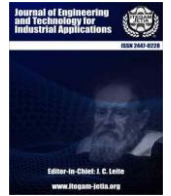




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SUSTAINABLE SELF-COMPACTING CONCRETE: INVESTIGATING THE SIZE EFFECTS OF COAL BOTTOM ASH AS A LIGHTWEIGHT AGGREGATE

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ABSTRACT

The mining and processing of coal generate significant waste, often disposed of in landfills, with coal slag heaps in southwestern Algeria forming artificial mountainous structures. This study investigates the potential of reusing coal bottom ash (CBA) as a lightweight aggregate in self-compacting concrete (SCC), fully replacing natural fine and coarse aggregates. The research focuses on the effect of CBA aggregate size on the fresh and hardened properties of SCC. Experimental results show that replacing natural coarse aggregate (NCA) with coarse CBA (CCBA) enhanced self-compactability, while fine CBA (FCBA) reduced workability. The use of CBA resulted in lower dry densities (1920.6–2134 kg/m³), qualifying the mixtures as lightweight SCC according to EN 206-1 standards. Although compressive and flexural strength decreased and porosity increased due to the lightweight and porous nature of CBA, strength values met ACI standards for structural applications. Microstructural examination indicated a rise in porosity within the concrete matrix; however, a limited formation of supplementary calcium-silicate-hydrate (C-S-H) gel was observed, which contributed to partially offsetting the reduction in mechanical strength. This study demonstrates the viability of CBA, particularly as a coarse aggregate, for producing lightweight SCC, offering a sustainable solution for recycling industrial waste and developing eco-friendly construction materials with acceptable structural properties.



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I. INTRODUCTION

The growing demand for construction materials has intensified pressure on natural resources, highlighting the urgent need for alternative materials and technologies. Conventional construction practices are increasingly unsustainable due to resource depletion and environmental impacts. Consequently, the development and adoption of innovative, resource-efficient alternatives have become essential to ensure the long-term sustainability of the construction industry [1]. The Bechar region in southwestern Algeria has a significant history of coal mining, beginning in 1918 at Kenadsa. Mining operations transitioned from open-cast to underground methods, reaching depths of 600 meters. Production peaked between 1942 and 1960, but the discovery of oil and gas reserves in the 1950s led to a decline in coal mining, with operations ceasing entirely by 1975. This left behind approximately 3.7 million cubic meters of coal waste in the form of slag heaps, covering 167.71 hectares and posing environmental and health risks due to toxic emissions [2].

Coal Bottom Ash (CBA), a byproduct of coal combustion, has been studied as a sustainable alternative in concrete production. While its use as a fine aggregate replacement often reduces workability and strength, it exhibits pozzolanic properties that enhance long-term performance [3-5].

The substitution of sand with coal bottom ash (CBA) often leads to a decline in workability, density, and strength. However, furnace bottom ash (FBA) has demonstrated comparable performance when used as a complete replacement for fine aggregate [3-5]. According to [3] found that replacing 10-25% of fine aggregate with CBA led to an increase in compressive strength. This improvement can be attributed to CBA's pozzolanic properties, which align with ASTM Class F classification, enabling strength development over time [6]. In [4] reported enhanced flexural and tensile resistance in mixtures containing 75% bottom ash and 20% fly ash, particularly after extended curing periods. While initial strength reductions were observed due to the slow pozzolanic reaction, these were counterbalanced by substantial gains in later stages. According to [5] noted that the use of coarse bottom ash resulted in a slight reduction in slump flow, whereas fine bottom ash showed no significant effect. Despite its potential, the majority of research has concentrated on CBA as a fine aggregate, with limited exploration of its application as a lightweight coarse aggregate in self-compacting concrete [7-10]. Lightweight self-compacting concrete (LWSCC) combines the benefits of lightweight aggregates (LWAs) and SCC, offering reduced density, improved insulation, and enhanced flow properties without vibration [11].

Research has explored various lightweight aggregates (LWAs), natural, industrial and agriculture waste, such as pumice, expanded clay, expanded polystyrene (EPS), crushed olive kernel (COK) shells, oil palm shells (OPS), walnut shells (WS), and sintered fly ash aggregates (SFAA), to enhance the properties of self-compacting lightweight concrete (SCLC). Studies show that LWAs reduce density and improve thermal insulation but often lower compressive strength and increase water absorption. For instance, pumice and EPS improve thermal performance and reduce structural weight, while COK and OPS offer sustainable alternatives with acceptable strength. Fly ash and supplementary materials like silica fume (SF) and metakaolin (MK) enhance mechanical properties and workability. However, challenges such as segregation, reduced workability, and durability issues remain. Overall, LWAs show promise for sustainable, lightweight concrete applications, though further research is needed to optimize their performance [12-16]. These advancements highlight the potential of LWSCC as an eco-friendly construction material. This study investigates the use of CBA as a lightweight coarse and fine aggregate replacement in LWSCC, aiming to address environmental challenges posed by coal waste while promoting sustainable construction practices. Present work focuses mainly to evaluate the effect of CBA aggregate size on the rheological and mechanical behavior of SCC. By integrating CBA into SCC, the research seeks to optimize material performance, reduce natural resource consumption, and provide a viable solution for managing industrial waste. The findings contribute to the development of sustainable concrete production, offering insights into the mechanical and durability properties of CBA-based LWSCC.

II. MATERIALS AND METHODS

II.1 MATERIALS

II.1.1 Cement

Ordinary Portland Cement (CEM I 42.5) supplied by GICA MOUDHAD from its manufacturing plant in Bechar, southwestern Algeria, was used in the experimental investigation. The cement satisfies the provisions of the Algerian standard NA 442 and the European standard EN 197-1. The chemical composition of the used cement is reported in Table 1.

II.1.2 Coal Bottom Ash

The coal bottom ash (CBA) investigated in this study was obtained as a by-product from an obsolete thermal power station in Algeria. Following manual fragmentation, it was further processed using a jaw crusher and sieved into coarse (3/8 mm and 8/15 mm) and fine (0/3 mm) fractions as depicted in Figure 1. Scanning electron microscopy (SEM) analysis revealed its irregular morphology, high porosity, and rough surface texture. Energy-dispersive spectroscopy (EDS) confirmed its silica-alumina composition, with oxygen, aluminum, and silicon as the predominant elements (Figure 2).

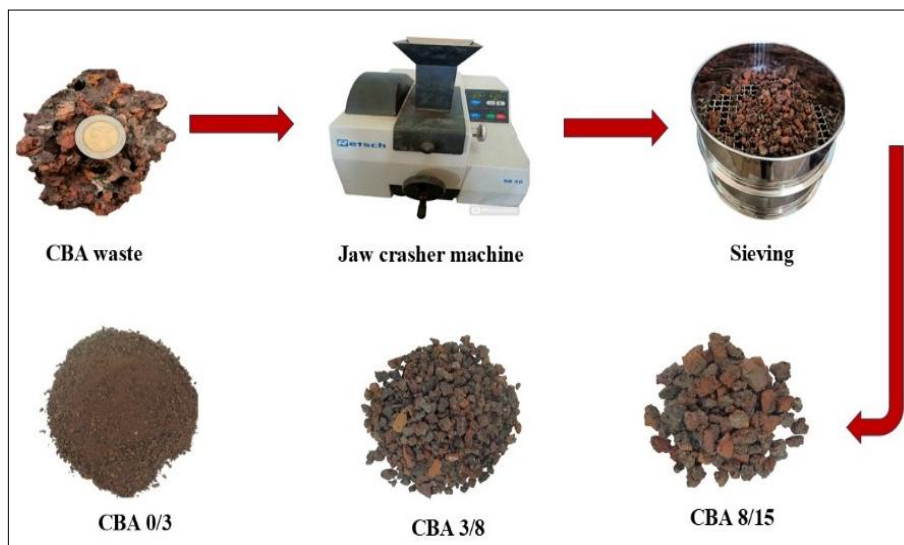


Figure 1: CBA aggregate processing.
Source: Authors, (2026).

The chemical composition of the coal bottom ash (CBA) was characterized by X-ray fluorescence (XRF) analysis. The results indicate that silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and iron oxide (Fe₂O₃) are the dominant constituents, representing 83.47% of the total oxide content. The remaining fraction consists of minor quantities of sulfates, calcium oxide, magnesium oxide, and other trace elements. In accordance with the requirements of ASTM C618, this chemical composition classifies the CBA as a Class F pozzolanic material. The detailed oxide composition of the CBA is presented in Table 1. In addition, the physical properties of the aggregates employed in this study are presented in Table 2, while their particle size distribution curves are shown in Figure 3.

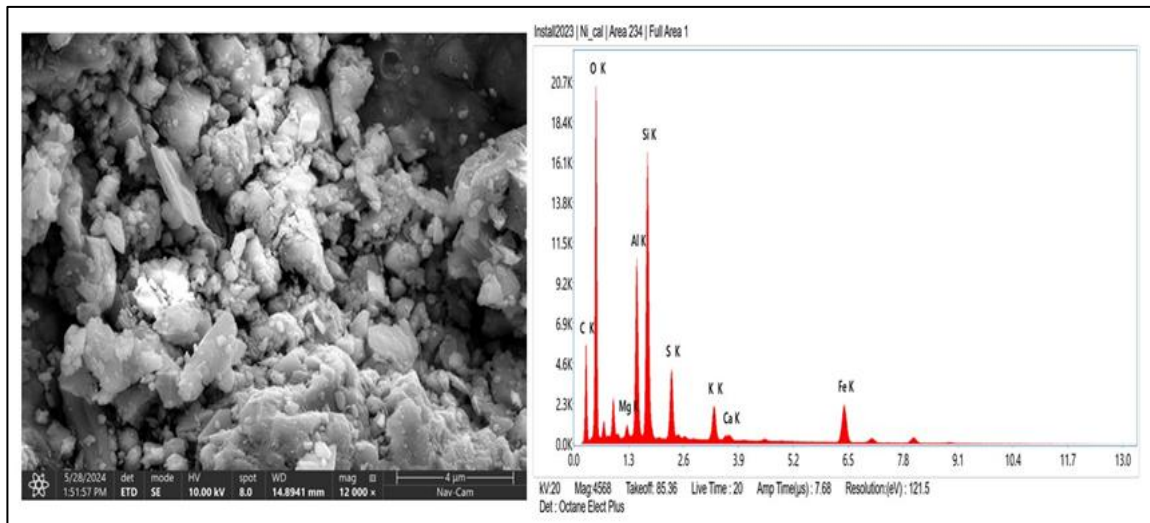


Figure 2: CBA SEM / EDS analysis.
Source: Authors, (2026).

Table 1: Chemical composition of CBA and cement.

Composition (%)	CBA	Cement
SiO ₂	44.78	18.91
Al ₂ O ₃	15.79	4.30
Fe ₂ O ₃	22.90	4.74
CaO	2.47	60.33
MgO	1.43	3.82
SO ₃	4.37	2.29
K ₂ O	2.38	0.84
LOI	1.2	<0.5

Source: Authors, (2026).

II.1.3 Natural Aggregate

The natural fine aggregate (NFA) used in this investigation was river sand collected from the Bechar region of Algeria, with a maximum particle size of 3 mm. The natural coarse aggregate (qNCA) consisted of crushed limestone with nominal size ranges of 3/8 and 8/15, sourced from a local quarry in Bechar, Algeria. The physical characteristics of the used aggregates are summarized in Table .2, and their particle size distribution curves are illustrated in Figure 3.

Table 2: Aggregate physical properties.

Properties	0/3 NFA	0/3 FCBA	3/8 NCA	3/8 CCBA	8/15 NCA	8/15 CCBA
Bulk density (g/cm ³) [NF P18-555]	1.6	0.99	1.39	0.70	1.40	0.66
Absolute density (g/cm ³) [NF P18-555]	2.5	2.35	2.66	1.93	2.67	1.81
Fineness modulus [NFP 18-540]	2.53	2.76	/	/	/	/
Water absorption (%) [NF EN 1097-6]	1.62	5.42	0.85	7	0.95	8

Source: Authors, (2026).

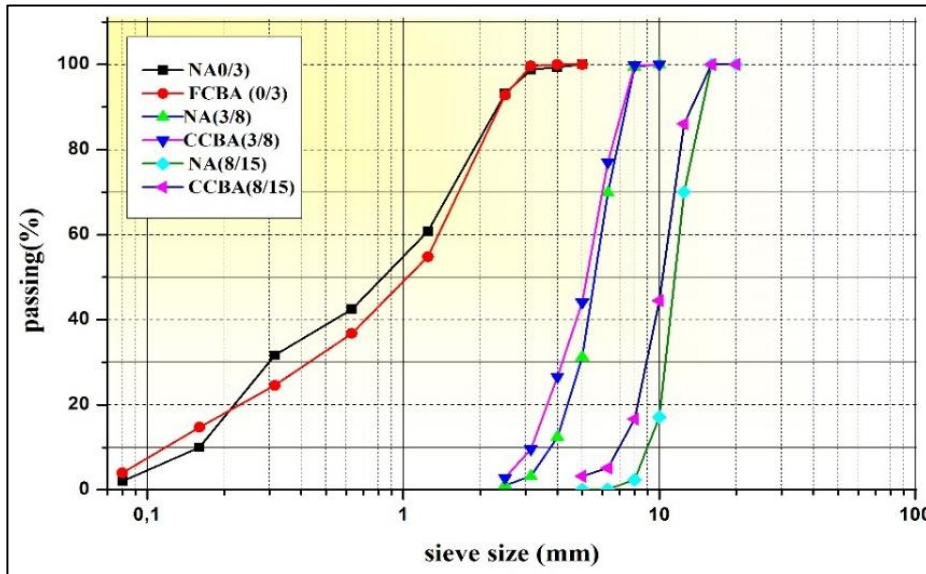


Figure 3: Aggregates particle size curves.
Source: Authors, (2026).

II.1.4 Superplasticizer and Mixing Water

To obtain adequate workability, a high-range water-reducing admixture (superplasticizer), commercially designated as MAX SUPERFLOW S180 and manufactured by the Algerian company Technachem, was used in conformity with the requirements of NF EN 934-2. The mixing water consisted of potable water meeting the quality criteria specified in NF EN 1008. This water, treated in accordance with drinking water standards, was supplied directly from the laboratory distribution system.

II.2 MIX PROPORTIONS

Three self-compacting concrete (SCC) mixtures were prepared following AFGC guidelines [17], maintaining a constant water-to-binder ratio of 0.48 and a superplasticizer dosage of 2% by binder weight (Table 3). The reference mix (RSCC) used natural aggregates, while two additional mixes assessed the impact of coal bottom ash (CBA) aggregate size. In FSCC, fine CBA (FCBA) replaced natural fine aggregate, whereas in CSCC, coarse CBA (CCBA) substituted natural coarse aggregate. Due to CCBA’s high water absorption, it was pre-soaked for 24 hours, then drained and weighed for precise batching. FCBA, with minimal absorption, was mixed with water to reach a saturated surface-dry (SSD) state and rested for 15 minutes before use [18].

Table 3: SCC mix composition.

Composition (kg/m3)	Cement	NFA	FCBA	NCA 3/8	CCBA 3/8	NCA 8/15	CCBA 8/15	Water	SP	W/C
RSCC	520	900	/	150	/	580	/	256	2%	0.48
FSCC	520	/	836	150	/	580	/	256	2%	0.48
CSCC	520	900	/	/	111.36	/	394.65	256	2%	0.48

Source: Authors, (2026).

II.3 EXPERIMENTAL PROCEDURES

To evaluate the influence of coal bottom ash (CBA) aggregate size on the properties of self-compacting concrete (SCC), a series of tests were conducted on both fresh and hardened concrete as shown In Figure 4. For fresh concrete, assessments included slump flow, L-box, sieve segregation, and fresh unit weight measurements. Specimens were cast using standardized steel molds in various geometries, including prismatic (7 × 7 × 28 cm) and cubic (10 × 10 × 10 cm) forms, to facilitate testing of dry density, porosity, compressive strength, and flexural strength. Furthermore, microstructural analysis was performed using scanning electron microscopy (SEM) coupled with energy-dispersive spectroscopy (EDS) to examine the internal structure and elemental composition of the SCC mixtures, as detailed in Table 4.

Table 4: Tests conducted.

Tests		Standards
Workability	Slump flow	AFGC, 2008
	L-box	AFGC, 2008
	Sieve stability	AFGC, 2008
Physical tests	Dry density	EN 12390-7
	Porosity	AFREM, 1997
Mechanical strength	Compressive strength	EN 12390-1
	Flexural strength	EN 12390-5

Source: Authors, (2026).



Figure 4: Different tests conducted on fresh and hardened state.

Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS

III.1 SCC FRESH STATE RESULTS

The results from fresh concrete tests, as presented in Table 5, reveal that the use of coal bottom ash (CBA) as a fine aggregate in the FSCC mixture slightly reduced workability, with a slump flow diameter of 68 cm compared to 72.7 cm for the reference mix. This decrease is attributed to the higher water absorption capacity and porous nature of CBA, which absorbs a portion of the mixing water. Conversely, when CBA was used as a coarse aggregate in the CSCC mixture, the slump flow diameter increased to 80 cm. This improvement is likely due to the pre-soaking of coarse CBA (CCBA) to achieve a saturated surface-dry (SSD) condition, which reduces water absorption during mixing and enhances workability. These findings align with previous studies by [7] and Raju et al. [10], highlighting the influence of CBA aggregate size and preparation methods on the workability of self-compacting concrete. The experimental results demonstrated that the passing ability of all mixtures ranged from 0.78 to 0.94. The FSCC mixture, incorporating fine CBA aggregates (FCBA), exhibited a blocking ratio below the 0.8 threshold set by the AFGC standard [19], indicating restricted flowability.

In contrast, the CSCC mixture, which utilized coarse CBA aggregates (CCBA), met the required range, showcasing improved flow performance. This discrepancy is attributed to reduced inter-particle friction in mixtures with larger aggregates, enhancing flowability. Specifically, FSCC mixture tend to experience higher friction, limiting flow, while CSCC mixture exhibit better flow characteristics, enabling smoother movement through the formwork [13],[19]. These findings highlight the influence of aggregate size and type on the flow properties of self-compacting concrete. The segregation resistance tests presented in Table 5 indicate that replacing natural aggregates with coal bottom ash (CBA) reduces the segregation ratio compared to the control mix. All mixtures remained stable, with sieve stability values between 6.44% and 9.24%, well below the 15% limit set by AFGC standards [20]. The use of CBA, whether as fine or coarse aggregate, significantly improved segregation resistance by lowering plastic viscosity, which slows coarse particle settling and enhances stability. These findings align with previous studies, emphasizing the benefits of lightweight aggregates in maintaining SCC uniformity and performance in its fresh state [10].

Table 5: SCC fresh state results.

Mix	Slump-flow(cm)	L- box (H2/H1)	Sieve Stability(%)
Limit values	550-850 mm	≥ 0.8	≤ 15 %
RSCC	72.7	0,94	9.24
FSCC	68	0,78	6.44
	80	0,90	8.5

Source: Authors, (2026).

III.2 SCC HARDENED STATE RESULTS

III.2.1 Compressive Strength Results

The compressive strength results, presented in Figure 5, indicate a progressive increase in strength with curing time, reaching peak values at 90 days. The reference SCC (RSCC) exhibited the highest strength, measuring 56.1 MPa at 90 days. Substituting river sand with fine coal bottom ash (FCBA) in the FSCC mix led to a strength reduction of approximately 33%, while the incorporation of coarse CBA (CCBA) in the CSCC mix resulted in a comparatively lower decrease of about 16% relative to RSCC at 90 days. The FSCC mixture exhibited significantly lower compressive strength, barely meeting the minimum threshold of 17.2 MPa specified by ACI Committee for structural applications. This reduction is primarily attributed to the increased porosity of the concrete matrix caused by CBA inclusion. These findings are consistent with previous research, which has demonstrated that higher FCBA replacement levels adversely affect compressive strength [3-5],[20].

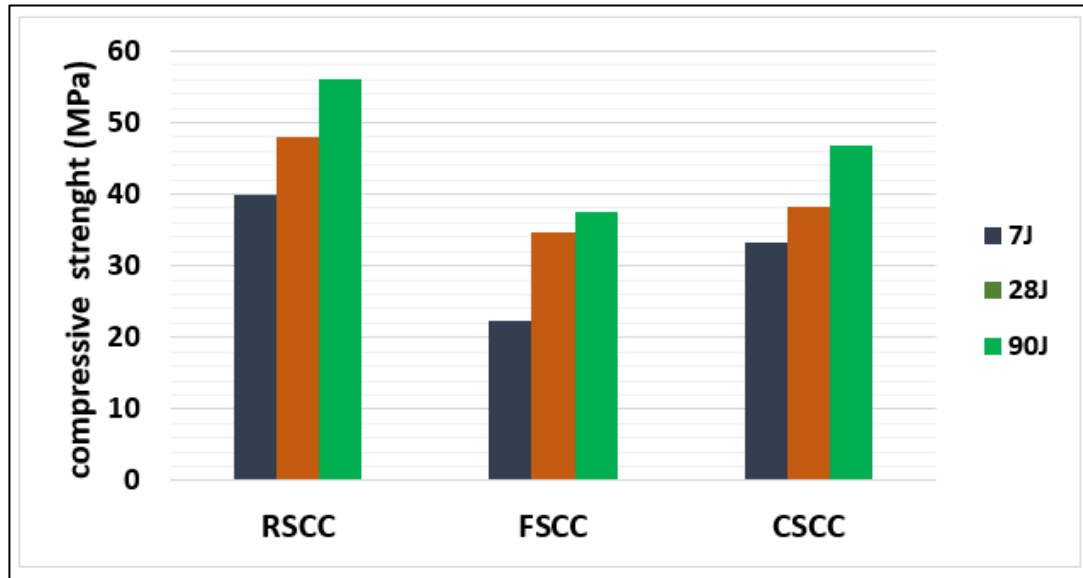


Figure 5: Compressive strength for SCC mixes.
Source: Authors, (2026).

III.2.2 Flexural Strength Results

The flexural strength results for all mixtures at 7, 28, and 90 days of curing are illustrated in Figure 6. The incorporation of coal bottom ash (CBA) as an aggregate replacement influenced the flexural performance of self-compacting concrete (SCC). Due to the lower strength and density of CBA aggregates, the mixtures in which fine CBA (FCBA) fully replaced natural sand exhibited reductions in flexural strength of 19% compared to the reference mix (RSCC). Similarly, replacing natural coarse aggregate with coarse CBA (CCBA) in the CSCC mix resulted in a 10% decrease in flexural strength at 90 days. The extent of strength reduction was found to be less pronounced when larger CBA particles were used, likely due to improved load transfer and mechanical interlocking between aggregates. In contrast, higher replacement levels with finer CBA particles led to weaker aggregate bonding and a more porous matrix, which negatively affected flexural performance. These findings align with previous research [20],[21].

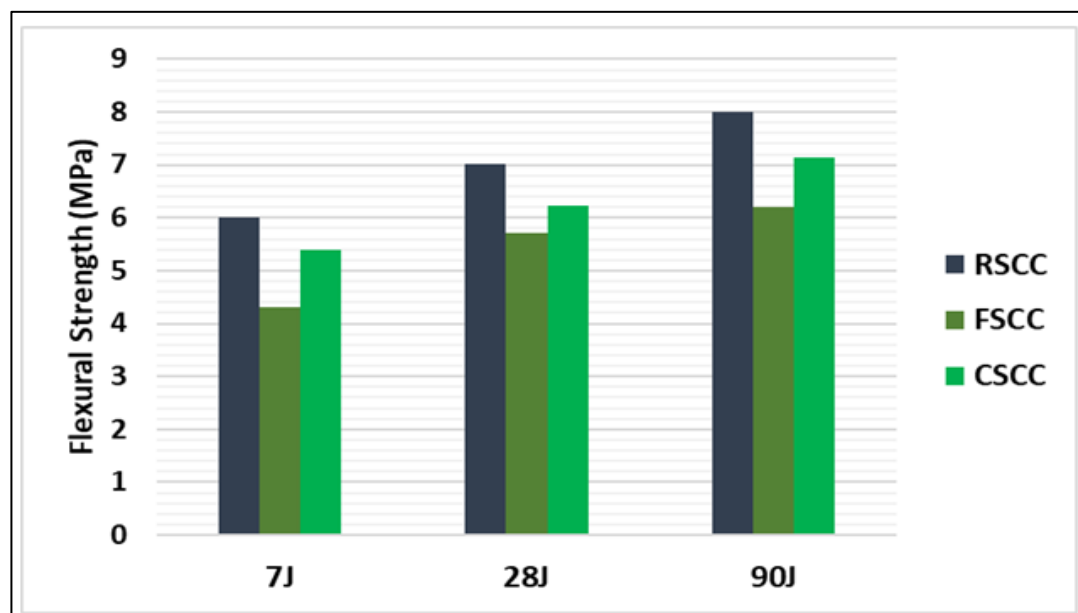


Figure 6: Flexural strength for SCC mixes.
Source: Authors, (2026).

III.2.3 Oven Dry Density Results

The oven-dry density results for all mixtures, as shown in Figure 7, indicate a clear reduction in density with the incorporation of coal bottom ash (CBA). Notably, mixtures with a dry density below 2000 kg/m³ met the lower limit for lightweight concrete (LWC) production, as specified by EN 206-1 standards, classifying them as lightweight self-compacting concrete. This decrease in density is primarily attributed to the lower intrinsic density of CBA compared to conventional aggregates. The recorded dry density values ranged from 1920.6 to 2133.96 kg/m³, with mixtures incorporating coarse CBA (CCBA) exhibiting lower densities than those containing fine CBA (FCBA). This variation is likely due to the larger particle size of CCBA, which affects the overall compactness and distribution of aggregates within the concrete matrix. [22].

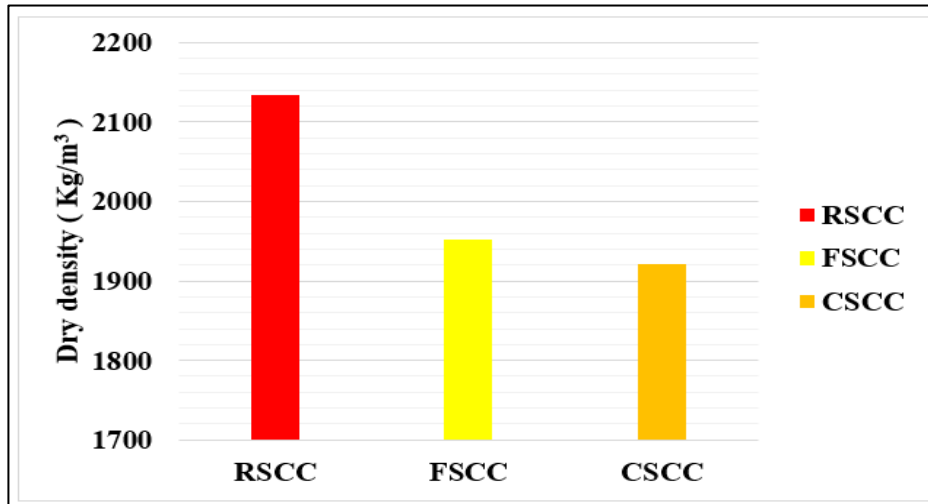


Figure 7: Oven dry density for SCC mixes.
Source: Authors, (2026).

III.2.4 Porosity Results

As shown in Figure 8, the incorporation of coal bottom ash (CBA) aggregates led to a noticeable increase in the porosity of both FSCC and CSCC mixtures when compared with the reference concrete. Specifically, mixtures containing fine CBA (FSCC) and coarse CBA (CSCC) exhibited increases in porosity of approximately 42% and 19%, respectively. This behavior is primarily attributed to the inherently porous microstructure and higher water absorption capacity of CBA aggregates relative to natural aggregates, with the magnitude of the effect being strongly influenced by particle size. Fine CBA (FCBA), owing to its larger specific surface area and more open pore network, tends to absorb greater amounts of mixing water, resulting in insufficient paste availability to effectively fill internal voids and interparticle spaces [6]. Consequently, this leads to a more porous hardened matrix. In contrast, the use of coarse CBA (CCBA) in a saturated surface-dry (SSD) condition limited additional water uptake during mixing, thereby preserving the effective water-to-binder ratio and promoting improved particle packing. This condition contributed to a comparatively lower porosity in CSCC mixtures than in FSCC mixtures. [23]

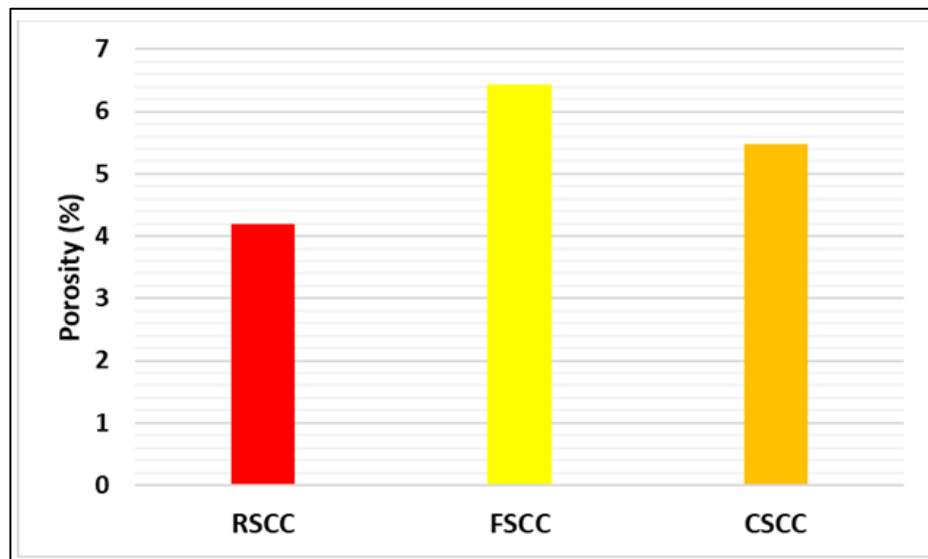


Figure 8: Porosity for SCC mixes.
Source: Authors, (2026).

III.2.5 SCC Microstructure Analysis

The SEM observations (Figures 9–11) demonstrate that the substitution of natural aggregates with coal bottom ash (CBA) significantly modifies the microstructural features of self-compacting concrete (SCC). The reference mix (RSCC) is characterized by a dense and homogeneous matrix with well-developed C–S–H gel and limited visible voids or microcracks (Figure 9). In contrast, concretes incorporating CBA exhibit a more heterogeneous microstructure, marked by increased pore volume, microcracking, and a less compact cementitious matrix (Figures 10 and 11). This effect is more pronounced when fine aggregates are replaced by fine CBA (FSCC), owing to its higher surface area and porous nature, which promote greater water absorption and hinder optimal paste densification. These microstructural deficiencies are consistent with the observed increase in porosity and the reduction in compressive strength [3],[24]. EDX analysis confirms the dominance of calcium (Ca), silicon (Si), and oxygen (O) in all mixtures, reflecting the typical composition of hydrated cement phases. The detection of aluminum (Al) and magnesium (Mg) indicates the contribution of supplementary cementitious phases associated with the presence of CBA. Mixtures containing CBA, particularly FSCC and CSCC, display enhanced silicon peaks in the EDX spectra (Figures 10 and 11), pointing to a silica-rich composition that may promote secondary pozzolanic reactions at later ages.

Additionally, the presence of trace elements such as iron (Fe) and molybdenum (Mo) can be attributed to the mineralogical composition of the ash or residual impurities inherited from the coal combustion process, in agreement with the findings of Moreno et al. [25]. The carbon (C) peaks observed in certain samples are likely associated with unburned carbon residues or carbonate phases, which may influence hydration kinetics and contribute to the observed microstructural heterogeneity. Overall, the combined SEM–EDX results provide clear evidence that the incorporation of CBA affects both the physical and chemical characteristics of SCC, with direct implications for its durability and mechanical performance.

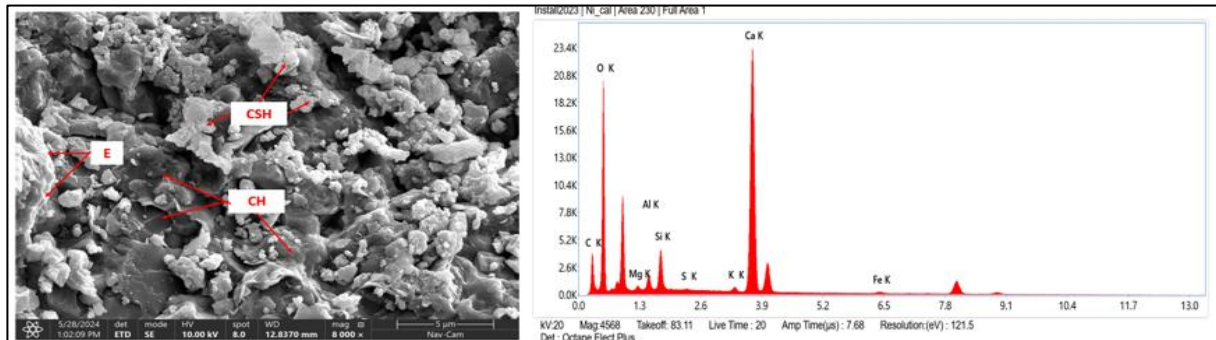


Figure 9: RSCC SEM / EDS analysis.
Source: Authors, (2026).

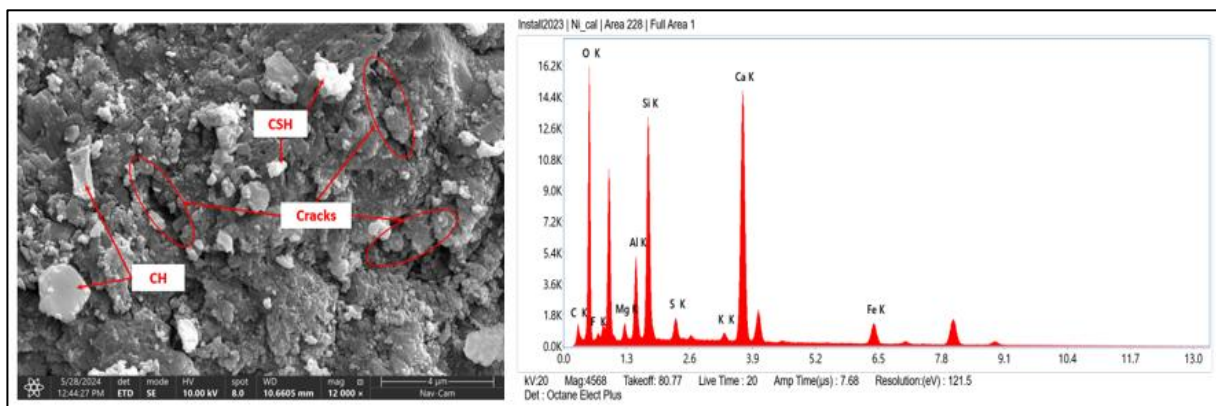


Figure 10: FSCC SEM / EDS analysis.
Source: Authors, (2026).

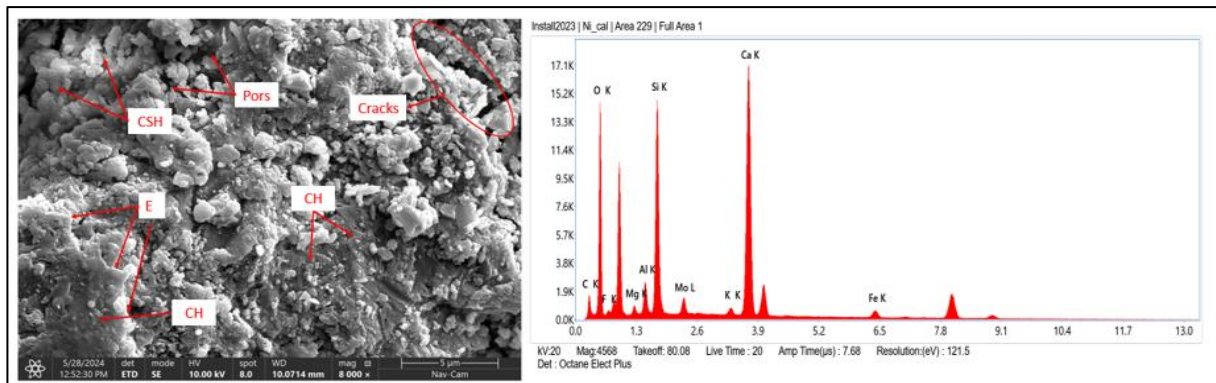


Figure 11: CSCC SEM / EDS analysis.
Source: Authors, (2026).

IV. CONCLUSIONS

This study demonstrates that incorporating coal bottom ash (CBA) as a replacement for natural aggregates in self-compacting concrete (SCC) significantly impacts its fresh, mechanical, and microstructural properties. While fine CBA (FCBA) reduced workability due to its porous nature, pre-soaked coarse CBA (CCBA) improved flowability. All CBA-based mixtures exhibited stable segregation resistance, with sieve stability values below the 15% limit. The mechanical performance of SCC declined with CBA incorporation, with compressive strength reductions of 33% in FSCC and 16% in CSCC compared to the reference SCC. Flexural strength also decreased, primarily due to increased porosity and weaker aggregate bonding. However, the resulting oven-dry density (1920.6–2133.96 kg/m³) classified these mixtures as lightweight self-compacting concrete (LWSCC) according to EN 206-1. Microstructural analysis confirmed increased porosity and crack formation, particularly in FSCC, but also highlighted a silica-rich composition and additional C-S-H gel formation, partially mitigating strength loss.

Despite reduced mechanical properties, CBA-based SCC presents a viable and sustainable alternative for lightweight concrete production, contributing to industrial waste recycling and eco-friendly construction. Future research should focus on optimizing CBA aggregate preparation and replacement ratios to enhance performance while maintaining sustainability.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Boulahya Ibtissam, Makani Abdelkadir, Tafraoui Ahmed.
Methodology: Makani Abdelkadir, Tafraoui Ahmed.
Investigation: Boulahya Ibtissam.
Discussion of results: Boulahya Ibtissam and Makani Abdelkadir.
Writing – Original Draft: Boulahya Ibtissam.
Writing – Review and Editing: Boulahya Ibtissam.
Resources: Boulahya Ibtissam.
Supervision: Makani Abdelkadir, Tafraoui Ahmed.
Approval of the final text: Boulahya Ibtissam, Makani Abdelkadir, Tafraoui Ahmed.

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