusilp [38] examined BAC using SEM and found particles with rough surfaces, large surface areas, and high porosity. Abbas [48] reported that spherical shapes and black spots present in unburnt samples disappear completely after heating, resulting in irregular shapes with heat-driven cracks. This change in surface morphology was attributed to high-temperature effects. Setyowati [49] found that burning temperature affects microcrack width behaviour in post-fire concrete. At 400°C, the burning temperature increases post-fire concrete strength compared to unburned concrete. As burning temperature increases, the load required to advance cracks decreases, with the effect being profound at 800°C. Despite extensive research on the fire resistance of concrete containing various SCMs, limited studies have focused on the fire performance of HPC incorporating SCBA and local aggregates like Bama gravel. The combined effect of SCBA replacement and elevated temperatures on compressive strength, weight loss, and microstructure requires comprehensive investigation. This study addresses this gap by evaluating the fire resistance of SCBA-blended HPC and developing predictive models for temperature rise in concrete subjected to fire.

3 MATERIALS AND METHODS

3.1 Materials

3.1.1 Cement

Ordinary Portland cement (OPC) of grade 42.5 N/mm² (Dangote brand) was used as the primary binder. The cement was obtained from the open market in Maiduguri, Nigeria, and stored in airtight containers to prevent moisture absorption.

3.1.2 Sugarcane Bagasse Ash (SCBA)

Sugarcane bagasse was obtained from an open sugarcane market in Maiduguri. The bagasse was sun-dried and then burned in an open furnace to produce ash. The ash was sieved through a 150 µm sieve to remove unburnt particles and coarse impurities. The chemical composition of the SCBA was determined using X-ray fluorescence (XRF) analysis.

3.1.3 Aggregates

Three types of aggregates were used: river sand (fine aggregate), Bama gravel (local coarse aggregate), and crushed stones (19 mm and 38 mm). River sand was obtained from Alau River (11°46'23"N, 13°12'52"E), Bama gravel from River Yadzaram bridge in Bama (11°32'21"N, 13°40'42"E), and crushed stones from Shira Quarry in Bauchi State (11°27'36"N, 10°01'50"E).

3.1.4 Chemical Admixture

Conplast SP430, a sulphonated naphthalene polymer-based superplasticizer, was used at a dosage of 0.75 litres per 100 kg of cementitious material. The admixture conforms to [50].

3.1.5 Water

Portable tap water was used for mixing and curing.

3.2 Mix Proportions

Three concrete grades were designed: 50, 60, and 65 N/mm². The mix proportions by mass were: Grade 50: 1: 0.44: 0.24: 0.15: 0.87: 0.25 (cement: river sand: Bama gravel: 19 mm crushed stone: 38 mm crushed stone: water). Grade 60: 1: 0.38: 0.21: 0.13: 0.77: 0.23. Grade 65: 1: 0.34: 0.19: 0.12: 0.68: 0.21. SCBA was incorporated at 0%, 5%, 10%, 15%, and 20% by weight of cement. Concrete mix designs were developed using a Microsoft Excel spreadsheet, based on B.S. 8500 Mix Design Method and Concrete Matrix Design approach by Onundi [57].

3.3 Specimen Preparation

A total of 540 cube specimens (150 mm × 150 mm × 150 mm) were produced for compressive strength testing. The specimens were cast using a mechanical mixer (0.5 m³ capacity) with a mixing duration of 120 seconds. An electric compactor was used for 60 seconds to remove voids. After casting, specimens were cured for 28 days in water at ambient temperature. This test was performed according to [56].

3.4 Elevated Temperature Exposure

After 28 days of curing, specimens were removed from the curing tank and allowed to air-dry for 24 hours. The specimens were then subjected to elevated temperatures of 600°C, 800°C, and 1000°C in a brick incinerator at the Industrial Design Department, Abubakar Tafawa Balewa University, Bauchi. The blower was operated at rotational speeds and air velocities of 3078 rpm and 24.5 m/s, respectively. Temperature was monitored using thermocouples at 15-minute intervals for durations of 100, 130, and 220 minutes for the three temperature levels. The heating rates were controlled to simulate actual fire conditions. The test was conducted in based on BS EN 934-2:2001 [58].

3.5 Testing Procedures

3.5.1 Compressive Strength Test

Compressive strength was determined based on BS EN 934-2:2001 [51] using a 3000 kN capacity testing machine at a loading rate of 3 N/mm² per second. The compressive strength was calculated using Equation 1:

$$S = P/A \quad (1)$$

where S = strength (N/mm²), P = applied load (kN), and A = cross-sectional area (mm²).

3.5.2 Weight Loss

Weight loss was determined by measuring the mass of specimens before and after elevated temperature exposure using a digital balance with 0.01 g precision.

3.5.3 Crack and Colour Assessment

Physical changes (cracks and colour) were assessed visually and using a crack width microscope with 40× magnification. Crack widths were measured at the surface of specimens after cooling.

3.5.4 Scanning Electron Microscopy (SEM)

Microstructural analysis was performed using a Phenom ProX scanning electron microscope (5th generation) at the National Steel Raw Materials Exploration Agency, Malali, Kaduna State, Nigeria. Samples were taken from the control and burnt cubes for all grades and SCBA replacement levels. The test was conducted based on ASTM E 1508 [58].

4 RESULTS AND DISCUSSION

4.1 Chemical Composition of SCBA

The chemical composition of the SCBA used in this study is presented in Figure 1. The summation of SiO₂, Al₂O₃, and Fe₂O₃ was **80.45%**, exceeding the minimum requirement of 70% specified by ASTM C618-08 [52] for pozzolanic materials. The CaO content was 4.12%, classifying the SCBA as Class F pozzolan.

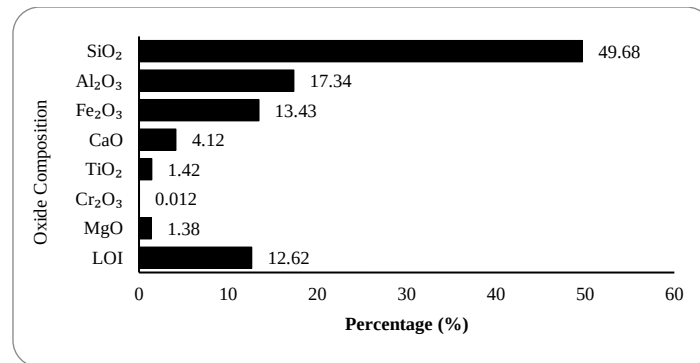


Figure 1. Chemical Composition of Sugarcane Bagasse Ash

4.2 Physical Properties of Cement and SCBA

The specific gravity of SCBA was 1.93, which is lower than that of OPC (3.06), as shown in Table 1. This lower specific gravity is attributed to the lightweight unburnt particles in the ash [53].

Table 1. Physical Properties of Cement and Bagasse Ash

Property	Cement	Bagasse Ash
Density (g/cm ³)	1.05	-
Specific Gravity	3.06	1.93
Strength at 28 days (N/mm ²)	41.75	-

4.3 Compressive Strength at Ambient Temperature

The compressive strength development for grades 50, 60, and 65 N/mm² at 28 days is presented in Figure 2. The optimum SCBA content was 10% for all grades, yielding compressive strengths of 54.13, 62.92, and 65.45 N/mm² for grades 50, 60, and 65, respectively. These values exceeded the control by 1.77%, 4.6%, and 0.7%, respectively. Similarly, the trend Across SCBA Replacement is shown in Figure 3. The increase in strength at 10% SCBA replacement is attributed to the complete reaction of free lime with the reactive silica of bagasse ash. Beyond 10% replacement, the relative cement content decreases, leading to reduced free lime content and lower strength [39].

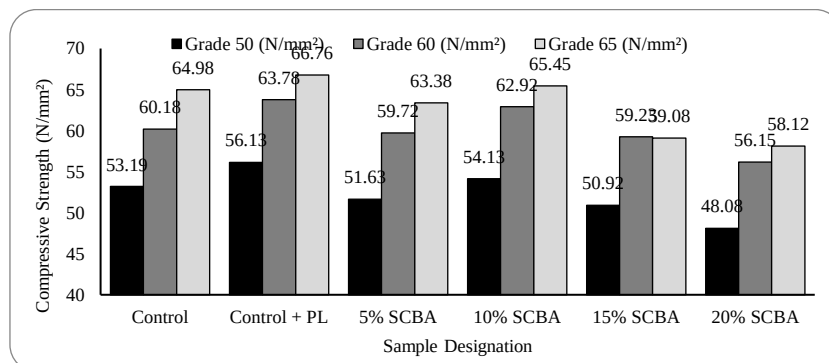


Figure 2. Compressive Strength at 28 Days (Ambient Temperature)

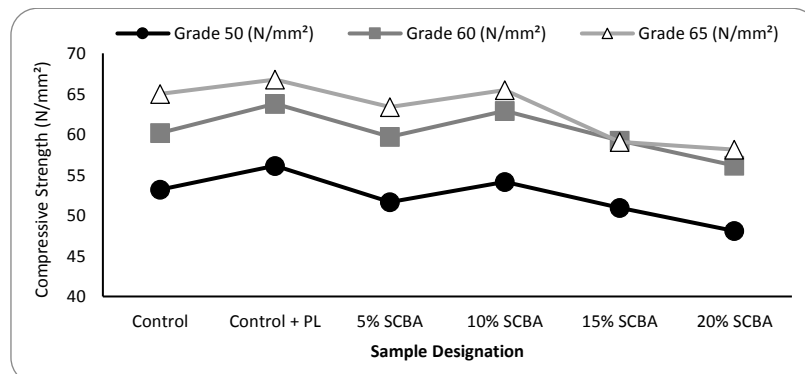


Figure 3. Compressive Strength at 28 Days – Trend Across SCBA Replacement

4.4 Weight Loss Due to Elevated Temperature

The weight losses of concrete cubes exposed to elevated temperatures are presented in Figure 4. The results show that weight loss increased with temperature and SCBA content. At 800°C, the highest weight losses of 11.57%, 19.39%, and 25.85% were recorded at 20% SCBA replacement for grades 50, 60, and 65 N/mm², respectively. The control specimens exhibited lower weight losses of 7.12%, 12.45%, and 16.43% for the same grades.

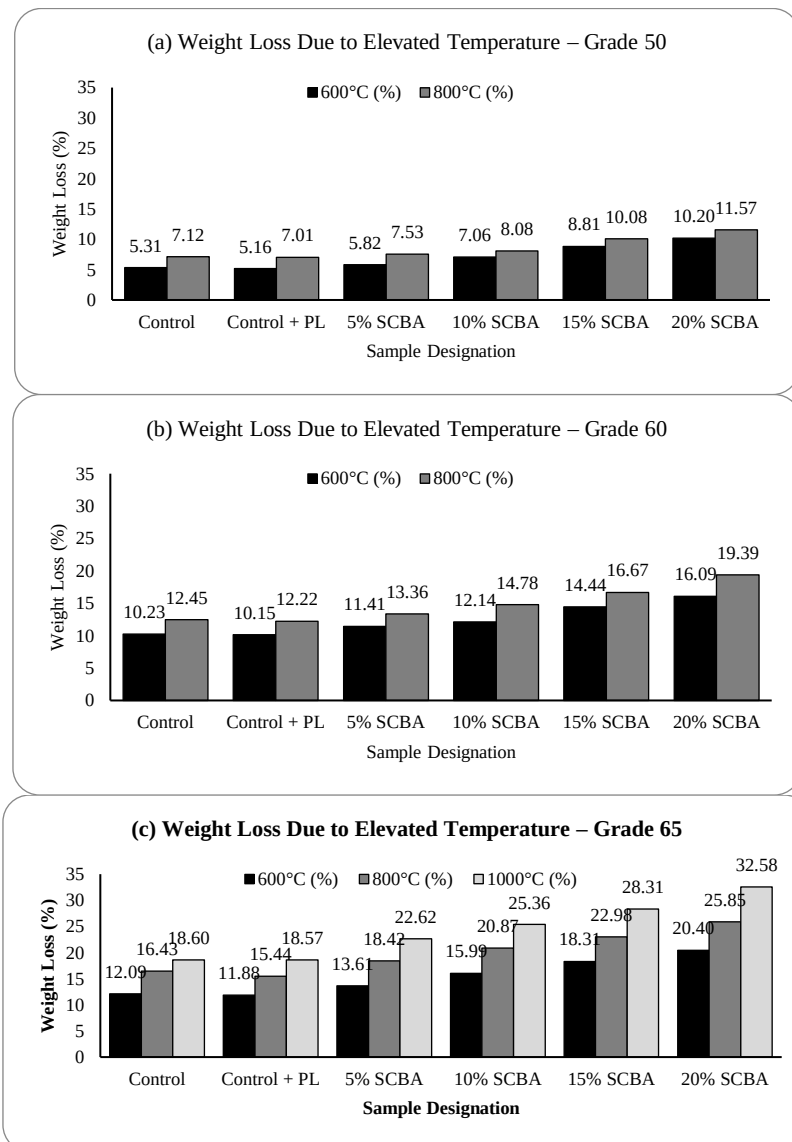


Figure 4. Weight Loss Due to Elevated Temperature

The massive reduction in concrete mass is consistent with Makinta [15], who attributed weight loss to dehydration of cement paste, decomposition of aggregates, and thermal decomposition of cement. The volumetric expansion of quartz at temperatures above 500°C also contributes to weight loss [14].

4.5 Compressive Strength Loss Due to Elevated Temperature

The compressive strength losses of concrete cubes exposed to elevated temperatures are presented in Figure 5. The results show that strength loss increased with temperature, concrete grade, and SCBA content. At 800°C, the highest strength losses of 63.04%, 70.26%, and 73.70% were recorded at 20% SCBA replacement for grades 50, 60, and 65 N/mm², respectively. The control specimens exhibited lower strength losses of 32.99%, 42.42%, and 42.54% for the same grades.

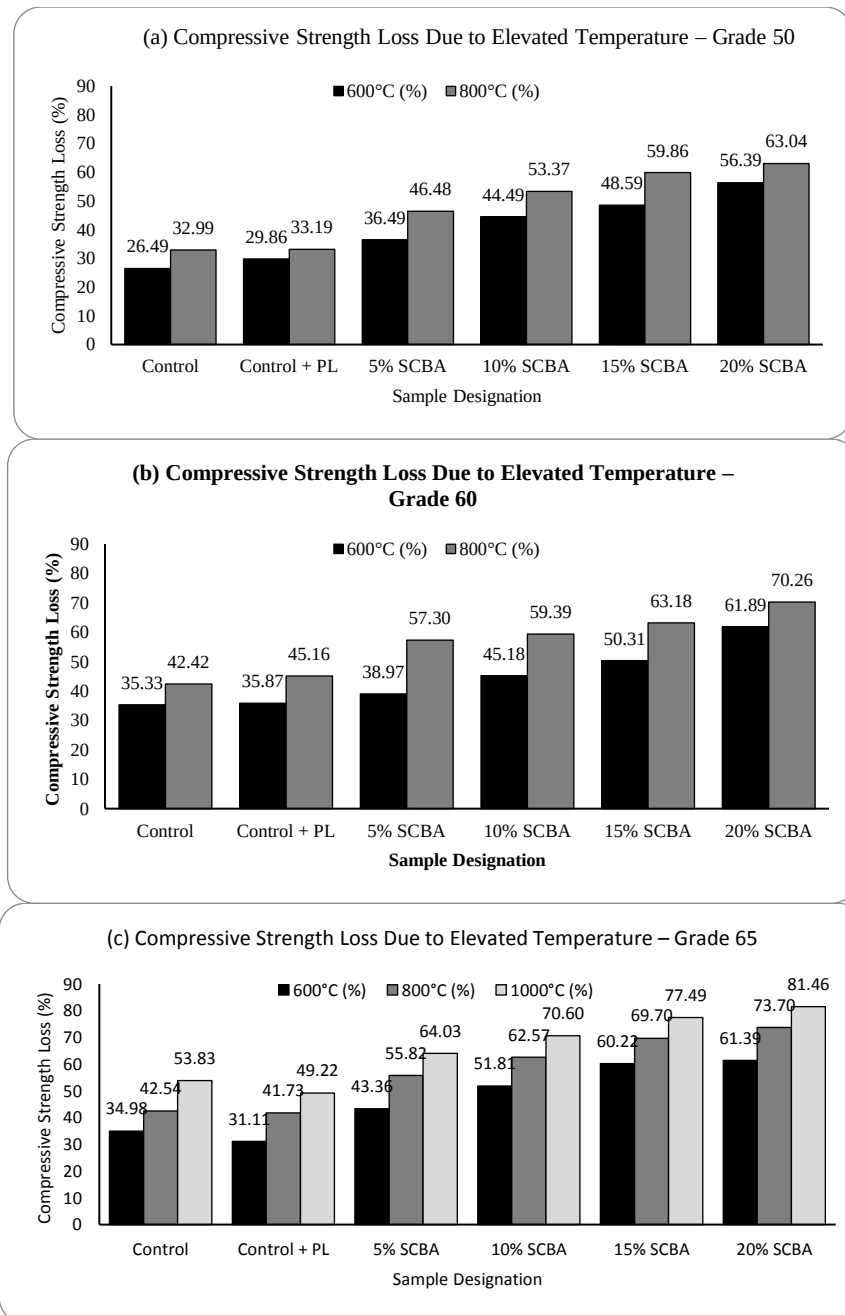


Figure 5. Compressive Strength Loss Due to Elevated Temperature

The higher strength losses in higher-grade concrete are attributed to pore pressure development within dense internal structures, increased thermal conductivity, and higher pore pressure [18]. The decomposition of C-S-H gel, the major strength-contributing compound in cement paste, occurs at temperatures above 600°C [13]. At 1000°C, specimens of grades 50 and 60 turned to ash and could not be tested for compressive strength. The grade 65 specimens exhibited 81.46% strength loss at 20% SCBA replacement. These results are consistent with Arioz [13], who reported that concrete crumbles at 800°C and turns to ashes when temperature exceeds 1000°C.

4.6 Physical Changes Due to Elevated Temperature

The physical changes observed in concrete cubes after elevated temperature exposure are presented in Table 2. At 600°C, hair-like cracks of 0.04 mm width were observed for all grades. At 800°C, visible cracks of 0.7-0.8 mm width appeared, exceeding the maximum allowable crack width limit of 0.5 mm for concrete [54]. The colour changes observed (light greyish purple at 600°C and greyish purple at 800°C) differ slightly from those reported by Lee [44] and Neville [45], this can be attributed to the influence of SCBA and Bama gravel in the concrete matrix.

Table 2. Physical Changes Due to Elevated Temperature

Grade (N/mm ²)	Crack Size (mm)		Colour	
	600°C	800°C	600°C	800°C
50	0.04 (hair-like)	0.8 (visible)	Light greyish purple	Greyish purple
60	0.04 (hair-like)	0.8 (visible)	Light greyish purple	Greyish purple
65	0.04 (hair-like)	0.7 (visible)	Light greyish purple	Greyish purple

4.8 Microstructural Analysis

The Microstructural Analysis (SEM) analysis revealed significant microstructural changes due to elevated temperature exposure. Plate 1 – 3 shows the SEM micrograph of BAC samples at 800°C for grade 50, 60, and 65. As indicated, the analysis was provided for the control samples, with and without plasticizer, for Unburnt and burnt BAC. The 5%, 10%, 15%, and 20% SEM for Unburnt and Burnt BAC samples was also presented. The basic elements (Ca, Si, Al, Fe, S, and Mg) constituted 92-95% of the burnt and unburnt samples. After heating at 800°C, spherical particles and black spots present in unburnt samples disappeared, resulting in irregular shapes with heat-driven cracks. The micrographs showed that: Control samples exhibited a relatively uniform structure with some microcracks after heating. 5% SCBA samples showed a more uniform and homogeneous structure. 10% SCBA samples exhibited a uniform structure with minor swelling. 15% SCBA samples appeared more uniform, more homogeneous, and stable than other replacement levels. 20% SCBA samples showed swelling and a less uniform structure with a porous appearance. The disappearance of bagasse ash fibers after heating was clearly observed, contributing to a more uniform structure at 15% replacement. These findings are consistent with Setyowati [48], who reported that spherical shapes and black spots in unburnt samples disappear after heating, resulting in irregular shapes with heat-driven cracks. The SEM results confirm that Ca, Si, Al, and Fe remain intact even after heating, demonstrating that SCBA can be used as a suitable and sustainable replacement material for concrete production. The 15% SCBA replacement appears optimal for microstructural stability at elevated temperatures. As illustrated in plates 1 – 3 in the appendix.

5 CONCLUSIONS

Based on the experimental investigation of the effect of high temperatures on the microstructure and compressive strength of HPC produced from cement partially replaced with SCBA, the following conclusions are drawn: The SCBA used in this study satisfies the requirements for pozzolanic materials, with $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content of 80.45%, exceeding the minimum 70% required Chemical Composition. The optimum SCBA replacement level was 10% for all concrete grades, yielding compressive strengths of 54.13, 62.92, and 65.45 N/mm² for grades 50, 60, and 65, respectively corresponding to the Ambient Temperature Strength. Weight loss due to elevated temperature increased with temperature and SCBA content. At 800°C, the highest weight losses of 11.57%, 19.39%, and 25.85% were recorded at 20% SCBA replacement for grades 50, 60, and 65 N/mm², respectively. Compressive strength loss increased with temperature, concrete grade, and SCBA content. At 800°C, the highest strength losses of 63.04%, 70.26%, and 73.70% were recorded at 20% SCBA replacement for grades 50, 60, and 65 N/mm², respectively. Control specimens exhibited lower strength losses of 32.99%, 42.42%, and 42.54% for the same grades. Hair-like cracks (0.04 mm) appeared at 600°C, while visible cracks (0.7-0.8 mm) developed at 800°C, exceeding the maximum allowable crack width of 0.5 mm. Colour changed from light greyish purple at 600°C to greyish purple at 800°C. SEM analysis revealed that spherical particles and black spots in unburnt samples disappeared after heating, resulting in irregular shapes with heat-driven cracks. The 15% SCBA replacement appeared optimal for microstructural stability at elevated temperatures. Fire Resistance Limitation: Concrete grades 50 and 60 turned to ash at 1000°C, while grade 65 exhibited 81.46% strength loss at 20% SCBA replacement. The effect of fire is irreversible, and SCBA has limited impact on improving fire resistance. The study concludes that while SCBA improves ambient-temperature properties of HPC, its presence significantly compromises fire resistance. These findings provide critical insights for the design and application of sustainable HPC in fire-prone environments.

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APPENDIX

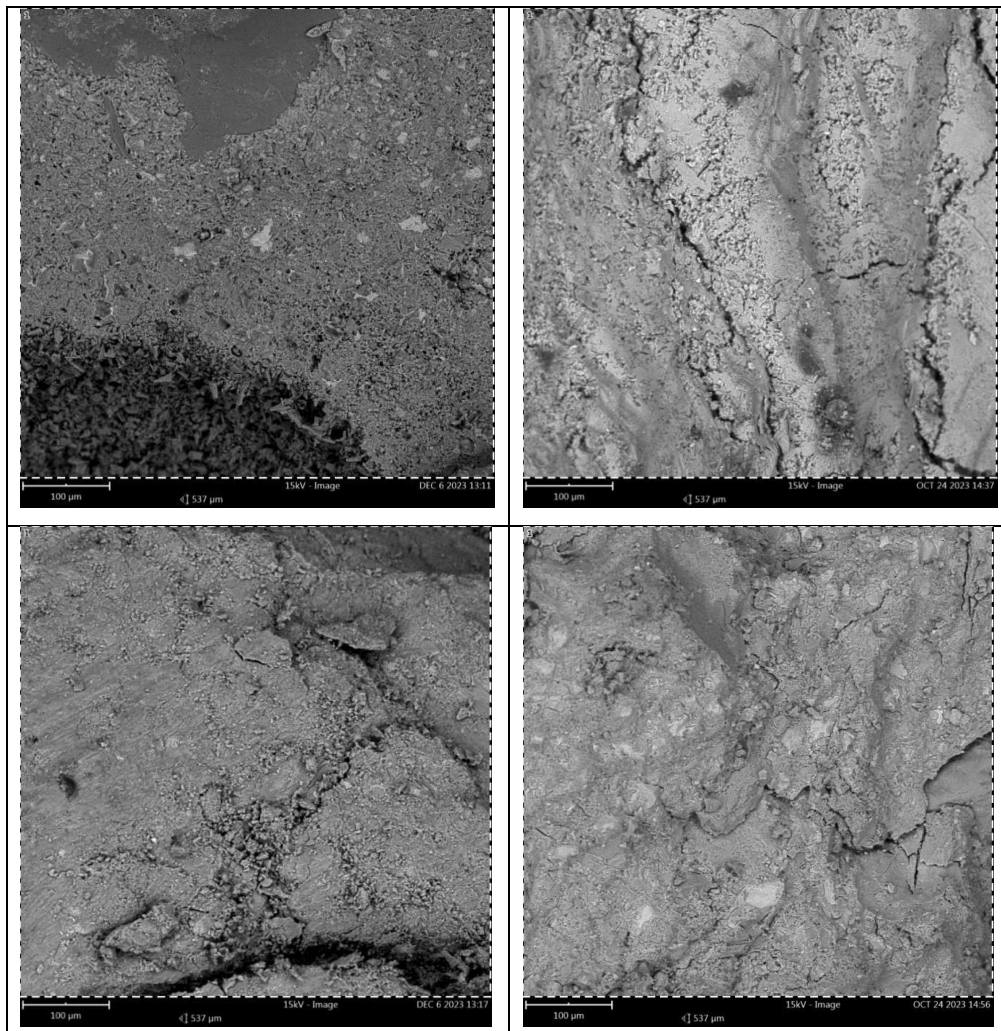
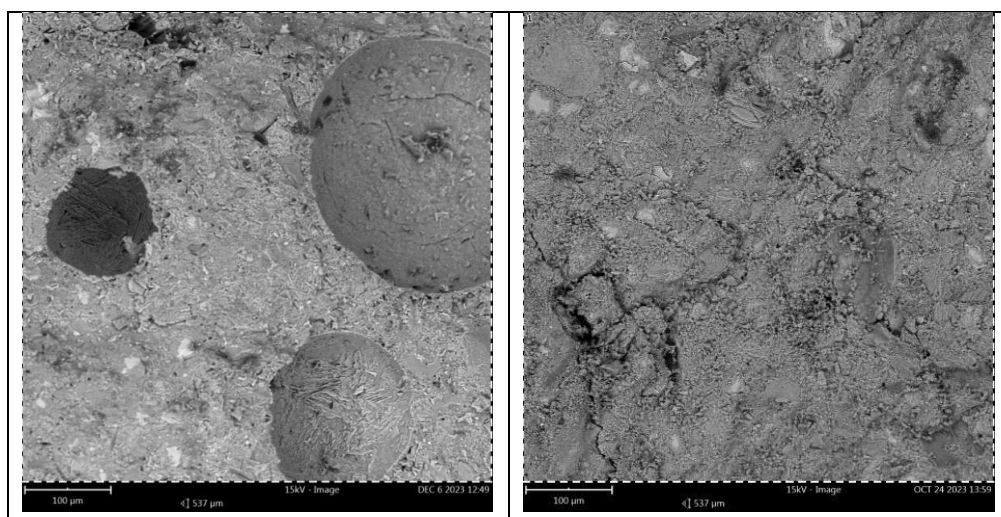


Plate 1a. SEM Micrograph for BAC samples: (a) Control Unburnt, (b) Control burnt, (c) Control + Plasticizer Unburnt (d) Control + Plasticizer Burnt at 800°C Grade 50



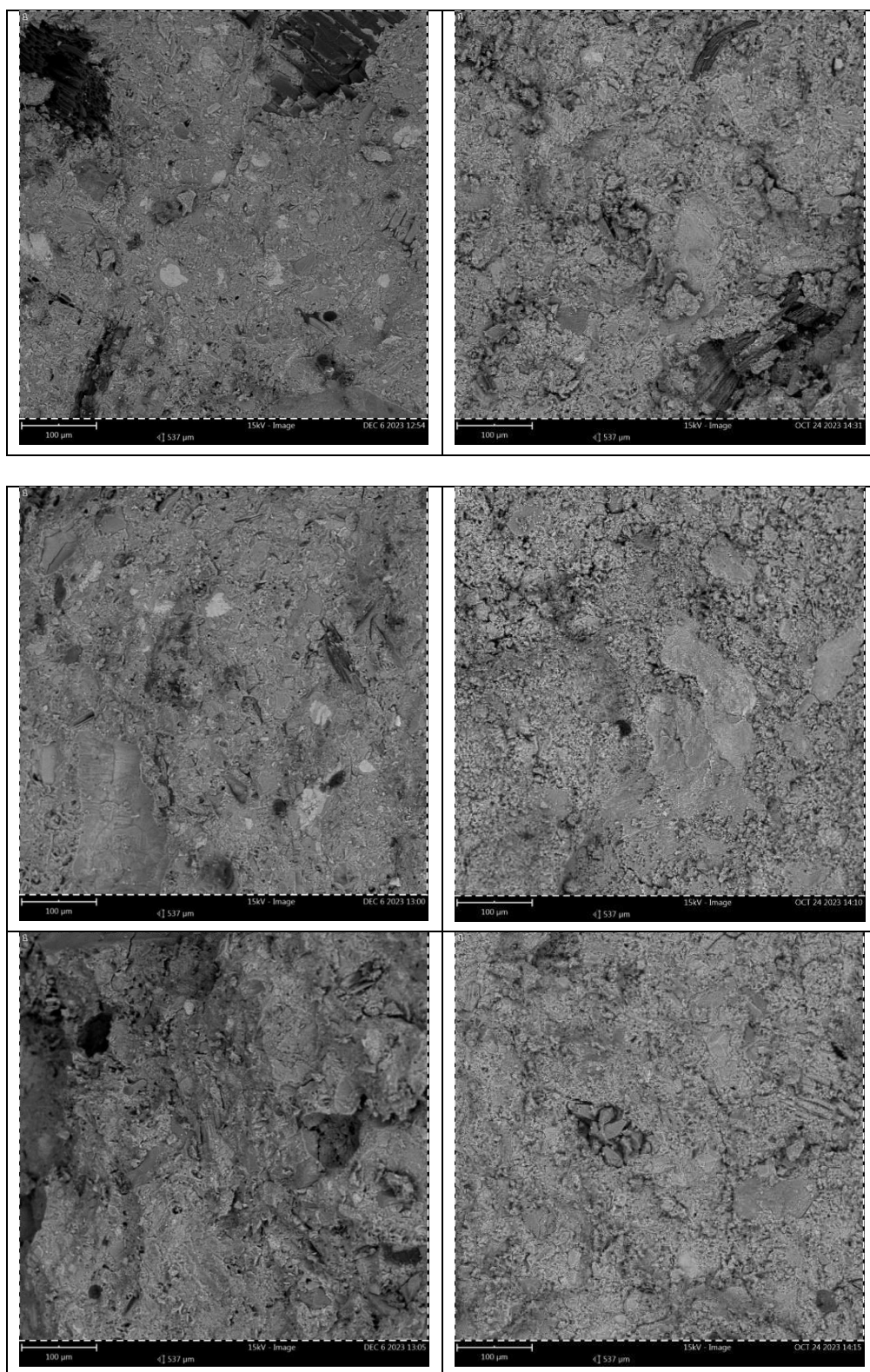


Plate 1b. SEM Micrograph for BAC samples: **(a)** 5%, Unburnt, **(b)** 5% burnt, **(c)** 10% Unburnt **(d)** 10% Burnt at 800°C **Grade 50**

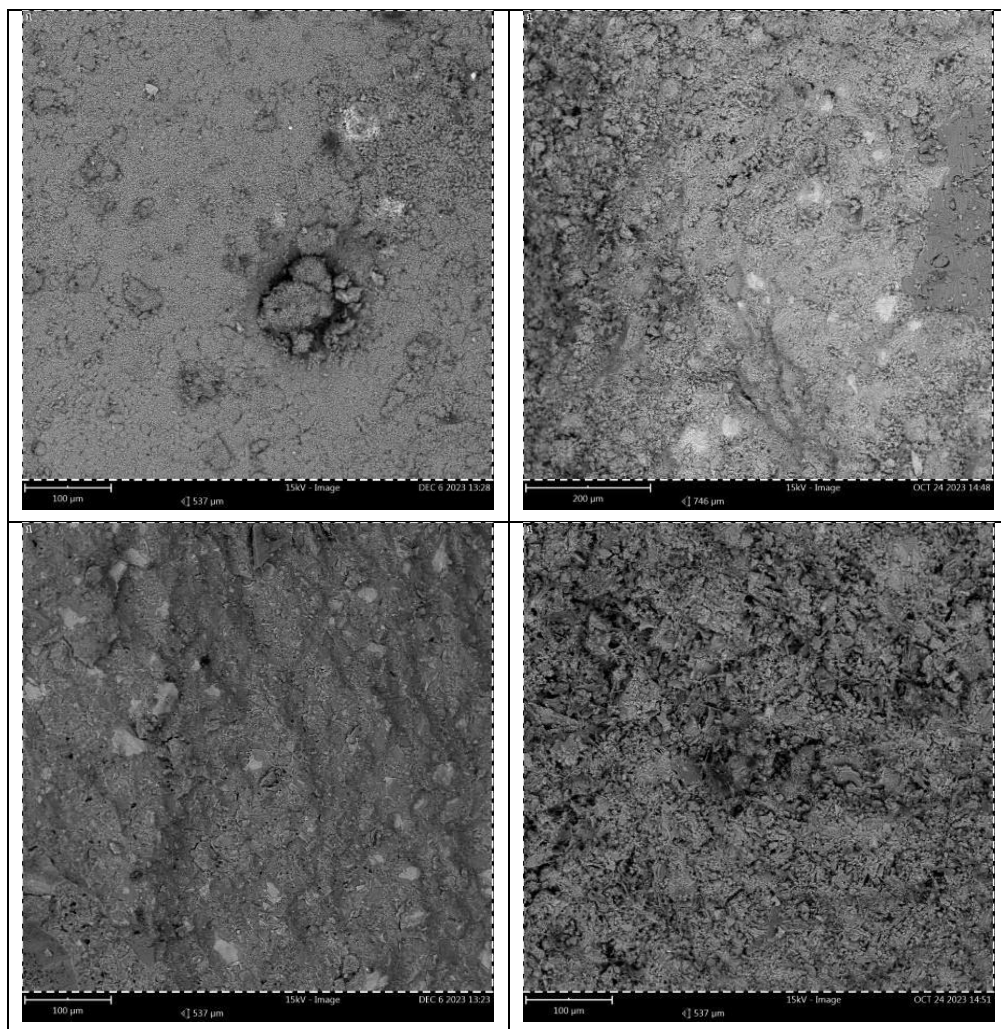
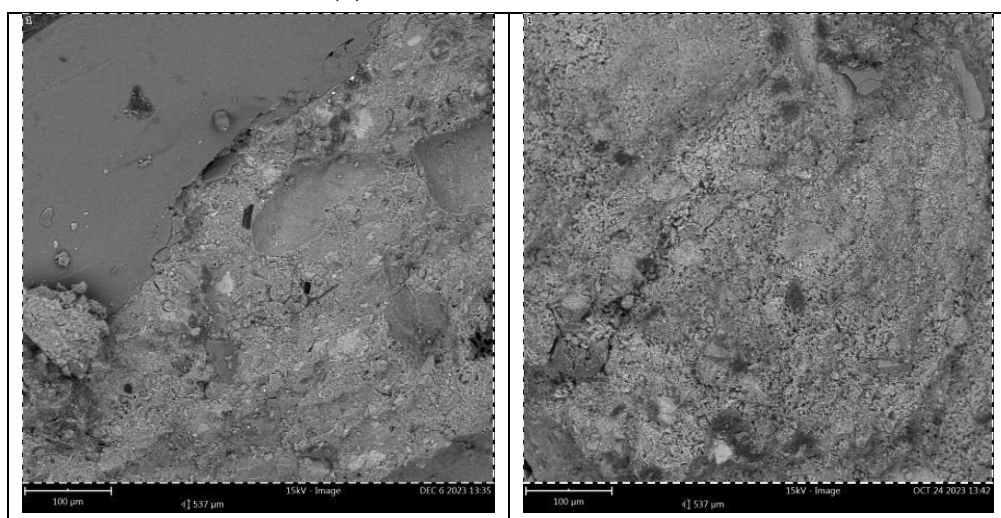


Plate 2a. SEM Micrograph for BAC samples: **(a)** Control Unburnt, **(b)** Control burnt, **(c)** Control + Plasticizer Unburnt **(d)** Control + Plasticizer Burnt at 800°C **Grade 60**



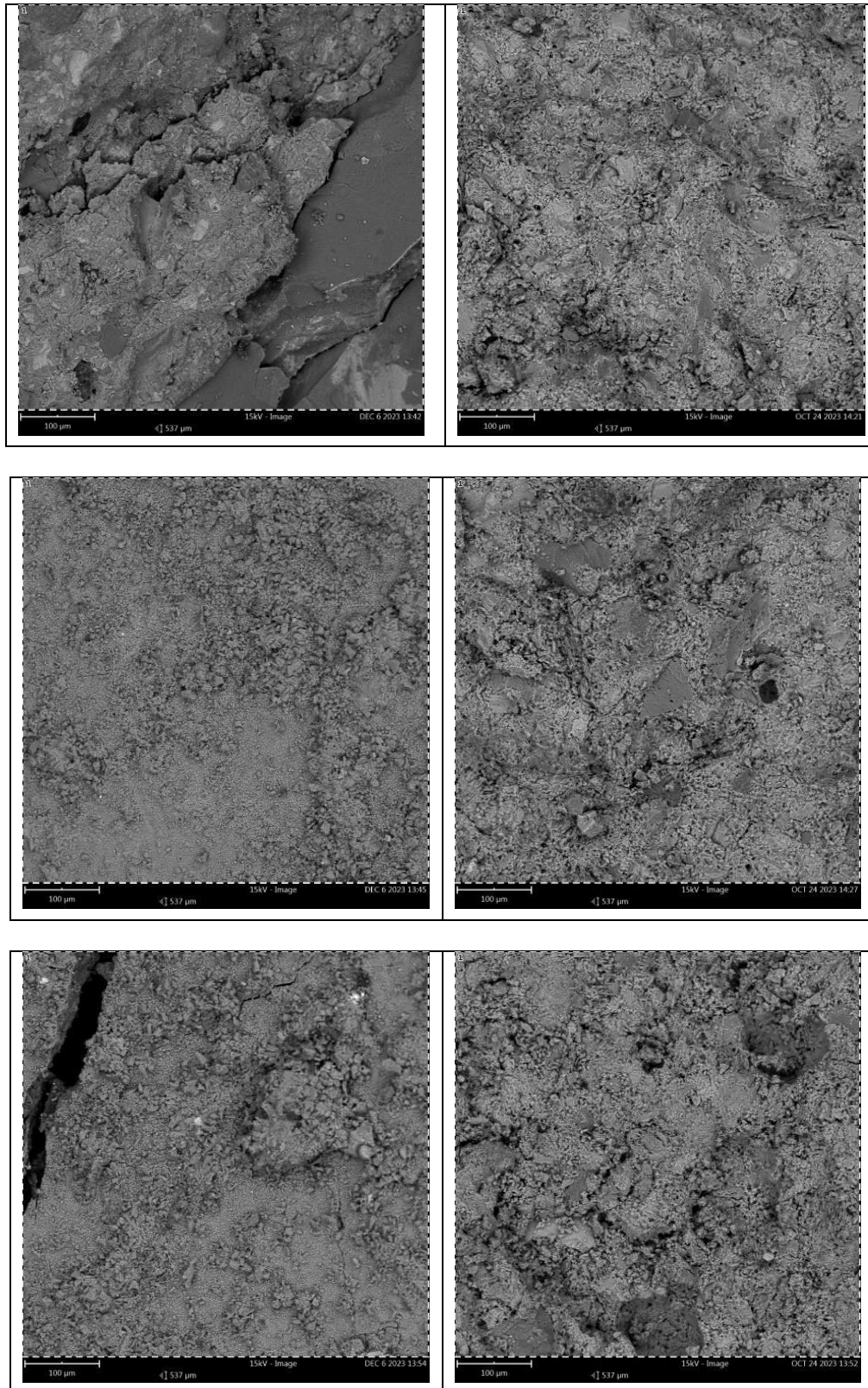


Plate 2b. SEM Micrograph for **BAC** samples: (a) 5%, Unburnt, (b) 5% burnt, (c) 10% Unburnt (d) 10% Burnt at 800°C **Grade 60**

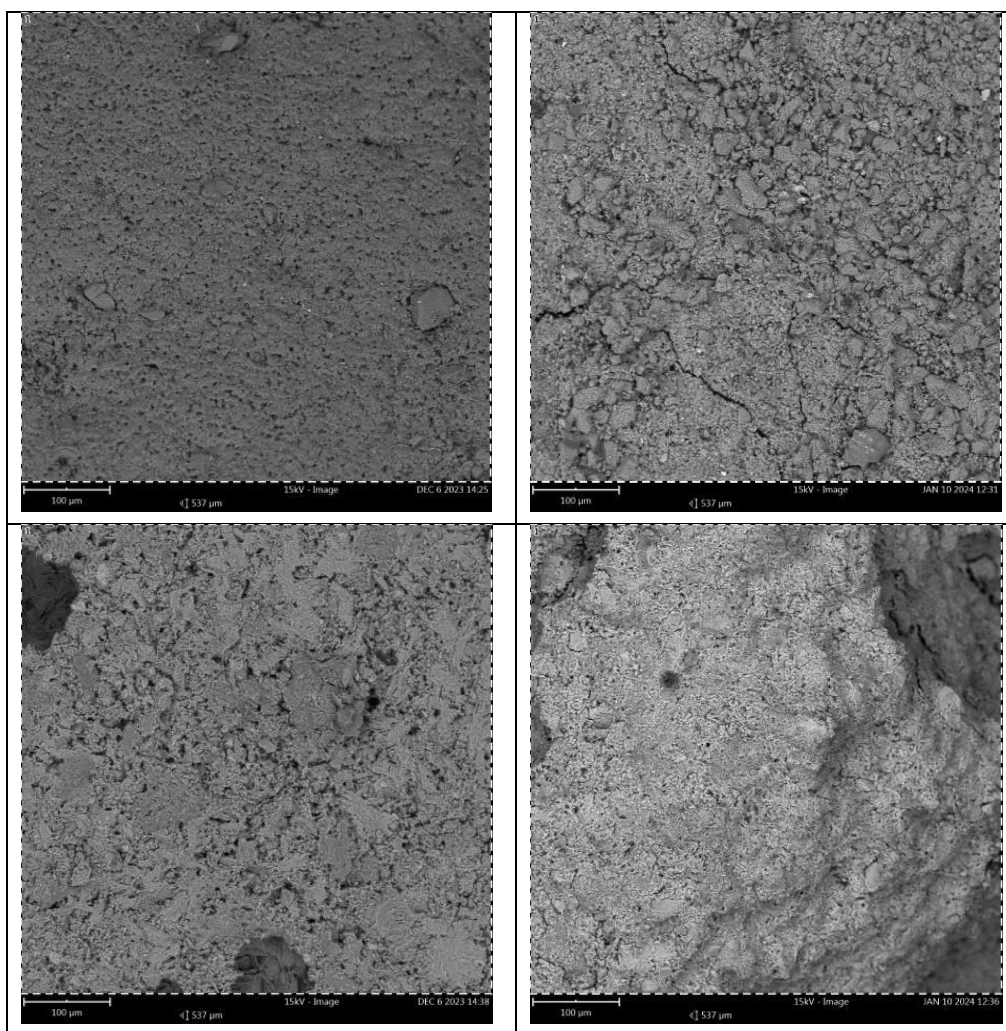
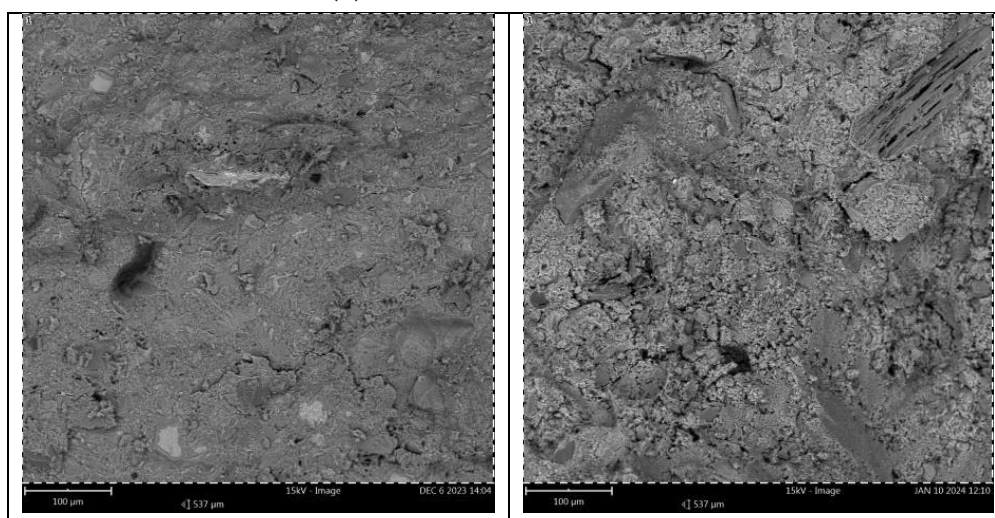


Plate 3a. SEM Micrograph for BAC samples: **(a)** Control Unburnt, **(b)** Control burnt, **(c)** Control + Plasticizer Unburnt **(d)** Control + Plasticizer Burnt at 800°C **Grade 65**



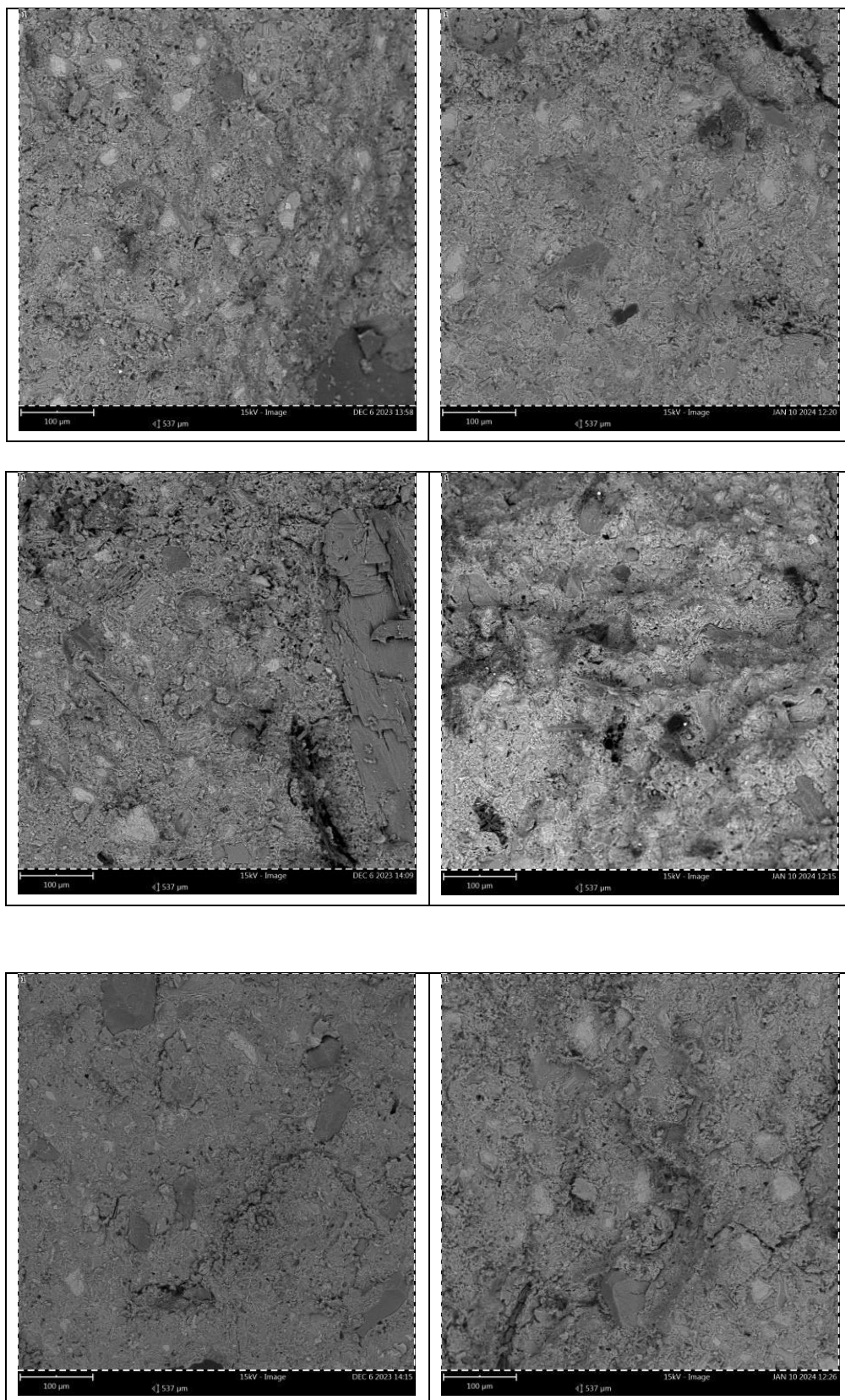


Plate 3b. SEM Micrograph for BAC samples: **(a)** 5%, Unburnt, **(b)** 5% burnt, **(c)** 10% Unburnt **(d)** 10% Burnt at 800°C **Grade 65**