

The Effect of Thermal Exposure on Carbonated Cow Bone Ash, Fly Ash Mixed Concrete

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Abstract

Concrete exposed to high temperatures during fire incidents or industrial operations often suffers loss of strength, durability, and microstructural integrity. This study investigates the thermal response of carbonation-cured concrete incorporating cow bone ash (CBA) and fly ash (FA) as partial ordinary Portland cement replacements, addressing both high-temperature performance and sustainable binder development.

Four mixes were evaluated: a control mix and three blended mixes containing 7.5, 12.5, and 17.5% combined CBA–FA replacement at a constant water–binder ratio of 0.40. Specimens were cured under standard conditions and exposed to 200, 400, 600, 800, 900, and 1000°C. Constituent materials were characterised using XRF, XRD, and SEM, while post-heating performance was assessed through compressive strength, split tensile strength, weight retention, and water absorption. SEM–EDS and TGA were used to examine microstructural changes and thermal decomposition behaviour.

The results showed that the 12.5% CBA–FA mix provided the best balance of residual strength, durability, and microstructural stability after thermal exposure. SEM–EDS confirmed the persistence of key cementitious elements, including Ca, Si, and Al, while TGA indicated improved thermal resilience and reduced mass loss compared with the control. The findings suggest that 12.5% CBA–FA replacement can support sustainable concrete production for thermally aggressive environments.

Introduction

Concrete is a heterogeneous material consisting of fine aggregate, coarse aggregate, water and cement as the main binder. Concrete is the most widely used construction material in the world, primarily due to its availability, ability to conform to any desired shape, durability, and strength. However, it is environmentally damaging as it accounts for a significant percentage of global CO₂ emissions, mainly from cement manufacturing [1], [2]. The need for a reduction of cement consumption and sequestration of CO₂ has inspired research for sustainable alternatives to cement, including supplementary cementitious materials (SCMs) [3]. Fly ash (FA), one of these SCMs, a coal combustion byproduct, has been utilised for its pozzolanic reactivity, as it can improve concrete's long-term strength and durability by forming calcium silicate hydrate (C-S-H) gel [4]. In addition, carbonated cow bone ash (CCBA) valorises agricultural waste and enhances concrete's mechanical properties through the calcium (Ca) rich composition of the ash, which reacts with CO₂ to produce stable calcium carbonate (CaCO₃) and is beneficial through its waste valorisation [5].

In the microstructure of FA concrete, the C-S-H gel gets dehydrated at high temperature, changing its porosity and density. The dehydrated C-S-H gel causes degradation in the concrete [6]. Thermal exposure on FA concrete also results in phase changes in the cement matrix and FA particles, which could alter the overall quality of the concrete [7]. The calcination of CBA, however, enhances its reactivity by producing a calcium-rich compound that reacts with Ca(OH)₂ to form C-S-H, ultimately leading to

increased concrete strength [2]. Furthermore, the carbonated calcium compounds can reduce overall porosity and enhance binding effectiveness within the concrete matrix [8].

The FA and CCBA combination for concrete is one of the most promising synergies in the construction industry. The FA particles improve the workability and reduce the permeability, while CCBA have a carbonation process that densifies the microstructure and alleviates shrinkage and alkali silicate reactivity [9]. In CCBA mixed FA concrete, the elevated calcium levels enhance the pozzolanic activity of the combination, leading to a greater production of C-S-H gel and a reduction in the porosity of the microstructure [10]. The decrease in free calcium hydroxide in FA and CCBA takes the place of the concrete matrix typically present in standard concrete [11].

However, the thermal resilience of CCBA mixed FA concrete is poorly understood. Physicochemical degradation of concrete occurs when many structural materials reach an elevated temperature, dehydrating C-S-H gel and decomposing calcium hydroxide (CH) and cracking on the micro scale, collectively damaging the mechanical integrity [6], [12]. Other studies have shown FA's thermal performance while it reduces CH contents by stabilising concrete up to 600°C [13], the role of CCBA under similar conditions is underexplored. Furthermore, there has been little reporting of phase transitions and permeability changes externally subjected to thermal stress that are isolated by FA and CCBA [14].

This study addresses these gaps by investigating the impact of thermal exposure (200–1000°C) on the microstructure and mechanical properties of CCBA-FA concrete. Four primary objectives guide the research:

1. Characterise the materials used (Carbonated Bone Ash, Fly Ash, aggregates, and cement).
2. Analyse carbonation product stability under thermal degradation using XRD and SEM.
3. Quantify pore structure and permeability changes post-exposure to correlate with mechanical performance.
4. Evaluate compressive and split tensile strength to identify optimal CCBA-FA replacement ratios.

The findings aim to advance the application of CCBA-FA concrete in fire-prone environments and high-temperature industrial settings, aligning with UN Sustainable Development Goals (SDGs) 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities), and 12 (Responsible Consumption) by promoting low-carbon, waste-derived construction materials.

Materials and Methods

Materials

The primary materials used include,

- a. Cement

Ordinary Portland cement (OPC) of grade 42.5 was used for this research. The OPC comprise of chemicals that participate in hydration processes upon contact with water, resulting in the formation of C-S-H gel and calcium hydroxide. It serves as the principal binder, uniting the aggregates and other components in concrete. It also supplies the requisite alkalinity for the pozzolanic reactions of fly ash and cow bone ash. A Grade 15 concrete mix, batched by weight, was used to produce all specimens.

b. Cow bone ash

Cow bone ash (CBA) is produced through the calcination of bovine bones, typically obtained from agricultural or meat processing industries. The bones are cleaned, dried, and subjected to high-temperature calcination to remove organic material and convert the bone into a fine ash.

Cow bone ash predominantly consists of calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$) and hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$), recognised for their thermal stability and capacity to enhance the mechanical qualities of concrete. CBA serves as a supplementary cementitious material (SCM), partially substituting cement to diminish the carbon footprint of concrete. The thermal stability of CBA renders it appropriate for examining the impacts of high-temperature exposure on concrete.

c. Fly Ash

Fly ash (FA) is a by-product of coal combustion in thermal power facilities. It is extracted from the flue gases via electrostatic precipitators or bag filters. FA is categorised into two types: Class F, characterised by low calcium content, and Class C, distinguished by high calcium level. This research utilises class F fly ash because of its pozzolanic characteristics. It enhances the workability and durability of concrete by decreasing water consumption and improving the packing density of the mixture.

d. Aggregates

Aggregates are classified into two categories: coarse aggregates and fine aggregates. The aggregates utilised in this study were procured locally and evaluated for characteristics including particle size distribution, specific gravity, and water absorption prior to application. It confers mass to the concrete, decreasing the quantity of cement used and enhancing dimensional stability. It also enhances the mechanical qualities of concrete, including compressive strength and abrasion resistance.

e. Carbon dioxide

Carbon dioxide (CO_2) is a naturally occurring gas in the Earth's atmosphere, produced by processes such as respiration, volcanic eruptions, and the decomposition of organic matter. A significant amount of CO_2 is emitted from industrial activities, including cement production, electricity generation, and chemical synthesis. Carbon dioxide (CO_2) can be extracted from industrial emissions using technologies such as carbon capture and storage (CCS) or carbon capture and utilisation (CCU). CO_2 interacts with calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the presence of moisture to produce calcium carbonate (CaCO_3). The process of

carbonation enhances the compressive strength and durability of concrete by densifying its microstructure and decreasing porosity.

f. Water

Portable water devoid of contaminants, including chlorides, sulphates, and organic matter, which may negatively impact the hydration process and durability of concrete, was used for mixing and curing the concrete. It is crucial for cement hydration, facilitating the development of C-S-H gel and other hydration byproducts.

Methods

Characterization techniques

- a. X-Ray Fluorescence (XRF): XRF analysis was used to determine the oxide composition of the cow bone ash (CBA). Samples were sieved through a 75 μm mesh, pressed into pellets, and analysed using an XRF spectrometer. The resulting spectra were interpreted to identify major oxides such as CaO , SiO_2 , P_2O_5 , Al_2O_3 , Fe_2O_3 , and MgO , which affect the material's pozzolanic reactivity and blending compatibility with OPC.
- b. Scanning Electron Microscopy (SEM): SEM imaging was carried out to investigate the morphology of fly ash and cow bone ash (CBA). Powdered samples were first oven-dried at 105°C to remove moisture, then sputter-coated with a thin layer of gold to make them conductive. Samples were placed on aluminium stubs using carbon tape and examined using a scanning electron microscope (SEM) at magnifications ranging from 500x to 2000x. The images revealed surface texture and particle shape, which were interpreted in terms of reactivity and packing characteristics.
- c. X-Ray Diffraction (XRD): To determine the mineralogical phases in cow bone ash (CBA), XRD analysis was performed. The sample was ground to a fine powder and scanned in a diffractometer using Cu-K α radiation at 40 kV and 30 mA. The scan range was set from 5° to 70° (2θ), with a step size of 0.02° . The peaks were identified to detect phases such as CaO , SiO_2 , and P_2O_5 , which indicate the presence of pozzolanic and cementitious compounds.
- d. Sieve Analysis: Sieve analysis was conducted to determine the particle size distribution of the aggregates in accordance with ASTM C136. For each test, approximately 500 grams of oven-dried aggregate was weighed and poured into the top of a sieve stack arranged from largest to smallest aperture sizes. A mechanical sieve shaker was used to agitate the samples for 10 minutes. The retained mass on each sieve was recorded, and the percentage passing or retained was calculated. This test was performed separately for fine and coarse aggregates.
- e. Bulk Density: Bulk density of both fine and coarse aggregates was determined using the method outlined in ASTM C29. A cylindrical container of known volume was filled with dry aggregate in three layers, each tamped 25 times with a standard rod. The top was levelled, and the net mass of the aggregate was divided by the container's volume to obtain the bulk density in kg/m^3 .

- f. **Specific Gravity:** Specific gravity was measured in accordance with ASTM C127 for coarse aggregate and ASTM C128 for fine aggregate. For fine aggregate, a pycnometer was used. The oven-dried sample was mixed with water, and the weight of the pycnometer filled with the saturated sample was recorded. For coarse aggregate, the samples were soaked in water for 24 hours and surface dried before weighing in air and water to compute the apparent and bulk specific gravities.
- g. **Water Absorption:** The water absorption test followed ASTM C127 and C128. Oven-dried samples were submerged in water for 24 hours. After soaking, samples were surface-dried and weighed. The difference in weight before and after soaking was expressed as a percentage of the dry weight. This indicates the capacity of the aggregate to absorb water, which is crucial for adjusting the water-cement ratio.
- h. **CO₂ Sequestration Process:** Specimens were subjected to accelerated carbonation for 7 hours in a sealed carbonation chamber filled with CO₂ gas. The chamber was equipped with a regulated gas supply system to maintain a CO₂ concentration of $10 \pm 0.5\%$ by volume throughout the exposure period. Relative humidity was controlled at $60 \pm 2\%$, and the temperature was kept at $23 \pm 2^\circ\text{C}$ to optimise carbonation reaction rates without inducing excessive drying. This process enhances the mechanical properties and microstructure of concrete by reacting with calcium hydroxide (Ca(OH)₂) to form calcium carbonate (CaCO₃), which densifies the concrete matrix and improves its strength.

Mix proportions

The mix proportion used is shown in Table 1.

Table 1
Mix proportions for concrete

Mix type	OPC (%)	CBA (%)	FA (%)	Aggregates	Water to cement ratio (w/c)
Control	100	0	0	Yes	0.4
CBA-FA mix 1	92.5	2.5	5	Yes	0.4
CBA-FA mix 2	87.5	5	7.5	Yes	0.4
CBA-FA mix 3	82.5	7.5	10	Yes	0.4

Experimental testing

- a. **Compressive Strength:** The compressive strength test was performed to evaluate the ability of the concrete specimens to withstand axial loads under compression. Concrete cylindrical specimens measuring 75 mm in diameter and 150 mm in height were cast for each mix, including the control and the various CBA-FA replacement levels. After demoulding at 24 hours, the specimens were cured in CO₂ for 6 hours. Tests were conducted at 7, 14, and 28 days. The compressive strength was

determined using a calibrated universal testing machine (UTM). The load was applied vertically at a constant rate until failure occurred. The maximum load was recorded, and the compressive strength was calculated using the formula:

$$\text{Compressive Strength (N/mm}^2\text{)} = \text{Maximum Load (N)} / \text{Cross-sectional Area (mm}^2\text{)}$$

- b. Split Tensile Strength: The split tensile strength test was conducted to assess the tensile capacity of concrete. Cylindrical specimens of 75 mm diameter and 150 mm height were used. After 28 days of curing, the samples were tested in accordance with ASTM C496. In the test setup, each specimen was placed horizontally between the platens of a universal testing machine. A line load was applied along the longitudinal axis of the cylinder. The load was applied gradually until failure occurred along the vertical diameter. The split tensile strength was calculated using the formula:

$$\text{Split Tensile Strength (N/mm}^2\text{)} = 2 \times \text{Maximum Load (N)} / (\pi \times \text{Diameter} \times \text{Length})$$

- c. Water Absorption: Samples were oven-dried for 24 hours, weighed (W_{dry}), soaked in water for 24 hours, and re-weighed (W_{wet}). Absorption was calculated as:

$$\text{Absorption (\%)} = [(W_{\text{wet}} - W_{\text{dry}}) / W_{\text{dry}}] \times 100$$

- d. Thermal Exposure: At 7, 14 and 28 days after curing, the specimens were subjected to thermal exposure in a programmable electric furnace. The temperature was increased at a rate of 5°C/min to the target temperatures of 200°C, 400°C, 600°C, 800°C, 900°C and 1000°C. The specimens were held at the target temperature for 2 hours to ensure uniform heating. After thermal exposure, the specimens were allowed to cool naturally in the furnace to room temperature.
- e. Thermogravimetric Analysis (TGA): The microstructure of the concrete specimens was examined using TGA to evaluate the thermal stability and decomposition behaviour of the concrete samples, providing an insight into the phases lost at various temperatures. This targets particularly the bound water lost, the decomposition of calcium hydroxide and the decarbonation of calcium carbonate compounds.
- f. Scanning Electron Microscopy (SEM): The microstructure of the concrete specimens was examined using SEM to observe changes in the cementitious matrix and interfacial transition zone (ITZ) after thermal exposure.

Results and Discussion

Material characterization

a. Chemical analysis of cowbone ash (CBA)

Table 2 presents the chemical composition of cow bone ash. Major compounds include calcium oxide (CaO), silica (SiO₂), iron oxide (Fe₂O₃), and alumina (Al₂O₃), with values of 58.06, 3.72, 1.85, and 1.23%, respectively. These constitute less than 60% of the total weight, which is below the 70% minimum specified by ASTM C618-12 (2012) for pozzolans. Therefore, while cow bone powder contains pozzolanic compounds, it cannot be classified as a natural pozzolan.

Table 2
Chemical composition of cow bone ash

Compound	Chemical Formula	Percentage (%)
Calcium Oxide	CaO	58.06
Silica	SiO	3.72
Iron Oxide	Fe ₂ O ₃	1.85
Alumina	Al ₂ O ₃	1.23

b. Scanning electron microscopy (SEM) analysis of fly ash

The SEM analysis of Fly Ash (FA) revealed significant morphological and elemental composition characteristics. The analysed micrograph in Fig. 1 showed spherical particles, which are characteristic of fly ash and are beneficial in enhancing workability and packing density in concrete mixes.

Elemental analysis from the SEM evaluation showed the following weight concentrations: Silicon (Si) 56.21%, Calcium (Ca) 24.94%, Aluminium (Al) 6.72%, Iron (Fe) 6.28%, Potassium (K) 2.99%, Sodium (Na) 1.95%, Sulfur (S) 0.26%, Manganese (Mn) 0.26%, Magnesium (Mg) 0.22%, and Titanium (Ti) 0.18%.

c. X-ray diffraction of cow bone ash (CBA)

The X-ray diffractogram for cow bone ash is shown in Fig. 2. The major phase is amorphous, indicated by a broad hump between 23° and 27° 2θ. This confirms the presence of an amorphous phase typical of pozzolanic materials.

d. Particle size distribution

The particle size distribution was carried out by sieve analysis. Figure 3 shows the distribution curves for fine and coarse aggregates. The fine aggregate showed a continuous grading curve with 84.12% passing the 4.75 mm sieve and 0.56% passing the 0.075 mm sieve. The coarse aggregate was mostly retained on the 9.5 mm and 4.75 mm sieves, indicating a gap-graded distribution with a sharp curve. The coefficient of uniformity (Cu) and coefficient of curvature (Cc) calculated for both aggregates confirm that the fine aggregate is poorly graded, while the coarse aggregate is well graded.

e. Specific gravity and bulk density

The specific gravity of the fine aggregate was 2.62, while that of the coarse aggregate was determined as 2.61. These values fall within the typical range of 2.4 to 3.0 for normal-weight aggregates as specified by ASTM C127 (2015). The bulk density of the fine aggregate was 1.75 g/cm³, while the bulk density of the coarse aggregate was 1.47 g/cm³, both conforming to the BS 812-2 (1990) range of 1200–1750 kg/m³.

f. Water absorption and moisture content

Water absorption values for the fine and coarse aggregates were 0.25% and 0.47%, respectively. These values are below the 5% limit specified by ASTM C127 (2015), indicating that both aggregates are suitable for concrete production in terms of absorption. The low absorption also implies low porosity and a denser material, which is beneficial for strength development and durability.

g. Fineness Modulus

The fineness modulus (FM) for the fine aggregate was calculated based on the sieve analysis data and was found to be 2.82, which lies within the acceptable range of 2.3 to 3.1 for fine aggregates as stipulated by ASTM C33/C33M-21 (2021). This value indicates that the sand is moderately coarse and suitable for concrete work.

Microstructural analysis test results

a. SEM-EDS analysis of 12.5% CBA-FA concrete sample at 600°C

As shown in Table 3, the EDS spectrum showed that Silicon (Si) and Calcium (Ca) are the most prevailing elements in the exposed concrete sample, confirming the existence of C-S-H gel despite the exposure to high temperature.

Table 3
EDS Analysis of 12.5% CBA-FA Concrete at 600°C

Element	Symbol	Atomic Concentration (%)	Weight Concentration (%)
Silicon	Si	44.20	40.16
Calcium	Ca	14.94	19.37
Aluminium	Al	12.50	11.25
Iron	Fe	3.28	5.93
Potassium	K	3.31	4.18
Sodium	Na	4.31	3.21
Carbon	C	3.62	4.88
Titanium	Ti	2.36	0.56
Sulfur	S	0.19	0.19
Magnesium	Mg	0.24	0.19
Oxygen	O	11.05	10.07

b. Thermogravimetric Analysis (TGA) of Control Mix at 800°C

Thermogravimetric analysis showed that control samples experienced major mass loss between 400°C and 800°C, corresponding to CH and CaCO_3 decomposition. CCBA-FA blends displayed delayed mass loss onset and reduced total loss, indicating improved thermal stability. As shown in Fig. 4, the primary stages of weight loss for the control mix are,

c. Stage 1 (Up to 200°C): Loss of free moisture and physically bound water. This phase corresponds to evaporation and drying.

d. Stage 2 (200–550°C): Decomposition of calcium hydroxide (Ca(OH)_2). This endothermic phase is typically where portlandite begins to degrade, releasing water vapour.

e. Stage 3 (550–800°C): Decarbonation of calcium carbonate (CaCO_3). This is the most critical stage where CO_2 is released, leaving CaO behind, resulting in irreversible chemical breakdown of the concrete matrix.

The most significant mass loss was observed between 600°C and 800°C.

Mechanical properties

a. Compressive strength test results

The compressive strength test results, as shown in Table 4, reveal that all mixes experience strength loss with increasing temperature, but the degree of deterioration varies depending on the CBA-FA replacement level. The key trends deduced across the mix types include:

- a. Control Mix: Rapid deterioration begins between 200°C to 400°C, with losses at 600°C and more at 800°C.
- b. CBA-FA mix 1: Maintains good strength up to 600°C, but degradation accelerates beyond 800°C.
- c. CBA-FA mix 2: Best performer overall, retains more than half of its original strength at 800°C, and even at 1000°C, it remains structurally more competent than other mixes.
- d. CBA-FA mix 3: Performs better than control up to 600°C but suffers faster loss beyond that point, possibly due to excessive ash leading to increased porosity.

The test results show that the 12.5% CBA-FA mix exhibited the highest residual strength across all temperature exposures.

Table 4
Compressive strength test results for the concrete specimens

Mix	Day	Sample	Fm (KN)	Area (mm ²)	Temp (°C)	Weight Loss (%)	Strength (N/mm ²)
Control (S0)	7	1	67.42	4417.86	25	0.00	15.26
		2	60.79	4417.86	200	2.10	13.76
		3	45.86	4417.86	400	4.50	10.38
	14	1	56.13	4417.86	25	0.00	12.71
		2	29.09	4417.86	600	7.90	6.58
		3	18.63	4417.86	800	11.30	4.22
	28	1	87.61	4417.86	25	0.00	19.83
		2	40.20	4417.86	900	14.20	9.10
		3	28.49	4417.86	1000	17.80	6.45
7.5% Replace (S1)	7	1	64.63	4417.86	25	0.00	14.63
		2	57.48	4417.86	200	2.25	13.01
		3	43.07	4417.86	400	4.70	9.75
	14	1	53.10	4417.86	25	0.00	12.02
		2	27.04	4417.86	600	8.05	6.12
		3	17.14	4417.86	800	11.80	3.88
	28	1	80.67	4417.86	25	0.00	18.26
		2	37.77	4417.86	900	14.50	8.55
		3	26.55	4417.86	1000	18.20	6.01
12.5% Replace (S2)	7	1	61.36	4417.86	25	0.00	13.89
		2	53.63	4417.86	200	2.40	12.14
		3	39.49	4417.86	400	5.10	8.94
	14	1	50.19	4417.86	25	0.00	11.36
		2	22.23	4417.86	600	8.25	5.71
		3	15.24	4417.86	800	12.10	3.45
	28	1	75.77	4417.86	25	0.00	17.15

Mix	Day	Sample	Fm (KN)	Area (mm ²)	Temp (°C)	Weight Loss (%)	Strength (N/mm ²)
17.5% Replace (S3)		2	35.39	4417.86	900	15.00	8.01
		3	24.25	4417.86	1000	18.50	5.49
		1	58.36	4417.86	25	0.00	13.21
		2	50.63	4417.86	200	2.55	11.46
		3	36.98	4417.86	400	5.40	8.37
		1	47.46	4417.86	25	0.00	10.74
	14	2	23.33	4417.86	600	8.40	5.28
		3	13.78	4417.86	800	12.60	3.12
		1	72.54	4417.86	25	0.00	16.42
	28	2	32.60	4417.86	900	15.4	7.38
		3	22.00	4417.86	1000	19.0	4.98

b. Compressive strength vs temperature

Figure 5 presents a comparative trend of compressive strength decline across replacement levels under increasing temperature exposure. It shows the performance ranking among the mixes at each temperature, the temperature thresholds for rapid strength loss, and the relative thermal stability of each mix. From the graph, it is deduced that the 12.5% mix retained the most strength post-heating.

c. Split Tensile Strength and Water Absorption Tests

The split tensile strength test results indicate a modest improvement in tensile performance at the 7.5% and 12.5% CBA-FA replacement levels, with a peak strength of 3.12N/mm² observed at 12.5% replacement. This trend correlates with the compressive strength behaviour previously observed, suggesting improved matrix densification and bonding at these levels. However, a decline is seen at 17.5%, indicating excessive replacement may compromise tensile integrity. It is shown in Table 5.

Water absorption results exhibit a rising trend with increasing CBA-FA content. The control mix recorded the lowest absorption at 4.1%, while the 17.5% replacement level absorbed the most water at 5.4%. This increase is attributed to the porous nature of CBA-FA particles, which increases the overall porosity of the concrete.

Table 5
Split tensile strength and Water absorption test results

Cement Replacement Level	Split Tensile Strength (N/mm ²)	Water Absorption (%)
0% (Control)	2.8	4.1
7.5%	2.95	4.6
12.5%	3.12	4.9
17.5%	2.76	5.4

d. Weight Retention VS Temperature

Figure 6 shows the relationship between temperature and percentage weight retention of concrete specimens subjected to elevated temperatures.

e. Temperature vs Weight Change Analysis

This graph, as shown in Fig. 7, shows similar critical points of deterioration as the TGA graph. It shows that chemical decomposition accelerates beyond 600°C, correlating with the sharpest drop in compressive strength. The 12.5% CBA-FA mix mitigates these losses by reducing thermally vulnerable CH content. The weight loss pattern, as shown by the TGA stages include:

- a. Minimal loss up to 200°C (free water removal).
- b. Plateau from 200 to 400°C (matrix stability).
- c. Rapid drop after 600°C (decomposition of hydration products and aggregates).

The weight percentage change of the control mix at different stages of thermal exposure is shown in Table 6.

Table 6
Weight retention for control mix

Temperature (°C)	Weight (kg)	% Change from RT
Room temperature	1.45	0.0
200	1.40	-3.45
400	1.40	-3.45
600	1.35	-6.90
800	1.25	-13.79

Discussion

With the combination of FA and CBA, there was an increase in the microstructural density because the FA could provide a remarkable microsphere packing, and CBA could fill the micro-hole. The strength deteriorations at high temperatures were natural, and mixes containing moderate CBA proved more resistant. This is explained by better packing and reactivity of the pozzolanic activity, which has minimised microcracking.

The compressive as well as the split tensile strength values showed that concrete mixtures with 12.5% percent CBA-FA added to it performed better at both ambient temperature and at higher temperatures, especially at 200°C and 400°C. Such results are explained by the effect of pozzolanic reactivity in the CBA that introduces extra calcium silicate hydrate (C-S-H) phases, increasing the density and cohesion of the concrete composition under heat stress.

At increased temperatures, there was a significant loss in mechanical strength in the control samples, and this is in tandem with calcium hydroxide and calcium carbonate phases, a decomposition effect, which is true due to Thermogravimetric Analysis (TGA). The critical weight loss values of the control mix were evident in the temperature range (600–800°C), where a significant quantity of decarbonation and structural carbon breakages took place. Conversely, CBA-FA blended mixes demonstrated a slower degradation rate, which means improved thermal stability.

SEM-EDS test on 12.5 per cent CBA-FA mix subjected to 600°C showed that the durability of the cementitious elements like Silicon (Si), Calcium (Ca) and Aluminum (Al) remained. These components are indicators of stable hydration products, especially C-S-H and calcium aluminate phases, in enhancing thermal durability. The underlying idea that CBA brings a mineralogical diversity to stabilise the matrix under the condition of thermal cycling can be further confined by the trace amounts of alkali metals as well as minor oxides.

Conclusion

This paper concludes that cow bone ash mixed with fly ash is a viable and sustainable partial OPC replacement in the usage of thermally exposed concrete. Other important conclusions made include:

- a. CBA-FA provides an increased compressive and tensile strength under ordinary and high temperatures.
- b. CBA-FA blends are more resistant to thermal decomposition.
- c. The negative impact that heat has on OPC concrete is reduced by the blended mixes that enhance the residual strength and characteristics in terms of the microstructural cohesion.

Overall, including CBA and FA in concrete mixes would not only increase thermal conductivity and mechanical stability but also allow pursuing a sustainable building process over OPC avoidance. The outcomes substantiate the implementation of the 12.5% CBA-FA as an ideal substitute level in fire-destined or hot zones, particularly.

Declarations

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Clinical Trial Registration

Not applicable. This study is not a clinical trial and did not involve human participants, patients, clinical intervention, or medical data.

Ethics and Consent to Participate, and Consent to Publish

Not applicable.

Competing Interests

The authors declare no competing interests.

Consent to Publish Declaration

Not applicable.

Author Contributions;

Olatoyan O.J. conceived the study and developed the research design;

Alli A.D., Oyewo S.T., Olayanju O.K., and Alabi A. contributed to material preparation, specimen production, carbonation curing, and laboratory testing;

Alli A.D., Olaiya S.A., and Awolola O.J. contributed to the thermal exposure programme and interpretation of high-temperature performance;

Olaiya. S.A., Achinede E., Bello, O.A., and Lasebikan A.B. analysed the compressive strength, split tensile strength, water absorption, weight retention, SEM–EDS, XRD, XRF, and TGA results;

Olatoyan O.J., Olaiya S.A., Alli A., and Fajinmi I. A. wrote the main manuscript text;

Olayanju O.K., Bello O.A., and Lasebikan A.B. prepared the tables and figures;

Olatoyan O.J. and Olaiya S.A. supervised the research, coordinated revisions, and reviewed the manuscript for intellectual content;

All authors reviewed and approved the final version of the manuscript;

Data Availability

All data supporting the findings of this study are available within the paper.

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Figures

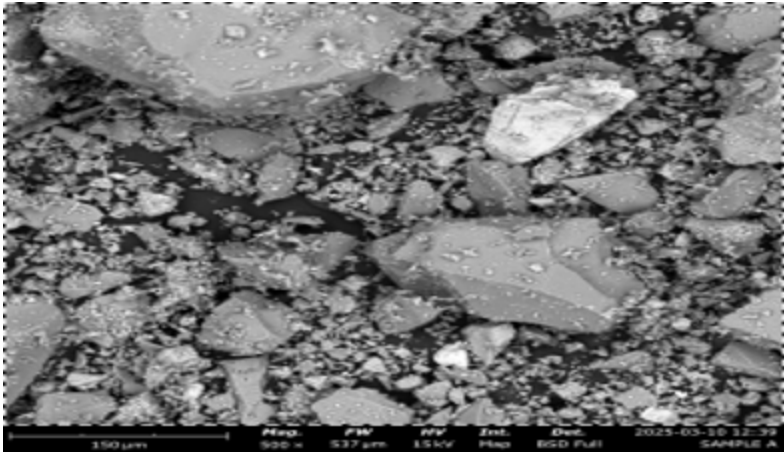


Figure 1
SEM micrograph of Fly Ash

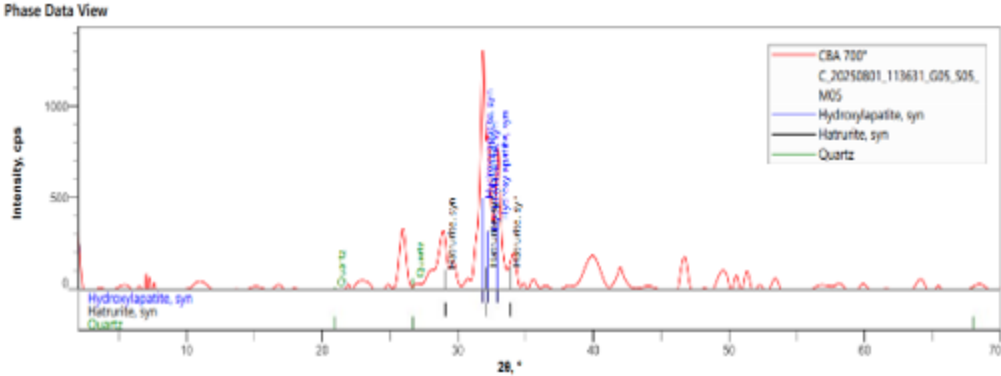


Figure 2
X-ray diffraction pattern for cow bone ash

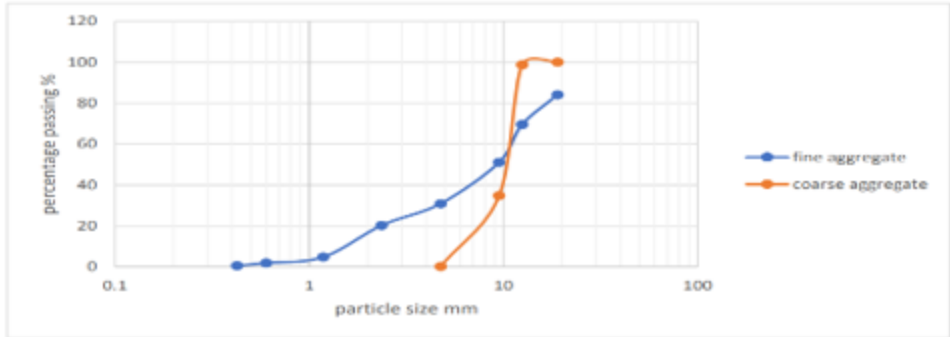


Figure 3

Particle size distribution curves for fine and coarse aggregate

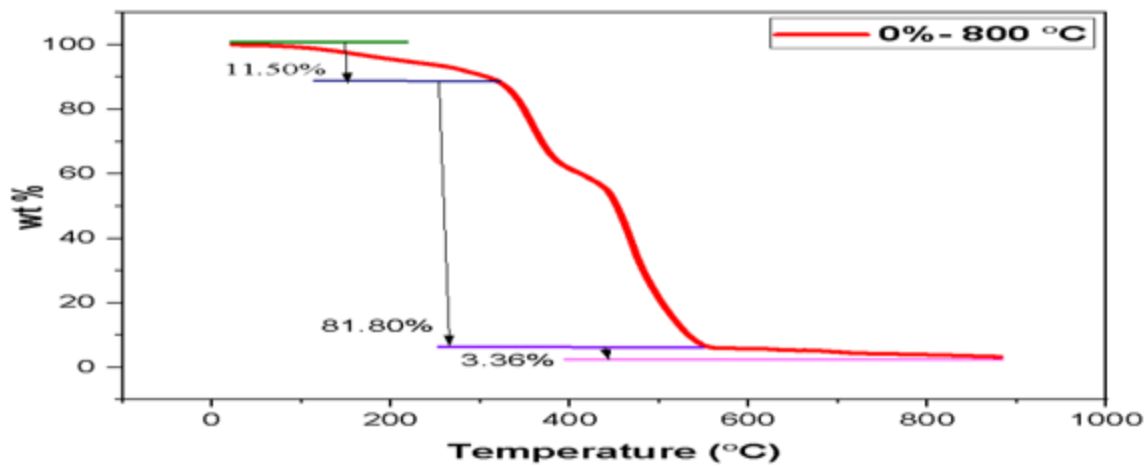


Figure 4

TGA Curve of Control Mix Exposed to 800

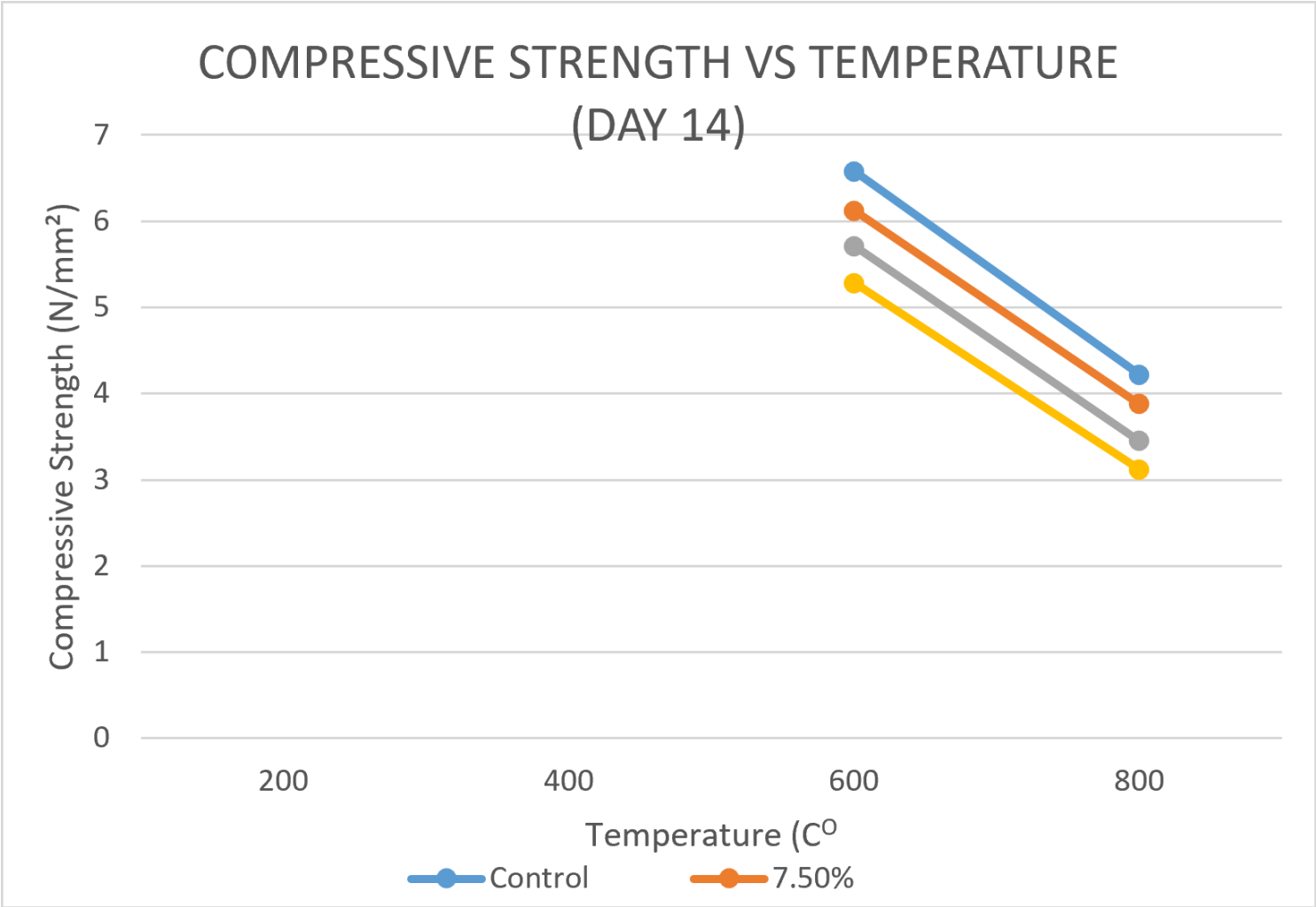


Figure 5

Compressive Strength vs. Temperature for all replacement levels

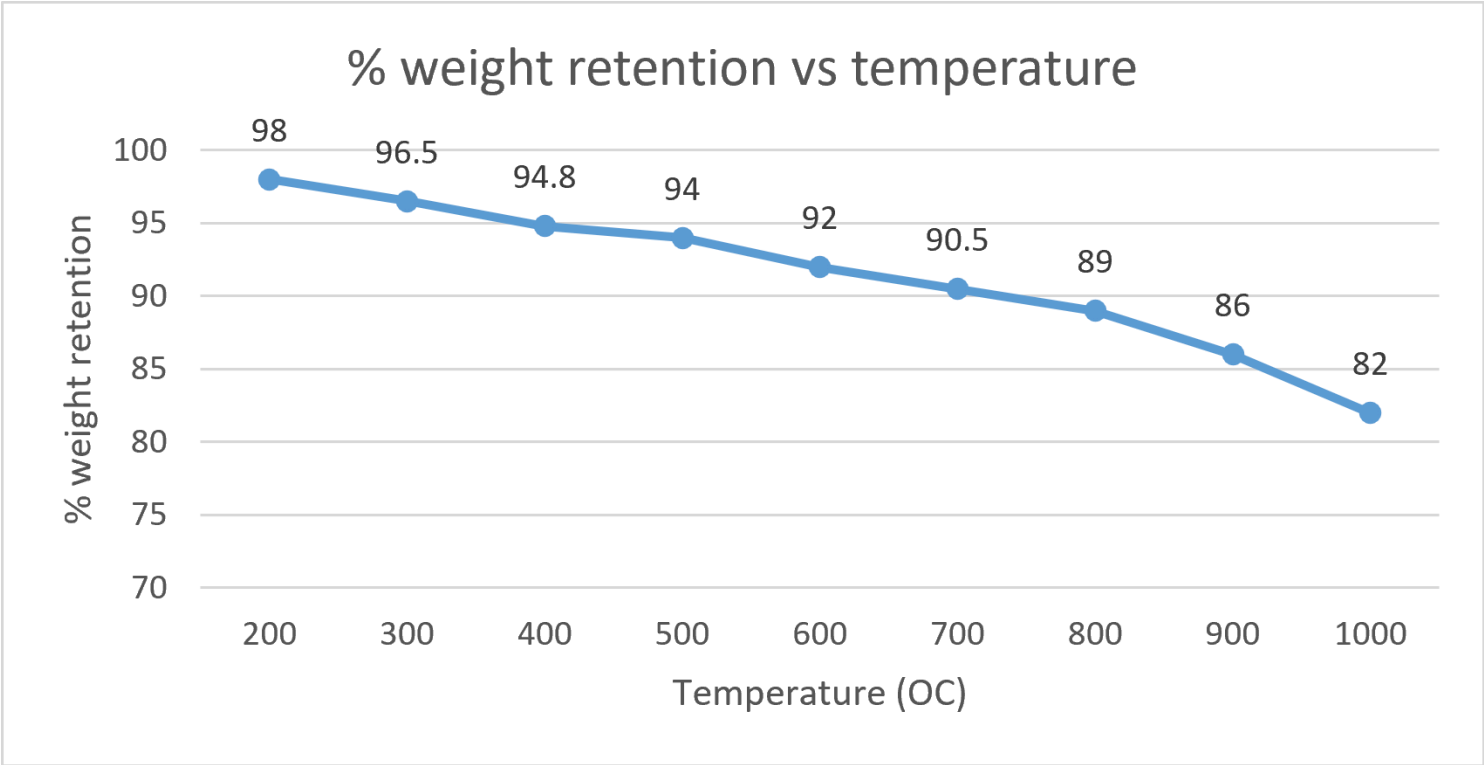


Figure 6

Weight Retention vs Temperature for concrete samples at various replacement levels.

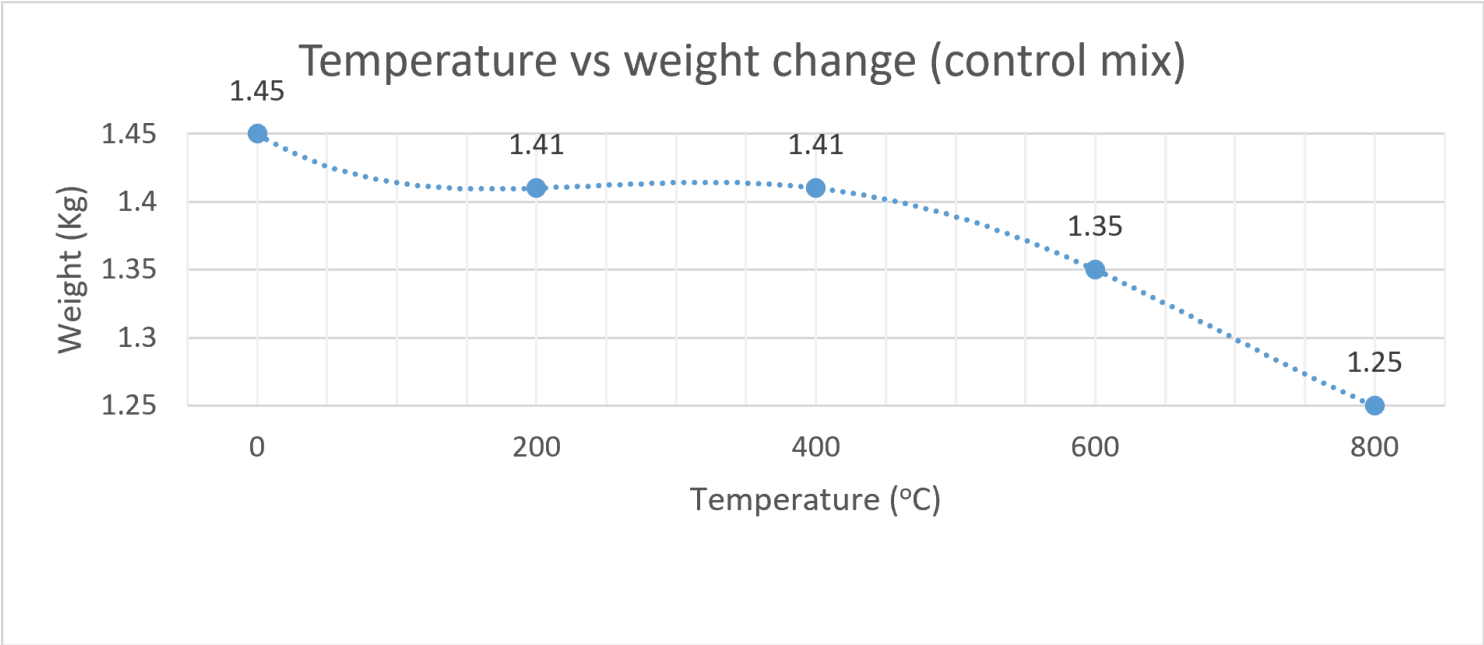


Figure 7

Temperature vs weight change (control mix)